making communications work
for everyone

Award of the 700 MHz and 3.6-3.8 GHz spectrum bands

Annexes 5-18 – supporting information

Contents

Annex

N.B In some places in this document we draw on commercially sensitive evidence supplied to us in confidence. This evidence is redacted in the published version of this document. Where we have redacted passages of text or illustrations it is indicated by [✂ REDACTED].

A5. Alternatives to a UK wide award

A5.1 This annex addresses alternatives to awarding licences on a UK wide basis, including suggestions submitted in reponse to our March consultation on mobile coverage.

A5.2 Our proposal to award the 700 MHz and 3.6-3.8 GHz spectrum bands through an auction of UK-wide licences is based on a recognition that these bands are particularly suitable for mobile broadband use, for which we expect there to be national demand.

A5.3 Some stakeholders have suggested awarding the spectrum in alternative ways – such as through local or regional licences – to enable different uses of the frequencies.

A5.4 Alongside this publication, we have also published our proposals to support opportunities for innovation by enabling shared access to spectrum bands supporting mobile technology. We propose to enable shared access to three bands supported by mobile technology (these are the 3.8-4.2 GHz, 1781.7-1785 MHz paired with 1876.7-1880 MHz ("1800 MHz shared spectrum) and 2390-2400 MHz("2300 MHz shared spectrum")). We also set out our proposals for new users to access awarded mobile spectrum in locations where we agree this does not impact upon the incumbent licensee.

A5.5 In summary, we consider that alternative uses for mobile spectrum could be supported by using spectrum bands identified for shared access and/or proposed mechanisms to facilitate access to all mobile spectrum. We believe these approaches have a much lower opportunity cost than making the 700 MHz and 3.6-3.8 GHz spectrum available in a different way.

A5.6 In this annex, we set out an assessment of some of those other potential uses and our proposals to facilitate these uses through alternative spectrum access solutions. Our assessment in this annex is set out as follows:

- We outline the interest some potential providers have in alternative uses of the spectrum, particularly the 3.6-3.8 GHz spectrum band;
- We explain the difficulties that providers with localised demand for spectrum have in bidding for national licences;
- We discuss the complexity of an auction with local or regional licences;
- We explain the opportunity cost of reserving spectrum for local or regional use; and
- We discuss proposals to facilitate access to other spectrum bands for sharing including 3.8-4.2 GHz, 2.3 GHz shared spectrum and the 1800 MHz shared spectrum. We also set out proposed mechanisms to improve access to all mobile spectrum for alternative uses.

Alternative uses and interest in 3.6-3.8 GHz spectrum

A5.7 Some stakeholders have suggested that we should use this auction to facilitate spectrum access for providers of innovative alternative services. In particular, the following alternative uses have been suggested:

- **mobile coverage improvement schemes**: to provide localised mobile coverage, whether indoor (e.g. shopping centres) or outdoor, in areas without good existing coverage from mobile operators;
- **rural fixed wireless access**: to provide broadband connections in rural areas using wireless consumer equipment; and
- **private industrial networks**: to enable the use of 5G band chipsets to increase the use of automation or robotics for factories.

Mobile coverage improvements schemes

A5.8 These schemes would allow any provider (e.g. through a joint venture between an MNO and a third party) to deploy a new network in areas that are currently complete mobile 'not spots' without good coverage from any mobile operator (and, potentially, in partial 'not spots' where only some mobile operators have good coverage). The provider then allows access to customers of all mobile operators. The new network may be deployed to give consumers better indoor coverage, for example.

A5.9 In these circumstances the solution would work to complement an existing service provided by an operator. Using this model, the provider operates a Radio Access Network (RAN) sharing spectrum with the MNOs through a set of Multi Operator Core Network (MOCN) standards. A provider could alternatively operate roaming agreements with operators to provide a service.

A5.10 Due to the nature of the service they provide (i.e. the end user is a consumer using a regular mobile handset), mobile coverage improvement scheme providers are restricted to spectrum already supported by mobile handsets. Providers are therefore seeking access to spectrum in the 3.6-3.8 GHz band, since it has been identified as a leading band for 5G and is therefore likely to be supported by mobile handsets in future[1].

Rural Fixed Wireless Access

A5.11 Fixed Wireless Access (FWA) systems are a means of making fixed connections between users' premises and telecommunications networks. By connecting to the premises wirelessly they can deliver a range of electronic traffic solutions, including high speed data which enables access to broadband.

---

[1] See Annex 8 Mobile Spectrum Bands "we believe that devices supporting the whole 3.4-3.8 GHz band for 5G will start to be available between 2019 and 2020"

A5.12 A report published by Plum Consulting on High Performance Wireless Broadband claims that FWA systems can bypass many of the issues of cost and complexity associated with delivering broadband, particularly in rural areas.[2]

A5.13 The report also says that modern FWA solutions could be key to delivering the Broadband Universal Service Obligation (USO), providing a higher quality service at lower cost than fixed fibre.[3] On 5 December 2018 we published a consultation on designating a USO provider.[4]

A5.14 We consider that fixed wireless and mobile network wireless technologies, currently operating between two or more fixed points, can meet the specification in the USO order. However, the bandwidth offered by an individual mast may be limited by the amount of spectrum available and because this bandwidth is typically shared by several users. This could either cause the speed of connections to drop in busy periods (leading to poorer quality of experience as the number of customers or committed data rate increases) or require more masts to be built (with cost implications).

A5.15 There are a variety of solutions based on the wireless broadband model. These include both a) fixed/mobile approach, which uses 4G LTE mobile networks with a local Wi-Fi connection to deliver a services and b) satellite solutions. Both services are currently available in the UK market. Providers of FWA already operate in the UK using mainly (licence exempt) 5.4 GHz and (light-licensed) 5.8 GHz bands and have built up their businesses on this basis.[5]

A5.16 While there may be some issues with reliability, developments in fixed wireless services, in particular fixed wireless provided using mobile technology, could potentially improve the role providers play in delivering decent and affordable broadband under the USO. Ofcom is keeping these developments under review.

A5.17 Although there are some larger operators in the market with interests across several regions, we understand the market is largely made up of small providers who serve local communities. Operators range from those who service around 300,000 premises to those who service eight premises with the desire to scale up to 30 premises. These are not services currently operating on a basis of national availability.

A5.18 The Plum Report says that using the 3.6-3.8 GHz band would be preferable to existing 5.4 GHz and 5.8 GHz because the propagation characteristics of the 3.6-3.8 GHz band would allow them to cover a wider rural area with fewer base stations, thereby saving costs.

---

[2] http://plumconsulting.co.uk/high-performance-wireless-broadband-opportunity-rural-enterprise-5g/.

[3] In March 2018 the Government introduced a broadband Universal Service Obligation (USO) providing a legal right to request a broadband connection capable of delivering at least 10 Mbps download speeds and 1 Mbps upload speeds. Ofcom are in the process of deciding which provider(s) to designate as Universal Service Providers to deliver the USO. We plan to consult on proposals for who should be designated by the end of 2018. It will be the responsibility of each Universal Service Provider to decide what technology to use to deliver USO connections, but whatever technology they use must meet the technical specifications of the USO.

[4] https://www.ofcom.org.uk/__data/assets/pdf_file/0024/129408/Consultation-Delivering-the-Broadband-Universal-Service.pdf

[5] UK Broadband before being purchased by H3G used 3.4 GHz - 3.6 GHz to provide an LTE based FWA (Relish)

A5.19 FWA potentially encounters more issues with interference than fibre, which can mean it is less reliable and may struggle to reach the speeds that can be achieved by a fibre connection. The Plum Report argues that because of its improved physical radio propagation characteristics, lower frequency spectrum is better able to deal with interference than higher frequency spectrum. However, providers in the 5 GHz band have access to 125 MHz of contiguous spectrum, and if greater reach or capacity is required, additional 5.8 GHz sites could be used.

A5.20 The Plum Report highlights that there is a distinct preference for access to 3.6-3.8 GHz spectrum as opposed to other higher frequency bands because a mature device ecosystem already exists at 3.6 GHz, which saves on the cost of developing equipment that can operate in other mid-range bands. This solution is focused on rural areas, and the Plum Report suggests that regional licences would be necessary to allow area-based FWA services.

A5.21 In support of this approach, Plum suggests that MNOs are unlikely to deploy regular 3.6-3.8 GHz services in many rural areas, so spectrum awarded under a national licence would therefore go unused.

A5.22 However, it is our view that demand for new national services will drive MNO deployment in both urban and rural areas. We note that the maturity of existing infrastructure networks places MNOs in an ideal position to deploy across both urban and rural areas.

Private Industrial Networks

A5.23 Companies seeking to deploy private LTE or 5G networks to support connected factories have also expressed interest in the 3.6–3.8 GHz band. Private LTE networks already exist, both in the 5 GHz band and in potentially any other LTE band subject to agreement with relevant spectrum holders. However, the level of control over the quality of service (e.g. high reliability requirements) cannot be achieved using unlicensed spectrum, and secured spectrum is therefore seen as the ideal solution. The newly available 3.6-3.8 GHz frequencies could create the opportunity for faster and more efficient processing for automated factories. This solution is based on local access across a small area (within a factory or enclosed building).

The difficulties of providers with localised demand bidding for national licences

A5.24 The alternative uses discussed above generally aim to provide a service on a localised basis and require access to spectrum at a specific location rather than nationally. Some stakeholders have said that awarding national licences for spectrum restricts access to alternative providers with valuable innovative solutions to local network challenges.

A5.25 Ofcom supports new forms of innovation that may benefit consumers and we have in parallel set out our proposals to support localised deployment of e new services in the consultation Enabling Opportunities for Innovation[6]. However, given the expected importance of both the 3.6-3.8 GHz and the 700 MHz band for developing UK-wide services, we need to consider the impact that local or regional licensing might have on the efficient use of spectrum.

A5.26 Providers of solutions based on geographical or local deployment of spectrum face two key issues in an award of national licences. First, individual providers with localised spectrum demand are unlikely to be able to bid successfully against operators who value a national licence (or would pay a high price for a national licence relative to their expected revenues).

A5.27 Second, there could be barriers to a series of small providers with spectrum demand in different local areas successfully aggregating their demand. Establishing a consortium or single bidding vehicle before the auction might be possible but could be costly and complex to achieve.

A5.28 For example, providers potentially have varying demands for spectrum so that each provider may assess the value of the spectrum at different levels. This could complicate the terms of the consortium, such as the contributions each would make to pay the auction price for a national licence. Further, an individual provider might have incentives to 'free-ride' on other providers, such as those who are only willing to bid a small sum for spectrum seeking to benefit from those who are willing to pay more.

A5.29 A more viable option for local providers to access spectrum may be through agreement with a primary licence holder. Whilst this is possible within the trading framework for mobile spectrum, in practice these agreements work best in circumstances where large amounts of spectrum are required across wider areas rather than locally.

The challenges to adopting alternative approaches

A5.30 Given there is likely demand for 3.6-3.8 GHz spectrum from both new *national* mobile services (to be delivered by MNOs) and for alternative *local* solutions as described above, there are two main alternative approaches to that of proceeding with a UK-wide award for the 3.6–3.8 GHz spectrum. We could award licences on a geographical (regional or local) basis; or we could award most of the spectrum on a national basis but reserve some of the spectrum for innovative uses.

A5.31 There are two key challenges that apply to both approaches:

- They would introduce a level of complexity to the auction process which could create strong disincentives for bidders; and/or
- They could result in less spectrum being available for operators who have the capacity to deploy valuable UK-wide services.

A5.32 These challenges are discussed in turn below.

[6] https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation

Complexity of the auction

A5.33 We consider that the award should only include complexities that are justified to promote the achievement of our objectives. We also consider that it is important to avoid delays in making the spectrum available. We consider that having a local or regional licence award would be significantly more complicated than awarding national licences and could significantly delay the auction.

A5.34 Designing an auction that would divide spectrum up geographically would be complex to deliver. The first requirement would be to divide the country into separate areas, noting that some stakeholders might want very localised areas to be available in the auction. This could result in thousands of different areas across the UK. Alternatively, the UK could be divided into a handful of areas, but this is unlikely to help bidders that want only a small area licence.

A5.35 Once the specific areas have been defined, it would be possible to construct a single auction for all of these areas. This would require having specific lots for every separate area.

A5.36 Bidders with localised spectrum demand could bid for licences in the specific area(s) of interest to them. Bidders with more aggregated demand could bid for licences in all of the areas relevant to them, e.g. bidders with national demand could bid for licences in all areas.

A5.37 In an auction format with individual bids for different lots (such as in an SMRA format), bidders with aggregated demand would face a large increase in complexity. The larger the number of areas, the more onerous it would be for bidders with aggregated demand to value each individual area that they wished to acquire and submit an extremely high number of bids. Moreover, they are likely to face significant aggregation risk. They would be exposed to the risk that they might win licences in some areas but fail to win licences in other areas in circumstances where their value for a licence in a specific area is likely to depend on which other areas they acquire licences for.

A5.38 An auction format with package bidding (such as CCA) would avoid this aggregation risk. Bidders would submit bids for a package of lots, such as across all the areas they were interested in, and such bids would either win or lose in their entirety.

A5.39 However, the large number of areas would result in an extremely high number of combinations that could be won. This would increase the complexity of the package auction. With a very large number of areas, this complexity could become unmanageable.

A5.40 The complexities set out above could be reduced with a smaller number of regional licences. However, as stated above, it is unlikely that regional licences would address the needs of most of the stakeholders that would be interested in alternative uses, because many alternative uses require localised access.

A5.41 If a provider of an alternative use did secure a regional licence, only to deploy locally, spectrum that could be used for mobile services could go unused in large areas of the region. There would therefore be a risk of compounding the problems: areas that are too aggregated to meet the needs of providers of alternative uses, but also sufficiently disaggregated to create complexities for bidders with national demand.

Limiting the spectrum available for mobile broadband

A5.42 Some stakeholders have suggested that reserving a portion of spectrum for alternative uses would mitigate some of the challenges posed by auctioning regional or localised licences for all the spectrum. The amount that would be required varies depending on the use case but suggestions range between 10 and 40 MHz[7]. However, such an approach would result in less spectrum being available for operators who have the capacity to deploy it nationally.

A5.43 We assess the opportunity costs of national licences to be high. While there is clear and well documented demand for mobile broadband, which is expected to grow, the level of demand for alternative uses is subject to more uncertainty.

A5.44 We expect high demand from MNOs for all the available 3.4-3.8 GHz spectrum given the capacity and speed benefits of additional spectrum. Equally, it is generally acknowledged that large contiguous bandwidths are desirable for the delivery of high throughput and certain low latency 5G services and to maximise spectral efficiency.

A5.45 Many industry stakeholders, including manufacturers and operators, consider it important to deploy 5G NR on large contiguous bandwidths of the order of 80 to 100 MHz (for example, the ECC report on defragmentation in the band says that industry has said that 5G networks may require 80 – 100 MHz contiguous spectrum).

Figure 5.1: Current spectrum holdings 3.4-3.8 GHz

Licensee	Bandwidth licensed in the 3.4-3.8 GHz band
H3G (including UK Broadband)	140 MHz
Vodafone	50 MHz
BT/EE	40 MHz
O2 (Telefónica)	40 MHz

A5.46 The total spectrum already licensed in the band is therefore 270 MHz, leaving 120 MHz to be allocated in the forthcoming award of 3.6-3.8 GHz. We accept that the available evidence suggests that there are no specific 5G services that are critically dependent on contiguous carriers of 80-100MHz spectrum. However, we do consider that making all the remaining 120 MHz available for national mobile use would increase MNOs’ opportunity to

[7] WIG and ip.access have suggested 20 MHz. Trade body WISPA has asked for 160MHz, however, industry has also suggested that 40MHz would be sufficient. Qualcomm has said “multiple 10MHz or 20MHz channels” though it is unclear if this would need to be in 3.6-3.8GHz or spread across multiple bands.

develop their new services effectively, and the likelihood of investment, innovation and effective competition in the provision of mobile services, including 5G, to UK consumers in future.

A5.47 Even if the opportunity cost of 3.6–3.8 GHz spectrum could be lower or higher than the 3.4–3.6 GHz spectrum auctioned earlier in 2018, we consider that auction price provides a benchmark for possible market value (or marginal opportunity cost). The price paid by most winners was £37.8m per 5 MHz or just over £150m per 20 MHz. In section 7 we propose reserve prices for UK-wide licences of 3.6-3.8 GHz spectrum, which we expect to be materially *lower* than the opportunity cost, between £15m and £25m per 5 MHz or £60-100m per 20 MHz.

Our proposals to facilitate new uses through spectrum sharing

A5.48 As already noted, alongside our proposal to award 700 MHz and 3.6-3.8 GHz spectrum bands through an auction of UK-wide licences, we are consulting on proposals[8] to support opportunies for innovation by enabling shared access to several spectrum bands supporting mobile technology. We propose to enable shared access to three bands supported by mobile technology (these are the 3.8-4.2 GHz, 1781.7-1785 MHz paired with 1876.7-1880 MHz (1800 MHz shared spectrum) and 2390-2400 MHz (2300 MHz shared spectrum). We also set out our proposals for new users to seek access to all awarded mobile spectrum[9] in locations where we agree that this would not adversely impact the incumbent licensee's planned use of the spectrum.

A5.49 We believe that our proposals would provide a better spectrum solution to address the alternative uses identified above. We summarise the potential uses that could be enabled by our proposals below.

Figure 5.2: Spectrum bands considered for alternative uses

Uses	3.8-4.2 GHz	1800 MHz shared spectrum	2300 MHz shared spectrum
Private network	✓	✓ (narrowband)	✓
Mobile coverage (rural)	✗	✓	Certain locations[10]
Mobile coverage (indoor)	✗	✓	✓
Fixed Wireless Access	✓	✗	✗

[8] https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation
[9] Under the Mobile Trading Regulations
[10] Due to coexistence with other users, the availability of medium power use will likely be limited to rural areas only.

3.8-4.2 GHz

A5.50 The 3.8-4.2 GHz band could be used for private industrial networks and provide additional spectrum for FWA to complement existing spectrum solutions. Both applications use bespoke equipment as opposed to mass market consumer devices (such as mobile handsets) where use of internationally harmonised bands would be required.

A5.51 Furthermore, we understand that 5G chipsets supporting the 3.8-4.2 GHz band are available (covering 3.3-4.2 GHz) that could support bespoke 5G equipment. We also understand that some FWA equipment already adopts proprietary technology which could be tuned to the 3.8-4.2 GHz band. We also note interest in using this band in other countries, including the USA and Japan. As such, we believe that there is clear evidence of the development of equipment that could support the utilization of this band for new services.

1800 MHz shared spectrum and 2300 MHz shared spectum

A5.52 Both bands are already supported by mobile networks and handsets, meaning it can be used immediately, for example by mobile coverage improvement schemes to extend mobile coverage in rural areas and in-building, or to provide private localised mobile networks.

Our proposal for access to mobile spectrum

A5.53 Stakeholders asking for access to the 3.6-3.8 GHz band to support new localised services have also suggested that these services could be supported in awarded mobile bands which are currently licensed but "unused" in some locations.

A5.54 Ofcom has acknowledged the increasing demand for access to all spectrum and has taken steps to promote and encourage spectrum sharing. In 2016 we published a revised sharing framework which set out a new approach to Ofcom's assessments of requests to share spectrum.[11] Currently, parties seeking access to licensed spectrum (including mobile bands) are encouraged to follow the process set out by Ofcom for spectrum trading.

A5.55 Section 30 of the Wireless Telegraphy Act 2006 provides for parties to trade spectrum by transferring the rights and obligations to another party. Agreements to trade spectrum can be permanent, temporary and or geographically limited meaning spectrum can be traded nationally, regionally or locally. Several Spectrum Access licences have been traded in their entirety.[12]

A5.56 We propose to make the award licences tradable by amending the Wireless Telegraphy (Mobile Spectrum Trading) Regulations 2011 (the "Mobile Trading Regulations") to include the new frequency bands of the 700 MHz and 3.6-3.8 GHz frequencies. Early next year, we

[11] https://www.ofcom.org.uk/__data/assets/pdf_file/0032/79385/spectrum-sharing-framework.pdf
[12] EE and Three and Energis Local Access Ltd for example.

plan to give formal notice of our proposals for amending the Mobile Trading Regulations, including the draft regulations that we propose to make to amend these regulations.

What about Spectrum Leasing?

A5.57 In 2011 we sought to simplify the trading process and consulted on a process that would introduce spectrum leasing, initially, for certain licence classes of spectrum[13].

A5.58 Leasing differs from spectrum transfer (or trading) because the licence holder does not transfer rights and obligations to the new user and as such remains liable for the actions of the new user. The leasing agreement is between the licence holder and the new party. It does not require Ofcom to be notified or to issue new licences (unlike a spectrum transfer which is processed by Ofcom and results in new licences being issued to all parties), this carries with it a number of risks, including that the process includes no assessment of the impact on competition.

A5.59 We have not extended leasing to a broader set of licences (including mobile) because of a general lack of demand and because we believe there are elements of the process which are unattractive. As such we are not proposing to include leasing provisions in the new licences for 700 MHz and 3.6-3.8 GHz spectrum. However, as set out in our 2016 review of spectrum sharing, we will keep this position under review. We would consider extending leasing if we think there are likely to be net benefits, including sufficient evidence of demand to lease spectrum, particulary in the light of responses to our alternative local licensing proposal.

Local Licensing in mobile bands - our proposal

A5.60 Some stakeholders have suggested that, if Ofcom were to extend spectrum leasing this mechanism could provide an effective vehicle to enable licensed users to share access to their spectrum bands in areas where they are not in use. Sharing spectrum in this way could support innovative local services. For instance, Rural First (a 5G testbed and trials project) have told us that they would like access to mobile spectrum to provide mobile broadband for consumers and smart agriculture applications in rural areas.

A5.61 We share the objective, set out in the Department for Digital, Culture, Media and Sport's *Future Telecoms Infrastructure Review*, of wanting third parties to be able to have access to mainstream mobile spectrum in places where it is not being used by the MNOs[14]. However, we believe that the best way to do this will be to create a process for new, local licences for third parties who wish to exploit unused mobile spectrum. In our view, this approach would achieve the same objective as extending leasing to mobile bands but without some of the drawbacks of leasing. In our proposed approach the third party is licensed by Ofcom instead of becoming the responsibility of the licensee.

[13] https://www.ofcom.org.uk/consultations-and-statements/category-1/simplify
[14] https://www.gov.uk/government/publications/future-telecoms-infrastructure-review

A5.62 Under this approach, a third party applies to us for a local licence to use specific frequencies at a location (which can be in any of the mobile bands licensed to MNOs). If the relevant MNO(s) raised a reasonable objection, then the application is declined. If not, then a local licence will be issued for a minimum term of 3 years.

A5.63 We intend to monitor how MNOs respond to applications for access. Our expectation is that they should behave reasonably.

A5.64 We will grant a longer duration licence if this has support of the relevant MNO(s) - this could be on the back of a commercial agreement between the MNO(s) and the third party (as would be needed for a lease). For a third party wishing to provide coverage extension, inbound roaming agreements with MNOs will need to be negotiated, so MNO support is essential.

A5.65 In light of the above, we are not proposing to include leasing provisions in the new licences for 700 MHz and 3.6-3.8 GHz spectrum but note that our new proposal for licensed local access will apply to all awarded mobile bands.

Conclusion

A5.66 We have a statutory duty to have regard, where we consider it to be relevant, to the desirability of encouraging innovation and investment. In our view, facilitating access to spectrum for new uses has an important role to play in developing new innovative services of benefit to business and consumers.

A5.67 The demand for mobile broadband is well documented. It is our view that this demand is what will initially drive deployment of the new spectrum bands in the auction. Both the 700 MHz and 3.6-3.8 GHz band are likely to be used by MNOs to meet this growing demand and could eventually deliver further innovative uses that go beyond mobile broadband including Ultra reliable and low latency communications (URLLC) and mMTC (massive Machine Type Communications)[15].

A5.68 We consider it important to enable productive use of spectrum by both MNOs and providers of alternative uses. To some extent there is a trade-off between these two sets of uses, given the interest of providers of both in having access to 3.6–3.8 GHz spectrum.

A5.69 Taking account of the different spectrum demand for alternative uses, the complexity of local licensing in an auction, the range of spectrum available and the opportunity costs associated with each, we consider that the best approach to facilitate significant benefits from the alternative uses requiring localised access to spectrum would be through our proposal[16] to authorize users on a per location basis to access a number of spectrum bands supporting mobile technology.

A5.70 Our provisional view is therefore that a national approach to spectrum licensing in the 700 MHz and the 3.6–3.8 GHz bands in the auction would be most likely to ensure efficient use of the spectrum.

[15] See Annex 7 Market Trends in 5G Evolution

[16] 3.8-4.2 Consultation [correct title]

A6. Current state of the UK mobile market

Summary and introduction

A6.1 In this annex we provide information on the current state of the provision of mobile services in the UK. We use this to assess whether competition is currently working well for mobile consumers in the UK, which forms the starting point for our competition assessment for this spectrum award. We consider subscriber growth, market shares, spectrum shares and pricing trends, mobile data growth and consumer preferences.

A6.2 As discussed in section 5, we consider that competition is generally working well, with prices decreasing over time, consumer satisfaction at a high level, and continued innovations and investment by operators.

A6.3 There are four mobile network operators (MNOs) in the UK: BT/EE, Vodafone, O2 and H3G. These MNOs have their own mobile network services and use them to provide retail services. They are also wholesalers who sell access to their mobile network services to mobile virtual network operators (MVNOs). All MNOs currently host at least one MVNO.

A6.4 The existence of four credible MNOs supports retail competition directly because MNOs are major competitors in supplying retail mobile services to consumers. It also supports retail competition indirectly because the MNOs compete to provide wholesale access to MVNOs.

A6.5 Some of our key findings include:

- Mobile data traffic has been rapidly increasing over the recent years, which may be attributed to increasing mobile subscriptions and smartphone penetration.
- Machine to machine (M2M) connections[17] accounted for most of the changes in mobile subscriptions over the most recent years (2015 – 2017).
- The four UK MNOs have different market shares. H3G is the smallest with c. 12% of wholesale subscribers, O2 and BT/EE each have around 33% of wholesale subscribers, and Vodafone has 22%.[18]
- The four MNOs appear to exert a competitive constraint on each other. H3G and O2 have been increasing their wholesale market shares over the years, leading to a moderate decline in market concentration.

[17] Cellular M2M connections refer to machine-to-machine connections using a cellular network, which are automated mobile connections between two non-human endpoints. One such example is smart energy meters, which use a mobile network to relay usage readings back to the energy provider. M2M connections are considered as post-pay.
[18] Analysys Mason Telecoms Market Matrix: Western Europe

- At a retail level, O2 has the highest retail market share, followed by BT/EE, Vodafone and H3G. Some of the independent MVNOs in the retail market have been performing well, including iD, Sky and Virgin.[19] TalkTalk, however, has decided to cease its MVNO activities.
- The market concentration index of the UK is at a similar level as of other comparable Western European countries with four MNOs despite having the highest spectrum concentration.
- UK mobile prices have generally been decreasing over time. Notwithstanding this, our basket approach showed there was an increase in price for some baskets for some years, and our econometric approach showed an increase in price between 2014 and 2015. The European Commission and Telecompaper found that prices in the UK were relatively low/cheaper compared to other countries within their analysis.
- The composition of mobile revenue has changed over the years. Revenues from out-of-bundle messaging and calls have decreased over the last seven years, whilst revenue from access and bundled services has significantly increased over the same period.
- We consider MNOs to be financially viable. EBITDA minus capex continued to be positive when spectrum purchases were excluded from capex. EBITDA margins of all four MNOs are generally improving. Mobile service revenues continued to grow except for Vodafone, but it had the highest contract net adds in the most recent quarter.
- H3G had the highest share of data traffic until 2017, when BT/EE started to overtake it on this measure. Generally, all MNOs have experienced an upward trend in mobile data traffic per MHz (of spectrum) holding. However, H3G's mobile data traffic per MHz started declining in late 2017. H3G's customers consume by far the most data compared to those of other MNOs. The average H3G customer consumes twice as much as data as an average customer with BT/EE, which has the second highest data consumption per subscriber.
- Consumer satisfaction with UK mobile services remains high, despite small decreases in some satisfaction indicators. A number of dimensions are important to consumers, and the key drivers of consumers' decisions on mobile provider are price and network quality. Customer service ranks higher than data speeds, though data speeds are becoming more important. Network quality can be broken down into various factors: the most important to customers are network reliability and coverage. In addition, accessing the web is the most important mobile service for customers, followed by calls and then video streaming.
- Carphone Warehouse as a third-party retailer plays a part in the provision of retail mobile services, although its position has weakened over the past year. According to Dixons Carphone Annual Report, the declining post-pay market and contractual commitments with the networks are causing challenges in its UK mobile business.

[19] From the Enders Analysis report "Covert growth in UK mobile".

- MNOs continued to innovate their mobile offerings to consumers. For example, there are schemes available which allow customers to use data-intensive apps and services without using their inclusive data allowances.

A6.6 This annex is structured as follows:

- Relevant trends in the mobile services sector
- Recent changes to the structure of the market
- Provision of wholesale mobile services
- Provision of retail mobile services
- International comparison of market shares and spectrum shares
- Evolution of UK mobile prices
- International comparison of mobile prices
- Mobile revenues
- Financial position of MNOs
- Mobile Data Traffic
- International comparison of network quality
- Factors considered by mobile consumers when choosing providers
- Additional competition considerations

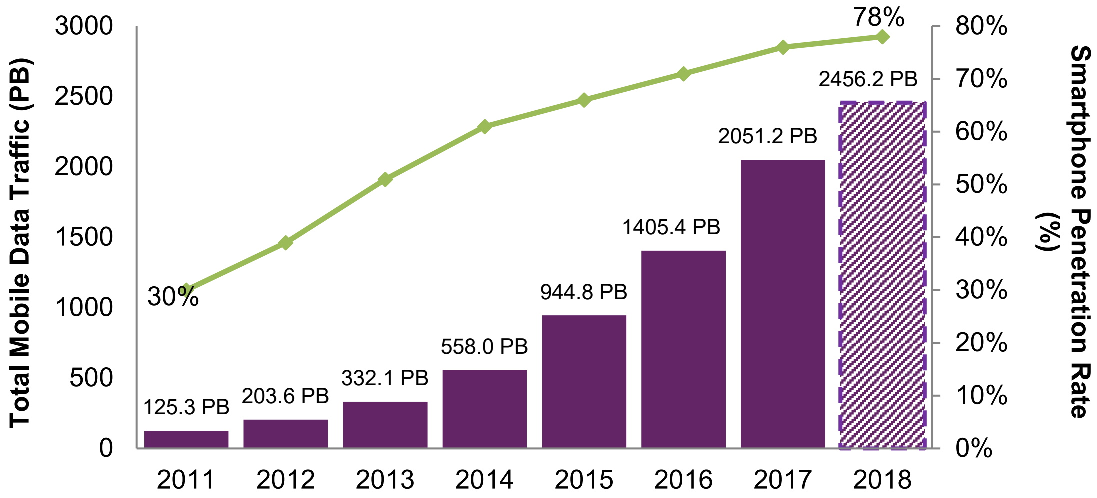
Relevant trends in the mobile services sector

A6.7 There has been a rapid increase in the growth of mobile data traffic and smartphone penetration in recent years (Figure A6.1). The smartphone penetration rate has increased to 78% in H1 2018 from 71% in 2016.[20] Mobile data traffic increased by 46% between 2016 and 2017.[21]

[20] Source: Ofcom Technology Tracker, Quarter 1 2011 - 2014, Half 1 2015-2017, Base: all adults age 16+, QD4 (QD24B): Do you personally use a smartphone?

[21] Data on mobile data traffic were provided by Enders Analysis in their quarterly UK mobile report. We summed up the data of all the quarters within the year to calculate the annual figures.

Figure A6.1: Total Mobile Data Traffic and Smartphone Penetration Rate, 2011-2018[22]



Source: Enders Analysis for total mobile data traffic and Ofcom Technology Tracker for smartphone penetration rate

A6.8 The average monthly data use per mobile subscriber increased eight-fold in five years to June 2017,[23] which is partly due to increasing smartphone penetration and mobile subscriptions. Smartphones have become a further channel to access the internet and use data-intensive services such as streaming videos and music, especially on the go. Ofcom research found that 67% of mobile phone users have used their phones for general browsing/surfing the internet, up from 28% in 2011, and 76% used mobile phones for web and data access in 2018, up from 35% in 2011.[24]

A6.9 The total number of mobile subscriptions in the UK, including M2M connections, has grown continuously in recent years, up to the end of 2017 (Table A6.2:). Subscriptions reached 92 million by the end of 2017. This highlights the fact that some people had more than one active mobile phone at the end of 2017 and M2M subscriptions grew rapidly in the same period.

A6.10 The changes in the total number of mobile subscriptions between 2016 and 2017 were mainly driven by M2M subscriptions. M2M subscriptions accounted for more than a half of the c.486,000 net increase in total mobile subscriptions between 2016 and 2017.

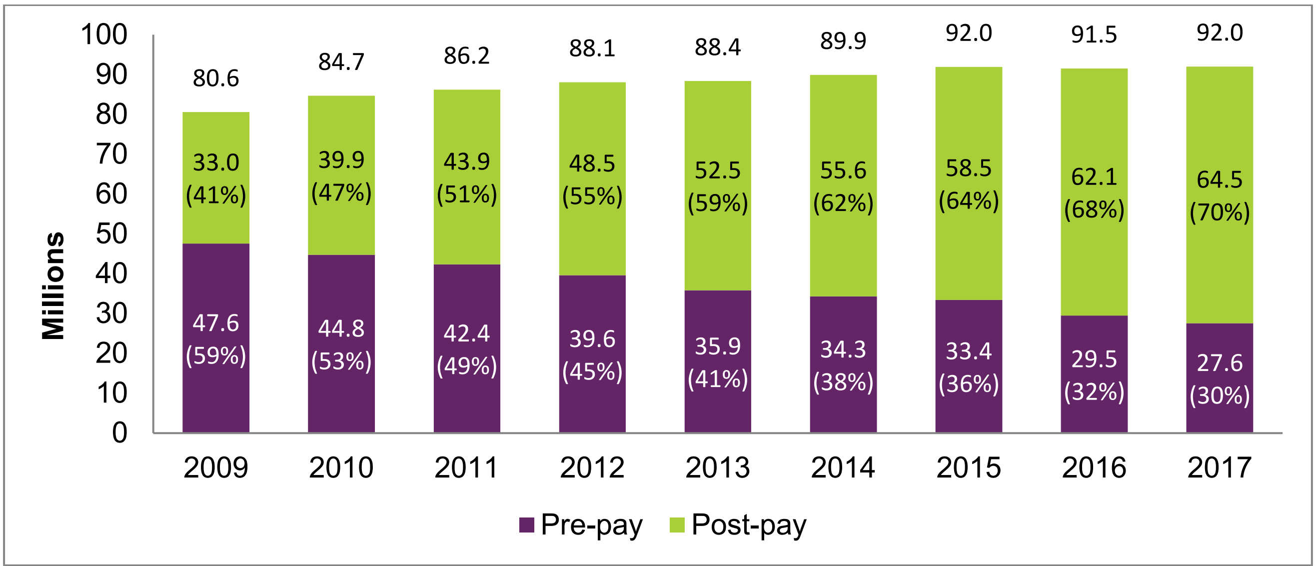
---

[22] Note that 2018 mobile data traffic is only an estimate. We have acquired mobile data traffic from Enders Analysis which estimated it to be around 614 PB in Q1 2018 and 688 PB in Q2 2018. Assuming this is also true for the next half of 2018, the estimated mobile data traffic for the whole year of 2018 is $(614 + 688) \times 2 \approx 2{,}603$ PB

[23] Ofcom, Communications Market Report 2018

[24] Ofcom, Communications Market Report 2018

Figure A6.2: Mobile subscriptions, by pre-pay and post-pay



Source: Ofcom/operators
Note: Active subscribers at the end of each period: includes M2M from 2010 and estimates where Ofcom does not receive data from operators.

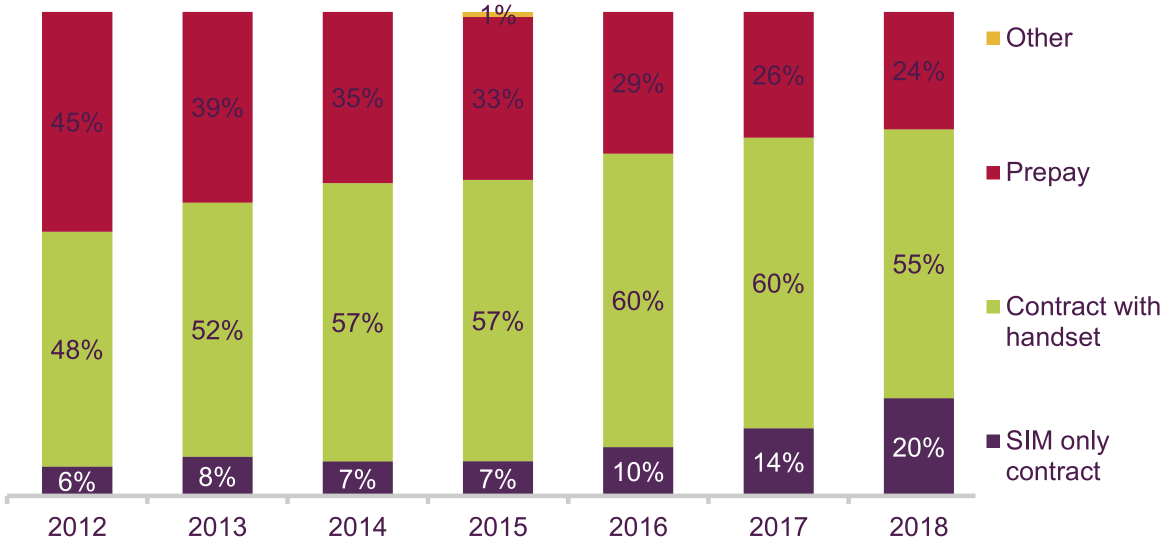
A6.11 Although the distinction between post-pay and pre-pay subscriptions is becoming less[25] clear, post-pay subscriptions continue to grow, while pre-pay subscriptions continue to decrease. Specifically, post-pay subscriptions only accounted for less than a half of mobile subscriptions ten years ago. However, they accounted for more than two-thirds of mobile subscriptions in 2017. This may suggest that post-pay offerings have become more important within the provision of mobile services.

A6.12 Within the post-pay segment, SIM-only subscriptions have been growing over the years, especially during the last two years. In 2016, the share of SIM-only tariffs was 10% of all subscriptions. This doubled to 20% in the two years in 2018 (Figure A6.), meaning that a lower share of post-pay contracts includes a handset element.[26]

[25] For example, some pre-pay tariffs involve subscribers making regular monthly payments for minutes and data that must be used in the following month, which are similar in form to post-pay tariffs. There are also some post-pay tariffs with very short termination periods that are not unlike some pre-pay tariffs. For more on the blurring of the distinction between pre-pay and post-pay see paragraphs 14 to 18 of Appendix B of the CMA's decision on BT/EE merger.

[26] 2018 Pricing trends for communications services

Figure A6.3: Take-up of mobile packages (%)



Source: Ofcom Technology Tracker, data as at Q1 2012-2014; H1 2015-2018

Recent changes to the structure of the market

A6.13 In 2010, Deutsche Telekom (T-Mobile) and France Telecom (Orange) agreed to merge their UK mobile operations into Everything Everywhere (now EE), thereby reducing the number of MNOs in the UK market from five to four.

A6.14 In 2012, Vodafone acquired Cable and Wireless' (C&W) global operations including those in the UK.[27]

A6.15 In 2015, BT agreed to acquire EE, and the merger was completed in 2016 after receiving clearance from the CMA.28

A6.16 Before the BT/EE merger, there was an expectation that BT would use its spectrum to launch its own mobile service, albeit one largely reliant for national coverage on wholesale access as an MVNO.

A6.17 In 2015, H3G agreed to acquire O2's UK mobile operation, which would have reduced the number of MNOs in the UK to three. However, this proposed merger was blocked by the European Commission in 2016.[29]

A6.18 In 2017, H3G acquired UK Broadband, which currently provides Fixed Wireless services to approximately 15,000 subscribers in the central London area. [30] UK Broadband holds a

[27] European Commission Competition Cases - Vodafone and Cable & Wireless
[28] CMA cases - BT Group/EE merger inquiry
[29] European Commission Competition Cases - Hutchison 3G UK and Telefonica UK
[30] H3G news page - "Three UK reaches agreement to acquire UK Broadband Limited"

spectrum licence, which we varied on 14 December 2018, for the use of certain frequencies in the 3.4-3.8 GHz band.

A6.19 In May 2018, BT announced a plan to launch a brand called "BT Plus". The new brand will further integrate BT and EE, whereby consumers can buy mobile services with their broadband and pay television services as part of a single package.[31]

Provision of wholesale mobile services

A6.20 There are currently four UK (wholesaler) MNOs: BT/EE, H3G, O2 and Vodafone. MNOs have their own mobile network services and use these to provide retail mobile services under their own brand name. MNOs also provide mobile network services (wholesale services) to a number of mobile virtual network operators (MVNOs). MVNOs use these services to provide their own retail mobile services. For example, Virgin purchases access on BT/EE's network in order to provide retail services under the brand of Virgin Mobile.

A6.21 Currently all MNOs host at least one MVNO. For example, BT/EE hosts Virgin Mobile, O2 hosts Sky, Vodafone hosts Lebara, and H3G hosts iD. We consider that the existence of four credible MNOs supports retail competition directly because MNOs are major competitors in supplying retail mobile services. It also supports retail competition indirectly because the MNOs compete to provide wholesale access to MVNOs. Competition at the wholesale level between these MNOs enables MVNOs to obtain wholesale access commercially, without regulation.

A6.22 In principle, market shares can be measured in a range of ways based on subscriber numbers, revenue,[32] volume of (data) traffic etc. Most of the evidence set out below is for shares of subscribers (which is the information most easily obtained on a comparable basis across operators). Later in this annex, we also include some evidence on shares of data traffic.

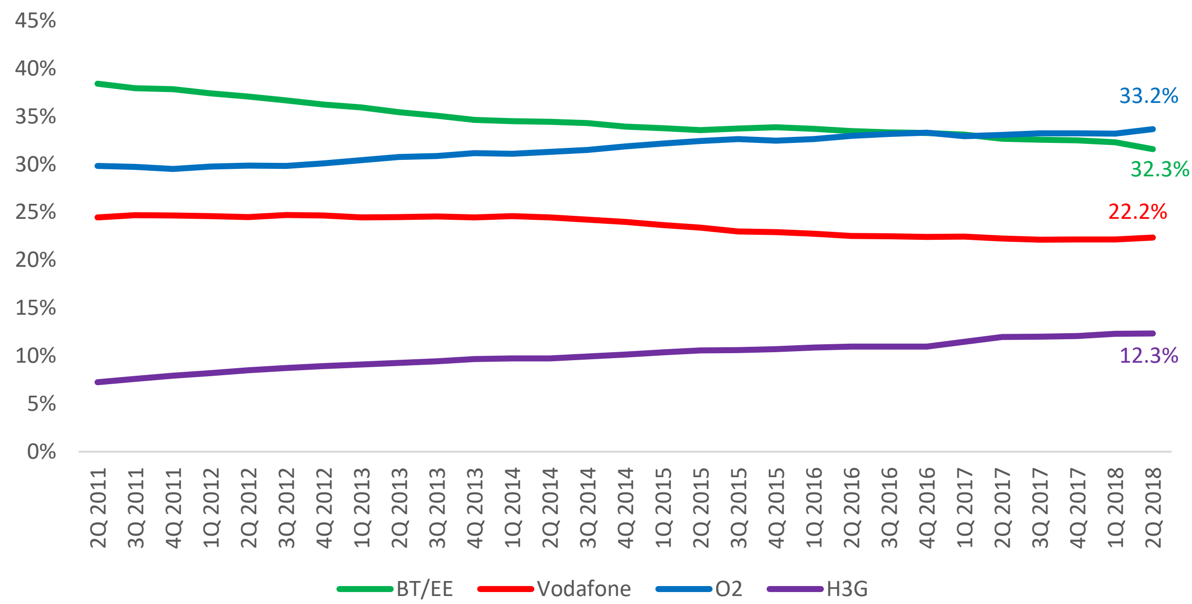
A6.23 The wholesale market shares of MNOs include both the MNOs' own retail subscribers and hosted MVNOs' subscribers. H3G and O2 increased their wholesale market shares between 2011 and Q2 2018, whilst the shares of BT/EE and Vodafone decreased (Figure A6.).

A6.24 Currently, O2 has the largest wholesale share of 33.3%, followed by BT/EE just behind with 32.3%, then Vodafone (22.2%) and H3G (12.2%). O2 recently overtook BT/EE's wholesale market share in Q2 2017 (Figure A6.).

[31] Financial Times - "BT presses button on deeper integration of consumer arm with EE"

[32] We have not included revenue market share comparisons because of the difficulties in making such comparisons meaningful and accurate, for example due to the effect of handset revenues, potential differences in accounting treatment (e.g. potential inclusion of non-mobile related revenues), and challenges in the treatment of MVNOs.

Figure A6.4: Wholesale market shares by network – Analysys Mason data[33]



Source: Analysys Mason

A6.25 The HHI[34] shows that the provision of wholesale mobile services in the UK is slowly becoming less concentrated over time. The HHI decreased by 171 between 2011 and 2017 (Table A6.1 below), which may be partly attributed to the rising wholesale market shares of H3G.

Table A6.1: HHI index for the UK wholesale mobile market

	2011	2012	2013	2014	2015	2016	2017	Change [2011-2017]
HHI	2,970	2,917	2,891	2,893	2,877	2,845	2,799	-171

Source: Ofcom analysis of Analysys Mason data

[33] Excludes M2M. Our analysis for this consultation is based on data provided by the operators to Ofcom as part of their regular information submissions to us. However, as we do not publish this information, we are including market share data based on published Analysys Mason data. There are no significant differences between these datasets.

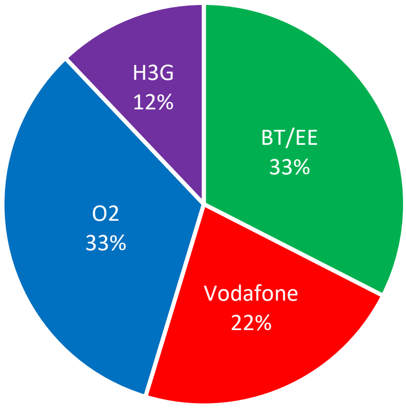
[34] A common measure of the level of market concentration is the Herfindahl-Hirschman Index (HHI). This index is estimated by taking the absolute value of the market share of each firm in the industry (e.g. 25 if the market share is 25%) and then squaring this number. The sum of these values for all firms is the HHI and can theoretically range from close to zero for a market with a very large number of small firms, all with little market shares (e.g. less than 1%), to 10,000 for a market with one operator with 100% market share. If all firms in a four-player market had the same market share, the HHI would be 2,500, i.e. 4 x $(25\% \times 100)^2$.

Provision of retail mobile services

Evolution of market shares

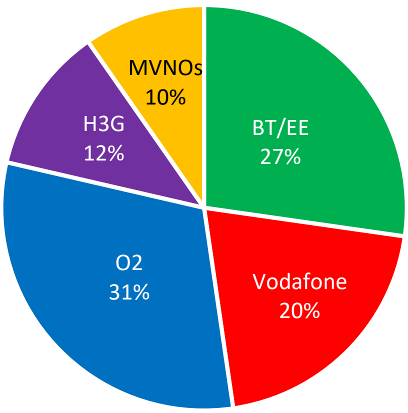
A6.26 Retail market shares only include MNOs' own subscribers and omit hosted MVNOs' subscribers. Some MVNOs are partly owned by the host MNO and therefore we consider these MVNOs not to be wholly independent and include them in the MNO retail market share.[35] Therefore, we do not include these non-independent MVNOs when calculating the total retail market shares of all MVNOs.

Figure A6.5: UK mobile wholesale market shares, Q4 2017[36]



Source: Analysys Mason
Note: Excludes M2M

Figure A6.6: UK mobile retail market shares, Q4 2017[37]



Source: Enders Analysis

---

[35] For example, Tesco Mobile is a 50:50 joint venture between Telefonica (O2) and Tesco. Therefore, in our calculations, Tesco's market shares are included in O2's market shares.
[36] Analysys Mason Telecoms Market Matrix: Western Europe
[37] From Enders Analysis report entitled "Covert growth in UK mobile". Figure 14, page 10.

A6.27 The difference between the wholesale and retail market shares in Figure A6.5 and A6.6 above highlights the effect of hosting MVNOs. For example, BT/EE and O2 each have around a third of the wholesale market share. However, in terms of retail market shares, the difference between O2 and BT/EE's shares are more pronounced. O2 still has the largest market share in the retail segment with 31%, whilst BT/EE's retail share is 27%. This implies that BT/EE hosts more MVNO subscribers than O2.[38]

A6.28 Similar to trends in the wholesale market shares, H3G and O2 increased their retail market shares, while EE and Vodafone's market shares declined between 2011 and 2017.[39] [✂ REDACTED].

Figure A6.7: Total mobile subscription market share by retail operator[40]

[✂ REDACTED]

A6.29 The HHI mentioned above can also be used to measure the level of concentration of the retail mobile services sector. The HHI shows that the retail mobile services sector has slowly been becoming less concentrated since 2010 (Table A6.2). The HHI decreased by around 10% between 2011 and Q1 2018 (Table A6.2 below), which can be attributed, among other things, to the rising retail market shares of H3G and of MVNOs. However, this sector is still relatively more concentrated than in 2009, which is the year before T-Mobile and Orange merged to form Everything Everywhere (EE). BT acquired EE in 2016.

Table A6.2: HHI index for the UK retail mobile market[41]

	2009	2010	2011	2012	2013	2014	2015	2016	2017	Q1 2018	Change 2010-Q1 2018
HHI	1,871	2,478	2,427	2,370	2,363	2,370	2,318	2,344	2,290	2,251	- 227

Source: Ofcom analysis of operator data

A6.30 The contract net additions (difference between customers won and lost) and churn (percentage of customers lost in a given period) may also give an indication of the position of MNOs and MVNOs in the retail mobile services segment. In terms of contract net additions, Vodafone was lagging behind the other MNOs but in the recent quarter (Q2 2018) Vodafone performed relatively strongly with the highest contract net adds. BT/EE was performing relatively strongly until the recent quarter, when its level of contract net

---

[38] Our analysis for this consultation is based on data provided by the operators to Ofcom as part of their regular information submissions to us. However, as we do not publish this information, we are including market share data based on published Analysys Mason data.

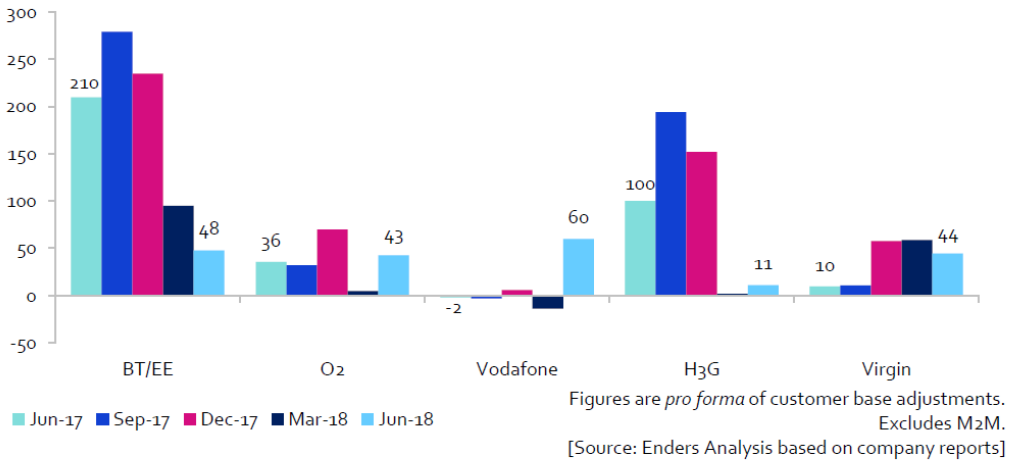
[39] Analysys Mason Telecoms Market Matrix: Western Europe

[40] BT subscribers are included in EE number for 2016 and 2017. We have updated the numbers for 2011 to 2017 from the PSSR statement with amended data as submitted by stakeholders.

[41] This table takes into account the market shares of some MVNOs as well as MNOs. The MVNOs taken into account are: Virgin, Lycamobile and Lebara Mobile. Tesco and O2 are not treated separately. For the estimation of the HHI, each of the MVNOs included in the calculation is treated separately. We have modified our methodology to include Tesco's subscribers in O2 for 2011 to 2017, which revised the HHI figures from the July 2017 statement.

adds decreased. O2's position has improved compared to Q1 2018. H3G performed strongly in 2017 but has had a weaker first half of 2018. Virgin, an MVNO, had higher net adds than O2 and H3G in Q2 2018 (Figure A6.8).

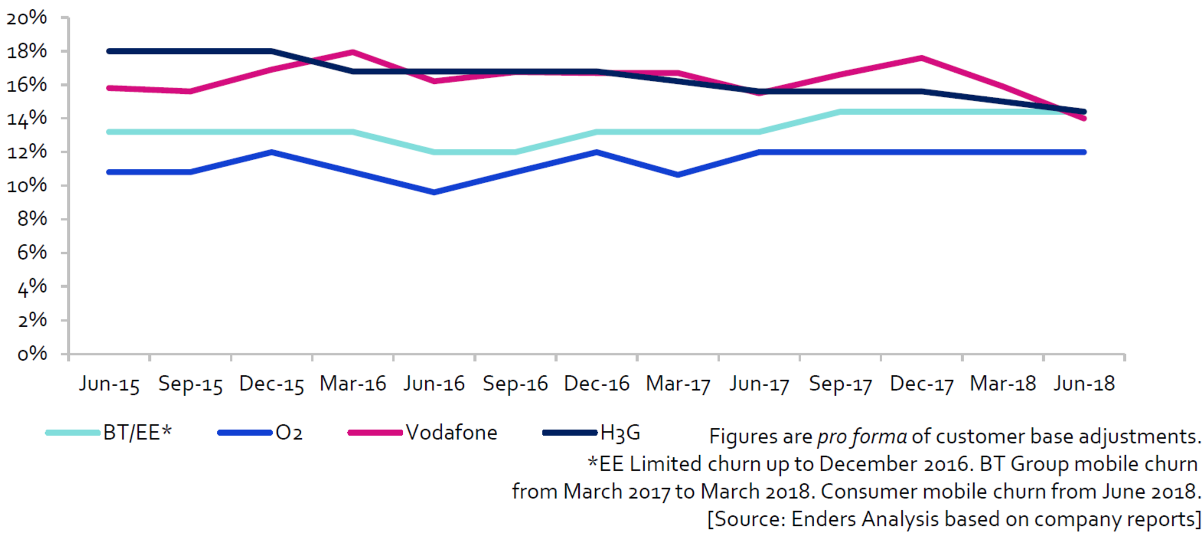
Figure A6.8: Contract net additions (thousands)



Source: Enders Analysis

A6.31 According to Enders Analysis, O2 had the lowest contract churn rates at 12.0%, followed by Vodafone (14.0%) and then EE and H3G which both had 14.4% in Q2 2018 (Figure A6.9). Vodafone's churn rate has recently fallen below that of BT/EE. H3G and Vodafone have tended to have the highest churn rates over the past few years, though they are now comparable with BT/EE.

Figure A6.9: Annualised contract churn



Source: Enders Analysis

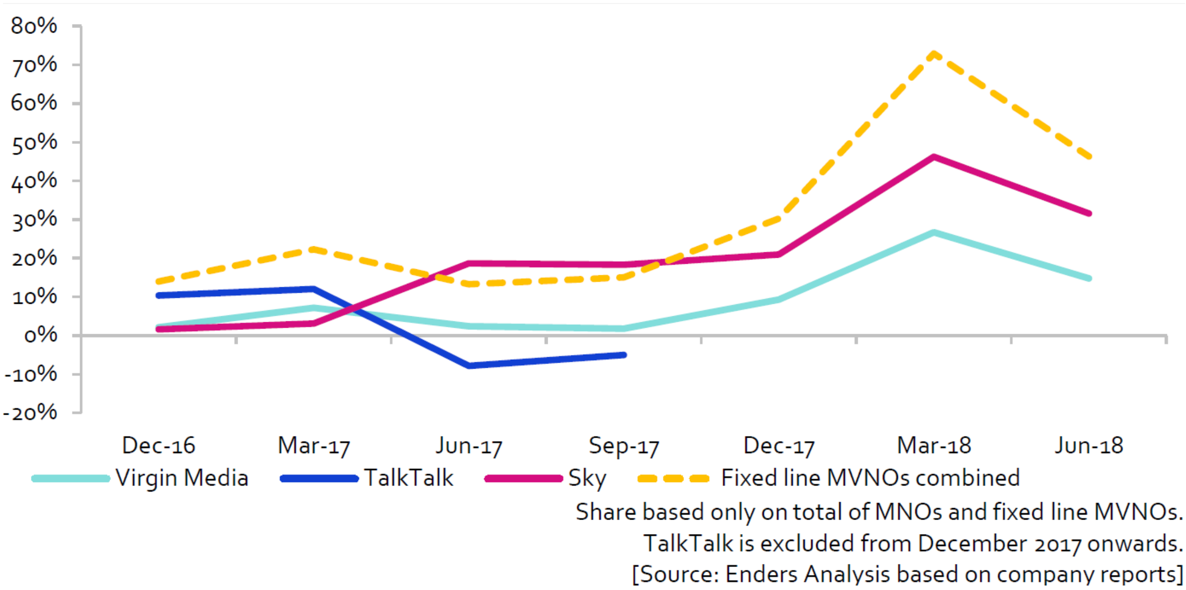
The role of MVNOs in the provision of retail mobile services

A6.32 Retail competition in mobile services today is characterised by the competition between both MNOs and MVNOs. Some MVNOs target a certain type of customers. For example, Lebara and Lycamobile focus their offerings to include cheap international minutes.[42]

A6.33 The MVNOs' individual performance is a mixed picture. Sky, iD and Virgin are growing their subscriber numbers, albeit from a small base for Sky and iD. On the other hand, TalkTalk announced in its March 2018 that it expects to completely cease its MVNO activities by early 2019.[43] The difference in MVNOs' performances can be observed from the recent trends of the MVNOs' contract net adds (Figure A6.10).

A6.34 According to Enders Analysis, fixed line MVNOs significantly increased their share of contract net adds at the beginning of 2018. However, fixed line MVNOs' share of contract net adds decreased to 46% in Q2 2018 (Figure A6.10). Sky and Virgin continued to perform well in Q2 2018. Sky had around a third of the share of contract net adds and Virgin had a 15% share of contract net adds.

Figure A6.10: Fixed line MVNO contract net additions share



Source: Enders Analysis

A6.35 We have been able to extract subscription numbers from the recent quarterly and annual reports of Sky Mobile and iD Mobile. Both iD and Sky have rapidly grown their subscriber numbers, albeit from a small base. Sky's contract net adds in Q2 2018 were c.95,000,[44]

[42] We note however that the new EU regulation limiting the price of international calls may weaken these retail competitors, by removing their unique selling point.
[43] TalkTalk Full Year Results FY18, p.9
[44] See page 7 at Sky's Results in Q4 17/18 (FY). Please note that Sky does not appear to offer pre-pay subscriptions, and thus we assumed that subscription numbers quoted in this report were all post-pay subscriptions.

which is higher than Vodafone's contract net adds of ca. 60,000. iD's net adds[45] were c.115,000 between Q2 2016 and Q2 2017. [46] Net adds of Sky and iD have been consistently positive since their launch in 2016 and 2015 respectively.

International comparison of market shares and spectrum concentrations

A6.36 We compared the spectrum holdings and market shares of different operators in other European countries where there are four MNOs: Denmark, France, Italy, Netherlands, Spain and Sweden. We carried out a similar analysis for the 2.3 and 3.4 GHz auction and the analysis is outlined in the Annex 4 of the July 2017 statement.[47]

A6.37 We are mindful that spectrum is not the only resource on which the market performance of an MNO hinges and that market shares are only one indication of this. However, we compared the spectrum shares and market shares as an indication of how MNOs have performed.

A6.38 Our provisional view on the basis of our current analysis is that:

a) Although O2 has won all of the immediately useable 40 MHz from the 2.3 and 3.4 GHz auction, when we only consider the current useable spectrum,[48] the spectrum asymmetry in the UK is still generally higher than in other comparable countries.

b) The UK has a market concentration similar to other European countries that we have considered in our analysis.

A6.39 This is in line with the results of the analysis that we carried out for the 2.3 and 3.4 GHz auction, which we set out in the July 2017 statement.

A6.40 We also compared the spectrum concentration in the UK with Denmark, France, Italy, Netherlands, Spain and Sweden, having regard to the spectrum already assigned but not currently useable. This includes spectrum within the 3.4-3.8 GHz band. In our sample of countries, only the UK, Spain and Italy have auctioned and awarded spectrum within the 3.4-3.8 GHz band. When we include the spectrum already assigned but not currently useable in our analysis, the UK has the second highest spectrum concentration.

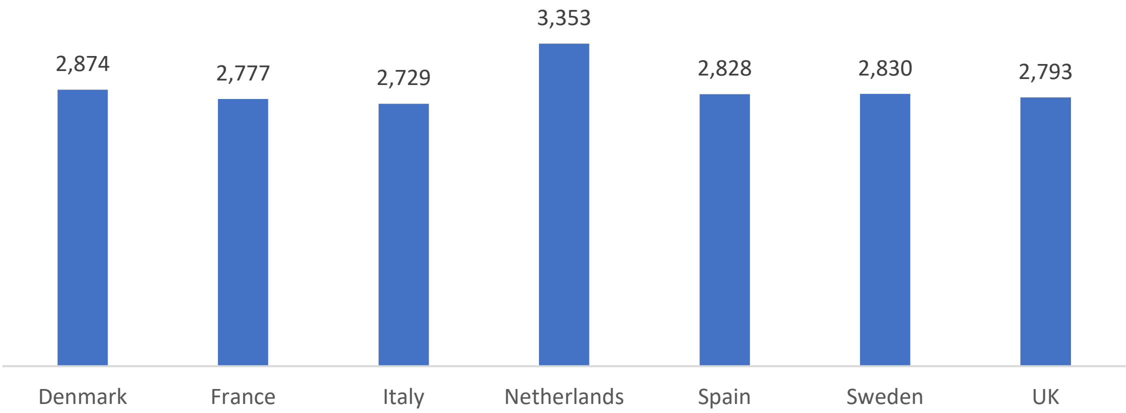
A6.41 We have made a few adjustments to the data used in this benchmark. As a result, there are some minor differences between the results of the current analysis and the July 2017 analysis. These differences do not change the main results from our analysis.

---

[45] Net adds includes both post-pay and pre-pay new subscribers, unlike contract net adds which only accounts for post-pay subscribers.
The number of subscribers quoted in Dixons Carphone's reports were not separated between pre-pay and post-pay subscriptions. Therefore, our estimate of iD's net adds included both pre-pay and post-pay subscriptions, unlike the contract net adds estimated by Enders Analysis which only accounted for post-pay subscriptions.
[46] See page 4 at http://www.dixonscarphone.com/~/media/Files/D/Dixons-Carphone/investors/reports-and-presentations/2017/interim-results-2017-18.pdf
[47] https://www.ofcom.org.uk/consultations-and-statements/category-1/award-of-the-spectrum-bands
[48] Current useable spectrum includes 800 MHz, 900 MHz, 1800 MHz, paired 2.1 GHz and paired and unpaired 2.6 GHz, plus 1400 MHz and 2.3 GHz in the UK.

Market concentration

Figure A6.11: Market HHI indices for different countries[49]



Source: Ofcom analysis of Analysys Mason data

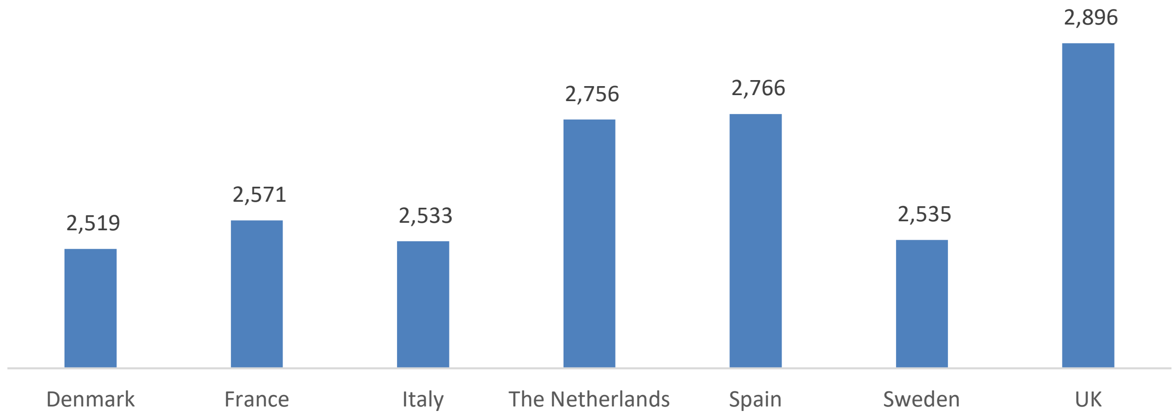
A6.42 We used the HHI to estimate the level of market concentration of different countries. In this benchmark, wholesale market shares were used in our calculation. In our July 2017 statement, we found The Netherlands to have the highest market concentration with HHIs above 3,400. The UK had a concentration which was similar to other countries in our sample.

A6.43 Our current analysis still shows The Netherlands to have the highest market concentration level (Figure A6.11). The UK's HHI is still similar to the other countries that we have considered for our benchmarking exercise.

[49] HHIs estimated using own and hosted subscribers, i.e. excluding MVNO market share for which we do not have data for other countries. As a result, the HHI for the UK is larger than the one estimated in Table A6.2 above as the shares of MVNOs have been excluded.
There have been significant changes in the Italian market over the past two years. It remains a four-MNO country despite H3G Italia and Wind merging in 2016 to form Wind Tre, with a new MNO -Iliad- being introduced into the market (Service launched in May 2018). For this benchmarking exercise, we are using Italy's market share as of 2015 because these are the latest data that are available before the merger and Iliad's entrance. For this international comparison we are comparing spectrum distribution across different countries and also trying to identify evidence of spectrum holdings having an effect on competition in the mobile market (as discussed further in Section 6). Therefore, we are using 'pre-merger' data for Italy as Iliad has only recently entered the market, and it is too early to draw any conclusions on how it will compete in the market and how this ability will be affected by its spectrum holdings.

Spectrum Concentration

Figure A6.12: Spectrum HHI of different countries[50]



Source: Ofcom analysis of data from Cullen International

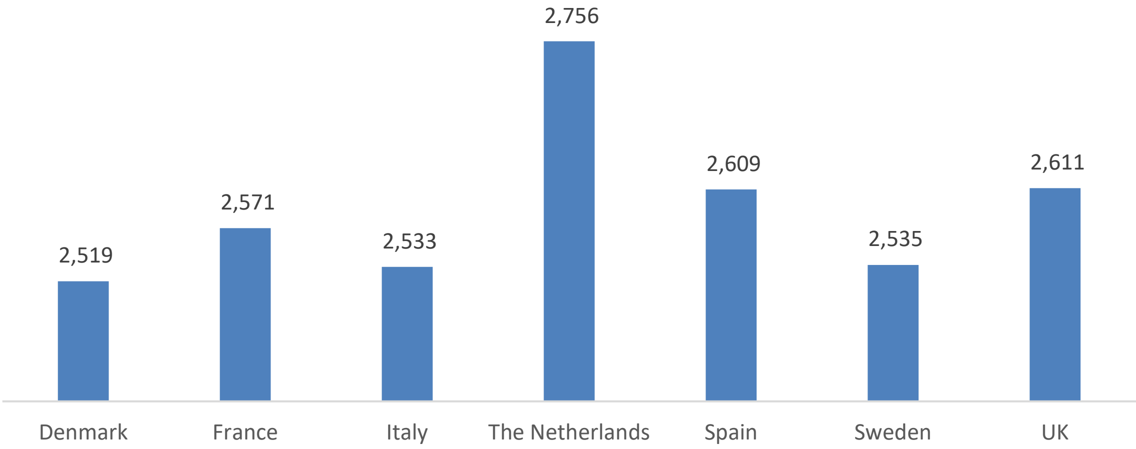
A6.44 We also used the HHI to compare the levels of spectrum concentration between the different countries, i.e. using spectrum shares rather than subscriber shares. We have included spectrum holdings in the 800 MHz, 900 MHz, 1400 MHz,[51] 1800 MHz, 2.1 GHz, 2.3 GHz,[52] and 2.6 GHz paired and unpaired bands.

A6.45 In our July 2017 statement, we found the UK had the highest level of spectrum concentration. This is still the case in our current analysis if we are only considering the current useable spectrum (Figure A6.12).

A6.46 In our current analysis, we also calculated the spectrum concentration with the inclusion of spectrum holdings that are already assigned but which will be useable soon or in the future, for example the spectrum holdings in the 3.4-3.8 GHz band. Only the UK, Spain and Italy have awarded spectrum in the 3.4-3.8 GHz band and, therefore, they are the only countries which have MNOs already holding spectrum in these bands.

[50] Unlike in the July 2017 Statement, we excluded Slovenia from our analysis because Slovenia's fourth MNO entrant, T-2, appears to be operating as a 'thick' MVNO. It has very low spectrum shares at 5.1% of Slovenia's spectrum in 800, 900, 1800 MHz, 2.1 GHz and 2.6 GHz bands. T-2 also uses the network of another MNO, Telekom Slovenjie, to provide its retail mobile service.
The European Commission had competition concerns on the proposed merger of Wind and H3G Italia in Italy. One of the remedies to address this concern was to divest spectrum in different bands to a new fourth MNO, which includes a total of 2x35 MHz of spectrum, comprising the 900 MHz (2x5 MHz), 1800 MHz (2x10 MHz), 2.1 GHz (2x10 MHz) and 2.6 GHz (2x10 MHz) bands. This means that currently the spectrum shares are as follows: Wind Tre has 33%, Telecom Italia and Vodafone Italia both have 28%, and Iliad has 12%, resulting in an HHI of 2,740.
For this benchmarking exercise, we are using spectrum shares as of 2016 because these are the latest data that are available before the merger and Iliad's entrance. As outlined in footnote 49, we are using 'pre-merger' data for this analysis because it is too early to draw any conclusions on how Iliad's spectrum holdings affect its ability to compete in the market.
[51] Only Italy and the UK have operators with 1400 MHz spectrum in this sample.
[52] Only UK have an operator with 2.3 GHz spectrum in this sample.

Figure A6.13: Spectrum HHI of different countries including the 3.4-3.8 GHz band[53]



Source: Ofcom analysis of data from Cullen International

A6.47 If we were to include spectrum holdings in the 3.4-3.8 GHz band in the calculation of the spectrum HHIs, the UK's spectrum HHI decreases to 2,611 meaning that spectrum concentration in the UK decreases if we include currently allocated spectrum in 3.4-3.8 GHz band. If we include the spectrum in the 3.4-3.8 GHz band, the UK has the second highest spectrum concentration and the Netherlands has the highest spectrum concentration (Figure A6.). Spain's spectrum HHI also decreases from 2,766 to 2,609, a similar level to the UK. This shows that the 2.3 and 3.4 GHz auction, and H3G's acquisition of UK Broadband have decreased the UK's spectrum concentration to a comparable level as other four-MNO European country.

A6.48 In conclusion, then, the UK remains one of the four-MNOs countries in Western Europe with the highest spectrum concentration, though it has fallen as a result of the 2.3 and 3.4 GHz auction.

Evolution of UK mobile prices

A6.49 We assessed the pricing trends of mobile services in our "Pricing trends for communication services in the UK" and "An econometric analysis of pricing trends in the UK" reports.[54] The reports have each taken different approaches to assessing mobile prices over time. The former used weighted average basket prices and the latter used an econometric approach. Nonetheless, both reports reached a similar conclusion, namely that there has been a general downward trend in UK mobile prices since 2013.

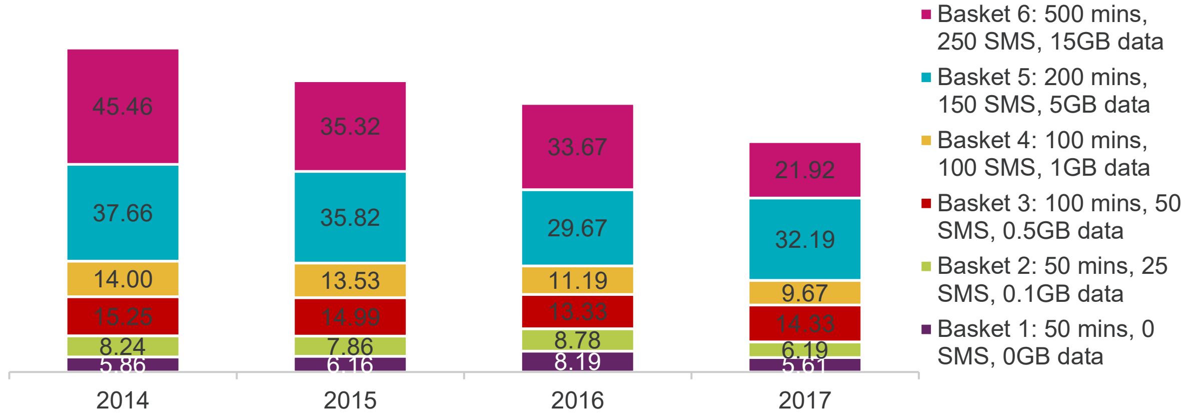
---

[53] Spectrum concentration shown in this figure will not be the actual concentration once the 3.4-3.8 GHz band is useable because the countries in our sample are planning to auction off (more) spectrum in 3.4-3.8 GHz band which may change actual spectrum shares used to calculate the spectrum concentration.
We are mindful that Italy has auctioned spectrum in 3.6-3.8 GHz bands. However, as we're focusing on the pre-merger situation for Italy, we have not included this spectrum in this chart. However, if we were to include it the HHI would be 2,752

[54] 2018 Pricing trends for communications services and An econometric analysis of pricing trends in the UK

Basket approach

Figure A6.14: Weighted average monthly prices of standalone mobile services: 2014 to 2017



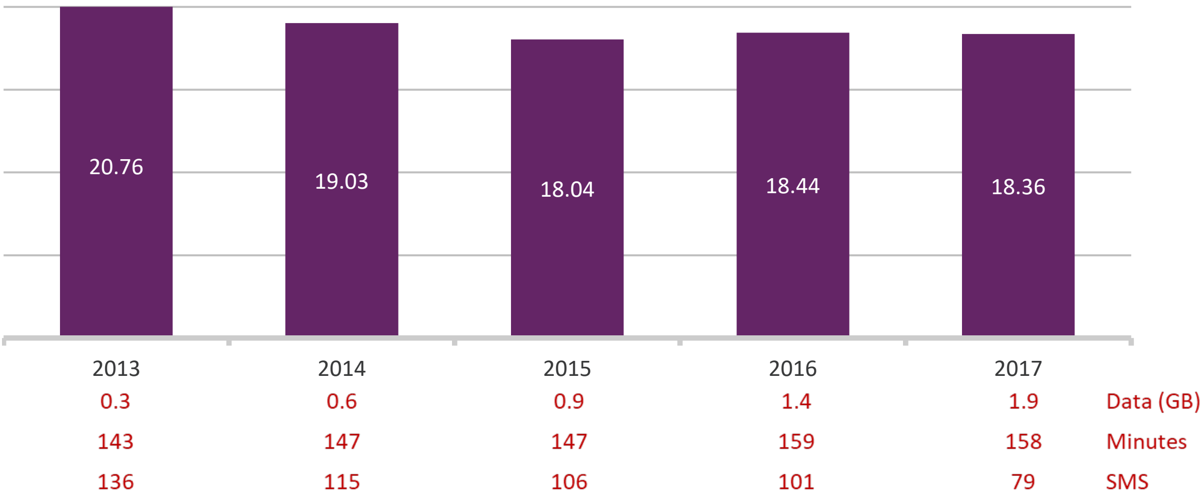
Source: Ofcom, using data provided by Teligen
Notes: Excludes handset cost; adjusted for CPI

A6.50 The 2018 Pricing report also looked at the pricing trends for different types of mobile users.[55] In real terms, basket prices decreased by 14.2% on average in 2017, notwithstanding the increase in prices for the lower use baskets (Basket 1, 2 and 3) for some years. As Figure A6.4 above shows, the basket with the largest data requirement (Basket 6) had the largest fall in price from 2014 to 2017.

A6.51 Enders noted that prices have remained steady instead of having a downward trend.[56] However, they attributed the recent upward trend to the higher cost of handsets rather than an increase in prices of mobile services. This is in line with one of the findings in our 2018 Pricing report, which shows that handset prices are contributing more to monthly prices than mobile services (Figure A6. below).

[55] 2018 Pricing trends for communications services, p.13
[56] Enders Analysis Report: "Covert growth in UK Mobile"

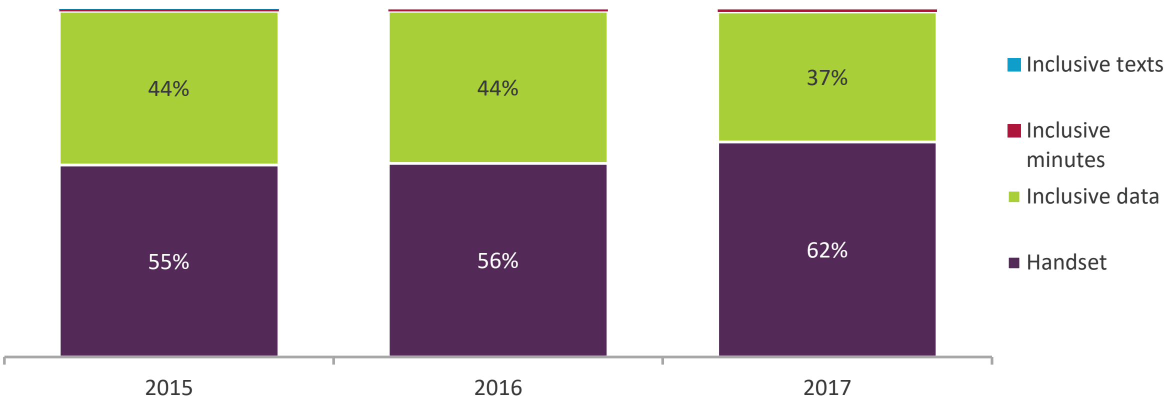
Figure A6.15: Weighted average monthly prices for average mobile use baskets (excluding handsets): 2013 to 2017 (£ per month)



Source: Ofcom, using data provided by Teligen; based on prices excluding handset costs; adjusted for CPI

A6.52 The weighted average price of a basket of mobile services (which changes over time to reflect shifting average) use fell by 11.5% in real terms to £18.36 per month between 2013 and 2017 (Figure A6.5). Over this period the average amount of mobile data consumed has increased five-fold.[57]

Figure A6.16: Relative weight of service factors in determining the monthly price of pay-monthly mobile services (%): 2016 to 2018



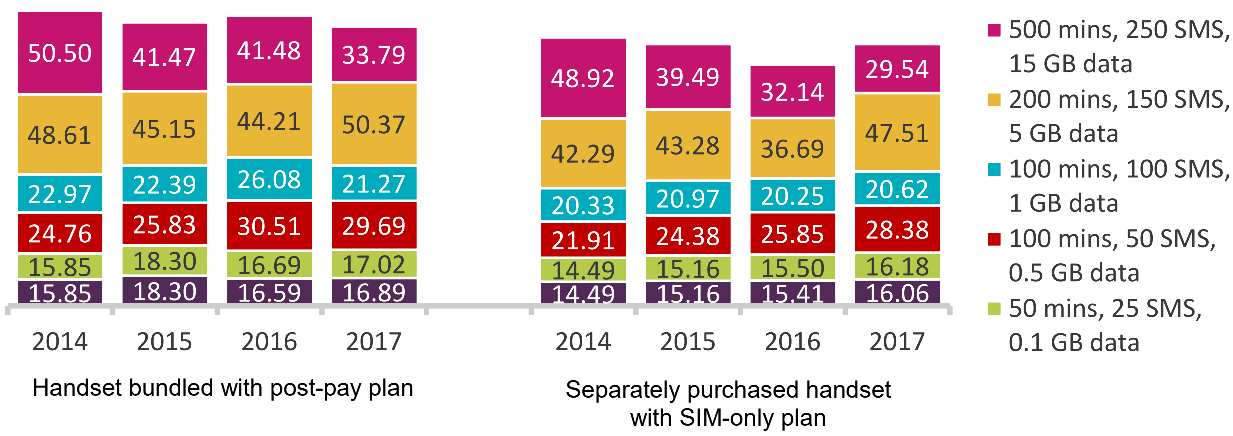
Source: Simplify Digital PCI model
Note: Based on 24-month pay-monthly contracts; Inclusive text amount range from 0% to 0.5%

A6.53 Simplify Digital's Price Competitiveness (PCI) model shows that between 2015 and 2017, the type of handset and inclusive data allowance were the most important factors in determining the price of pay-monthly mobile services (Figure A6.). The weighting of the handset in contributing to the monthly cost increased from 55% in 2015 to 62% in 2017.

[57] 2018 Pricing trends for communications services, p.12

This increase is likely to reflect increasing handset prices and declining mobile service pricing.

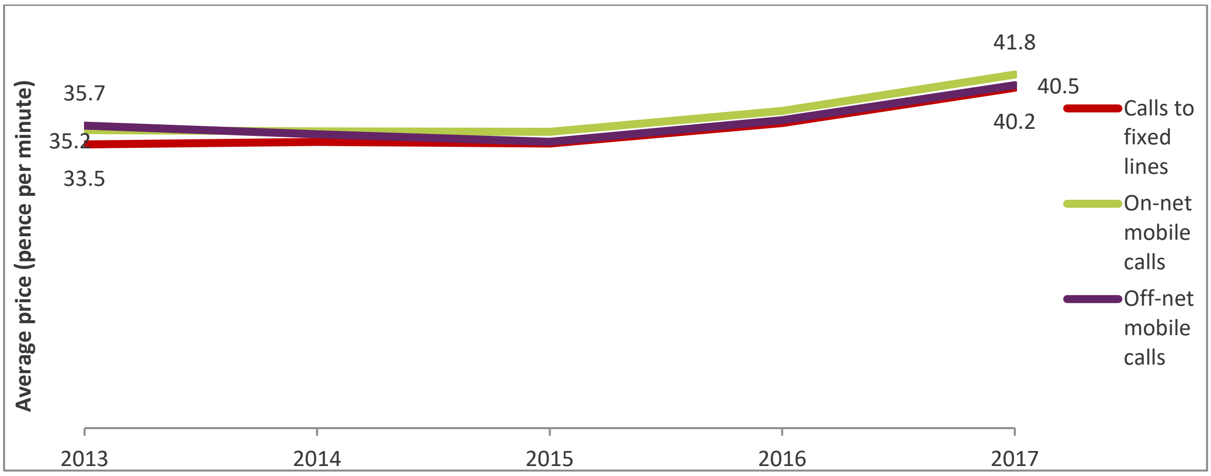
Figure A6.17: 'Weighted average' monthly price of a pay-monthly plan with handset and SIM-only plan with handset purchased separately: 2014 to 2017



Source: Ofcom, using data provided by Teligen

A6.54 SIM-only contracts with a handset purchased separately are cheaper than pay-monthly contracts which include a handset (Figure A6.17 above). According to our 2018 Pricing trends for communications services report, on average, buying mobile services with a phone included is around 7% more expensive than buying a phone separately and using a SIM-only contract.

Figure A6.18: Average out-of-bundle mobile call charges: 2013 to 2017 (pence per minute)



Source: Ofcom, using tariff data provided by Teligen
Notes: Excludes tariffs for which out-of-bundle call charges are not relevant for these call types; includes pay-as-you-go and pay-monthly tariffs; based on tariffs offered by EE, Orange, T-Mobile, O2, giffgaff, Vodafone, Three, Tesco Mobile, Virgin Mobile, Lebara and Lycamobile; includes VAT; adjusted for CPI.

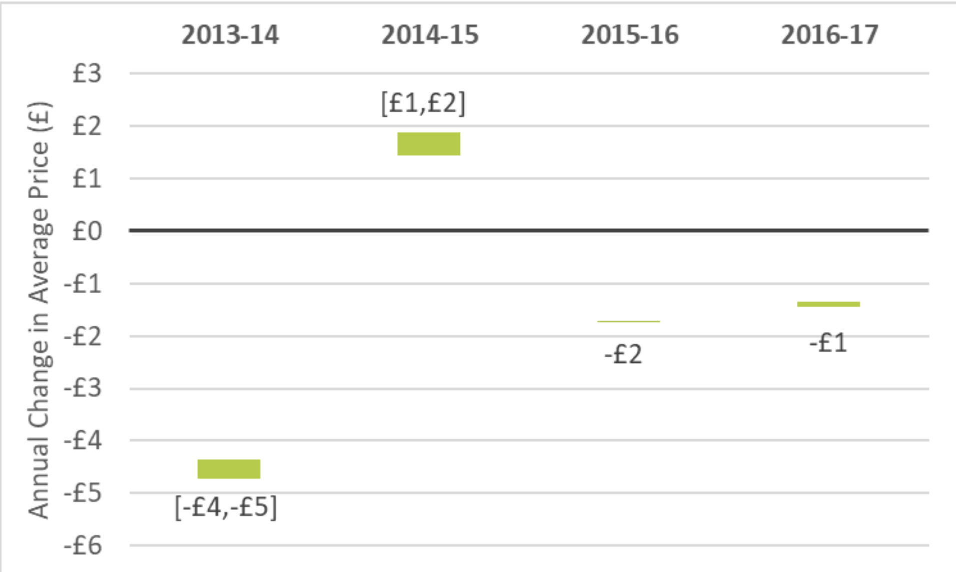
A6.55 Average out-of-bundle call charges increased between 13% and 20% in real terms between 2013 and 2017 (Figure A6.18), however, the proportion of pay-monthly tariffs that include 'unlimited' call minutes has increased, meaning that fewer services are subject to out-of-bundle charges for calls to UK landlines and mobiles.

Econometric approach

A6.56 In our report 'An econometric analysis of pricing trends in the UK, we used an econometric approach to estimate the change in mobile prices in the UK over time, controlling for relevant product features, firm-specific characteristics, handsets and time critical factors. Our analysis was based on tariffs with inclusive data allowances less than or equal to 20 GB.[58] More details on the methodology and modelling is outlined in our report.[59]

A6.57 We have estimated a range for the change in prices, represented in Figure A6.19 below by the upper and lower bounds of the green shaded area. For example, between 2013 and 2014, the monthly mobile prices of available post-pay tariffs with handsets fell by approximately £4-5. The findings suggest that, with the exception of the period 2014 to 2015, the prices of these tariffs are generally falling over time.[60]

Figure A6.19: UK mobile price trends for available post-pay plans including handsets for each year



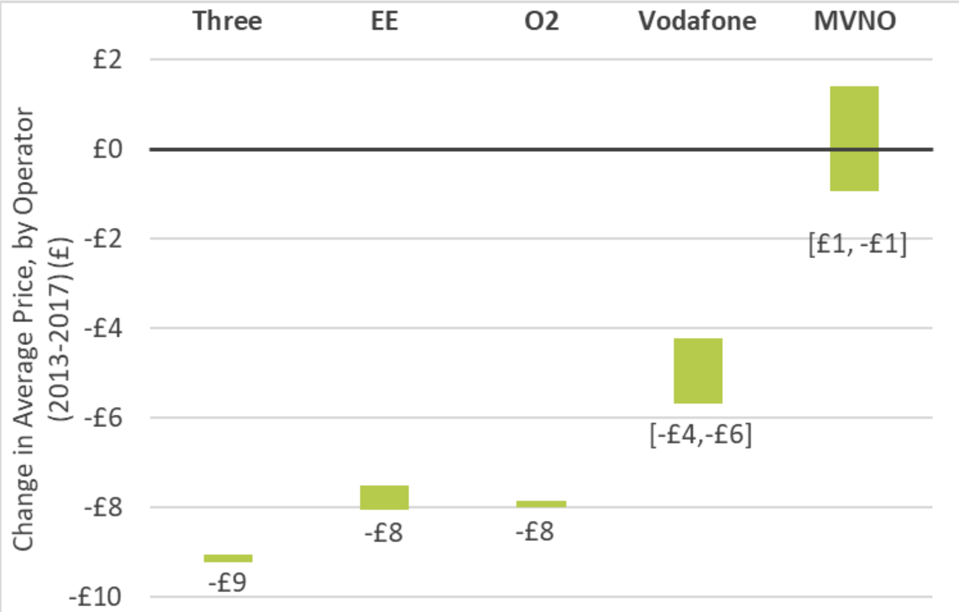
Source: UK mobile pricing trends: An econometric analysis report

A6.58 Our econometric approach also looked at the estimated pricing trend separately for each operator. As set out above, the analysis was based on tariffs with inclusive data allowances less than or equal to 20GB. The findings suggest that the average changes in prices over time varied across the operators. All MNOs decreased their prices over the period 2013–2017 (Figure A6.20 below). Prices declined more slowly for O2, EE and Vodafone compared

[58] Including tariffs with data allowances above 20GB would have led to results which were sensitive to data variations and so would not have provided robust price trends. Analysis from our Connected Nations report shows that average monthly data usage per person in 2017 was 1.9GB. This suggests that our decision to exclude tariffs with higher data allowances does not lead to a dataset which is unrepresentative of the prices paid by the wider population.
[59] See footnote 54.
[60] This effect was also observed in the 2.3 and 3.4 GHz consultation, where we considered that the price increase was possibly explained by an increase in the price of premium handsets and the additional cost of 4G packages.

to H3G, all else being equal. The results for MVNOs are mixed, but based on the preferred specification, MVNOs on average reduced their prices between 2013 and 2017.

Figure A6.20: UK mobile price trends for available post-pay plans including handsets for 2013 - 2017, by operator



International comparison of mobile prices

A6.59 The "Mobile Broadband Prices in Europe 2017" report, which was published by the European Commission, compared mobile broadband prices across the EU's member states as well as non-EU countries including the USA, Japan, South Korea, Norway, Iceland and Turkey.[61] The report compared handset mobile broadband price plans as well as those for tablets and laptops.

A6.60 The approach used for this report was the 2012 OECD methodology for mobile broadband, which calculated the total price of different baskets in order to identify the cheapest offers. It divided the offers into three types of mobile devices (handsets, tablets and laptops) and six usage baskets for each type of devices.

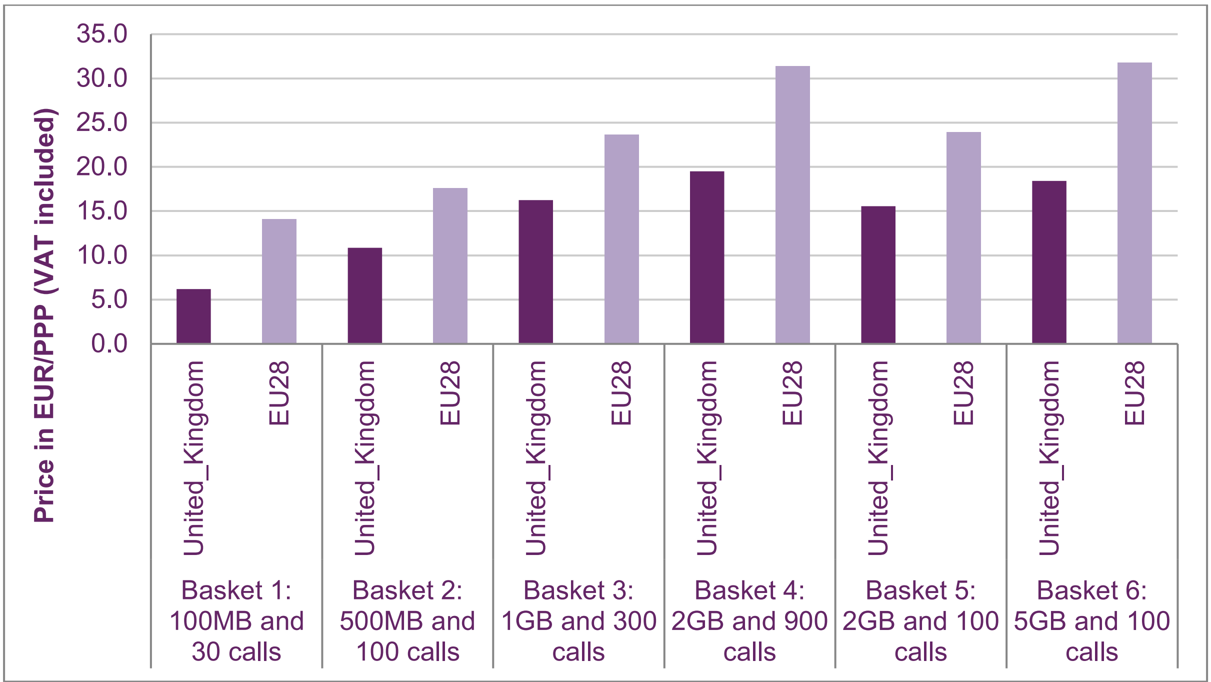
A6.61 The baskets used in the report have relatively low usage allowances. For example, the lowest basket for handset use included 100MB of data plus 30 number of calls, whereas the highest basket included 5GB of data and 100 calls. Laptop and tablet allowances ranged from 250MB and 20GB.

A6.62 The report found that the UK performed well compared to other EU countries with regards to handset plans. The UK was in the second cheapest cluster of countries (out of four clusters) for all but the first and fourth basket, which were in the cheapest cluster.

[61] See Mobile Broadband Prices Europe 2017.

A6.63 The UK handset plan prices were between 31% and 56% cheaper than the average of the 28 EU member countries (Figure A6.21).

Figure A6.21: Comparison of the least expensive handset offers UK vs. EU average



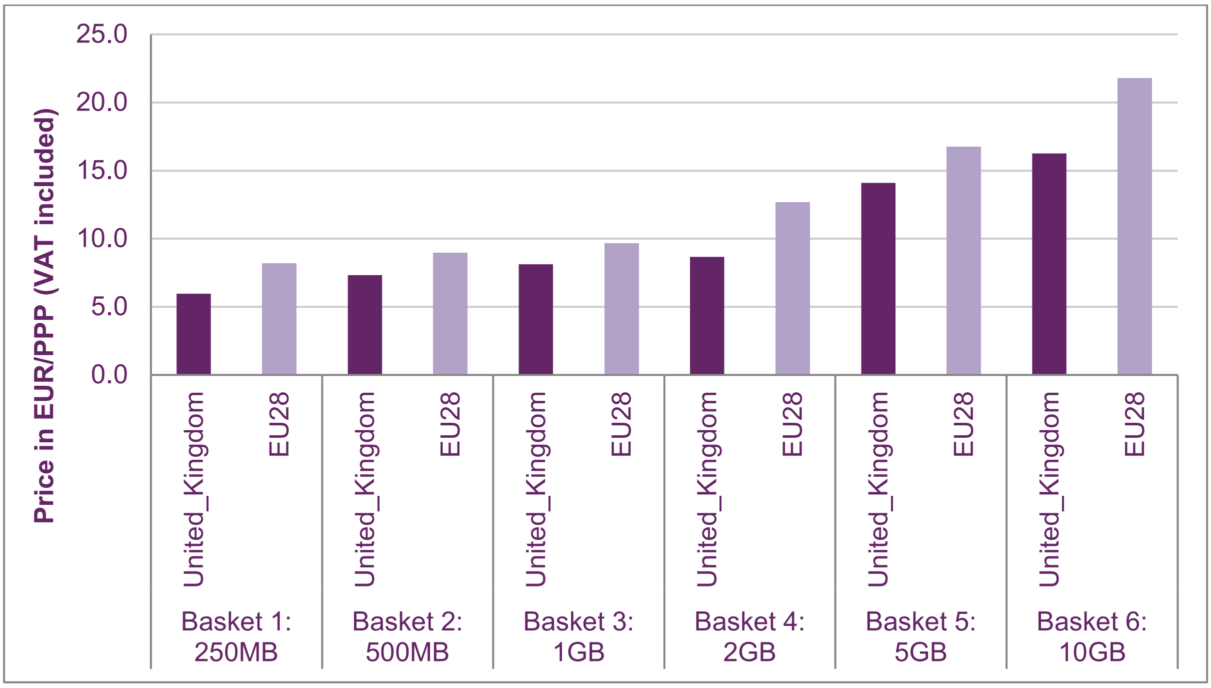
Source: EC Mobile Broadband Prices in Europe 2017 report – Simulation tool[62]

A6.64 With regards to laptop and tablet plans, the UK was in the second cheapest cluster for the baskets with data allowances between 256MB and 10GB, and in the cheapest cluster for the basket with data allowance of 20GB.

A6.65 For tablet plans, the UK was up to 32% cheaper than the EU average for all baskets (Figure A6.22).

[62] See EC Mobile Broadband Prices in Europe 2017 Report - Simulation tool

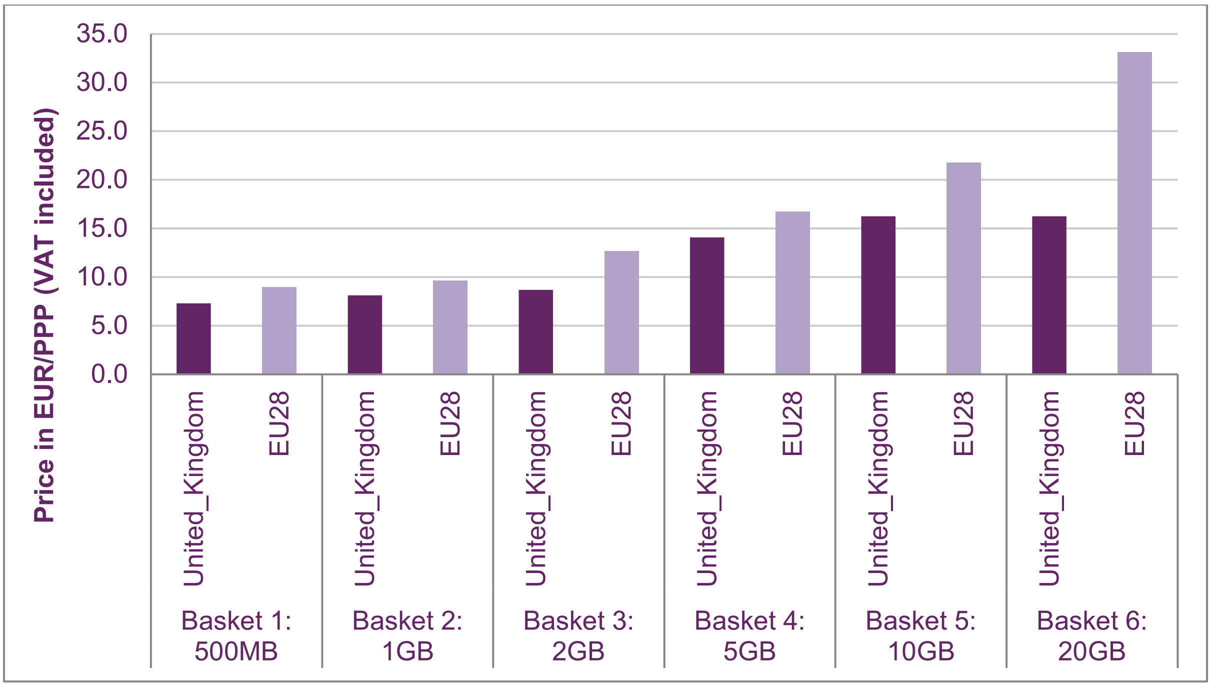
Figure A6.22: Comparison of the least expensive tablet offers UK vs. EU average



Source: EC Mobile Broadband Prices in Europe 2017 report – Simulation tool

A6.66 In line with the tablet plans, the UK's laptop plans were up to 51% less expensive than the EU average (Figure A6.23).

Figure A6.23: Comparison of the least expensive laptop offers UK vs. EU average



Source: EC Mobile Broadband Prices in Europe 2017 report – Simulation tool

A6.67 The report also found that, compared to 2016, prices of UK handset plans decreased by at least 14% in 2017, with decreases of up to 46% in the higher-end baskets. Tablet and laptop plans were between 32% (for 10GB data) and 62% (1GB data) less expensive than last year.

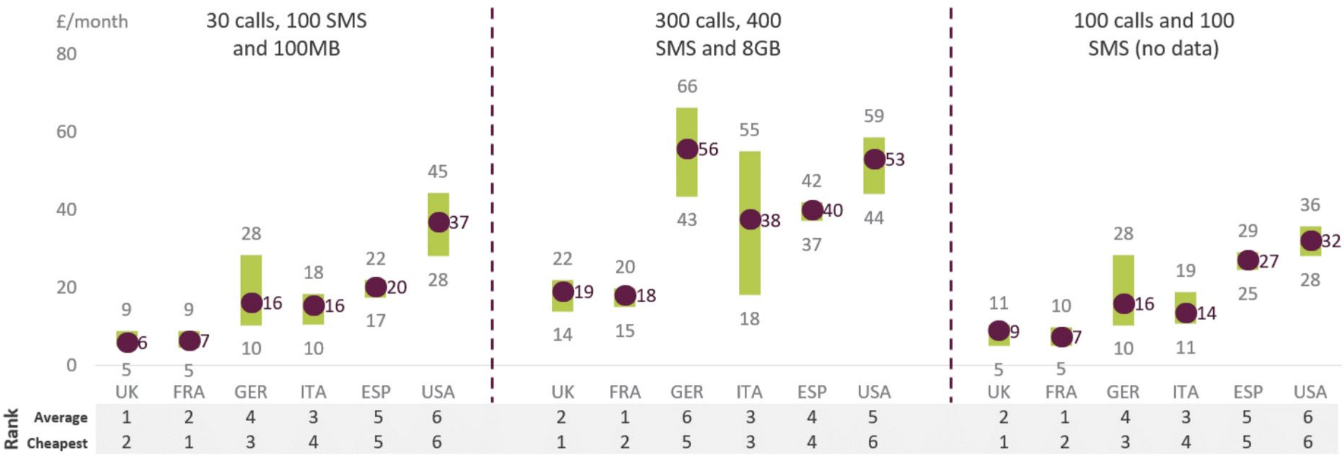
A6.68 The Telecompaper report[63] is in line with the European Commission's report discussed above. The study looked at the total cost of ownership (TCO) of a mobile plan, both with and without a high-end smartphone included in the plan, and compared the lowest and median prices on offer in each of 16 European country, after correcting for purchasing power parity (PPP).[64]

A6.69 This report found that the UK fell into the range of 'mostly cheap' countries, as UK's median was below the median of the 16 countries in most categories.

A6.70 Ofcom's 2017 International Communications Market Report compared three mobile basket prices for six countries: the UK, France, Germany, Italy, Spain and the USA.[65] Handset costs were excluded but selective discounts, such as 'friends and family' calls, were included.

A6.71 Across the three mobile phone baskets used in our analysis, the UK ranked either first or second out of the six countries (after France) in terms of average and lowest available prices (Figure A6.24).

Figure A6.24: Comparative mobile phone pricing



Source: Ofcom, using data provided by Teligen
Note: The purple dot shows the weighted average price across the providers included in the analysis, while the green bar shows the range of prices available.

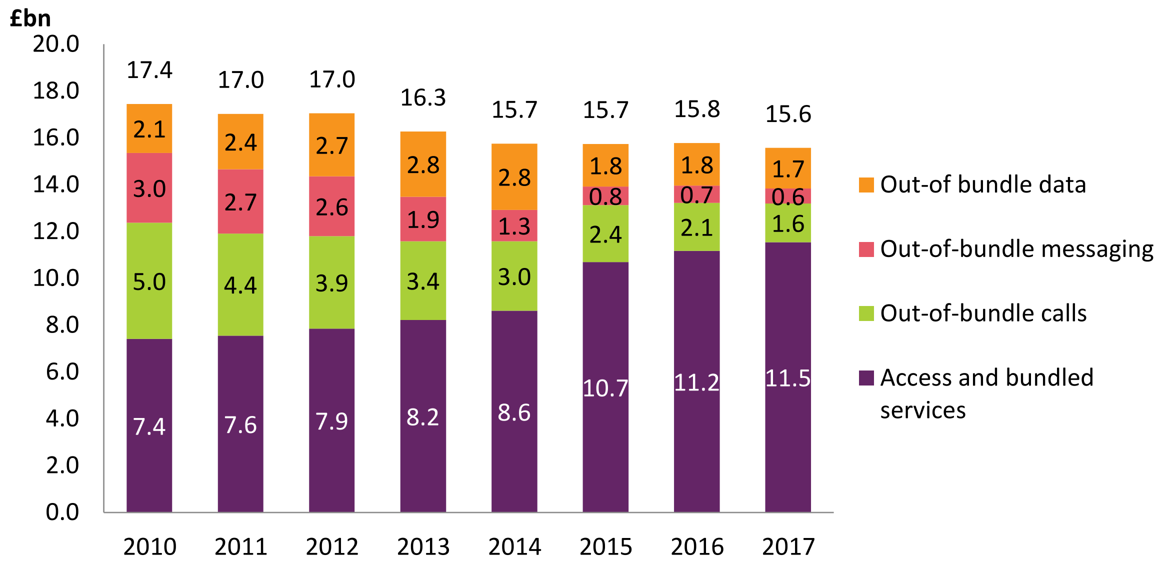
---

[63] See Telecompaper Mobile Prices Report
[64] Austria, Belgium, Denmark, Finland, France, Germany, Greece Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the UK
[65] Ofcom 2017 International Communications Market Report

Mobile revenues

A6.72 Mobile retail revenue stabilised in real terms between 2014 and 2017, having experienced a decrease from 2012 to 2014 (Figure A6.25). The composition of mobile retail revenue has changed over the years. Revenues from out-of-bundle messaging and calls have been decreasing since 2010. Out-of-bundle messaging revenue fell by 80%; and out-of-bundle calls revenue fell by 68% between 2010 and 2017. In contrast, access and bundled services revenue grew by £4.1bn over the same period, equivalent to an increase of 55%.

Figure A6.25: Mobile retail revenue by service



Source: Ofcom CMR 2018

Note: Data have been adjusted for CPI (2017 prices)

A6.73 Mobile retail revenue stabilised in real terms between 2014 and 2017, having experienced a decrease from 2012 to 2014 (Figure A6.25). The composition of mobile retail revenue has changed over the years. Revenues from out-of-bundle messaging and calls have been decreasing since 2010. Out-of-bundle messaging revenue fell by 80%; and out-of-bundle calls revenue fell by 68% between 2010 and 2017. In contrast, access and bundled services revenue grew by £4.1bn over the same period, equivalent to an increase of 55%.

A6.74 There are differences in the average retail revenue per subscriber between the different operators. [✄ REDACTED].

Figure A6.26: Average monthly retail revenue per pre-pay subscriber

[✄ REDACTED]

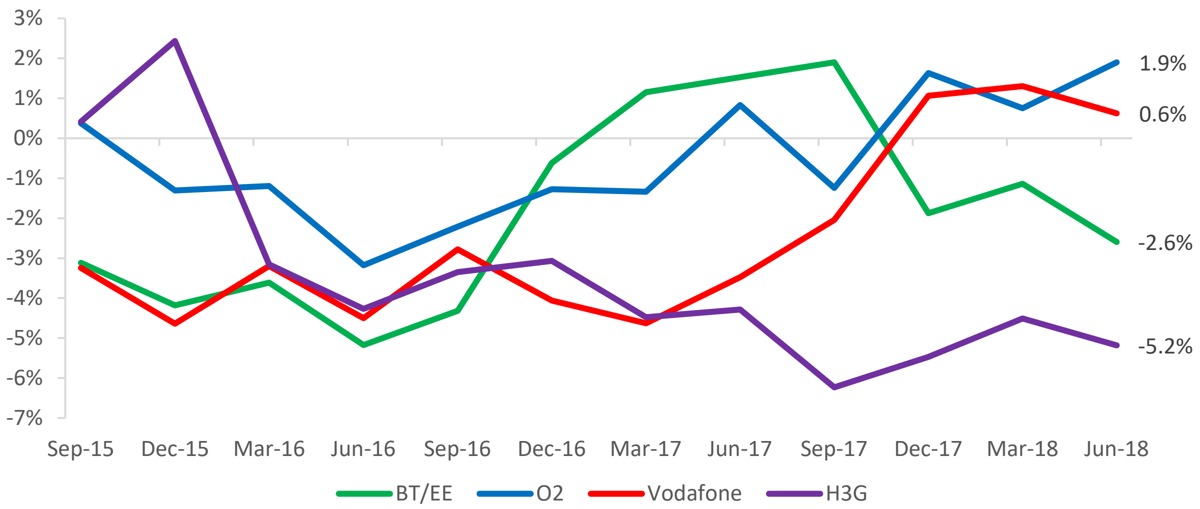
A6.75 Average post-pay retail revenue per customer[66] trends are different between the different operators. [✂ REDACTED].

Figure A6.27: Average monthly retail revenue per post-pay subscriber[67]

[✂ REDACTED]

A6.76 According to Enders Analysis, Vodafone and O2 experienced a growth in their contract ARPU, whilst BT/EE and H3G experienced a contraction in Q2 2018. H3G's contract ARPU growth continued to lag behind that of other MNOs in Q2 2018. O2 had the highest growth in the recent quarter.

Figure A6.28: Contract ARPU growth[68]



Source: Enders Analysis

A6.77 Overall, average monthly retail revenue for both pre-pay and post-pay customers has continued to decrease [✂ REDACTED].

Financial position of the MNOs

A6.78 In terms of MNOs' financial performance, we focus on EBITDA minus capex, which is a measure of the current operational earnings of their mobile businesses less capital expenditure. This measure abstracts from different forms of financing the business by ignoring interest payments and the treatment of depreciation and amortisation, providing an indication of the underlying financial strength of the business. In addition, we also compare the EBITDA margin between MNOs.

A6.79 We conclude that currently all MNOs appear to be financially viable.

[66] These figures include monthly handset revenues but not handset one-off fees.
[67] [✂ REDACTED]
[68] The contract ARPU figures for the Q2 2018 are in accordance with IFR15, aside from for Vodafone. This means that data for BT/EE, O2 and H3G at Q2 2018 were adjusted to remove the impact of handset financing.

A6.80 Table A6.3 below shows O2's EBITDA minus capex for the period 2012 to June 2018 (calendar years).

Table A6.3: O2's financial results[69]

£ millions	2012	2013	2014	2015	2016	2017
Revenues	5,711	5,682	5,692	5,690	5,605	5,729
EBITDA	1,298	1,359	1,406	1,400	1,396	1,436
Capex (including spectrum)	607	1,176	609	641	761	724
Capex (excluding spectrum)	607	565	609	641	761	724
EBITDA minus capex (including mobile spectrum purchases)	692	183	797	759	636	711
EBITDA minus capex (excluding mobile spectrum purchases)	692	794	797	759	636	711
EBITDA margin[70]	23%	24%	25%	25%	25%	25%

A6.81 We show EBITDA minus capex, both when mobile spectrum purchases are included within capex and when such purchases are excluded in order to isolate the effects of infrequent but significant purchases. For O2, there is a large increase in its capex in 2013 due to the £550 million (or €719 million) that it spent in the 2013 auction to obtain 2 x 10 MHz of 800 MHz spectrum.

A6.82 In the first half of 2018, the EBITDA minus capex was negative when the spectrum purchase of £318 million (€588 million) from the 2.3 and 3.4 GHz auction is included within capex. Therefore, EBITDA minus capex excluding spectrum purchases and EBITDA margin are a better measure of O2's financial viability. The EBITDA margin has been relatively consistent over this period, between 23% and 27%.

A6.83 H3G's EBITDA minus capex over the period 2012 to 2017 is shown below (Table A6.4). The table shows that the underlying financial position of H3G's business has strengthened over the period between 2012 and 2016, as shown by the increasing trend in EBITDA minus capex and EBITDA margin. According to H3G's 2017 annual report, the decrease in EBITDA in 2017 was mainly due to higher operating expenses on account of their network and IT infrastructure transformation programme.

Table A6.4: H3G UK's financial results[71]

£ millions	2012	2013	2014	2015	2016	2017
Revenues	1,948	2,044	2,063	2,195	2,276	2,425
EBITDA	281	417	547	686	719	702
Capex (including spectrum)	250	509	323	570	352	461

[69] From Telefónica's audited annual reports for 2012, 2013, 2014, 2016 and 2017. Using €/£ exchange rate published by Telefónica, namely, 0.811 for 2012, 0.849 for 2013, 0.806 for 2014, 0.726 for 2015, 0.817 for 2016 and 0.876 for 2017.
[70] We calculated EBITDA margin with the following formula: EBITDA/Revenues. We did not gather the EBITDA margin from the MNOs' financial accounts/reports.
[71] Sources: From H3G's annual reports: Annual Report 2012, p.64 ; Annual Report 2012, p.64 ; Annual Report 2015, p.60 (for 2014 and 2015); Annual Report 2016, p.56 ; Annual Report 2017, p.54

Capex (excluding spectrum)	250	271	323	358	352	459
EBITDA minus capex (including mobile spectrum purchases)	31	-92	224	116	367	241
EBITDA minus capex (excluding mobile spectrum purchases)	31	146	224	328	367	243
EBITDA margin[72]	14%	20%	27%	31%	32%	29%

A6.84 Vodafone's EBITDA minus capex over the period of 2012 to 2018 (fiscal years) are shown in Table A6.5. Over the period, EBITDA minus capex has stayed positive over the period. Vodafone's problems during the implementation of a new billing system is reflected by decreases in EBITDA minus capex and EBITDA margin in 2017. Vodafone has resolved its billing system and it appears that it did not had an impact on its performance in 2018 with EBITDA minus capex and EBITDA margin being the highest for the last 7 years.

Table A6.5: Vodafone UK's financial results[73]

£ millions	2012	2013	2014	2015	2016	2017	2018
Revenues	5,397	5,150	6,427	6,414	6,173	5,817	6,229
EBITDA	1294	1209	1418	1360	1289	1,018	1,551
Capex (including spectrum)	575	601	-	-	-	-	-
Capex (excluding spectrum)	-	-	932	980	867	798	782
EBITDA minus capex (including mobile spectrum purchases)	719	608	-	-	-	-	-
EBITDA minus capex (excluding mobile spectrum purchases)	-	-	486	380	422	220	768
EBITDA margin[74]	24%	23%	22%	21%	21%	18%	25%

A6.85 BT/EE's EBITDA minus capex has been positive over the period from 2012 to 2018 (Table A6.6). It appears to have weakened in 2016 but the main reason for the decrease in EBITDA minus capex and EBITDA margin was due to change in accounting treatment of EE's financial account when BT merged with EE.[75]

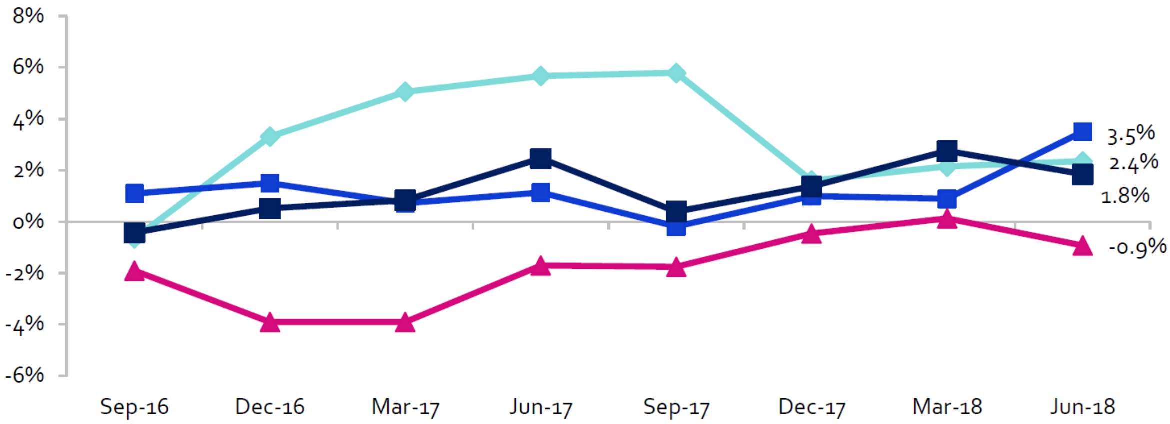
[72] See footnote 70
[73] From Vodafone's annual reports for all the years.
Vodafone's annual statement for years 2012 and 2013 did not define capex as excluding spectrum purchases thus we assumed that capex in these years included spectrum purchases. In years 2014 and beyond, capex is defined to exclude spectrum purchases.
For years 2017 and 2018, "EBITDA" was changed to "Adjusted EBITDA". In these years, Vodafone started reporting in Euros (€) instead of UK sterling (£). Using €/£ exchange rate published by Vodafone, namely, 0.84 for 2017 and 0.88 for 2018.
[74] See footnote 70
[75] Calendar years were used in financial statements of EE Ltd. BT used financial years in their statement for 2016 to 2018, meaning 2016 figures only reflects 3 months (January to March) instead of a full year.

Table A6.6: BT/EE's financial results[76]

£ millions	2012	2013	2014	2015	2016	2017	2018
Revenues	6,657	6,482	6,327	6,311	841	5,090	5,294
EBITDA	1,105	1,313	1,030	1,672	173	1,156	1,353
Capex (excluding spectrum)	649	583	596	594	96	616	628
EBITDA minus capex (excluding mobile spectrum purchases)	456	730	434	1078	77	540	725
EBITDA margin[77]	17%	20%	16%	26%	21%	23%	26%

A6.86 According to Enders Analysis, O2, H3G and BT/EE continued to have positive mobile revenue growth in Q2 2018, but Vodafone's revenue growth turned negative (Figure A6.29).

Figure A6.29: Reported mobile service revenue growth



From June 2018 growth figures are *pro forma* of IFRS 15, excluding Vodafone.
*Adjusted to remove revenue impact of O2 Refresh.
†Adjusted to remove impact of handset financing.

Source: Enders Analysis

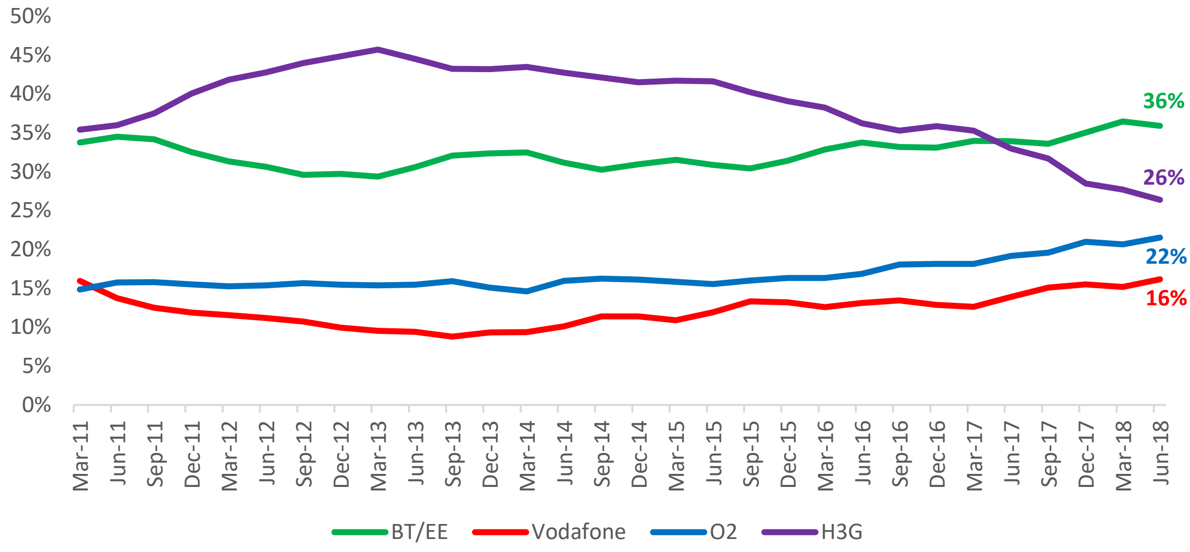
A6.87 Overall, the measurements presented above indicate that all MNOs appear to be financially viable. EBITDA minus capex has continued to be positive, and EBITDA margins are generally improving. Mobile service revenues have continued to grow, apart from Vodafone, but Vodafone had the highest contract net adds in the most recent quarter as shown in Figure A6.8 above.

Mobile Data Traffic

A6.88 The share of data carried by the networks of the four MNOs is very different to their subscriber shares. As shown in Figure A6.30, H3G, with the lowest wholesale share (Figure A6.5), has the second highest data share (26% of total data in Q2 2018).

[76] From EE Ltd's financial statement for 2012 to 2015, and BT annual group report for 2016 to 2018.
[77] See footnote 70

Figure A6.30: Data traffic share on MNOs' networks



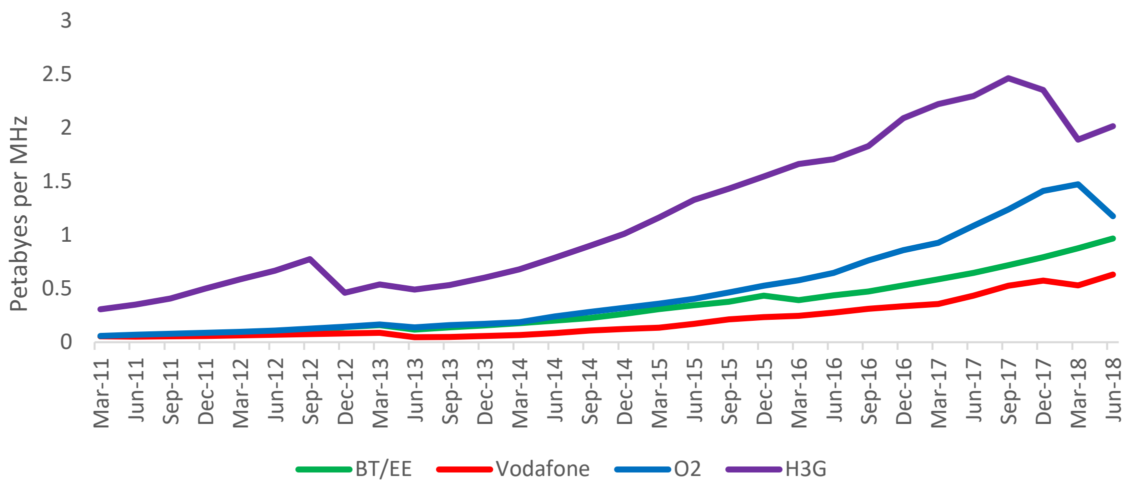
Source: Enders Analysis

A6.89 According to the latest report by Enders Analysis, in Q2 2018 Vodafone had the highest data growth out of all MNOs at 64% while H3G had a slight increase at 13%. Data growth for BT/EE and O2 was 49% and 58% respectively.

A6.90 BT/EE's data share rose above that of H3G for the first time around the second half of 2017 and has remained above it since then. H3G's data growth rate fell significantly from 35% to 13% between Q3 2017 and Q2 2018, which suggests a strategy to manage data growth on its network by increasing the price of 'All You Can Eat' offers and using traffic management techniques.[78]

[78] See https://www.independent.co.uk/life-style/gadgets-and-tech/news/tariff-almost-doubles-on-threes-all-you-can-eat-mobile-phone-contract-a6843656.html and http://support.three.co.uk/SRVS/CGI-BIN/WEBISAPI.DLL?Command=New,Kb=Mobile,Ts=Mobile,T=Article,varset_cat=signal,varset_subcat=3804,Case=obj(4046)

Figure A6.31: Mobile data traffic per MHz of MNOs' spectrum holdings[79]



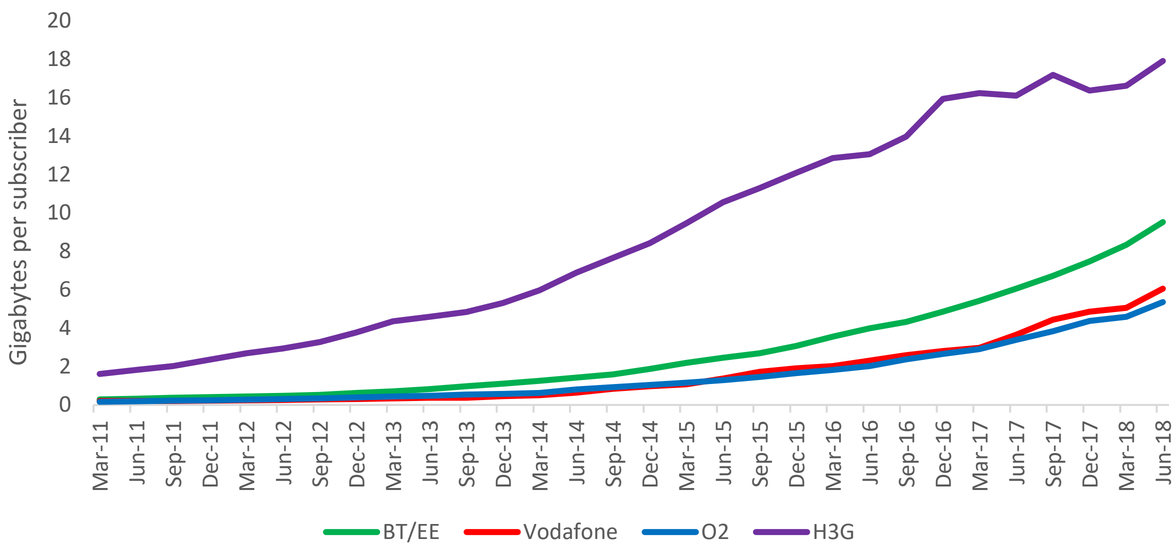
Source: The mobile data traffic is from Enders Analysis and MNOs' spectrum holdings are from Ofcom

A6.91 This is consistent with the trend shown in Figure A6.31 where H3G has continued to have the highest data traffic per MHz of its spectrum, despite a decline between Q3 2017 and Q1 2018. The increase in H3G's data traffic per MHz in the recent quarter may be due to H3G's 'Go Binge' offer translating to higher data consumption. O2's mobile data per MHz decreased between Q1 2018 and Q2 2018. This is however more likely to be a reflection of the immediate deployment of the additional 40 MHz in the 2.3 GHz band acquired in the 2.3 and 3.4 GHz spectrum auction.

A6.92 H3G's data consumption per subscriber rose until Q4 2016, and then stabilised for the whole year of 2017 on a quarterly basis and Q1 2018 (Figure A6.32). This again may reflect H3G's management of data traffic in their network.

[79] Spectrum holdings was the useable spectrum at the time. Q1 2011 to Q3 2012 includes holdings of 900 MHz, 1800 MHz and 2.1 GHz. Then, at Q4 2012, EE divested 30 MHz of 1800 MHz band to H3G. The 4G auction increased the useable pool of spectrum to include 800 MHz and 2.6 GHz (paired and unpaired) in Q2 2013. The CMA approved the acquisition of EE by BT in 2016 so from Q1 2016, EE started using the undeployed 50 MHz of 2.6 GHz which BT won. As of Q1 2018, we assume that 1400 MHz becomes useable, and 2.3 GHz has been useable since Q2 2018.

Figure A6.32: Quarterly mobile data consumption per subscriber[80]



Source: The mobile data traffic is from Enders Analysis and network subscribers, which include hosted MVNO subscribers, are from Analysys Mason. [81]

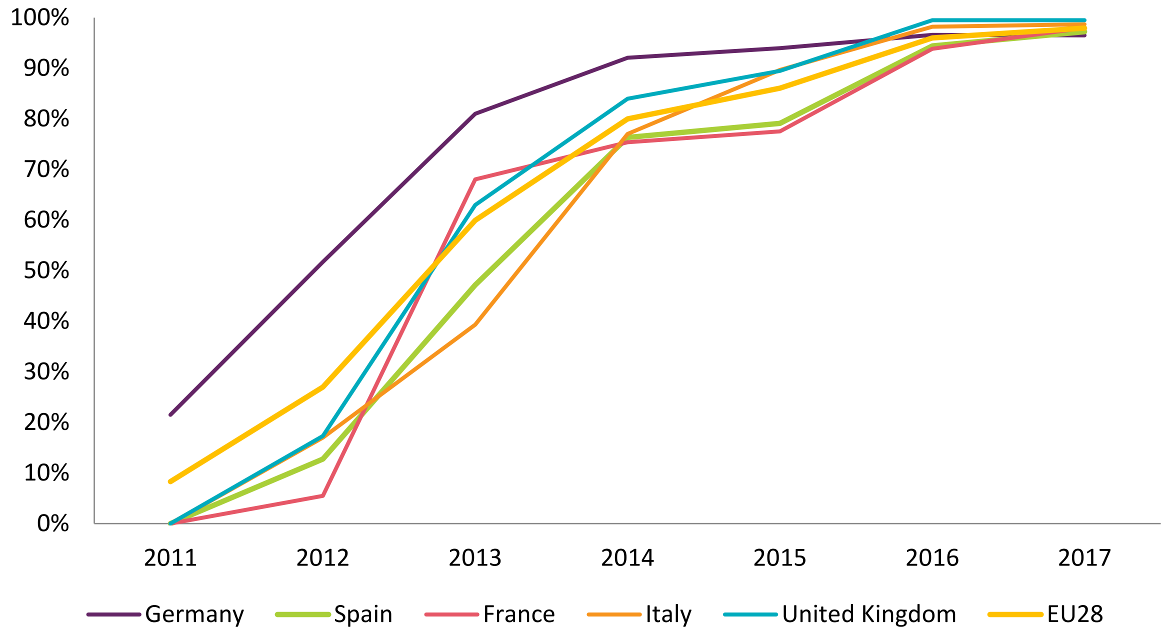
A6.93 We discuss the future growth of mobile data traffic in Annex 7.

[80] The graph shows mobile data consumption per subscriber per quarter instead of monthly because mobile data traffic from Enders Analysis and network subscribers from Analysys Mason are provided in quarterly figures.

[81] The overall average monthly data usage per subscriber using these sources is 2.79GB. We note that this is slightly higher than the figure published in our Connected Nations Report 2018, where the same methodology but a different source (operator data) was used.

International comparison of network quality

Figure A6.33: European 4G network availability, percentage of population[82]

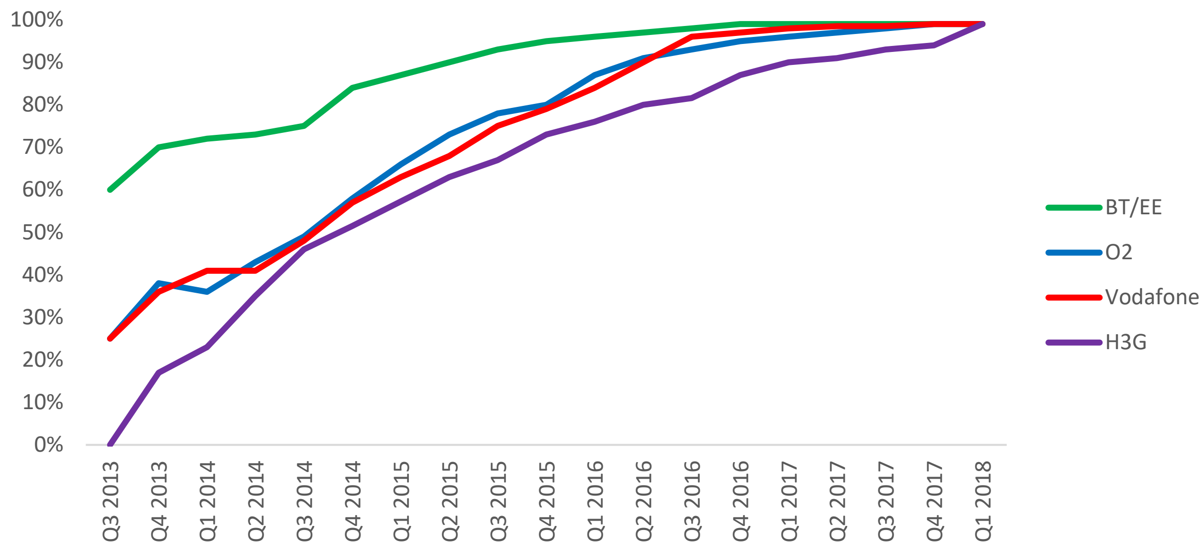


Source: EU Digital Agenda Scoreboard

A6.94 In our Digital Communications Review,[83] we carried out a comparison of international 4G deployment. We have also carried out a similar analysis with the most recent data we have available. We find that the UK is still broadly in line with its EU5 peers in terms of 4G deployment. Germany had the highest 4G coverage, in terms of percentage of population, until 2015. The UK had a higher 4G coverage than Germany, in terms of percentage of population covered, in 2016 and 2017 (Figure A6.33). The UK's 4G coverage has been higher than the average of EU28 countries since 2013.

[82] See European Digital Scoreboard 4G Mobile Broadband Coverage
[83] Digital Communications Review, p.22

Figure A6.34: UK MNOs 4G network roll-out (% of the population)



Source: Enders Analysis

A6.95 In addition to our own findings, recent data from Enders Analysis shows that all UK MNOs had reached a 4G coverage of 99% of the population (Figure A6.34) in Q1 2018. BT/EE reached a 4G coverage of 99% of the population in Q4 2016, which was earlier than the other MNOs. From Q3 2013 to Q4 2017, BT/EE had the highest 4G coverage. Over the same period, O2 and Vodafone had similar 4G coverage to each other. H3G's 4G coverage was the lowest out of all the MNOs until recently.

A6.96 We note that the above data from Enders focuses on coverage of population, rather than landmass. As we explain in Annex 11, we consider that there are limits to the extent that the market and MNOs' commercial decision can deliver further increases in coverage, particularly in areas that are sparsely populated. We also note that, even at these relatively high levels of population coverage that competition has contributed to delivering, there are still some areas where people live and move about that good quality coverage is not present, and where there would be further social benefit in coverage footprints expanding.

Factors considered by mobile consumers when choosing provider

Introduction

A6.97 This section considers specific consumer drivers for choosing a mobile network. Here we extend earlier consumer-related discussion on market trends including overall subscriptions, rates of churn and market share. We assess the reasons consumers report for choosing a mobile network, revealing what they specifically value from a mobile service, and hence what factors may drive retail competition. Reasons for choosing a network vary across consumer surveys but key drivers largely fall within a few areas:

- Price level - the cost of the whole service. The individual services offered in the mobile contract/plan act as a function of price. However, the 'price-plan' is considered as an additional consideration beyond price so consumer views are measured separately.
- Quality of the Network experience – this includes aspects such as reliability, coverage, download and upload speeds, latency, webpage browsing times, call quality and call success rates.
- Price plan/Bundle – what services are included, for example data allowance and speed, call and text allowance.
- Device – both the availability as part of the price plan and the range of handsets available. This factor also acts as a function of the price plan and therefore price.
- The quality of Customer Service – which includes the ease of making contact, the courtesy and politeness of advisors and willingness to help resolve issues.

A6.98 We considered these factors in our July 2017 Statement on the 2.3 GHz and 3.4 GHz PSSR Award and identified that price and network quality were the most essential drivers of consumer choice of mobile service provider. We also considered the impact of peak speeds on consumer experience and competition. [84]

A6.99 Since then, we have updated our analysis based on Ofcom Consumer Engagement Quantitative Research[85], Enders Analysis research published in 2018[86], the 2018 Ofcom Customer Satisfaction Tracker[87], and the Which? 2018 report on "Best and worst UK mobile networks".[88]

A6.100 In summary, little has changed. Price and network quality remain the key drivers of consumer decisions about which service provider to choose.

A6.101 Exploring network quality specifically, reliability and coverage are viewed as the most important factors for quality. Data speeds are considered significantly less important, but this figure has grown marginally since 2014 (there has been no change in rates since 2016).

A6.102 The demand for data (volume) generally continues to increase, this is largely driven by 4G penetration. That said, most consumers still consider making calls and browsing the web the most important mobile services.

A6.103 On the whole, consumers continue to express reasonably high levels of satisfaction with their mobile service (91%), and their signal strength/reception (84%). This is true across the board for all four of the Mobile Network Operators. MVNOs tend to experience particularly high customer satisfaction rates. The rural urban divide remains, and customer satisfaction rates are significantly lower for rural consumers.

[84] https://www.ofcom.org.uk/__data/assets/pdf_file/0013/104305/Statement-annexes-Award-of-the-2.3-and-3.4-GHz-spectrum-bands.pdf

[85] https://www.ofcom.org.uk/research-and-data/multi-sector-research/general-communications/consumer-engagement-with-communication-services

[86] http://www.endersanalysis.com/publications?date%5Bvalue%5D%5Bdate%5D=&title=covert+growth+in+mobile

[87] Customer Satisfaction Tracker Summary of Research Findings 2018

[88] https://www.which.co.uk/reviews/mobile-phone-providers/article/best-mobile-networks-overview - Which?

A6.104 Ofcom Consumer Engagement Quantitative Research undertaken in 2018 reports that price and network coverage are key priorities over other considerations (including price plan and data allowance and use). Price, whether of their previous contract or on their new contract, was mentioned by 70% and 65% of respondents respectively when asked what factors they considered when they took out their current mobile phone deal. 56% of respondents listed coverage and reliability**.** 43% listed how much data they would get with their plan.[89]

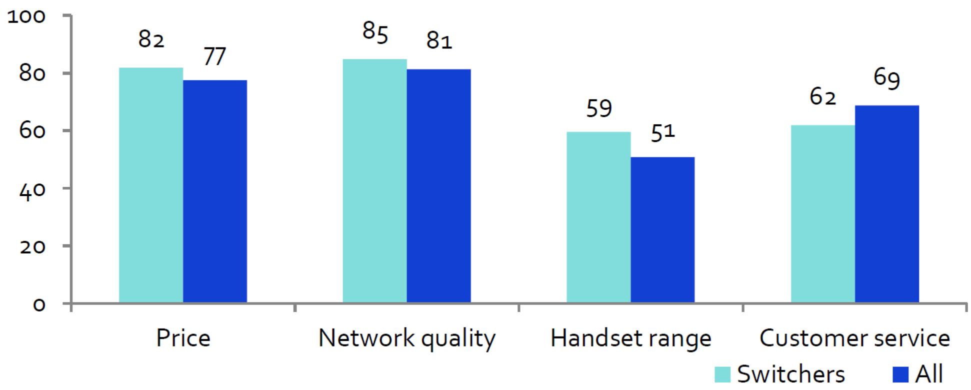
Figure A6.35: Ofcom Consumer Engagement Quantitative Research 2018 - What did you consider when taking out your current mobile phone deal?

	Mobile
How much you had been paying each month	70%
How much data you were using each month	54%
How many minutes or calls you were using each month	42%
How many texts you were sending each monthc	36%
What types of internet/ online activities you were using mobile data for	23%
What types of numbers you were calling at the time	15%
TOTAL USAGE	**89%**
How much you would pay each month	65%
How much mobile data you would get each month	43%
How many minutes for calls you would get each month	37%
The upfront cost of the handset	35%
The deals available for the handset you wanted	35%
How many texts would be included in your allowance each month	33%
What added extras would be included	13%
TOTAL DEAL	**84%**
Coverage and reliability	56%
Reputation/ good customer service	38%
TOTAL SERVICE	**65%**

A6.105 Enders Analysis[90] reports a similar pattern, although placing network quality as a more important factor than price for most consumers.

[89] https://www.ofcom.org.uk/research-and-data/multi-sector-research/general-communications/consumer-engagement-with-communication-services
[90] http://www.endersanalysis.com/publications?date%5Bvalue%5D%5Bdate%5D=&title=covert+growth+in+mobile published in 2018 based on 2017 survey.

Figure A6.36: Enders Analysis assessment of features considered when choosing a mobile network provider



Base: Mobile phone owners 16+; switchers comprise the subset of users that switched operators in the 24 months to July 2017
Figures rebased from scale where 1 = not at all important and 5 = most important
[Source: Enders Analysis/TNS-RI survey July 2017]

A6.106 As shown in Figure A6.36, Enders Analysis reported that network quality is the number one priority for customers, followed by price, customer service and then handset range. This remains the case for consumers who have changed operators ("switchers"). Switchers are more likely to report network quality, price and handset range as the most important factors when choosing a mobile provider.

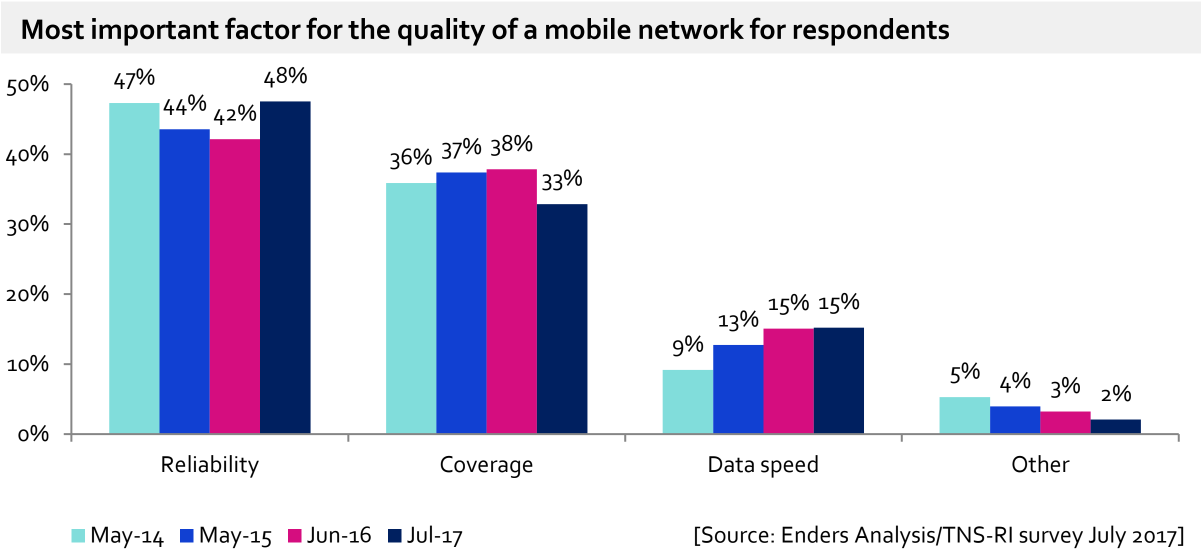
Coverage and reliability

A6.107 As stated earlier, network quality is a broad concept, covering aspects such as reliability, coverage, download and upload speeds, latency, webpage browsing times, call quality and call success rates. Some of these parameters are interrelated, for example coverage and download speed taken together could be consider important for consumers to qualify a network as 'reliable'.

A6.108 Figure A6.37 shows Enders Analysis research published in 2018[91] on the most important factor for the quality of a mobile network. Reliability is considered the most important, with coverage being a very close second consideration (coverage and reliability are closely linked and are often used interchangeably to describe difficulty gaining access to the network, equally where mobile coverage is available people report a good experience with reliability for example call quality). Data speeds are considered significantly less important.

[91] Enders Analysis published in 2018 however based on a survey undertaken in 2017.

Figure A6.37: Enders Analysis assessment of factors to determine quality



A6.109 **Global Wireless Solutions**[92] also reports that, when asked to consider the 5 most important factors for choosing a network, respondents were twice as likely to identify reliability over network speed.

Customer satisfaction

A6.110 **Which?**[93] conducts an annual satisfaction survey of mobile networks, asking almost 3,700 people about a number of aspects of their mobile phone service including customer service, ease of contact and value for money. It also awards each provider an overall customer score by considering how satisfied each person is with their provider and how likely they were to recommend it. In total, 13 MNOs and MVNOs were considered in its most recent survey. The overall customer scores for the MNOs based on a survey that Which? carried out in February 2018 are as follows:

Table A6.7: Which? 2018 satisfaction scores

Category	BT/EE	O2	H3G	Vodafone
Customer score	56%	61%	64%	49%

Source: Which?

A6.111 H3G had the highest score of the four MNOs, offering very good value for money and decent customer service. O2 had the second highest score due to good incentives and reward scores and decent customer service, albeit obtaining a much lower rank for value for money. BT/EE received the second lowest score of all MNOs and MVNOs, with customers unimpressed by all aspects of its service. Vodafone received the lowest score at just 49%, with particularly low scores in customer service and value for money.

---

92 http://news.gwsolutions.com/2018/04/24/poor-signal-drives-half-a-million-millennials-to-throw-their-phones-in-anger/

93 https://www.which.co.uk/reviews/mobile-phone-providers/article/best-mobile-networks-overview

A6.112 Ofcom research suggests that consumer satisfaction with their mobile service is heavily driven by their experience of coverage and reliability. Ofcom's 'Comparing service quality 2017' highlighted that, of those consumers who had cause to complain, the most common reason for complaint were issues associated with network reliability – 52% of consumers reported complaints about their service "not performing as it should".[94] The detail of complaints in this category included poor calls or line quality, loss of service and voicemail being delivered too late. This figure went up from 2016, when it was reported to be 42%.

A6.113 Similarly, data from the 2018 Ofcom Customer Satisfaction Tracker shows that where customers express dissatisfaction with the overall service from their mobile service provider, they are most likely to report poor reception or coverage as the reason – 47% of these respondents said this was the case. The next most common reason given was price (too expensive, not value for money), with 20% of these respondents stating this as the reason they were dissatisfied with their service.

A6.114 Nevertheless, nine in ten (91%) of customers reported that they were satisfied with their overall mobile service. Generally, MVNO providers ranked highest, with 98% of giffgaff customers and 97% of Tesco Mobile customers reporting that they were satisfied with their mobile service overall.

A6.115 84% of customers were satisfied with their mobile reception/signal strength[95]. Satisfaction with coverage varies between network operator and type of coverage. Of all the mobile providers, MVNO customers were the most content with their reception/signal strength, with giffgaff (91%) and Tesco Mobile (88%) recording the highest levels of satisfaction on this measure. H3G had the lowest level (82%), although the differences in satisfaction levels on this measure between the various MNOs and the market average for this sector were not statistically significant.[96]

Figure A6.38: Customer Satisfaction with mobile provider

	Average mobile	EE	giffgaff	O2	Tesco Mobile	Three	Virgin Mobile	Vodafone
Satisfaction with overall service	91%	93%	98%*	92%	97%*	89%	86%*	88%*
Satisfaction with reception or signal strength	84%	83%	91%	83%	88%	82%	86%	84%

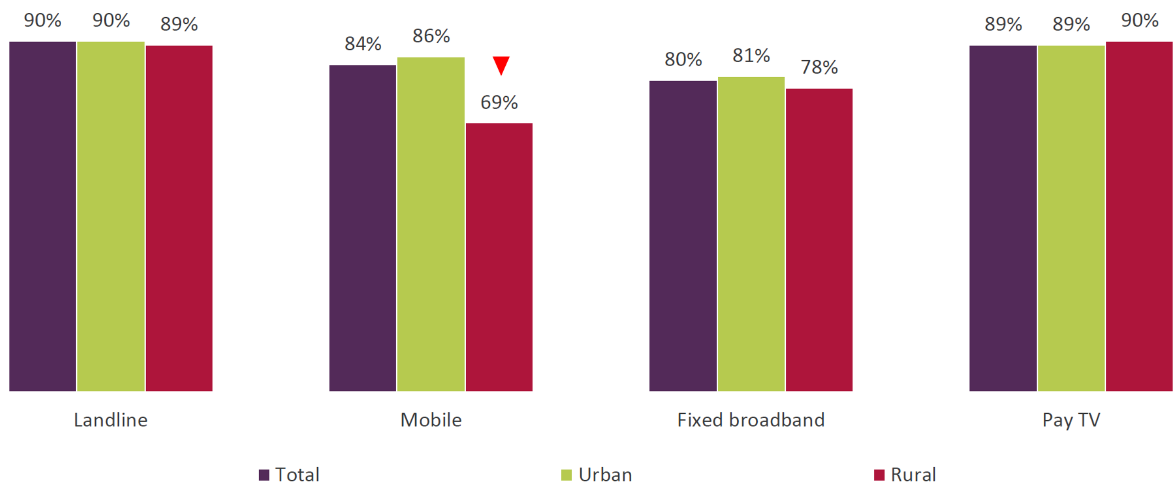
Source: Comparing Service Quality 2017

A6.116 There are also clear differences with the rates of customers satisfied with network reliability (reception/signal strength for mobile service) when rural and urban areas are compared. According to the 2018 Ofcom Customer Satisfaction Tracker, in urban areas,

[94] https://www.ofcom.org.uk/__data/assets/pdf_file/0023/113639/full-report.pdf
[95] The rating was 86% in 2016. However, the difference is not considered to be statistically relevant.
[96] Customer Satisfaction Tracker Summary of Research Findings 2018

satisfaction for reliability among mobile customers was 86%, while for rural areas it was significantly lower at 69%.[97]

Figure A6.39: Percentage satisfied with reliability of service from communication provider by location

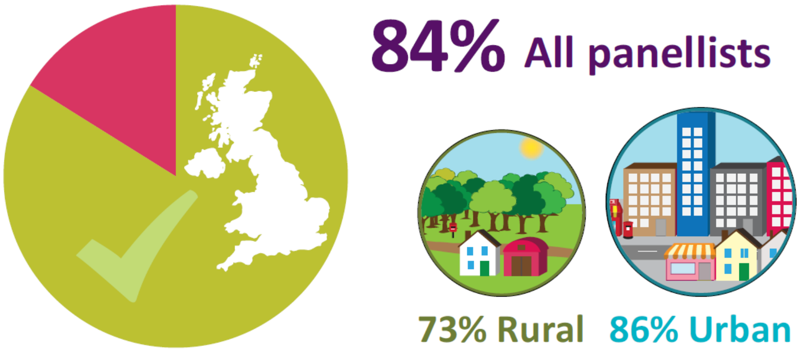


Source: Customer Satisfaction Tracker 2018

A6.117 A similar pattern is reported by the Ofcom Consumer mobile experience 2018[98] which (although limited to the experience on Android) reported that on most occasions (84%) Android smartphone users were 'very' or 'fairly' satisfied with their overall mobile network performance. The level of satisfaction varied between rural and urban areas with reports of 86% and 73% respectively.

[97] Customer Satisfaction Tracker Summary of Research Findings 2018
[98] https://www.ofcom.org.uk/research-and-data/telecoms-research/mobile-smartphones/consumer-mobile-experience

Figure A6.40: Overall satisfaction with mobile network, by rurality



User base: Mobile users with access to 4G mobile technology (n=3,471)
Q: How satisfied are you with the overall network performance of your mobile provider?
Note: Include 'very' or 'fairly' satisfied responses. All figures have been rounded to the nearest whole percentage.

Source: Consumer Mobile Experience Report

Satisfaction with indoor coverage

A6.118 The consumer experience of network coverage and reliability extends to both an indoor and outdoor service. Consumers' satisfaction across both aspects of coverage, when compared, can be quite different. The Connected Nations 2018 reports that voice call coverage from all four operators is available to 93% of UK premises (up from 90% in 2017), 77% of premises have good indoor 4G coverage from all four operators. Good indoor coverage is available to 41% of rural premises, compared to 24% in 2017. The data accounts for any reduction arising from signals struggling to penetrate walls.[99]

A6.119 However, a recent survey by uSwitch published in 2017 suggests that, despite improvements in coverage, consumers are still struggling with network reliability indoors. The 2017 uSwitch survey reported that 29% of mobile users experience poor or no indoor reception. Comparing locations provides a much starker picture, with 50% of customers in rural areas reporting a poor signal at home compared to 32% of customers in inner city areas.

A6.120 Equally, the consumer experience of indoor reliability differs between network provider. The 2017 uSwitch survey reported that O2 customers reported significantly higher rates of satisfaction with their indoor coverage. O2 customers were most likely to rate their indoor

[99] https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2018

mobile signal as ‘excellent’ (71%), while H3G and BT/EE customers were the least likely (68%).[100]

A6.121 That said, it is uncertain whether the quality of indoor coverage was a significant consumer driver independently. Where there is a poor or limited indoor service, customers seemed to be finding other solutions. The 2017 uSwitch survey reported that, when indoor coverage failed, 36% of respondents said they used a landline, and 32% said they relied on WiFifi to send messages or make calls.

The importance of data

A6.122 However, while the high value that consumers place on reliability and coverage seems well established, there has been steady growth in the importance of data speeds (see Figure A6.37). Data speed as a consumer driver has grown in importance from 9% in 2014 to 15% in 2017. The growth is moderate, but evidence suggests that it may have occurred in parallel to the growth in demand for data.

A6.123 Figure A6.41 shows the distribution of data plans in the UK up until 2017. Enders Analysis reports that increasing numbers of consumers are opting for more expensive and larger data plans driven by greater 4G usage.

[100] https://www.uswitch.com/media-centre/2017/11/three-in-ten-mobile-users-suffer-patchy-or-no-call-reception-at-home/

Figure A6.41: Enders Analysis assessment of UK Data Plan Distribution Smartphone Users on a Contract

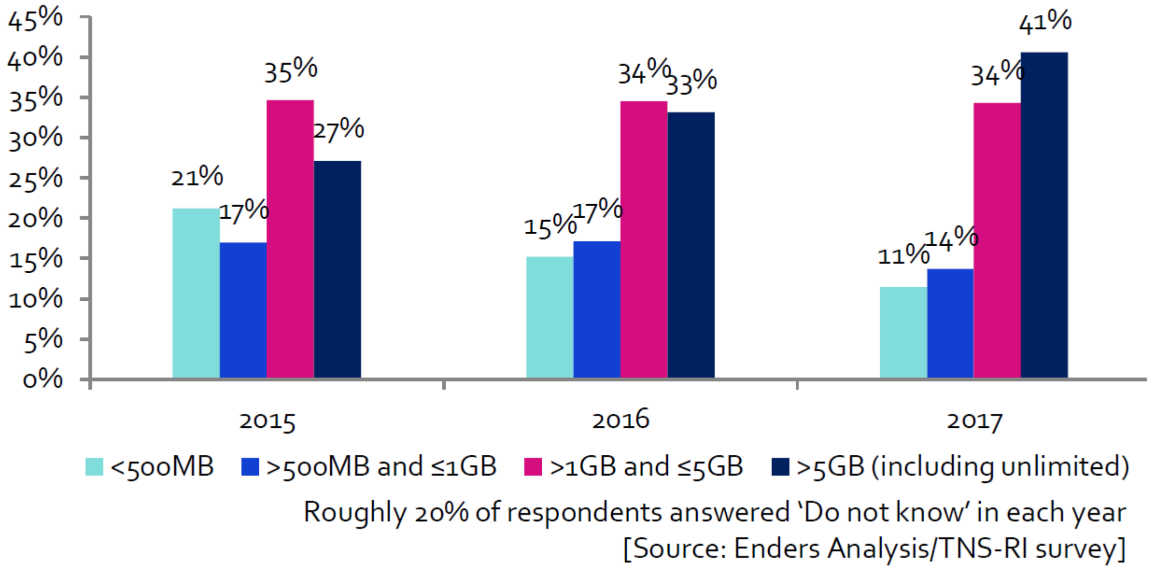
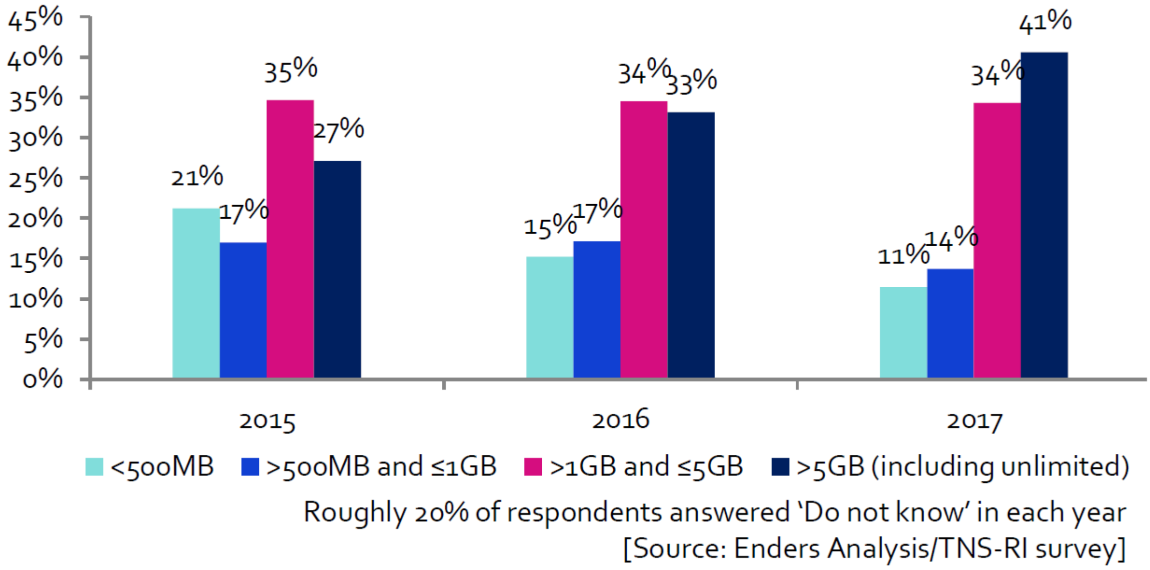


Figure A6.42: Analysys Mason Connected Consumer Survey 2017



A6.124 Analysys Mason's "Connected Consumer Survey 2017: mobile services and devices in Europe and the USA"[101] reports a similar trend on consumer spending. Specifically, that spend on mobile services has increased alongside the growth in popularity of 4G. Analysys Mason reports that the UK has experienced a 106% uplift in spending on mobile services as

[101] http://www.analysysmason.com/Research/Content/Reports/mobile-services-europeusa-rdmm0-rdmd0/#16%20March%202018

LTE is "becoming the norm". The UK is reported to have the second largest penetration of 4G behind the USA.

A6.125 The Communications Market Report 2017[102] also reports that the increased penetration of 4G has led to a 44% increase in data usage year on year and that the take-up for 4G has increased across all demographic groups.

A6.126 That is not to say that the growing consumer demand for data is the same as the growing importance of data speeds, but that the importance of data is growing more generally. The growth in the importance of data is often attributed to the penetration of 4G, the new ways that consumers can and are using their phones, and the growth of smartphone ownership. However, assessing these factors does not necessarily lead to the conclusion that there is demand for access to data at peak or even high speeds.

What mobile services do consumers consider most important?

A6.127 The consumer experience, and therefore satisfaction, with the reliability of their network is largely driven by how they are using their handsets. A consumer making a call or browsing the web may experience greater reliability than a consumer trying to stream video content or upload a file.

A6.128 Recent Ofcom's research on "The consumer mobile experience" reported that access to web browsing was recorded as 'extremely' or 'very' important in more cases than access to voice calls. [103] Figure A6.43 shows the overall importance of mobile services, by rurality. Figure A6.44 shows the same by age.

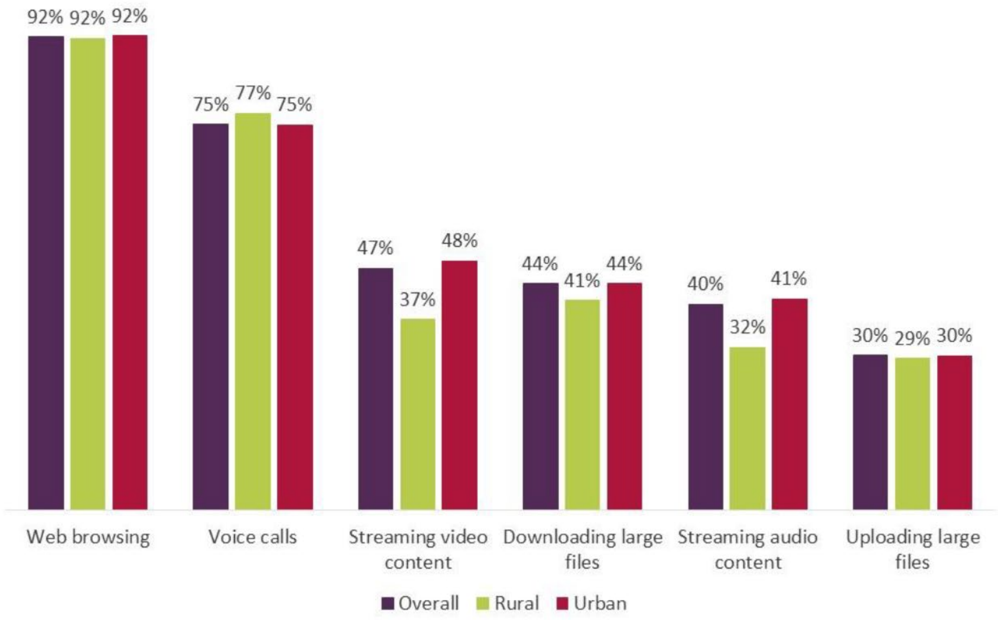
A6.129 There is some evidence that the penetration of smartphones may be slowly changing the way consumers use their phones. According to Deloitte's "State of the Smart 2017" report, smartphone adoption among UK adults continues to rise.[104] As of mid-2017, ownership was at 85%. This is from 52% in 2012. Deloitte also reports a five-fold increase in the proportion of adults using their smartphones to watch video. That said, Deloitte's report is clear that watching video via smartphone is still relatively infrequent especially for longer content (TV programmes, live TV).

[102] https://www.ofcom.org.uk/research-and-data/multi-sector-research/cmr/cmr-2017/uk

[103] https://www.ofcom.org.uk/research-and-data/telecoms-research/mobile-smartphones/consumer-mobile-experience

[104] https://www2.deloitte.com/uk/en/pages/technology-media-and-telecommunications/articles/mobile-consumer-survey.html

Figure A6.43: Overall importance of mobiles services by rurality

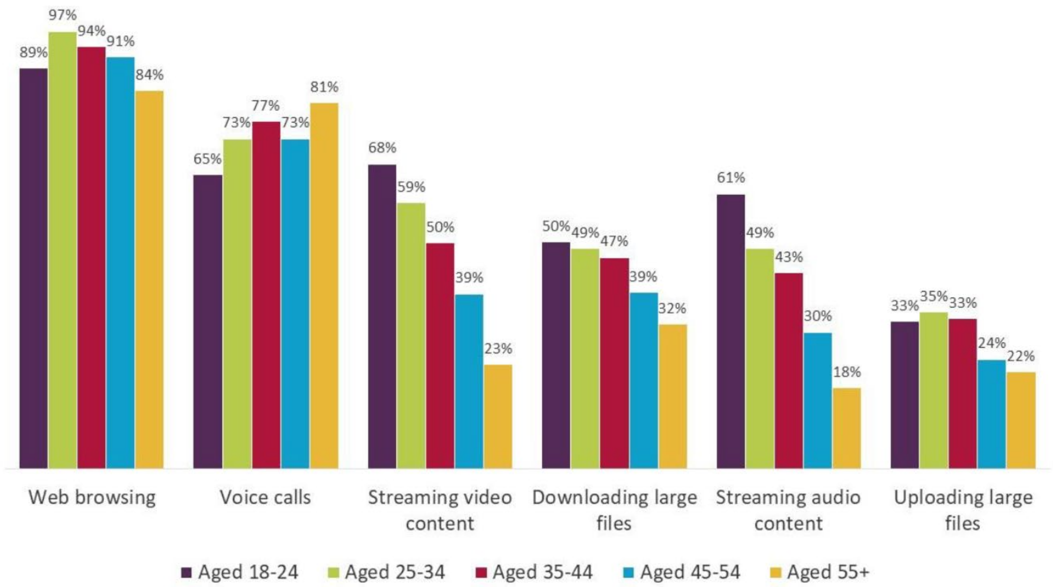


User base: Mobile users with access to 4G mobile technology (n=2,512)
Q: How important is it that you are able to access and use the following services on a daily basis?

Source: Consumer Mobile Experience Report

Note: Includes 'extremely' and 'very' important responses. All figures have been rounded to the nearest whole percentage.

Figure A6.44: Overall importance of mobiles services by age



User base: Mobile users with access to 4G mobile technology (n=2,512)
Q: How important is it that you are able to access and use the following services on a daily basis?
Notes: Includes 'extremely' and 'very' important responses. All figures have been rounded to the nearest whole percentage.

Source: Consumer Mobile Experience Report

A6.130 Global Wireless Solutions, however, reported that consumers rated making calls and sending text messages as more important than browsing the internet or watching videos.[105]

Additional competition considerations

A6.131 There are different channels through which customers can purchase mobile services. Customers can purchase directly from MNOs through their high street shops and websites. In some cases, other shops, such as supermarkets and off-licences, also sell mobile services to customers. One distinctive feature in the provision of retail mobile services in the UK is the existence of large independent specialist retailers such as Carphone Warehouse (and formerly Phones 4U, although it is no longer trading). Recently, however, Carphone Warehouse's performance has weakened. Its UK mobile like-for-like growth remained flat in the financial year of 2017 – 2018,[106] and there was a decline in mobile sales growth

[105] http://news.gwsolutions.com/2018/04/24/poor-signal-drives-half-a-million-millennials-to-throw-their-phones-in-anger/
[106] Metric used to measure growth in sales, taking into account exactly the same number of stores, businesses, activities, etc., with no new ones added. For example, sales from shops that were open for less than a year are ignored in like-for-like comparisons as these shops did not exist in the previous year.

during the first half of this financial year.[107] This may be due to consumers purchasing more SIM-only contracts and changing their phone less frequently.

A6.132 There has also been continued innovation in the UK market. O2 launched Refresh tariffs in 2013[108] whereby it allows users to be able to upgrade their handsets early. Recently, O2 introduced the Flexible tariff scheme,[109] allowing Refresh customers to increase or decrease the cost of their plan every billing month, depending on their anticipated usage within the next month.

A6.133 MNOs have been launching innovative mobile data offerings to attract customers. H3G introduced its Go Binge service which allows customers to use certain apps, such as Snapchat and Netflix, without using their data allowance included in their monthly plans. Vodafone offers a similar scheme called Vodafone Passes that allows customers to use certain apps without using their data allowance, depending on which type of pass they purchase on top of their monthly bill.[110] BT/EE has introduced its Data Gifting service which is aimed at families and enables data allowances to be moved around families' devices.[111]

A6.134 Some MNOs also provide free gifts exclusively to customers who have joined their network. O2 and H3G offer benefits to their subscribers through the Priority programme and Wuntu app respectively. Both schemes offer discounts in selected shops and restaurants, and O2 also offers presale access to concert tickets. H3G recently partnered with EasyJet for its 'Hands Free' scheme, offering H3G's customers to be able to upgrade their EasyJet flights with priority boarding and bag drop for free.[112] O2 also provides a free Netflix subscription for selected tariffs, whilst BT/EE provides an Apple Music subscription to its new subscribers.

---

[107] See page 20 of http://www.dixonscarphone.com/~/media/Files/D/Dixons-Carphone/investors/reports-and-presentations/2018/annual-report-2018.pdf

[108] See https://news.o2.co.uk/press-release/o2-launches-new-tariff-allowing-customers-to-get-the-latest-phone-whenever-they-want/

[109] See https://www.o2.co.uk/refresh/flexible-tariffs

[110] For example, a Video Pass costs an additional £7.00 per month, which enables a customer to stream a number of video services such as Netflix and YouTube without affecting their monthly allowances. For information on other Passes and their monthly costs, see https://www.vodafone.co.uk/mobile/pay-monthly/vodafone-passes

[111] See https://www.techradar.com/news/ee-launches-uk-first-service-that-lets-you-gift-data

[112] See http://www.three.co.uk/go-roam/easyjet

A7. Future evolution of services and networks

Summary and introduction

A7.1 We are awarding 120 MHz of spectrum in the 3.6–3.8 GHz band which is part of the wider 3.4-3.8 GHz band. This will be an important band for 5G as it is likely to be the first band to deploy 5G New Radio (NR) technology.

A7.2 The analysis in this annex informs our assessment in section 5 of whether there are any competition concerns relating to the award of this spectrum, e.g. whether competition could be affected by significant asymmetries of holdings of this spectrum. This annex therefore sets out our initial view and expectations of:

- future data usage;
- 5G services in early launches and their future evolution;
- the deployment and technology requirements for offering such services; and
- the spectrum likely to be necessary to offer such 5G services in both early and later deployments.

A7.3 The assessment in this annex is subject to large uncertainties and requires a significant degree of judgement: the technology is in its early stages; its deployment has not yet started; and business models are still developing around 5G services and applications.

Mobile data traffic is set to increase

A7.4 As discussed in annex 6, data traffic in the UK is increasing year on year. Over the period from 2011 to the second quarter of 2018, the average yearly growth has been c. 60%.[113]

A7.5 We expect this data growth to continue, particularly given that 5G deployments (in parallel with evolutions of LTE) will lead to a better quality of experience for consumers. According to Cisco VNI, in the UK mobile data traffic will grow five-fold from 2016 to 2021, with the average mobile connection generating 5.24 GB of mobile data traffic per month in 2021.[114] Analysys Mason forecasts a similar figure, predicting that each handset will generate 5.86 GB of mobile data traffic per month in 2021, increasing to an average of 8.9 GB per month in 2023.[115]

A7.6 We expect this data increase to be driven by a number of interrelated factors:

[113] Enders analysis
[114] https://www.cisco.com/c/dam/m/en_us/solutions/service-provider/vni-forecast-highlights/pdf/United_Kingdom_2021_Forecast_Highlights.pdf
[115] Analysys Mason, Wireless Network Data Traffic: Worldwide Trends and Forecasts 2017-2022, April 2018

a) We expect users to be spending more time on their mobile handsets to connect to the Internet.[116] This includes time spent being connected via mobile data as well as Wi-Fi.[117]

b) The availability of better and faster technology, such as 5G, is likely to encourage further use, similar to what happened with 4G deployment.

c) We expect increased use of data-hungry applications, such as video streaming. This will particularly be the case if augmented reality (AR) and Virtual reality (VR) become mass market applications.

d) We expect to see growth in the number of devices connected to networks as the number of adults using a smartphone to access the internet continues to grow.

e) As discussed below, 5G could drive an increase in Internet of Things (IoT) connected devices, in turn, leading to more data traffic across the network.[118]

A7.7 In its Global Mobility Report, Ericsson forecast that video traffic over mobile networks would grow by around 45% annually until 2023, and would account for 73% of all global mobile data traffic.[119] An ITU report looking at IMT traffic estimates also highlights video usage as one of the main drivers of worldwide mobile traffic growth, particularly as consumers expect to be able to watch High Definition and Ultra High Definition content regardless of whether it is delivered over a mobile or fixed network.[120]

A7.8 Mobile operators will therefore require greater capacity than they have now to satisfy both the potential increase in devices connected to the network and their traffic demand.

A7.9 In addition, as we note in section 5, demand for Fixed Wireless Access (FWA) services may increase as new technologies are rolled out and higher frequency spectrum is made available, enabling FWA to be a closer substitute for services provided over a fixed access connection than existing FWA services. BT/EE already offers the FWA service '4GEE', and H3G has announced it plans to launch a 5G FWA a service in the second half of next year.[121,122] If a proportion of the data traffic currently carried over the fixed network shifts to being carried over the mobile networks, this would lead to a further increase in the amount of traffic carried over the mobile network.

---

[116] Smartphones have become the most popular internet-connected device (78% of UK adults use one), see https://www.ofcom.org.uk/__data/assets/pdf_file/0022/117256/CMR-2018-narrative-report.pdf

[117] Our consumer mobile experience research found that consumers with access to 4G technology used apps over Wi-Fi rather than mobile networks 75% of the time. https://www.ofcom.org.uk/__data/assets/pdf_file/0028/113689/consumer-mobile-experience-2018.pdf

[118] Ericsson forecasts that across Western Europe, the number of cellular IoT devices will increase from 142 million devices in 2017 to 442 million devices in 2023, a CAGR of 18%.

[119] https://www.ericsson.com/assets/local/mobility-report/documents/2018/ericsson-mobility-report-june-2018.pdf

[120] https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2370-2015-PDF-E.pdf

[121] http://www.threemediacentre.co.uk/news/2018/5g-wireless-home-broadband-predicted-to-double-internet-speeds-for-uk-households.aspx

[122] In partnership with SSE, H3G has already deployed a new fibre network reaching 20 data centres, it has deployed a new 5G core network and carrier aggregation and MIMO technologies in the access to add capacity to the existing mobile and home broadband networks. http://www.threemediacentre.co.uk/news/2018/three-UK-committed-to-invest-into-5g.aspx https://www.lightreading.com/mobile/5g/three-uk-to-go-big-on-5g-for-home-broadband/d/d-id/747490

Service evolution

A7.10 In order to meet consumers' and businesses' changing demands, wireless networks are evolving and becoming more efficient in order to provide a better, more consistent experience. We discuss the technology that is expected to enable this from paragraph A7.26 onwards.

A7.11 In our March 2018 document 'Enabling 5G in the UK'[123], we grouped the types of services and applications 5G is likely to support into three broad categories or usage scenarios: enhanced mobile broadband (eMBB), massive machine type communications (mMTC) and ultra-reliable low-latency communications (uRLLC). We provide a short description of each category below.

Enhanced Mobile Broadband (eMBB)

A7.12 The evolution of 4G networks will support faster speeds, more capacity and a better quality of experience. 5G is expected to provide additional capacity to mobile users at lower costs and lead to further service improvements, including very low latencies and high reliability (this also enables a whole set of new services). 5G is expected to bring the following benefits to consumers:

- **Better quality of experience for mobile services**: 5G will likely enable mobile networks to better meet the demand for increasing capacity. This may improve the consumer quality of experience of using mobile services, particularly when using capacity heavy applications, such as streaming high-quality video.
- **New and existing services that require much faster speeds**: 5G may support very high speeds and more responsive connections with less delay. In turn, this could enable more effective wireless delivery of newer services such as virtual and augmented reality, which will also require low latency, as well as enabling higher speeds for existing services such as fixed wireless access (FWA).

Ultra-reliable low-latency communications (URLLC)

A7.13 5G may also lead to the development of new applications given its very low latency capabilities. This is particularly the case when used in conjunction with other technologies such as robotics, automation, machine learning and artificial intelligence.

A7.14 These use cases are more speculative. However the UK mobile industry is actively trialling some use cases including for Industry 4.0 and Smart Tourism, as part of the DCMS-funded 5G Testbeds and trials programme.

[123] https://www.ofcom.org.uk/__data/assets/pdf_file/0022/111883/enabling-5g-uk.pdf

Massive machine type communications (mMTC) or IoT

A7.15 Consumers are already taking advantage of some Internet of Things (IoT) devices, especially in the areas of smart homes and wearable technology (such as fitness and health devices).

A7.16 Until 5G becomes available, the evolution of 4G and other wireless technologies will likely be capable of addressing much of the growing demand for IoT devices over the next few years. 5G may therefore initially play a limited role in the development of IoT. But future 5G evolutions are likely to target IoT, offering capacity for many more devices than other wireless technologies, as well as improved battery life and innovative capabilities, such as instant response communications.

These services could be delivered by both MNOs and new players

A7.17 In our document, 'Enabling 5G in the UK', we highlighted the potential for 5G to extend the use of the mobile connectivity beyond MNOs and to open up opportunities for other players to enter the market. As such, connectivity could be delivered by MNOs, but also by other players.

MNOs

A7.18 The increase in demand for data is likely to be the main driver for initial investment in 5G networks. As such MNOs are likely to be the first players to deploy 5G in the UK.

A7.19 MNOs are already implementing improvements to their 4G networks and architectures to deliver more capacity, increased flexibility and efficiency. In parallel to these 4G improvements, MNOs have now begun to actively deploy the first 5G sites. The greater capacity of 5G will likely be a cost-effective way for mobile operators to address rapidly growing mobile data demand, provided 5G mobile devices are widely adopted.

A7.20 In the longer term, development at the core network level will allow mobile networks to be sliced into virtual private networks, for use by different sectors (network slices), potentially enabling MNOs to access new revenue streams and to offer differentiated services. Over time they may use network slicing to offer services to manufacturing, healthcare, energy and logistics industries. These are often referred to as vertical industries (or industry verticals). Vertical industries have addressed their connectivity and communication needs with dedicated or industry specific solutions. 5G technology could provide a common base to provide a more cost efficient, open and interoperable solution for the various vertical industries.[124]

A7.21 We understand that initial deployments of 5G will aim to reduce network operators' costs to provide additional mobile data capacity. They will also aim, especially in the first phase of their deployment, to offer eMBB services and therefore a better, higher quality and more consistent experience to their customers. We expect this to be achieved by deploying

[124] GSA report on 5G network slicing for Vertical industries, see https://www.huawei.com/minisite/5g/img/5g-network-slicing-for-vertical-industries-en.pdf

new antenna technologies, including active antennas (massive MIMO) and deploying 5G new radio (new radio technology) on their future and existing spectrum holdings.

A7.22 UK MNOs have made a number of recent announcements about 5G trials as they begin to prepare their networks for commercial 5G deployments:

- BT/EE has announced plans to launch 5G in 16 cities in 2019, starting with London, Cardiff, Edinburgh, Belfast, Birmingham and Manchester.125 BT/EE is currently trialling a number of 5G sites across East London.[126]
- H3G has outlined the steps it has taken to upgrade its network as part of a wider £2bn infrastructure investment programme in preparation for 5G[127] It has also announced plans to launch a 5G wireless home broadband service in the second half of 2019.[128]
- O2 has launched a trial of Massive MIMO technology in Kings Cross and Marble Arch using its 2.3 GHz spectrum.[129] The operator has also outlined plans to launch a 5G test bed at the O2 venue in London later this year.[130]
- Vodafone has switched on a 5G trial in Salford, Greater Manchester[131], with plans to commence 5G trials soon in a further six cities before the end of the year.[132] In September, it used 5G technology to conduct a live holographic call. Vodafone has also outlined plans to have 1,000 5G sites by 2020.[133]

A7.23 MNOs who choose to deploy non-standalone 5G using their existing 4G core network will require 4G coverage in the areas where they intend to deploy 5G. However, MNOs who choose to deploy standalone 5G will need to deploy a new core network but will not require 4G coverage in the same areas. For both standalone and non-standalone networks, dual connectivity will make it possible for a 4G network to offload traffic onto 5G New Radio carriers in areas where there is both 4G and 5G coverage.

New players

A7.24 The extra versatility and capabilities of 5G could also open up opportunities for new wireless providers either directly offering services or by using a ‘slice’ of the network to resell wireless services.

A7.25 For example, connectivity solutions geared towards a particular class of users or uses could be delivered by new players or in new ways, such as at very localised areas or private networks. Depending on their requirements, industry verticals may choose to deploy their own private networks rather than enter into an agreement with MNOs, for example in a

[125] https://newsroom.ee.co.uk/ee-announces-5g-launch-locations-for-2019/
[126] https://newsroom.ee.co.uk/ee-switches-on-5g-trial-sites-in-east-london/
[127] http://www.threemediacentre.co.uk/news/2018/three-UK-committed-to-invest-into-5g.aspx
[128] http://www.threemediacentre.co.uk/news/2018/5g-wireless-home-broadband-predicted-to-double-internet-speeds-for-uk-households.aspx
[129] https://news.o2.co.uk/press-release/o2-launches-pilot-to-boost-london-network-ahead-of-5g/
[130] https://news.o2.co.uk/press-release/o2-launch-5g-test-bed-o2/
[131] https://mediacentre.vodafone.co.uk/news/vodafone-first-full-5g-in-the-uk/
[132] https://mediacentre.vodafone.co.uk/pressrelease/5g-trial-seven-cities/
[133] https://mediacentre.vodafone.co.uk/news/vodafone-makes-uks-first-holographic-call-using-5g/

connected factory. We also understand that there is some interest from new players to provide rural fixed wireless access, as well as indoor mobile coverage improvement scheme providers.[134]

Mobile technology continues to evolve

Timeline of technical specifications

A7.26 In this section we provide a summary of the latest developments for 4G LTE and 5G NR technical specifications and then provide a high-level comparison of the features of these two technologies. This helps inform our competition assessment in section 5 of the likely route each MNO has to offer higher capacity, 5G and innovative services.

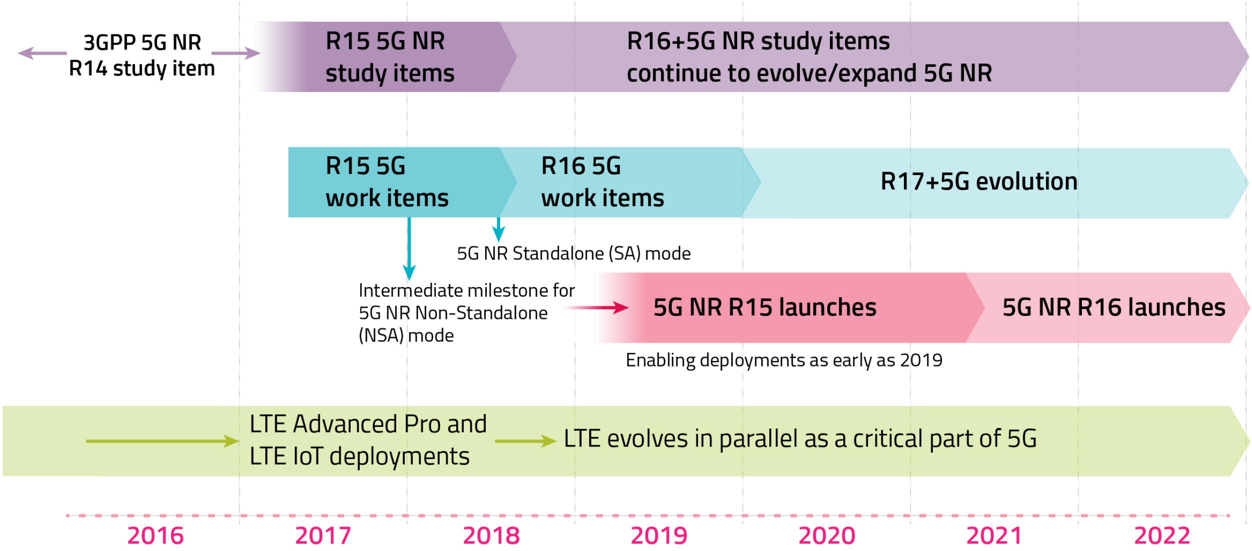
A7.27 While 4G standards (LTE) are still evolving, standardisation of 5G is underway in 3GPP.[135] The first technical 5G standard, 3GPP Release 15 comes in two versions, Standalone and Non-Standalone[136] (published in June 2018).

A7.28 The Non-Standalone version of Release 15 specifies how to use 5G NR carriers with an LTE access and core network, using a technique called *Dual Connectivity.* This enables an MNO with an existing LTE network to support early deployments of 5G without the need to upgrade the core network infrastructure. This is expected to ease the transition towards 5G but may not be the preferred option for all operators, some of whom may choose to migrate straight into a full Standalone 5G network. Release 16 is expected to be ready in the second quarter of 2019. It will include further enhancements to the 5G specifications, support for 5G use cases not included in Release 15 (such as URLLC) and will include additional frequency bands (e.g. above 40 GHz). It is expected to be finalised at the end of 2019.

A7.29 As well as the introduction of 5G into the specifications, 3GPP has continued to develop 4G technologies. The latest 4G specification, often referred as LTE Advanced Pro[137], supports many of the same technology advances (e.g. active antenna systems) and use cases as 5G including eMBB services and others such as Narrow Band IoT.[138]

[134] By mobile coverage improvement schemes, we mean solutions where a single infrastructure provider deploys infrastructure to provide indoor mobile coverage for large buildings (e.g. shopping centres).
[135] The 3rd Generation Partnership Project (3GPP), a body that develops standards for mobile technology.
[136] In the Non-standalone version, 4G is used for the control elements of setting data sessions. The standalone version does not require existing 4G infrastructure. From 3GPP Release 15.
[137] See 3GPP Release 13 and 14,
[138] NB-IoT (Narrowband IoT) is a 3GPP standardised technology intended to improve coverage over existing mobile technology, enabling the deep in building coverage required for applications such as smart meters. It has been designed to support more than 50,000 devices per cell, in most cases it only requires a simple software upgrade of existing mobile networks and provides around 20dB additional link budget, enabling ten times better area coverage.

Figure A7.1: Timeline for 5G standards



Comparison between LTE and 5G NR

A7.30 The table below draws a comparison between the technical features of 4G and 5G technologies. In the short term, the expected improvements of 4G technology are likely to bring the performance of a 4G network close to the expected performance of early 5G for eMBB and IoT applications. In the long term, 5G is expected to enable new services, driven for example, by the use of new frequency bands, the new air interface and more versatile frame structure.

Figure A7.2: Comparison between LTE Advanced Pro and 5G New Radio

Feature	Availability in LTE Advanced Pro and 5G New Radio
Frequency bands supported	5G NR can be used in a very wide range of frequency bands, ranging from sub-1 GHz spectrum to mmWave bands, whereas 4G LTE Advanced Pro is only available in bands up to 6 GHz. It is also expected that 5G NR will have support for, at least, 23 of the 64 existing LTE bands. It may have additional support in the longer term, when MNOs seek to re-farm their existing spectrum holdings.
Single and aggregated channel bandwidth	5G NR can be deployed using a single carrier ranging from 10 MHz to 100 MHz at 3.4 – 3.8 GHz and 400 MHz above 6 GHz[139] whereas 4G uses 1.4 MHz to 20 MHz single carriers. Aggregation between different combinations of spectrum bands is possible on both 4G and 5G.

[139] This can be up to 800 MHz when aggregating two contiguous NR carriers of 400 MHz

Feature	Availability in LTE Advanced Pro and 5G New Radio
Use of new antenna systems	The use of new techniques such as beamforming and massive MIMO can lead to higher average and peak data rates. Due to the size of the active antenna systems which are likely to be used for massive MIMO, these techniques are expected to be fully exploited in the mid frequency (especially 3.4-3.8 GHz) and the mmWave band range because the size of the antennas is related to the wavelength of the spectrum used. Both LTE Advanced Pro and 5G NR standards include these techniques, so it would be possible to use advanced antenna techniques in both 4G and 5G networks.
Latency	Low latencies can be achieved in LTE Advanced Pro of around 1 ms[140] and 5G NR is expected to support ultra-low latencies of less than 1ms.[141] This reduction in the latency could be enabled in 5G NR by a shorter frame structure[142], although considerations about the synchronisation with other TDD licensees may have an impact on the latency. 5G NR small cells which are isolated from the macro-cell network (for example, in a warehouse with metal walls) may be able to operate unsynchronised and use the new 'mini-slot' sub-frame which will further reduce latency.
Control and User separation (decoupling)	Decoupling means that control and user planes are sent over separate connections (typically involving separate frequency bands).[143] Exploiting this separation can lead to increased user experienced data rates and network capacity. More recent versions of LTE support decoupling, whereas 5G NR has been designed to enable decoupling as a basic function.
Mobility	5G will provide better connectivity on devices travelling at high speeds, such as trains and aeroplanes.[144]
Reliability and availability	4G is used today for critical service provision, for example, the Emergency Services Network. 5G is focused on natively supporting critical services communications that require both reliability and availability of the network and could provide an enhanced service.

[140] Low latencies have been introduced in 3GPP Release 14 by sTTI (shorter Transmission Time Interval) which effectively means lowering the number of symbols transmitted in a subframe.
[141] https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2410-2017-PDF-E.pdf
[142] The LTE frame structure is based on a 15 kilohertz subcarrier spacing with 1 millisecond slots. 5G NR supports diverse subcarrier spacing, one of them a mini-slot version with 60 kHz and 250 microsecond time slot.
[143] This could mean, for example, that the control plane could be offered through a macro-layer level whilst the user plane uses a different frequency layer with better performance or access to wider bandwidths.
[144] The ITU specification for IMT2020 and the related 3GPP specification (TS 22261) describe the performance requirements for high data rate and traffic density scenarios including high-speed trains or vehicles and airplanes.

Feature	Availability in LTE Advanced Pro and 5G New Radio
Support for different use cases same frequency	TDD LTE can use a variety of synchronised frame structures to suit the services to be delivered using that spectrum. 5G NR also makes use of synchronised frame structures but has greater flexibility including using wider subcarriers.

Spectrum likely to be needed to offer a 5G service

A7.31 In this subsection, we discuss the spectrum likely to be needed to offer 5G services.

A7.32 In the July 2017 statement, we made the following comment: "While some MNOs may want to deploy 40 MHz or less of 3.4 GHz initially, this is unlikely to be sufficient to launch a service that meets the technical requirements of the IMT-2020 vision (5G standard). At least 80 MHz is likely to be needed to meet this standard" (paragraph 6.91). Since then:

- We have held the 2.3 and 3.4 GHz auction which included 150 MHz of 3.4 GHz spectrum of which EE won 40 MHz, H3G a further 20 MHz (they already held 124 MHz in the 3.4-3.8 GHz band), Vodafone 50 MHz and O2 40 MHz;
- MNOs have announced initial plans for 5G;
- The first 5G technical standards have been released (see above on 3GPP Release 15[145]) and include information on the bands that will be made available for 5G NR;
- The ITU has published Report ITU-R M.2410 on Minimum requirements related to technical performance for IMT-2020 radio interface(s)[146] and the ECC published Report 287 on the defragmentation of 3.4 – 3.8 GHz spectrum.[147]

A7.33 Notwithstanding these developments, there is currently no clear requirement in the published 5G standards (3GPP NR and IMT-2020) specifying the minimum spectrum bandwidth necessary to deliver a 5G service. Report ITU-R M.2410 does contain a bandwidth requirement of 100 MHz for spectrum below 6 GHz for the purposes of valuation of IMT-2020 radio interface technologies. But it is clearly stated that this is the maximum aggregated system bandwidth and that this can be supported by single or multiple radio frequency (RF) carriers.

A7.34 It is generally acknowledged that large contiguous bandwidths are desirable for the delivery of high throughput and certain low latency 5G services and to maximise spectral efficiency. For instance, CEPT Report 67 suggests that spectrum (in the 3.4-3.8 GHz band) should be provided in a manner allowing for at least 3x50 MHz of contiguous spectrum (i.e. to support at least three operators with 50 MHz each). Many industry stakeholders, including manufacturers and operators, consider it important to deploy 5G NR on large

[145] http://www.3gpp.org/release-15
[146] https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2410-2017-MSW-E.docx
[147] https://www.ecodocdb.dk/download/5ffb56c9-9c78/ECCRep281.docx

contiguous bandwidths of the order of 80 to 100 MHz (for example, the ECC report on defragmentation in the band says that industry has said that 5G networks may require 80 to 100 MHz contiguous spectrum[148]). However, we do not consider contiguous bandwidths of 80 to 100 MHz to be a minimum requirement.[149] The available evidence suggests that there are no specific 5G services that are critically dependent on contiguous carriers of 80 to 100 MHz.

A7.35 5G NR has been designed to be a very flexible technology that supports a wide variety of use cases within the three broad usage scenarios described above: eMBB, mMTC, and URLLC. Different use cases can have different requirements in terms of capacity, latency, reliability and spectral efficiency, even within the same overall usage scenario. For example, some Virtual Reality applications might need extremely low latency to avoid motion sickness, whereas 4K video streaming from a server would require higher speeds.

A7.36 5G NR will operate over different bandwidths and across different frequency bands, with the possibility of aggregating carriers across them. No single frequency range is likely to be capable of supporting all the use cases envisaged within the eMBB, mMTC and ULRLLC usage scenarios. We therefore expect that MNOs will likely deliver new 5G services using a portfolio of spectrum, including at low (<1.4 GHz), mid (1.8 – 6 GHz) and high (mmWave) frequencies.

A7.37 As noted above, MNOs in the UK have announced their initial 5G plans based on their current holdings at 3.4 GHz. We note that the first 5G usage scenario that the MNOs are likely to focus on is eMBB, and that eMBB use cases could be offered using:

- low frequencies to provide wide area and deep indoor coverage;
- mid frequencies to provide capacity and high data rate services, most likely in areas with higher traffic demand such as cities and towns; and/or
- high frequencies to provide very high capacity and very high data rate services, indoors and outdoors, using small cells and ultra-dense hotspots (though we expect high frequencies to be deployed some time after the MNOs have started offering services using mid and low frequencies).

A7.38 mMTC may, at least for many use cases, rely primarily on low frequency spectrum, though access to mid and high frequencies may allow the development of a wider set of mMTC use cases.

A7.39 URLLC would likely benefit mainly from spectrum in the low and mid frequency ranges, though access to high frequencies may allow the development of a wider set of URLLC use cases:

[148] ECC Report 287, 26 October 2018, https://www.ecodocdb.dk/document/7245

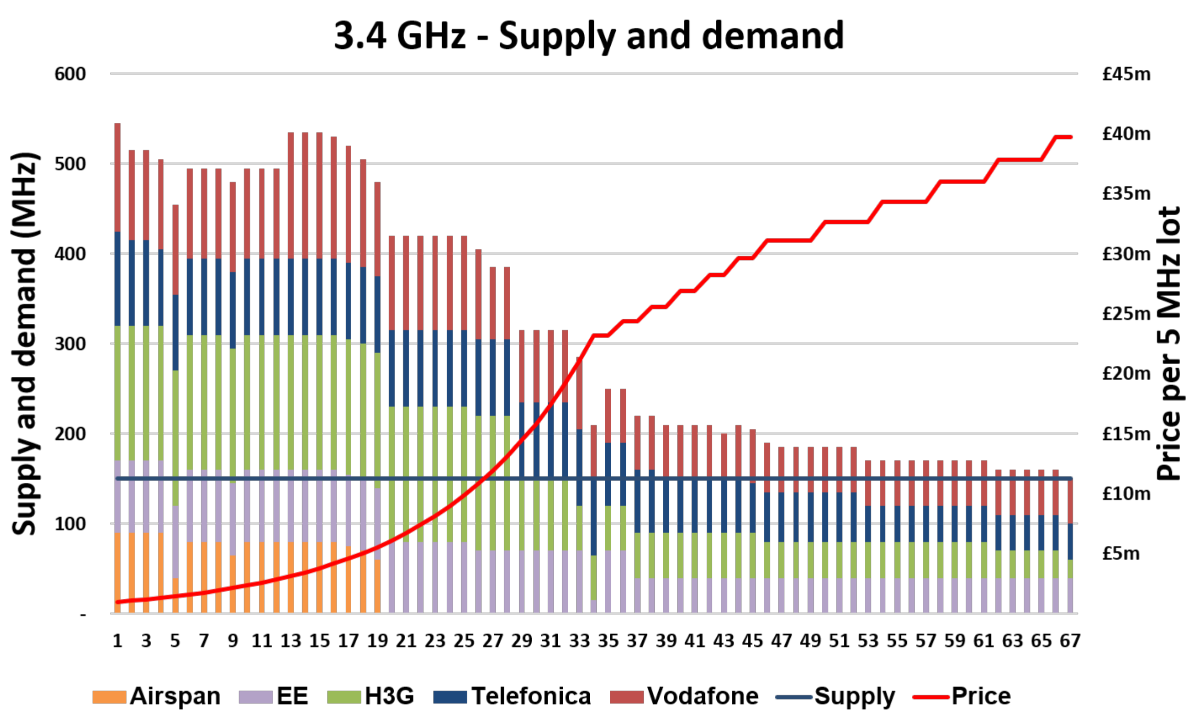
[149] Note that this is different from what we concluded in the July 2017 Statement for the 2.3 GHz and 3.4 GHz auction. At paragraph 6.91 of that statement, we said: "While some MNOs may want to deploy 40 MHz or less of 3.4 GHz initially, this is unlikely to be sufficient to launch a service that meets the technical requirements of the IMT 2020 vision (5G standard). At least 80 MHz is likely to be needed to meet this standard." However, as set out in the rest of this annex, we now consider new evidence.

- low frequencies to provide reliable communications in outdoor locations;
- mid frequencies to provide low latency for high data rate services;
- high frequencies for low latency, very high data rate services.

Bidding behaviour during the 2.3 and 3.4 GHz auction

A7.40 Bidding in the 2.3 and 3.4 GHz auction may be a useful indicator of the level of demand for the spectrum we are auctioning in the forthcoming award. In the 2.3 and 3.4 GHz auction, there was substantial demand for spectrum in the 3.4-3.6 GHz band. At the low reserve price of £1m per 5 MHz lot in the first round of the auction there was demand for 545 MHz (compared to the 150 MHz available). As the price increased, excess demand persisted, and it took 67 rounds of bidding until the market cleared. Figure A7.3 provides a summary of the bidding.

Figure A7.3: Bids for 3.4-3.6 GHz spectrum in the 2.34 and 3.4 GHz auction



A7.41 All five bidders for 3.4-3.6 GHz spectrum (i.e. the four MNOs who all won spectrum in the band, plus Airspan) placed bids for a large amount of spectrum of at least 80 MHz, in some rounds of the auction. The largest bids by spectrum amount were: BT/EE for 80 MHz (and it was limited by the overall spectrum cap to a bid of at most 85 MHz); Airspan for 90 MHz; Telefónica for 105 MHz; Vodafone for 140 MHz; and H3G for 150 MHz.

A7.42 However, all bidders dropped their demand as prices increased, and the winning bids were for smaller blocks of 20 MHz (H3G), 40 MHz (BT/EE and Telefónica), and 50 MHz (Vodafone). The last bid for a block of at least 80 MHz was by Telefónica in round 34 at a round price of about £21.1m per 5 MHz (and for 60 MHz, the last bid was by Telefónica in round 38 at a round price of about £24.4m per 5 MHz). This was well before the end of the auction in round 67, which finished with most of the winning bidders paying £37.824m per 5 MHz.

A7.43 This pattern of bidding does not clearly suggest strong synergies in an 80 MHz block compared to 40-50 MHz, as all MNOs made bids for at least 80 MHz in earlier rounds but dropped their demand and then persisted with demand at 40-50 MHz for many subsequent rounds whilst the round prices were increasing significantly. This bidding behaviour is consistent with a view that large contiguous holdings are desirable but not essential.

Early deployment of 5G

A7.44 We expect the MNOs to use spectrum in the 3.4-3.8 GHz band to offer 5G services in the initial phase of their 5G deployments. It is likely that they will also rely on dual connectivity with LTE to support early 5G roll-outs. Some of this spectrum has already been auctioned and the ecosystem is expected to be ready soon, with 5G devices supporting the 3.4-3.8 GHz band becoming available from 2019.

A7.45 All UK MNOs have access to some spectrum suitable for 5G NR via their existing holdings and recently awarded spectrum in the 3.4 GHz band.

Intra-band carrier aggregation

A7.46 We understand that it is currently not possible to aggregate carriers in non-contiguous holdings within the 3.4-3.8 GHz band (e.g. aggregate two non-contiguous carriers of 40 MHz). *Non-contiguous intra-band carrier aggregation*, as this type of aggregation is known, is currently available for 4G technology but it is not yet specified in the 5G standards and therefore unlikely to be supported in early 5G devices. Aggregation allows the combination of individual component carriers into a single wider bandwidth carrier and therefore offers the ability to transmit and receive at higher data rates (higher than could be achieved on a single component carrier). However, aggregation gives little or no benefit to capacity and evidence from one MNO indicated that it did not employ carrier aggregation in LTE cells where capacity is a significant constraint (e.g. in heavily loaded cells).

A7.47 Even without non-contiguous intra-band aggregation, 5G NR can be deployed on separate, non-contiguous carriers within the 3.4-3.8 GHz band to increase the overall capacity of a cellular site. However, we recognise that with or without carrier aggregation, there will be some small to moderate capacity inefficiencies associated with using 5G NR in two non-contiguous spectrum blocks when compared with a single spectrum block of the same total bandwidth. From our discussions with mobile operators we understand that the capacity penalty might be in the range 2–15% including losses to additional guard bands and additional signalling overheads.[150]

A7.48 We understand that there could be some practical deployment concerns when there is a large frequency separation between non-contiguous spectrum blocks. At present, vendors and operators are suggesting that a frequency range of approximately 100 MHz is achievable for 5G base station equipment including active antenna systems.[151] They report that this might increase to 200 MHz (or slightly more)[152] within the next year but it is unclear when, or if, active antenna systems will support the whole 3.4-3.8 GHz band with a single antenna.[153] There may also be demand for active antennas which span more than 300 MHz[154] and this will encourage manufacturers to produce such equipment and/or improve their products to offer solutions that avoid deploying multiple active antenna units. We do not see any insurmountable technical challenges in achieving active antenna systems spanning 300 MHz in the reasonably near future. However, there are likely to be technical challenges with producing active antennas that can span the full 400 MHz needed to cover the entire 3.4-3.8 GHz band with a single active antenna system whilst also meeting the filtering requirements needed to protect radars below 3.4 GHz. Therefore, our view is that active antennas spanning the full 400 MHz are unlikely to be available in the near future.

A7.49 This means that an operator with holdings spanning a wider frequency range than around 200 MHz, and planning to deploy active antenna systems, may face additional challenges for their early deployments. Active antenna systems are relatively heavy and large (compared to passive antennas) and it may not be possible to deploy separate antenna systems on each mast for operators with a large frequency separation between spectrum

---

[150] The 2 – 15% penalty range considers several scenarios when operating two discontiguous carriers instead of a single 100 MHz carrier. The lower end of this range considers the loss associated with more guard bands only. The middle of this range also accounts for the typical losses associated with using non-contiguous intra-band carrier aggregation or load balancing in a heavily loaded network. The higher end of this range is based on the maximum losses associated with discontiguity as reported to us in further discussions with certain MNOs, [✄ REDACTED]. The penalty might be higher than this for some consumer handsets if 4x4 downlink single-user MIMO (SU-MIMO) and 2x2 uplink SU-MIMO are not available for all component carriers when aggregating carriers.

[151] Responses from two operators to further technical questions, [✄ REDACTED], and an e-mail from a vendor, [✄ REDACTED].

[152] Responses from [✄ REDACTED]; three equipment vendors [✄ REDACTED]; and two component manufacturers [✄ REDACTED].

[153] One operator reported that one of their equipment suppliers considered that AAS might support 400 MHz [✄ REDACTED] and another supplier considered that support for 400 MHz [✄ REDACTED]. Another operator reported that one of their equipment suppliers considered that 400 MHz might be supported in [✄ REDACTED]. Two equipment vendors said that AAS which support 400 MHz were under consideration in the next few years with [✄ REDACTED] saying that it was exploring supporting wider bandwidths with 400 MHz possible by [✄ REDACTED] and [✄ REDACTED] saying that it could be possible by [✄ REDACTED]. Two equipment vendors did not speculate on when AAS which support 400 MHz could be available with [✄ REDACTED] saying that it would respond to demand [✄ REDACTED] and [✄ REDACTED] saying that 300 MHz bandwidth might be supported by [✄ REDACTED]. Three component manufacturers observed that AAS support for wider bandwidths could be accompanied by some degradation in performance at the band edges and a reduction in power efficiency. One manufacturer believed that 400 MHz AAS designs should be possible using commercial-off-the-shelf components today [✄ REDACTED] whilst the others considered that it may take a year or two: [✄ REDACTED].

[154] Other spectrum awards in Europe (e.g. Spain and Italy) will mean that such a demand will not just come from within the UK.

blocks. This issue may be exacerbated by the presence of network sharing agreements such as MBNL and CTIL where the operators are already sharing base station masts.

A7.50 In the short term, it is likely to be difficult for MNOs to share active antennas because the MNOs may have different deployment strategies, so will be looking to deploy in different areas, and there are also some technical barriers.[155] However, in the longer term, they could find arrangements within their network sharing agreements to be able to deploy active antenna units with their partner MNO in a cost-effective way (e.g. if Vodafone and O2 have non-contiguous holdings at the end of the auction and technology makes it possible, they may consider deploying a joint active antenna for their holdings in 3.4-3.6 GHz spectrum and a second antenna for their holdings in their 3.6-3.8 GHz band instead of the four antennas they would need to deploy otherwise).

A7.51 While recognising there might be some inefficiencies, in the shorter term MNOs with holdings in different bands can still deploy active antenna systems for a selected carrier (e.g. 40 MHz only in the 3.4 GHz band). They could use dual connectivity[156] to achieve a peak throughput similar to a single 80 or 100 MHz 5G NR carrier by using inter-band carrier aggregation to combine the throughput of an 5G NR carrier in 3.4-3.8 GHz with 4G LTE carriers in other spectrum holdings outside of the 3.4 – 3.8 GHz band (noting that we expect inter-band carrier aggregation to be available earlier than non-contiguous intra-band carrier aggregation).[157] However, this would require greater network complexity (requiring LTE and 5G NR coverage in the same places); may lead to greater device power drain (as receiving data from multiple carriers consumes more battery power); and may only be supported in higher-end devices at first.

A7.52 It is also worth noting that, whilst MNOs are likely to want to use active antenna systems on their busiest sites (typically in more urban environments), it is less clear whether they will wish/need to deploy them in other areas. It may be that in less busy areas the MNOs will continue to use traditional passive antennas and consequently the bandwidth and weight constraints associated with active antenna systems will not apply.

A7.53 5G NR has been designed with carrier aggregation in mind so that operators can efficiently utilise combinations of carriers from different bands (both TDD and FDD), including licence exempt spectrum, to provide users with larger bandwidth services than they would otherwise be able to in a single band. Unlike intra-band aggregation, we therefore expect inter-band aggregation (e.g. aggregation between completely different frequency bands for instance with 1800 MHz or 2.6 GHz bands) to be supported in devices at a relatively early stage.

[155] Active antenna systems (AAS) are highly integrated systems with no external RF input ports which means conventional RF combining, as used for passive antenna sharing, is not possible. AAS take a baseband signal as an input which means that antenna sharing would require MNOs to share baseband generation units or for equipment vendors to develop new baseband combiner products.
[156] Dual connectivity allows for carrier aggregation between a single 5G NR carrier and multiple LTE carriers
[157] We note however that in Release 15 2.3 GHz spectrum cannot be aggregated, meaning that Telefonica will not be able to use this spectrum for earlier deployments. See TS 38.101-3 https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3285

Longer term deployment of 5G

A7.54 We expect the limitations set out above and inherent to the early stage of the new technology will reduce in the future as the technology develops and matures. In this respect, we note the following points.

A7.55 Many of the technology enhancements that underpin 5G NR (e.g. massive MIMO, high(er) order modulation schemes, a more flexible frame structure) are also being incorporated into the LTE specifications (e.g. in LTE-Advanced Pro) so that the performance of upgraded LTE networks may come very close to matching the performance of early 5G networks in most respects (on a bandwidth per bandwidth comparison).

A7.56 Whereas LTE is only defined for sub-6 GHz frequency bands, 5G NR has been designed to also work on mmWave frequencies. It is likely that 5G NR will be specified for the majority of the bands commonly used for LTE. In the longer term, 5G NR may well be deployed in more spectrum bands than LTE.

A7.57 Technical developments may erode the additional deployment costs associated with the use of active antenna systems in non-contiguous spectrum blocks which are far from each other in frequency. It is likely that AAS with an IBW of 300 MHz will be supported in the near future according to vendor roadmaps. There are a number of other technological changes which may mitigate the costs associated with a split spectrum assignment including:

- future AAS using new architectures such as “split-mode” may be able to support non-contiguous, non-proximate (i.e. not within the 200 MHz IBW) spectrum blocks with a single antenna panel, although this is likely to come at some cost to performance;
- MNOs may be able to share AAS which will reduce the overall number of antennas which need to be deployed on sites, but we acknowledge that sharing could be complex for AAS; and
- in time, MNOs may be able to acquire more sites to deploy more AAS or expand and strengthen some of their existing sites.

A7.58 In general, we expect technology and services to develop further and provide MNOs with further solutions to offer competitive services. For example, any shortcomings on data capacity in selected areas might be overcome by using other methods, such as LTE-LAA in unlicensed spectrum (e.g. 5GHz TDD) or by deploying mmWave small cells.

A8. Mobile spectrum bands

Summary and introduction

A8.1 This annex is composed of three contains three main parts. The first two consider the technical characteristics of low frequency spectrum and possible alternatives to its use. This informs our assessment of any potential concerns, discussed in section 5, that competition could be weakened as a result of MNOs' asymmetric holdings of low frequency spectrum. The last part sets out our proposal on what bands should be included in the pool of relevant spectrum based on the timing of availability of different bands for the purposes of assessing any competition concerns for the auction.

A8.2 Specifically, we present our evidence and conclusions on:

- What we consider to be low frequency spectrum and the properties and relevance of the downlink-only spectrum in the 700 MHz and 1400 MHz bands;
- Alternative ways to improve coverage in hard to serve areas, such as indoors, other than deploying additional low frequency spectrum; and
- Spectrum usability (timing of availability of different bands).

What we consider to be low frequency spectrum

A8.3 Our view is that the spectrum in the 700 MHz, 800 MHz, 900 MHz, and 1400 MHz bands should be considered to be low frequency spectrum; other spectrum bands below 6 GHz should be deemed mid frequency spectrum and spectrum above 24 GHz should be deemed high frequency spectrum.[158]

A8.4 We have also considered the properties and likely use cases for downlink-only spectrum in the 700 MHz and 1400 MHz bands, in particular how we should take account of its use for supplemental downlink (SDL) in our competition assessment.[159] As we explain in this annex, our coverage analysis shows that, due to the current power limits set in the licence conditions, the 1.4 GHz band could reach similar coverage as lower frequency bands such as 800 MHz or 900 MHz.

A8.5 The current licence conditions permit a maximum E.I.R.P.[160] in a 5 MHz block of:

- 68 dBm in the 1400 MHz band;
- 61 dBm and 65 dBm in the 800 MHz and 900 MHz bands;

[158] Note that we have not yet categorised frequencies between 6 and 24 GHz as either mid or high frequency spectrum. Spectrum in this range is not currently being proposed to be used for the mobile access network, there is therefore no pressing need define a specific boundary between mid and high frequency spectrum between 6 and 24 GHz.
[159] We refer to downlink-only spectrum to emphasize that this spectrum can be used for SDL as well as for broadcasting. We refer specifically to the SDL use when this relates to mobile services based on the 3GPP technical standards.
[160] Effective Isotropic Radiated Power.

- 65 dBm in both 1800 MHz and 2100 MHz bands; and
- 61 dBm in the 2600 MHz band

A8.6 We are also proposing a maximum E.I.R.P of 64 dBm per 5 MHz in the 700 MHz band. We conclude that 1.4 GHz downlink-only spectrum should be included in the pool of low frequency spectrum.

Alternative ways to improve coverage in hard to serve areas

A8.7 We look at ways to improve coverage in 'hard to serve' locations, other than deploying low frequency spectrum. Low frequency spectrum is particularly suited to provide wide area and good in-building coverage due to the propagation characteristics of these frequency bands. Here we focus on the ability to deliver a mobile service to 'hard to serve' locations, i.e. locations that are more challenging to reach with a macro-cell network, when it is not possible to use any additional low frequency spectrum.

A8.8 Coverage can be improved in several ways. For example, densifying the network (i.e. building additional network sites) or deploying mid frequency spectrum (e.g. 1800 MHz) on additional sites. The latter would, however, be a costly method, especially to improve indoor coverage.

A8.9 In this annex we conclude that Wi-Fi, femtocells, repeaters and indoor small cells are the most effective alternative ways to improve indoor coverage, with Wi-Fi playing a more significant role than the other solutions – especially in residential buildings – because of its relatively low costs and wide availability. Wi-Fi is used to provide both voice and data services to mobile users, but it cannot yet fully replace low frequency spectrum as a means of achieving good indoor coverage as it relies on either the users or the MNOs having access to a backhaul connection (e.g. fixed broadband for residential users) and may depend on access to third parties' infrastructure or login permissions.

Useability of spectrum bands

A8.10 In this section we discuss which spectrum bands can be considered as useable and relevant for our competition assessment. We use the same framework for useability that we have used in previous auctions, namely that:

- the band needs to have been awarded;
- there should be a sufficiently developed ecosystem of devices; and
- there should not be any material constraints to the deployment of the band.

A8.11 Our initial conclusion is that:

- 800 MHz, 900 MHz, 1400 MHz, 1800 MHz, 2100 MHz, 2.3 GHz and 2.6 GHz spectrum is currently useable;
- 700 MHz paired will be useable from mid-2020;
- 700 MHz downlink-only will also be usable by mid-2020 or shortly after;

- 3.4-3.6 GHz will be useable from 2019;
- Spectrum in the 3.6-3.8 GHz band will be useable in some parts of the UK before mid-2020 (and possibly earlier), subject to coordination requirements to account for existing users.
- We do not consider mmWave spectrum, nor the 1900 MHz, the unawarded parts of the 1400 MHz and the 2.3 GHz bands to be useable in the context of this auction.

What we consider to be low frequency spectrum

Spectrum categorisation: low, mid and high-frequency spectrum

A8.12 As described in our discussion document Enabling 5G in the UK[161], we have identified spectrum bands at low, mid and high frequencies with different characteristics that can be used to deliver different benefits.

A8.13 More broadly, we identify three different types of spectrum for the current and future mobile bands:

a) **Low frequency spectrum:** we consider that this covers spectrum bands from 700 MHz to 1400 MHz (including the downlink-only spectrum in these bands). These frequencies tend to be used to provide wide-area coverage, due to their beneficial propagation characteristics.

b) **Mid frequency spectrum:** from 1800 MHz up to 6 GHz. The 3.4-3.8 GHz band has been identified as the primary band for 5G in Europe and it will offer increased capacity for mobile broadband over similar areas to other mid frequency spectrum. The use regime for 3.8-4.2 GHz in the UK is still under consideration.[162]

c) **High frequency or 'millimetre wave' spectrum**: covering spectrum bands in frequencies from 24.25 GHz up to 71 GHz. High frequency spectrum has not yet been used to deliver mobile services, but is expected to support new 5G applications, in particular those that require very high capacity and very low latency by both MNOs and other players.

Properties and relevance of the downlink-only spectrum in the 700 MHz and 1400 MHz bands

A8.14 During our assessment for the 800 MHz and 2.6 GHz award in 2012,[163] we stated that, despite there being important alternatives to low frequency spectrum to provide good quality coverage, we considered it likely that there would remain some indoor coverage advantage from holding **sub 1 GHz spectrum** compared to 1800 MHz or 2.1 GHz spectrum,

---

[161] https://www.ofcom.org.uk/__data/assets/pdf_file/0022/111883/enabling-5g-uk.pdf p
[162] Alongside this consultation we are consulting on use of the 3.8-4.2 GHz band, among others https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation
[163] Paragraph 4. 82 of https://www.ofcom.org.uk/__data/assets/pdf_file/0031/46489/statement.pdf

especially for low-data-rate services. We therefore considered that sub 1 GHz spectrum was relevant low frequency spectrum with enhanced coverage capabilities.

A8.15 In 2015, Ofcom decided to vary the 1452 – 1492 MHz licence held by Qualcomm UK Spectrum Ltd, to enable its use for mobile or fixed communication network as downlink-only spectrum in the UK.[164] H3G and Vodafone subsequently acquired 20 MHz each of 1400 MHz spectrum. At the time we noted that we might include 1400 MHz in the pool of what we considered as low frequency spectrum. This was mainly due to the higher permitted power levels set out in the 1400 MHz licence, which give the band a coverage advantage when compared to mid frequency spectrum (e.g. in the 1800 MHz and 2600 MHz bands). We considered that this higher power might enable 1400 MHz to achieve similar coverage ranges to those of sub-1 GHz spectrum since these bands have a lower permitted power level, as currently set out in the licenses.

A8.16 Based on the analysis described below, we provisionally include 1400 MHz in the pool of low frequency spectrum:

- Given the current licence conditions which allow a higher permitted power level than 800 MHz or 900 MHz, the 1400 MHz downlink-only band can achieve similar coverage to sub-1 GHz spectrum and, as such, we are considering it as relevant low frequency spectrum;
- Higher bands such as 1800 MHz, 2100 MHz and 2600 MHz have different propagation characteristics and a substantially lower coverage reach and therefore we do not consider these to be relevant low frequency spectrum bands.

A8.17 In relation to the downlink-only nature of the 700 MHz and 1400 MHz bands, we observe that they can be used, for example, for SDL or for broadcasting. Unlike broadcasting, however, SDL carriers cannot be used standalone and need to be used in conjunction with paired Frequency Division Duplex (FDD) carriers. The downlink-only spectrum in the 700 MHz band shares similar propagation characteristics of other sub-1 GHz spectrum and all MNOs now hold some sub-1 GHz paired spectrum which can be used in conjunction with SDL carriers in downlink-only bands.

A8.18 At present, SDL carriers in the 1400 MHz band can only be paired with FDD carriers in the 800 MHz band under 3GPP requirements, which supports the view for considering 1400 MHz downlink-only spectrum as low frequency spectrum. MNOs holding 1400 MHz have the relevant spectrum to pair it with.

Our analysis of the coverage properties of the 1400 MHz band

A8.19 We have conducted an analysis to assess whether we should consider 1400 MHz to be low frequency spectrum. When assessing the potential coverage of a mobile network cell we consider the area where users can establish and maintain a network connection at a certain quality of service. The level of coverage depends mainly on factors such as the

---

[164] https://www.ofcom.org.uk/__data/assets/pdf_file/0022/74461/1.4ghz-consultation.pdf

emitted power levels (or E.I.R.P.), the height, location and orientation of the antenna, the technology used (e.g. 3G or 4G) and, to a lesser extent, the spectrum bandwidth.

A8.20 Our analysis is aimed at understanding the coverage that an outdoor macro-cell base station might be able to provide to users indoors. To do so, we have estimated the relative potential coverage under the same environmental conditions for the 700 MHz, 800 MHz, 900 MHz, 1400 MHz, 1800 MHz, 2100 MHz and 2600 MHz frequency bands (using 800 MHz as the normalised baseline).

A8.21 We have modelled a 5 MHz downlink carrier to a user terminal situated within a building, applying the building entry losses described in Figure A8.2 below. We then calculate the coverage area within which a user terminal in an indoor environment would receive a signal with an RSRP[165] equal to or greater than -105 dBm.[166]

A8.22 This approach is useful for comparing the relative performance of different frequency bands under the specific model conditions. However, the results should not be interpreted as a prediction of the likely actual coverage that could be achieved by real network deployments.

A8.23 We have assumed a base station with a height of 20m above ground (a value typical of macro-cell deployments). Each base station only includes an omnidirectional antenna transmitting at the maximum permitted power E.I.R.P.[167] as stated in the current licenses.[168]

A8.24 To estimate the link propagation losses, we have used the modified version of the Extended-Hata model[169] in three different propagation environments (urban, suburban and open).

A8.25 We have derived building entry losses using Recommendation ITU-R P.2109.[170] The output of this recommendation is in the form of a cumulative distribution function (CDF) of the probability that a given loss will not be exceeded.

A8.26 ITU-R P.2109 includes building entry loss estimates for two types of buildings: traditional, and thermally efficient (TEF). Modern TEF buildings usually present significantly higher building entry losses than traditional buildings due to their construction materials. We do not hold detailed information about the UK stock of TEF dwellings, though it is our understanding that these represent a small fraction of the overall UK housing stock. We have therefore concluded that basing results on losses for traditional buildings is reasonable for the purposes of this analysis.

---

165 Reference Signal Received Power, this is the average power received by the mobile from the reference signals transmitted by the base station.

166 As we stated in our consultation on "Improving mobile coverage: proposals for coverage obligations in the award of the 700 MHz spectrum band"[166], we consider a 4G signal strength of -105 dBm[166] to be required to achieve outdoor geographic mobile coverage.

167 Effective Isotropic Radiated Power.

168 For 700 MHz the maximum permitted E.I.R.P. is the proposed level in the draft licence (see annex 22).

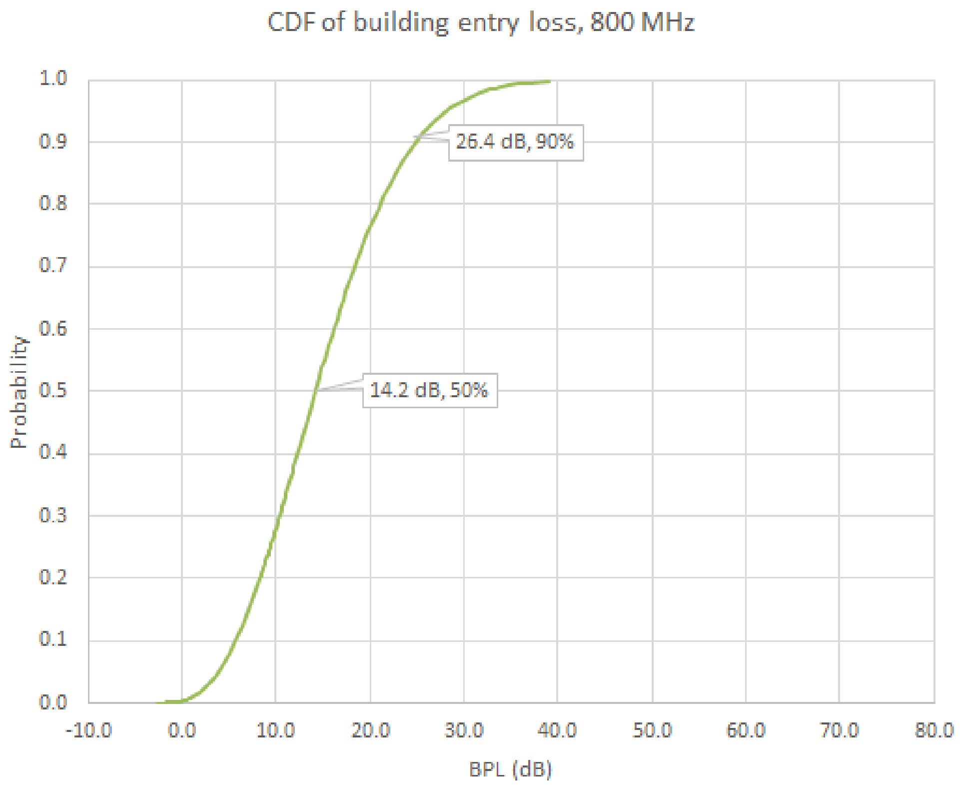
169 http://ecocfl.cept.org/display/SH/A17.3+EXTENDED+HATA+MODEL

170 https://www.itu.int/rec/R-REC-P.2109/en

A8.27 We have considered two types of indoor environments:

- **Shallow indoor**, derived from the 50th percentile of the Cumulative Distribution Function (CDF) from ITU-R P.2109 for traditional buildings, i.e. a 50% probability that the loss is not exceeded. This is intended to represent comparatively easy-to-reach areas, such as those fairly close to windows or external sides of buildings, or further deep into buildings with relatively low penetration losses.
- **Deep indoor**, derived from the 90th percentile of the CDF from ITU-R P.2109 for traditional buildings, i.e. a 90% probability that the loss is not exceeded. This is intended to represent comparatively hard-to-serve locations areas, such as within enclosed rooms away from external walls or in basements, or shallower within buildings with relatively high penetration losses.

Figure A8.1: Cumulative Distribution Function (CDF) of building entry loss and 800 MHz and 2.6 GHz



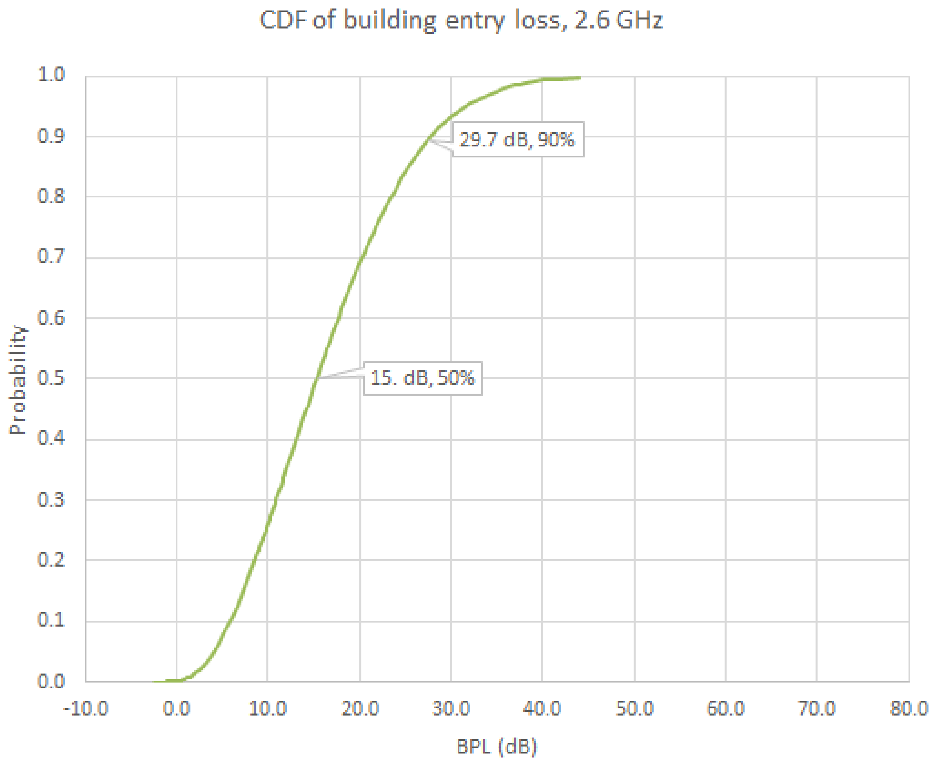


Figure A8.2: Building entry losses from ITU-R P.2109

Frequency (MHz)	Building Entry Loss (dB) Shallow 50th percentile CDF	Building Entry Loss (dB) Deep 90th percentile CDF
700	14.2	26.4
800	14.2	26.5
900	14.3	26.9
1400	14.6	28.0
1800	14.9	28.6
2100	15.0	29.1
2600	15.3	29.7

Results: estimated coverage

A8.28 Figure A8.3 and Figure A8.4: compare the estimated potential coverage for each of the scenarios considered. The height of each bar represents the relative coverage estimated for the respective band and the three propagation environments considered: urban, suburban and rural or open environment.

A8.29 We have normalised the results with respect to the 800 MHz as we are not assessing absolute coverage; rather we are comparing the estimated potential coverage of different bands.[171] This means that the 800 MHz results will have a value of 1 for the three propagation environments.

A8.30 Results with a value higher than one represent coverage larger than that of the 800 MHz band under the same conditions; results with a lower value than one represent coverage smaller than that of the 800 MHz under the same conditions.

[171] The reason for this is that, at present, the 3GPP specification only allows 1400 MHz SDL to be aggregated with 800 MHz.

Figure A8.3: Relative potential coverage estimated for the 50th percentile of building entry loss in shallow indoor locations, normalized to 800 MHz coverage

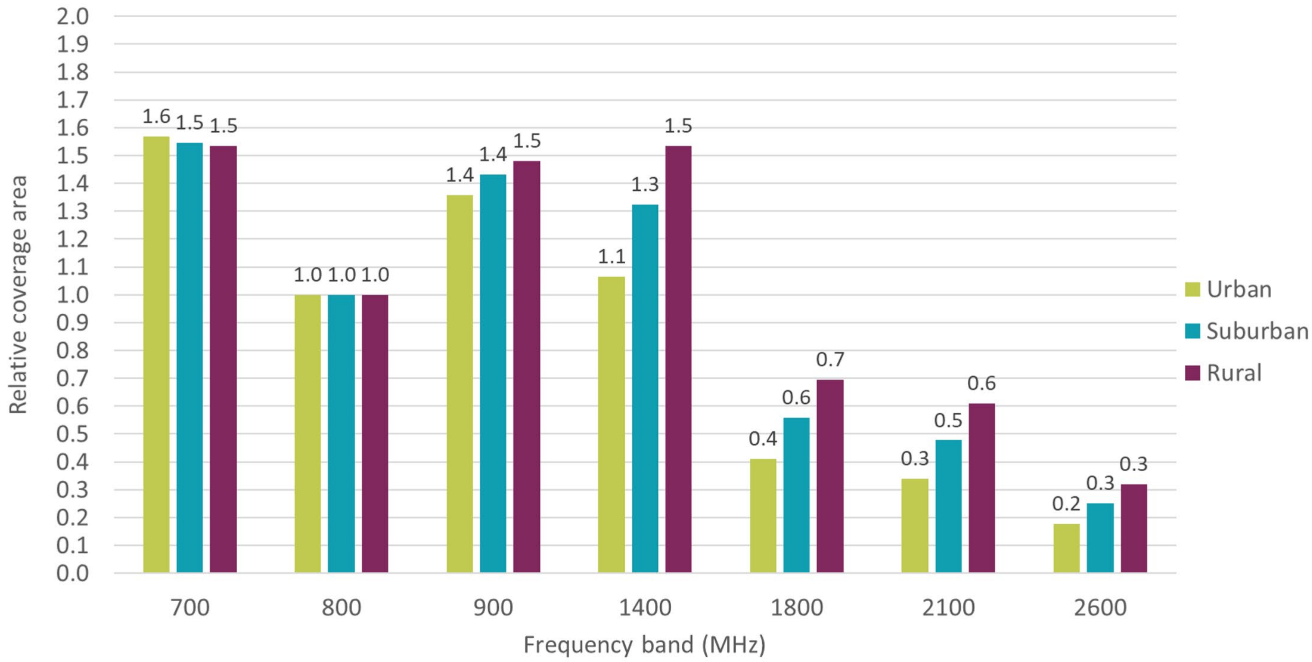
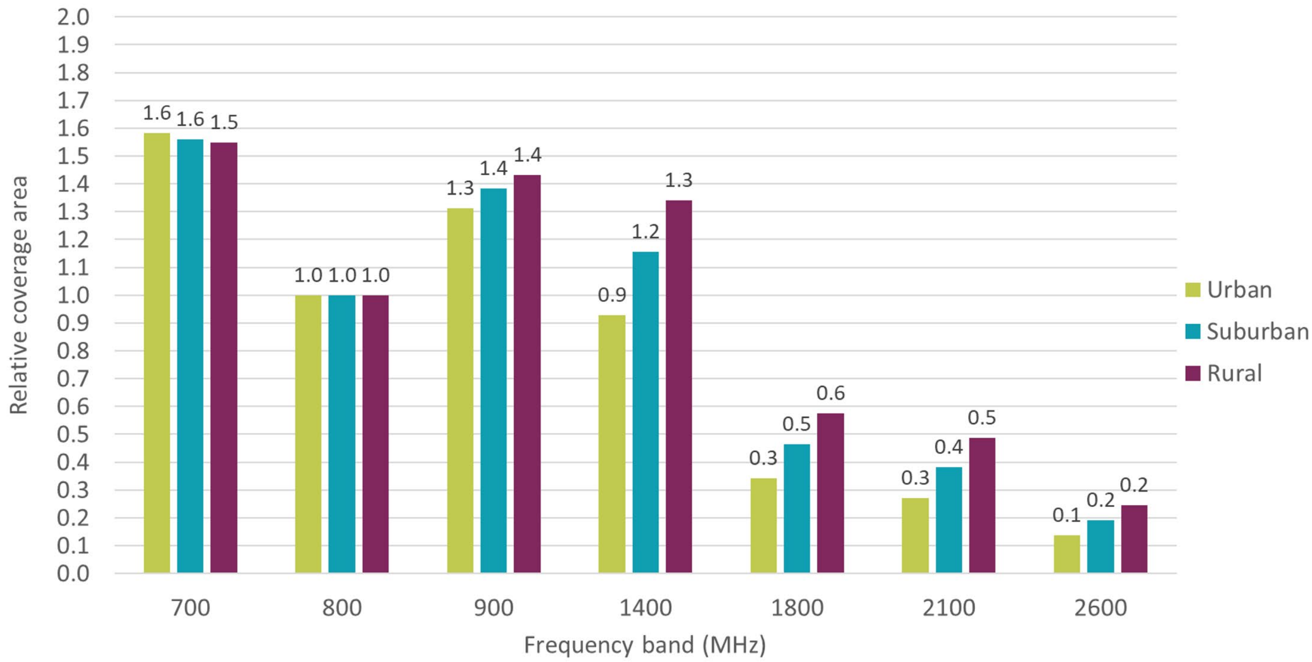


Figure A8.4: Relative potential coverage estimated for the 90th percentile of building entry loss in deep indoor locations, normalized to 800 MHz coverage



A8.31 These results show that the 1400 MHz potential coverage is estimated to be greater than the 800 MHz potential coverage in all cases, with exception of the 90th percentile losses (deep indoor locations) in urban environments, which is estimated to be approximately 10% less. On the other hand, the potential coverage from 1800 MHz and higher bands is estimated to be significantly lower than from the 700 MHz, 800 MHz, 900 MHz and 1400 MHz bands.

We consider downlink-only spectrum as relevant spectrum

A8.32 In this section, we examine the properties of downlink-only spectrum to assess whether it should be included in the pool of relevant spectrum for the purposes of assessing any competition concerns for the auction.

A8.33 Downlink-only spectrum, as the name implies, is spectrum that is used for transmissions from the access network to user terminals and can be used for both SDL and broadcasting. SDL is a technique using additional spectrum to boost the capacity of downlink connections in mobile networks. SDL carriers must be aggregated with downlink carriers from paired FDD bands.

A8.34 As recalled above, in 2012 we defined 'low frequency spectrum' as spectrum at frequencies below 1 GHz (sub-1GHz) spectrum. In 2015, H3G and Vodafone each acquired 20 MHz of 1400 MHz downlink-only spectrum. Newly usable 700 MHz downlink-only spectrum (the 20 MHz centre gap) will also be part of this auction. We have therefore considered whether downlink-only spectrum should be included within the pool of low frequency spectrum and, if so, whether we should extend the definition of low frequency to include the 1400 MHz band.

A8.35 Downlink-only spectrum in the 700 MHz band shares similar propagation characteristics with other sub-1 GHz spectrum.[172] Although SDL cannot be used in isolation, all MNOs now hold some sub-1GHz paired spectrum which can be used in conjunction with their downlink-only bands (used as SDL). This suggests that SDL use of downlink-only spectrum could assist MNOs by providing greater downlink capacity in their coverage layer.

A8.36 However, we also recognise that the value of using this spectrum for SDL will be strongly influenced by the ratio of downlink to uplink data volumes from users, and whether the operator already holds other downlink-only spectrum (e.g. at 1400 MHz). This means that MNOs with existing downlink-only spectrum or with a lower ratio of downlink to uplink data may place less value on further downlink-only spectrum. Additionally, we recognise the device ecosystem may develop later for SDL use of the 700 MHz spectrum, and this could mean that the downlink-only spectrum at 700 MHz becomes usable for SDL at a later date than when other 700 MHz spectrum becomes usable for paired (FDD) mobile use.[173]

A8.37 Regarding the 1400 MHz band, Vodafone and H3G are permitted to transmit on their 1400 MHz spectrum at a higher power than they can on their sub-1GHz downlink spectrum, and, in theory, this should allow them to achieve similar coverage to sub-1GHz spectrum.

A8.38 We consider that what constitutes low-frequency spectrum should be driven by the feasible coverage benefits that bands can deliver in general. We recognise an operator

[172] In general, the propagation characteristics of the band do not depend on the type of technology (FDD, TDD or SDL) used.

[173] Downlink-only spectrum at 700 MHz is already available for broadcast services.

could face practical challenges in using 1400 MHz spectrum for SDL to match the coverage they could achieve at 800 MHz. For instance, there may be limited availability of amplifiers and antennas capable of fully exploiting the licenced power. This may limit the coverage benefits accruing to that operator from 1400 MHz spectrum. For example, MNOs may be practically limited to matching 800 MHz coverage with only a subset of their 1400 MHz spectrum. However, we would expect that, over time, the practical challenges will decrease as amplifier and antenna technologies advance so that in a few years' time an operator with 1400 MHz spectrum will be able to use their entire 1400 MHz holding (e.g. all 20 MHz of it) in a way that matches the footprint of their 800 MHz coverage.

Typically downlink traffic exceeds uplink traffic

A8.39 Current traffic demand shows asymmetries between downlink (DL) and uplink (UL) traffic. In general, mobile users tend to retrieve information from the internet rather than generating content themselves and uploading it. According to Report ITU-R M.2370[174], the overall average traffic asymmetry ratio (DL/UL), is currently dominant in favour of downlink, with asymmetry estimates ranging from 4:1 to 9:1 and expected to increase in the future.

A8.40 Data from the current mobile FDD deployments in the UK show that the DL/UL traffic ratios range from 5:1 to 14:1.[175] Different applications have different DL/UL requirements: for example, applications such as video calling require a reasonably balanced ratio, whereas applications such as streaming videos or live streaming over the internet require much higher traffic on the downlink.

There are various ways for MNOs to manage greater requirements for downlink traffic

A8.41 In a mobile network, the DL is generally more spectrally efficient than the UL.[176] Consequently, more traffic can typically be carried in the DL than in the UL, given the same spectrum resources in both directions. However, in many cases, this difference in spectral efficiency is not sufficient to fully match the DL/UL asymmetry in traffic. It may, therefore, be more spectrally efficient overall to dedicate more spectrum resources to the DL than to the UL.

A8.42 Time Division Duplex (TDD) networks, in principle, allow operators to flex the resources dedicated to the DL and UL by adjusting the TDD frame ratio. However, in practice, the need to synchronise with neighbouring operators in TDD networks to avoid interference means that the DL/UL ratio can only change if all operators agree.

A8.43 In current TDD mobile networks, the frame ratio is typically set between 3:1 and 4:1. For instance the preferred frame structure in current UK 3.4-3.6 GHz licences is a 3:1 structure.

---

[174] https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2370-2015-PDF-E.pdf
[175] Operator traffic data submitted to Ofcom to inform our work on the Connected Nations.
[176] There are various reasons for this, including differences in the way the modulation and coding apply to uplink and downlink connections and the need to ensure a longer battery life for the users' handsets (e.g. more power efficient but less spectral efficient modulation and coding schemes are used to save battery power).

In a recent meeting with Ofcom, Sprint stated that, in their experience, to cope with peak DL/UL traffic ratios of [✂ REDACTED] efficiently they use a 3:1 TDD frame ratio.

A8.44 In FDD networks, the ratio of DL to UL resource is fixed (usually 1:1 in terms of spectrum) as the DL and UL use different frequency carriers. Changing the ratio of DL to UL spectrum available in FDD networks is usually not practical. However, SDL spectrum can help cater for asymmetric traffic in an FDD network by aggregating additional DL carriers from a dedicated downlink-only band. However, this may require additional equipment at the base station (e.g. antennas and power amplifiers) and support in user devices.

A8.45 We note, however, that:

- Only a limited number of FDD bands are currently able to be aggregated with bands designated for SDL.[177]
- Under the same propagation conditions, higher frequency bands tend to suffer greater losses: an SDL carrier operating at a higher frequency than that of the FDD DL carrier it is aggregated with will either have a smaller coverage footprint (reducing its utility) or it will need to transmit at a higher power to compensate.

A8.46 Currently, SDL technology is not supported by all handsets, however, several newer handsets do support it.[178] Therefore, whilst SDL can be used by the operator, only a subset of users may benefit directly, at least until the penetration of handsets supporting the feature increases.

700 MHz downlink-only spectrum for SDL use

A8.47 At present, the 3GPP specifications only allow the aggregation of SDL carriers in the 700 MHz band (3GPP Band 67) with FDD DL carriers in the 800 MHz band (3GPP Band 20) using 5 MHz, 10 MHz, 15 MHz or 20 MHz SDL carriers to achieve a maximum of 40 MHz aggregated bandwidth across both bands.

A8.48 So, for instance, either Vodafone or O2 (which both have 2x10 MHz of 800 MHz spectrum), could in theory acquire 20 MHz of 700 MHz spectrum for SDL use to achieve an overall aggregated downlink bandwidth of 30 MHz potentially giving them an DL:UL ratio of 3:1.

A8.49 On the other hand, either BT/EE or H3G (which both have 2x5 MHz of 800 MHz spectrum), could in theory acquire 20 MHz of 700 MHz spectrum for SDL use to achieve an overall aggregated downlink bandwidth of 25 MHz potentially giving them an DL/UL ratio of 5:1 (but with half the 800 MHz UL capacity of Vodafone and O2).

[177] The possible combinations depend on the relevant standard (3GPP) specifications support and the support in devices. 3GPP specifications evolve in time; band combinations (for aggregation) are often redefined to match requirements from industry.

[178] 700 MHz SDL is not yet supported but 1400 MHz SDL is supported by around 40 devices now including iPhone XR and XS, Samsung S9 and google Pixel 3.

1400 MHz downlink-only spectrum for SDL use

A8.50 At present, the 3GPP specifications only allow the aggregation of SDL carriers in the 1400 MHz band (3GPP Band 75) with FDD DL carriers in the 800 MHz band (3GPP Band 20) using 5 MHz, 10 MHz, 15 MHz or 20 MHz SDL carriers to achieve a maximum of 40 MHz aggregated bandwidth across both bands.

A8.51 Given that Vodafone and H3G each hold 20 MHz of 1400 MHz spectrum, this would mean that Vodafone could combine this with their FDD DL spectrum in the 800 MHz band to achieve an overall aggregated downlink bandwidth of 30 MHz, and similarly H3G could achieve an overall aggregated downlink bandwidth of 25 MHz.

A8.52 BT/EE and O2 do not hold any 1400 MHz spectrum so this option is not open to them.

A8.53 It should be noted that, at present, the 3GPP specifications do not include the option to aggregate 800 MHz DL spectrum with SDL carriers operating in both the 700 MHz and 1400 MHz bands simultaneously. So, unless the specifications are changed, if either Vodafone or H3G want to supplement their 800 MHz DL with SDL, they will have to either acquire some downlink-only 700 MHz spectrum or use their existing 1400 MHz holdings, but they cannot use SDL carriers from both bands simultaneously (at least not in the same area).

Alternative ways to improve indoor coverage

A8.54 In this section, we discuss ways to improve coverage in hard to serve areas (such as deep indoors) when it is not possible to use low frequency spectrum. As set out in annex 6, consumers increasingly value network availability as they use their mobile devices wherever they are at work, at home, or on the move. As consumers’ expectations of mobile services change, we expect network operators to focus their investments on improving mobile coverage and, generally, consumers’ experience where this is commercially viable.

A8.55 In general, mobile operators can increase coverage and provide additional network capacity in several ways. They can:

- deploy additional spectrum;
- build additional sites or use small cells, femto-cells and repeaters (network densification);
- increase the number of sectors per site (sector densification);
- make use of more efficient technologies, such as 4G and 5G;
- use more efficient antenna technologies such as beamforming and massive MIMO;
- offload traffic to alternative radio technologies such as Wi-Fi; and
- use traffic management techniques to ensure overall users’ quality of service does not deteriorate in peak hours.

A8.56 In our 2012 Statement for the 800 MHz and 2.6 GHz band awards,[179] we described other means of providing coverage – such as Wi-Fi and femtocells – and assessed to what extent a national wholesaler could provide good quality coverage by using these. Our view in 2012 was that, whilst an operator could use these alternative means like Wi-Fi, cellular repeaters or small cell technologies like femtocells in certain circumstances, these solutions did not fully remove the advantages of sub-1 GHz spectrum.[180]

A8.57 Our assessment then was based on the ability of an operator to provide low-data-speed services (e.g. up to 1 Mbit/s) to hard-to-serve areas, which we concluded would require some low frequency spectrum holdings.

A8.58 As all MNOs now have low frequency spectrum, our current analysis is more focused on the ability to provide higher data speed services (up to 2 Mbit/s), especially in hard-to-serve areas (i.e. in shallow and deep indoor locations). This is relevant when considering the impact of potential auction outcomes on operators such as BT/EE and H3G who have smaller holdings of low-frequency spectrum.

A8.59 Wi-Fi solutions (such as Voice over Wi-Fi for voice services), cellular repeaters, femtocells and indoor small cells are viable alternatives to provide good quality indoor coverage in many cases.

A8.60 Our analysis below finds that, following recent developments mainly related to its wider availability for data and voice, Wi-Fi is an effective technology and a cost-effective solution to provide indoor coverage and is more widely used than femtocells and cellular repeaters. However, we recognise that these alternative ways to provide coverage are not available in all cases as they might depend on the availability of a backhaul connection and third-party access or rights. There may also be limitations, especially for Wi-Fi, for visitors or temporary users who may not be able to connect to the network (for example if they do not know or are not given the Wi-Fi password).

A8.61 We consider these alternative methods and the extent to which they are used by consumers in the following paragraphs.

Wi-Fi, Voice over Wi-Fi (VoWi-Fi) and LTE-LAA

A8.62 In May 2018 we published a research paper showing that Wi-Fi continues to be a fundamental part of consumers' experience of using mobile phones, with consumers using apps over Wi-Fi rather than mobile networks 75% of the time, an increase of 6% since 2016.[181]

A8.63 This may be due to better experience over Wi-Fi, or users trying to minimise their mobile data use and save their data allowances at home or in public areas with Wi-Fi hotspots. However, it is likely that most Wi-Fi use is in the home: our results show that mobile

---

[179] https://www.ofcom.org.uk/spectrum/spectrum-management/spectrum-awards/awards-archive/800mhz-2.6ghz

[180] Paragraph 4.80 from https://www.ofcom.org.uk/spectrum/spectrum-management/spectrum-awards/awards-archive/800mhz-2.6ghz

[181] Ofcom, *The consumer mobile experience: Measuring the consumer experience of using Android mobile services*, 9 May 2018, https://www.ofcom.org.uk/__data/assets/pdf_file/0028/113689/consumer-mobile-experience-2018.pdf

networks were used more frequently during the day and Wi-Fi use was higher in the evening and at night.

A8.64 According to the Cisco VNI report,[182] smartphone-based data traffic is expected to exceed 80% of total data traffic generated by mobile networks in 2020 and studies have claimed that 65% or 70% of smartphone data traffic is being offloaded to Wi-Fi networks.[183]

A8.65 In public buildings Wi-Fi hotspots are becoming increasingly available, although the service take-up depends on factors such as fees, access restrictions and service quality offered in such public places.

A8.66 Recently, MNOs have started offering Voice over Wi-Fi (VoWi-Fi). This technology recognises that the mobile smartphone users are connected to a Wi-Fi network and routes voice calls over Wi-Fi, making use of a broadband connection (fixed or wireless) rather than the mobile access network.

A8.67 As VoWi-Fi is natively supported on a number of devices,[184] it does not depend on third party applications and there is no need to install additional software to support it. In recent years, this technology has increasingly been offered by mobile operators,[185] allowing users to make voice calls over Wi-Fi without needing to be in an area of mobile network coverage.

Table A8.1: Wi-Fi solutions and their limitations

Environment	Use of Wi-Fi solution	Possible limitations
Residential and workplace	Commercial Wi-Fi solutions usually offered by internet providers as part of a service package.	Requires a network connection (e.g. fixed or wireless broadband) which may not be available in all locations. Not ideal for visitors as it requires password.

[182] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015–2020, Cisco, San Francisco, Calif, USA, 2016.
[183] K. Lee, J. Lee, Y. Yi, I. Rhee, and S. Chong, "Mobile data offloading: how much can wifi deliver?" IEEE/ACM Transactions on Networking, vol. 21, no. 2, pp. 536-550, 2013. A. Salter, "A Carrier Roadmap for Monetizing Next Generation, Wi-Fi, iPass", Redwood Shores, Calif, USA, 2012.
[184] VoWiFi is defined under the IEEE 802.11 umbrella. The most popular handsets currently available, such as recent iPhones or Samsung Galaxy phones, support VoWiFi. However, it is still not supported by the entire handset ecosystem.
[185] https://ee.co.uk/why-ee/wifi-calling, https://www.vodafone.co.uk/network/calling-features/wi-fi-calling, https://www.o2.co.uk/connectivity/wifi-and-4g-calling, http://www.three.co.uk/Discover/Three_inTouch

Environment	Use of Wi-Fi solution	Possible limitations
Public buildings (e.g. shops) and on the move	Public or private Wi-Fi hot-spots	They may require access rights via a third party. Quality and availability of the network is not necessarily guaranteed.

A8.68 Wi-Fi cannot substitute for a good level of mobile coverage across a whole community (including the reasonable expectation of some in-building coverage). Wi-Fi might not be a feasible substitute in those situations where access to either a broadband line or fixed wireless access point is not available. In more rural communities, for example, not everyone has broadband or a Wi-Fi calling enabled handset.[186] In general, also, those visiting local shops or attractions, or coming into the area for work, may not be automatically connected to a local network and so could remain uncontactable.

A8.69 We also note that Wi-Fi solutions which are deployed over unlicensed spectrum do not provide a guaranteed quality of service and might lead to poorer user experience in certain circumstances. This could happen, for example, in areas where there is congestion or interference from other devices.

A8.70 It is also worth noting that recent mobile devices, such as Google Pixel 3 and the iPhone XR and XS[187], now include the use of LTE-LAA (LTE Licensed Assisted Access). This technology, already specified in the 3GPP Standards from Release 13, combines the use of licensed (mobile access spectrum) and unlicensed spectrum (5 GHz band) to offer higher data rates. The take up of this technology is still at the early stages in the UK and other countries.

Indoor small cells

A8.71 Another way to improve indoor coverage and capacity would be through the use of indoor small cells. These are low-powered base stations located inside a premise which are usually deployed as an addition to a macro-cell layer, re-using the same frequency or using a different one. We do not discuss outdoor small cells as they would not be directly relevant to indoor coverage improvements.

A8.72 Indoor small cell solutions can either provide coverage to areas where there is weak or no coverage, or to enhance capacity in 'hot-spot' areas, without the need to deploy additional

[186] In rural communities, as we note in our Connected Nations update from October 2018, there are circa 860,000 premises that cannot get a decent download and upload speed, although we expect a reduction in the number of such premises over the next few years, thus easing backhaul access for Wi-Fi systems, https://www.ofcom.org.uk/__data/assets/pdf_file/0019/122194/connected-nations-october-2018.pdf

[187] Other devices include the Samsung Galaxy S8 and S9, LG V30 and Huawei Mate Pro.

macro-cell sites. Currently operators have deployed or trialled small cells[188], although these deployments are limited to a few areas.

A8.73 There are caveats around the use of indoor small cells that might mean they are not an effective solution: access to high capacity backhaul may not be readily available, their installation may require access rights via a third party (as for Wi-Fi solutions) or there could be issues related to multiple operators accessing the same site, i.e. it might not be possible for additional operators to install their equipment. This could be overcome if several operators shared the same equipment, avoiding the need for additional permissions.[189]

Cellular repeaters and femtocells

A8.74 **Cellular repeaters** amplify the signal from outside a building and boost the indoor signal to improve coverage. Mobile phone repeaters can be operated in the UK under the terms of the MNOs' licences or under a licence exemption[190] (provided the repeater meets certain technical conditions). They can offer an effective solution in cases where there is mobile phone coverage outside a building but where the coverage inside is poor or non-existent.

A8.75 **Femtocells** are small, low-power base stations that provide a mobile signal and are connected to the MNO's network via a broadband connection (typically fixed). Some MNOs offer services using these devices which may provide improved in-building coverage and data rates. They offer an indoor solution for users with poor or non-existent mobile coverage but where a fixed broadband connection is available.

A8.76 However, there is limited take up of both of these solutions. In the case of repeaters, they rely on the availability of a reliable signal outside the building that can then be repeated inside it. For both solutions, either the mobile operators have to be willing to supply the devices to their customers (something they have, so far, only done for a minority of cases), or (in the case of repeaters) the end user has to buy a device. The extent to which femtocells and cellular repeaters are used to improve coverage today is marginal compared to the use of indoor Wi-Fi solutions. The availability of these solutions may change over time if, for example, 5G indoor solutions are adopted in the future.

Other ways to improve network performance

A8.77 We describe some techniques that can be used to improve network performance in hard to serve areas (Table A8.2), other than deploying low frequency spectrum and/or using the indoor coverage solutions discussed above. The solutions considered below may not be

[188] https://news.o2.co.uk/press-release/arqiva-and-o2-to-improve-mobile-connectivity-in-london-boroughs/ https://www.vodafone.co.uk/business/business-mobile-plans/mobile-plan-features/in-building-coverage Three UK trialing small cells in London.

[189] Companies like Qorvo, Ericsson, Huawei, Nokia have indoor small cells in their product portfolio. Although varied, they offer features like multi band and multi operator operation and use with unlicensed spectrum bands, mostly for commercial or public environments.

[190] See https://www.ofcom.org.uk/__data/assets/pdf_file/0019/107254/Repeaters-Statement-2017.pdf

cost-effective to provide additional coverage in hard to serve areas or may offer only marginal gains. However, they might help increase coverage in some cases.

Table A8.2: Other solutions to improve network performance

Solution	Where and how can it improve network performance
Macro-cell densification	Adding additional macro sites to the network may allow better coverage in harder to reach locations as the average distance to the base stations decreases and hence average signal strength increases. It may also allow the network to operate at a lighter load, thus potentially reducing inter site interference and increasing network performance in harder to reach locations. However, this would be a costly solution to improve indoor coverage and may have practical limitations. Finding new cell sites, especially in urban and dense urban areas is likely to be a challenge. A variant of network densification is to increase the sectorisation of sites from, say, 3 to 6 sectors each. This has the advantage that new sites are not necessary but not all sites are suitable for adding additional sectors without significant work and adding sectors may increase overall inter sector interference.
MIMO and beamforming	MIMO technologies increase the number of users that can be served from a single cell site whilst beamforming controls the direction of each beam assigned to each user, thus enhancing the received signal. This can enhance the throughput offered at the cell edge as the spectral efficiency of each beam would be higher than those of former non-directional networks.
Control/User plane decoupling and Carrier Aggregation	The first technique allows the control and user planes to be sent over different connections, e.g. the control plane over a stable macro-cell connection and the user plane over a small cell connection. The second technique allows connections to happen over different spectrum blocks (carrier aggregated). Both these techniques make efficient and tailored use of the radio resources in order to improve user data rates. They can in some cases improve capacity or coverage for users at the cell edge.

Assessment of usability of spectrum bands

A8.78 This subsection presents our current assessment of the usability of the different spectrum bands in the context of the 700 MHz and 3.6-3.8 GHz award.[191] Determining the usability of different spectrum bands is a key input for our competition assessment as it sets out the relevant pool of spectrum to consider when looking at MNOs' spectrum holdings; in other words which spectrum bands are usable and the expected timelines. Where the bands are not currently used for delivering mobile services, we also consider when they are expected to become useable.

A8.79 We regard mobile spectrum as being useable once it satisfies all of the following conditions:

- **Assignment**: Spectrum licences have been granted, for example by an auction, and the licences permit it to be used for mobile services. Licence holders will require some time to deploy the awarded spectrum but the timeframe for network roll-out varies depending on the licence holders' priorities and the technical changes required to the existing network infrastructure.[192]
- **No major constraints on use**: To the extent there are constraints on the use of the spectrum for mobile (e.g. due to a clearance programme of previous users or on-going requirements to address co-existence with other users), they must not be significant enough to undermine or substantially constrain the network deployment.
- **Ecosystem**: There is a sufficiently developed ecosystem for the spectrum for mobile services. In this regard, we see user devices (e.g. smartphones, tablets etc.) as the key constraint rather than network equipment. We also consider that spectrum can be useful for adding capacity and coverage even when it is supported in only a minority of user devices. This is because traffic can be offloaded to the new spectrum band for the enabled devices freeing up capacity on other bands.

A8.80 We detail our reasoning throughout this subsection, focusing first on the bands that will be awarded in this auction, namely 700 MHz and 3.6-3.8 GHz. In summary, we consider that:

- 800 MHz, 900 MHz, 1400 MHz, 1800 MHz, 2100 MHz, 2.3 GHz and 2.6 GHz spectrum bands are currently useable;
- 700 MHz paired will be useable from mid-2020;
- 700 MHz downlink-only will also be usable by mid-2020 or shortly after;

[191] For any future award, we would generally expect to make the assessment again in due course. If circumstances had changed between the two awards (e.g. if additional bands had become useable, or if it had become clear that some bands that were expected to become useable had not turned out to be useable), then the pool of relevant spectrum could change between the two awards.

[192] For example, O2's deployment of its recently acquired 2.3 GHz spectrum was extremely rapid. Conversely, 4G roll-out based on 800 MHz started within a few months of the auction especially for those operators requiring more substantial network changes. https://news.o2.co.uk/press-release/o2-to-connect-1000-locations-to-latest-4g-spectrum-in-rapid-roll-out/

- 3.4-3.6 GHz will be useable from 2019;
- Spectrum in the 3.6-3.8 GHz band will be useable in some parts of the UK before mid-2020 and possibly earlier, subject to coordination requirements to account for existing users. Most of the users will have left the band by mid-2020, thereby making the band useable nationwide by this date with only some minor deployment restrictions as a consequence of the coordination requirements. These deployment restrictions would be lifted if an agreement is reached with existing users early;
- We do not consider mmWave spectrum, nor the 1900 MHz and the unawarded parts of the 1400 MHz and 2.3 GHz bands to be useable in the context of this auction.

700 MHz

A8.81 We believe that 700 MHz paired spectrum will be useable by mid-2020, once the clearance of the band is completed and a sufficiently large device ecosystem will be available, there will not be any restrictions on the deployment of the band beyond coexistence requirements and we will have awarded the band by then.

A8.82 In October 2017 we published our 700 MHz clearance programme timescale review[193] where we confirmed that the programme was on track to meet our target of completion in Q2 2020 and that we expected the process to be completed as planned. This confirms the view on useability that we had set out in our July 2017 statement on the award of the 2.3 and 3.4 GHz spectrum bands ('July 2017 Statement').

A8.83 With regards to the centre gap, we expect that the band should be useable by mid-2020 or shortly after.

A8.84 In our July 2017 statement we concluded that the centre gap would be useable by the time clearance of the band was completed in mid-2020.

A8.85 Since we published our July 2017 statement we have learned that the Swiss regulator has also announced that it will carry out a 5G auction in 2019 which will include 15 MHz of 700 MHZ downlink-only spectrum.[194] Sweden has also proposed four licences of 5 MHz each for the centre gap.[195] Austria, Croatia, Hungary, Romania, the Slovak Republic and Slovenia have prepared frequency arrangements for border interference arrangements that includes downlink-only spectrum in the centre gap.[196] The Spanish regulator has recently consulted on the possible uses of the 700 MHz centre gap[197]; responses from stakeholders showed an interest in both SDL and PPDR applications. The 700 MHz auction is planned for early 2019. In Italy, 700 MHz SDL was made available during the auction run earlier in 2018 but received no bids and, to our knowledge, is currently unassigned.

[193] See https://www.ofcom.org.uk/__data/assets/pdf_file/0022/106933/700mhz-clearance-timescale-review.pdf
[194] https://www.newsd.admin.ch/newsd/message/attachments/53021.pdf
[195] https://www.pts.se/en/news/press-releases/2018/auction-in-the-700-mhz-band-to-improve-coverage-in-rural-areas/
[196] https://www.hakom.hr/UserDocsImages/2018/radiokomunikacije/700MHz-20180219.pdf
[197] https://www.mincotur.gob.es/telecomunicaciones/esES/Participacion/Documents/Informe_Resumen_Consulta_Publica_Banda_700_MHz.pdf

A8.86 In terms of ecosystem availability, 700 MHz FDD is available in several handsets (around 60 handsets at present, including Apple XS and XR, Samsung S9 and S9+, Google Pixel3, OnePlus, Xiaomi, LG, Sony and Huawei).

A8.87 We are not aware of any handsets currently supporting 700 MHz SDL (3GPP band 67). In recent discussions with UK MNOs, they have said that they were not aware of plans to include the band by manufacturers although some noted that similar bands are included in non-European models of handsets and could be included in handsets in 2020 or 2021.[198]

A8.88 In July 2018 [✂ REDACTED]

A8.89 In August 2018 [✂ REDACTED]

A8.90 Given that manufacturers usually respond to request from MNOs, it is unlikely that there will be much demand to include the band until it is awarded in the UK and other countries. This should happen in the next few years as several countries are likely to allocate the centre gap for downlink-only use.[199]

A8.91 Although we expect that MNOs will only demand support for the band from manufacturers after the award, we believe that it should be possible to include support in new handsets fairly quickly as all the necessary components are already in place. Therefore, we expect that the 700 MHz downlink-only spectrum should be useable by mid-2020 or shortly after.

3.6-3.8 GHz spectrum

A8.92 In our July 2017 statement we concluded that the 3.6-3.8 GHz band could not be considered to be useable in the same timeframe as 3.4-3.6 GHz as we did not expect the device ecosystem to develop at the same pace as for 3.4-3.6 GHz and, more importantly, there were significant constraints to the deployment of the band as a result of the incumbent users, namely fixed links and earth stations.

A8.93 However, a number of the incumbent fixed links users of the band have moved to alternative frequencies more quickly than we expected at the time of the 2.3 GHz and 3.4 GHz auction, and we therefore set out here our updated view on the timeframes in which 3.6-3.8 GHz spectrum will become usable. We first discuss the timeline of events, including the developments since our July 2017 statement, we then present the results of our interference analysis for the fixed links that are likely to remain in the band until the end of 2022 and an update on the device ecosystem and then conclude on the usability of the band.

---

[198] For example, the US version of all iPhones currently on sale include support for LTE band 29, which is a 700 MHz SDL band in the US as well as models by manufacturers such as Samsung and Sony.
[199] Sweden, Denmark, Austria, Croatia, Hungary Romania, the Slovak Republic and Slovenia have suggested SDL in their consultations.

Timeline of developments relating to clearance of the 3.6-3.8 GHz band

A8.94 The 3.6 – 3.8 GHz band has been harmonised for mobile and identified as part of the primary band for introducing 5G in Europe by the RSPG. In October 2017,[200] we therefore decided to make the band available for mobile services and confirmed our intended approach to existing fixed link and satellite earth station users of the band. We then commenced the statutory process to:

- revoke fixed links licences in the 3.6-3.8 GHz band; and
- vary the licences and grants of recognised spectrum access for satellite earth stations such that Ofcom would no longer take registered satellite earth stations with a receive component in the 3.6-3.8 GHz band into account for frequency management purposes.

A8.95 In February 2018, we published an update on the timing of availability of the 3.6-3.8 GHz band[201] which confirmed that we had issued notices to revoke all fixed link licences in the band with an effective date of 23 December 2022, and varied PES licences and grants of recognised spectrum access (RSA) with an effective date of 1 June 2020, with the exception of one grant of RSA where variation would come into effect on 1 September 2020.

A8.96 We note that, in our July 2017 Statement on the 2.3 and 3.4 GHz auction[202], we said that it might not be possible for operators to launch mobile services using the 3.6 – 3.8 GHz band nationwide before 2022, and therefore concluded that we were no longer certain that the 3.6 – 3.8 GHz band would develop as quickly as the 3.4 – 3.6 GHz band.[203] We therefore did not include 3.6 – 3.8 GHz spectrum in our consideration of the pool of available spectrum in the 'second transitional period', that is the period beginning when the 3.4 GHz became useable and ending when the 3.6-3.8 GHz becomes usable.

A8.97 However, since July 2017 Statement on the 2.3 and 3.4 GHz auction, we have engaged with all the fixed link users in the band and several have agreed to vacate the band before mid-2020. At the time of this consultation only one user [✂ REDACTED] operating several fixed links in northern Scotland as well as a link between Portsmouth and the Isle of Wight, has not agreed to move early and therefore is likely to remain in place until the end of 2022.

Interference analysis and device ecosystem for 3.6-3.8 GHz

A8.98 In Annex 15 we present the detail of our interference analysis focusing on the Portsmouth to the Isle of Wight fixed link, the only link potentially constraining deployments in densely populated areas between mid-2020 and end of 2022. This link operates a 30 MHz carrier with a centre frequency of 3740 MHz.

[200] https://www.ofcom.org.uk/__data/assets/pdf_file/0019/107371/Consumer-access-3.6-3.8-GHz.pdf
[201] See https://www.ofcom.org.uk/__data/assets/pdf_file/0018/110718/3.6GHz-3.8GHz-update-timing-spectrum-availability.pdf
[202] https://www.ofcom.org.uk/__data/assets/pdf_file/0022/103819/Statement-Award-of-the-2.3-and-3.4-GHz-spectrum-bands-Competition-issues-and-auction-regulations.pdf
[203] See paragraph 1.28 of the July 2017 Statement.

A8.99 Based on this analysis we conclude that, within a radius of 50 km of the Isle of Wight to Portsmouth link, roll-out of base stations is likely to be difficult with about 80% of the sectors we analysed failing to meet the protection criteria for this fixed link. For base stations further away, roll-out is likely to be minimally affected with about 4% of sectors that lie within a few kilometres either side of the extended baseline of the fixed link (affecting parts of London and the South East) failing to meet the protection criteria for the link. However, in this case the failure margin is relatively small implying that, with reasonable mitigation (e.g. reducing powers or careful pointing), most of the sectors that failed (in our analysis) could in fact be deployed with minimal impact on network performance therefore, this should not prevent MNOs from deploying this spectrum nationally. The population potentially affected by this link is estimated to be c. 500,000.

A8.100 Our intention is to require 3.6-3.8 GHz licensees to coordinate their base station deployment with incumbent satellite Earth stations and fixed links in the interim period before they vacate the band. See section 9 for further details.

A8.101 It is also important to highlight that it is still possible for all the spectrum to become unconstrained if, for example, those who win spectrum in the auction reach an agreement with existing users to move out of the band early.

Ecosystem availability

A8.102 We believe that devices supporting the whole 3.4-3.8 GHz band for 5G will start to be available in 2019. At the time of writing we understand that the only currently available handheld device that can use the band is the Essential PH-1 (as a LTE band). Currently, there are a few vendors offering LTE Band 43 in their FWA portfolio, including Huawei, Nokia, NetComm Wireless and Baicells.

A8.103 The list of spectrum bands in 3GPP Release 15[204] identifies bands n77 (3.3[205]-4.2 GHz) and n78 (3.3-3.8 GHz) as the relevant 5G NR bands. We expect that devices supporting the 3.4-3.6 GHz band will also support the 3.6-3.8 GHz band.

A8.104 We expect that 5G devices supporting the whole band will start to be available in 2019, although there have been some news reports indicating that some devices could start becoming available as soon as the end of 2018.[206]

A8.105 MNOs have also told us that they expect devices capable of using the band in 5G NR from 2019 or 2020.

Conclusion on usability of the 3.6-3.8 GHz band

A8.106 There have been significant developments since we published our July 2017 Statement. Firstly, we have taken decisions on our approach to existing users of the band, ensuring that PES licensees vacate the band by mid-2020 and fixed links licensees by the end of

[204] https://www.ericsson.com/assets/local/policy-makers-and-regulators/180119-3gpp-spectrum-bands.pdf
[205] 3.3-3.4 GHz is meant for indoor use in Asian markets only.
[206] http://wirelessone.news/10-r/1124-samsung-2018-complete-5g-chipset

2022. Further, through our engagement with fixed link stakeholders we have reached agreements with fixed link licensees to ensure that most fixed links users vacate the band by the March 2020.

A8.107 Secondly, we now have more certainty on the development of the ecosystem for the band, notably that upcoming 5G NR capable devices will support the whole 3.4-3.8 GHz band and that these should be available no later than 2019.

A8.108 Some fixed links may remain until the end of 2022. We have carried out an interference analysis and concluded that while some deployment restrictions will remain as a consequence of coordination requirements in a few areas of the country between mid-2020 and end of 2022, these are not material enough to prevent an MNO from deploying the spectrum nationally.

A8.109 Furthermore, these restrictions would disappear if the new licensees reach an agreement with the remaining users to clear the band before the end of 2022.

A8.110 We therefore conclude that the 3.6-3.8 GHz band should be useable, subject to coordination with existing users, from mid-2020 or earlier in some parts of the country.

Currently useable mobile bands

A8.111 We consider that the awarded spectrum in the 800 MHz, 900 MHz, 1400 MHz, 1800 MHz, 2.1 GHz, 2.3 GHz bands, and paired and unpaired 2.6 GHz is currently useable.

A8.112 As per our previous statements on the useability of different bands, we do not include all 50 MHz of the **unpaired 2.6 GHz spectrum** in our analysis of usable spectrum. This is because the top 5 MHz of the 2.6 GHz band (held by BT/EE) and the lowest 5 MHz of any individual company's holding in the unpaired 2.6 GHz band were restricted to a maximum power of 25dBm. This is to manage the risk of interference between two users of the unpaired spectrum as well as between users of unpaired spectrum and users of paired 2.6 GHz spectrum. These restrictions remain in place, and as a result, these portions of the 2.6 GHz unpaired spectrum continue not to meet our second criteria for useability, i.e. there are material constraints on the use of the band.

A8.113 We therefore count BT/EE's holdings at 2595-2620 MHz as representing only 15 MHz of unrestricted mobile spectrum and Vodafone's holdings at 2570-2595 MHz as representing only 20 MHz of unrestricted mobile spectrum.

A8.114 With regards to the **2.3 GHz band** we still consider that it is currently useable. In our July 2017 Statement we found that there was a significant number of 2.3 GHz-compatible devices (including some of the best-selling phones in the country such as the iPhone 7 and the newer models of the Samsung Galaxy range). Since then we have awarded the band and more devices have come into the market that support the band such as the iPhone XS/XR.[207]

[207] https://www.apple.com/iphone/LTE/

A8.115 We also continue to believe that the **1400 MHz band** is currently useable. In our July 2017 statement we concluded that the 1400 MHz band was useable as it had already been allocated to Vodafone and H3G, there were no constraints on its use and there was already a handful of devices that supported it (including the Google Pixel, the Sony Xperia XZ, the HTC 10 and some versions of the Samsung Galaxy S8). At the time of writing there are around 40 devices support the band including iPhone XR and XS, Samsung S9 and Google Pixel 3.

A8.116 We also noted that Telecom Italia was deploying the band in some cities and that Vodafone Germany was running trials of the band.

A8.117 Since we published our July 2017 statement, additional devices that support the 1400 MHz band have become available. Currently there are around 40 devices available including the iPhone XR/XS, Samsung S9, Google Pixel 3, OnePlus 6, and LG G7 ThinQ among others

3.4 GHz spectrum

A8.118 While it is likely that devices supporting the 3.4 GHz band for LTE will be limited, early devices supporting 5G NR will include support for the band. We expect that these devices will come into the market from 2019, including popular devices. Therefore, our view is that the band should be considered useable from 2019.

A8.119 In our July 2017 statement we said that we expected the 3.4 GHz band to be useable by 2019-2020. At the time we were only aware of one upcoming device that used the band but were aware that some of the latest chipsets included support for the band. In addition to the Essential PH-1 phone, we are now aware of more phones that support the 3.4 GHz band for LTE, namely Google Pixel 3, LG G7 ThinkQ, Essential PH-1 and Sharp Aquos Crystal 2.

A8.120 The May 2018 GSA report notes that there are 202 devices that support 3.4-3.6 GHz for LTE, although not all of these devices are handsets.

A8.121 The latest RF modules and antenna modules from Qualcomm, which are expected to be included in devices from 2019, include support for 5G NR bands n77 (3.3-4.2 GHz) and n78 (3.3-3.8 GHz).[208]

A8.122 We awarded the 3.4-3.6 GHz band earlier this year, and all MNOs won holdings of at least 40 MHz. Since the award there have been announcements from BT/EE, Vodafone and H3G about deploying 5G using this spectrum as early as 2019.[209]

[208] https://www.qualcomm.com/news/releases/2018/07/23/qualcomm-delivers-breakthrough-5g-nr-mmwave-and-sub-6-ghz-rf-modules-mobile
[209] See https://www.ispreview.co.uk/index.php/2018/05/bt-and-ee-aiming-to-uk-launch-commercial-5g-mobile-in-2019.html, https://www.mobileeurope.co.uk/press-wire/vodafone-to-kick-off-uk-5g-trials-ahead-of-2020-launch and http://www.threemediacentre.co.uk/news/2018/sse-unbundling-announcement.aspx

mmWave spectrum

A8.123 One of the key aspects of the 5G technology is that it allows transmissions using spectrum above 6 GHz, in particular, spectrum in the mmWave bands (i.e. frequencies at or above 24 GHz). This has the potential to provide high capacity given the large amounts of spectrum available.

A8.124 We have previously identified 26 GHz[210] as one of the key 5G bands[211] along with the 700 MHz and 3.4-3.8 GHz bands. The RSPG has also identified 26 GHz (24.25-27.5 GHz) as the "pioneer" mmWave band for 5G and in its Second Opinion on 5G, it also prioritised 66-71 GHz as a second stage high frequency band, alongside 40.5-43.5 GHz, which we have also identified as a priority band for study.

A8.125 We have recently made changes to the authorisation regime in the 57-71 GHz band,[212] including making the 64-66 GHz band licence exempt, and implemented common technical conditions across the 57-71 GHz band for fixed and mobile use on a licence exempt basis.

A8.126 In March 2018 we published our 'Enabling 5G in the UK' discussion document[213] in which we provided an update on the actions to facilitate 5G roll-out in the UK. In this document we noted that trial and innovation licences could be used in a range of bands, including 26 GHz.

A8.127 However, we have not yet set out plans to award the 26 GHz band and are currently continuing our work to understand demand.

A8.128 UK MNOs hold significant amounts of spectrum in mmWave bands above 26 GHz. In the 28 GHz band Arqiva holds a national licence for 2x224 MHz, H3G holds a national licence for 2x112 MHz and O2, Vodafone, Arqiva and H3G hold several regional licences for 2x112 MHz of the band as outlined in the Figure A8.7:.

[210] There are two segments to the 26 GHz band: the bottom 2 GHz (24.5 GHz to 26.5 GHz), which is currently used by fixed links and Permanent Earth Stations (PES) and the top 1 GHz (26.5 GHz to 27.5 GHz) which is mostly cleared except for limited use by the Ministry of Defence.
[211] https://www.ofcom.org.uk/__data/assets/pdf_file/0021/97023/5G-update-08022017.pdf
[212] https://www.ofcom.org.uk/__data/assets/pdf_file/0017/115631/statement-fixed-wireless-spectrum-strategy.pdf
[213] https://www.ofcom.org.uk/__data/assets/pdf_file/0022/111883/enabling-5g-uk.pdf

Figure A8.7: Spectrum access 28 GHz licences, frequencies and regions

Spectrum Access 28 GHz licences, frequencies and regions

	27.8285 – 28.0525 GHz paired with 28.8365 – 29.0605 GHz (2 x 224 MHz)	28.0525 – 28.1645 GHz paired with 29.0605 – 29.1725 GHz (2 x 112 MHz)	2 x 28 MHz	28.1925 – 28.3045 GHz paired with 29.2005 – 29.3125 GHz (2 x 112 MHz)	2 x 28 MHz	28.3325 – 28.4445 GHz paired with 29.3405 – 29.4525 GHz (2 x 112 MHz)
A	Arqiva	Telefónica UK		Arqiva		UK Broadband
B		Vodafone		Telefónica UK		UK Broadband
C		Telefónica UK		Vodafone		UK Broadband
D		Vodafone		UK Broadband (Spectrum traded to Arqiva Ltd at 6 locations)		UK Broadband (Spectrum traded to Arqiva Ltd at 6 locations)
E						
F						
G						
H						
I		Telefónica UK		Vodafone		
J		Vodafone		Vodafone		
K				UK Broadband		
L				Telefónica UK		
M				UK Broadband		
N		Telefónica UK				

Spectrum Access complying with IR 2048 – First awarded December 2000

Spectrum Access complying with IR 2048 – First awarded February 2008

Spectrum Access frequency packages				
National (Arqiva)	27.8285 – 28.0525 GHz	*paired with*	28.8365 – 29.0605 GHz	*(2 x 224 MHz)*
Package 1	28.0525 – 28.1645 GHz	*paired with*	29.0605 – 29.1725 GHz	*(2 x 112 MHz)*
Guard-band				*(2 x 28 MHz)*
Package 2	28.1925 – 28.3045 GHz	*paired with*	29.2005 – 29.3125 GHz	*(2 x 112 MHz)*
Guard-band				*(2 x 28 MHz)*
Package 3	28.3325 – 28.4445 GHz	*paired with*	29.3405 – 29.4525 GHz	*(2 x 112 MHz)*

January 2017

Region A:	Greater London
Region B:	Greater Manchester, Merseyside & Cheshire
Region C:	West Midlands, Warwickshire, Staffordshire, Worcestershire, Shropshire & Herefordshire
Region D:	Isle of Wight, Hampshire, Berkshire & Oxfordshire
Region E:	Essex, Hertfordshire & Buckinghamshire
Region F:	Suffolk, Norfolk, Bedfordshire, Cambridgeshire & Northamptonshire
Region G:	Derbyshire, Lincolnshire (other than North & North East Lincolnshire District Councils), Leicestershire, Nottinghamshire & Rutland
Region H:	Kent, Surrey, East Sussex & West Sussex
Region I:	East Riding of Yorkshire, North, West & South Yorkshire, North & North East Lincolnshire District Councils
Region J:	Tyne and Wear, Durham, Northumberland, Cumbria & Lancashire
Region K:	Bristol, Devon, Cornwall and the Isles of Scilly, Dorset, Somerset, Wiltshire & Gloucestershire
Region L:	Scotland
Region M:	Wales
Region N:	Northern Ireland

A8.129 BT/EE, MBNL, MLL Telecom Ltd and H3G also hold national licences for mmWave spectrum in the 32 GHz and 40 GHz bands as set out in Figure A8.2:. MNOs currently use these frequencies for mobile backhaul, i.e. to connect their radio base stations to the core network.

Figure A8.2: Allocation of 32GHz and 40GHz bands

Band	Amount of spectrum	Holder
32 GHz	2X252 MHz + 2X126 MHz[214]	BT/EE
32 GHz	2X252 MHz	MBNL
32 GHz	2X126 MHz	MLL
40 GHz	2X250 MHz	MBNL
40 GHz	2X250 MHz	MLL
40 GHz	2 X 1,000 MHz	H3G

A8.130 Qualcomm has recently announced that it has developed antennae modules and RF units which support 800 MHz of bandwidth in the 26.5-29.5 GHz band (5G NR band n257) as well as the entire 27.5-28.35 GHz band (n261) and 37-40 GHz band (n260).[215] Qualcomm expects devices that support the band to be made available in the first quarter of 2019.

A8.131 At present there have not been widespread international deployments of mmWave spectrum bands. Initial deployments on mmWave by Verizon in the US have focused on FWA services using the 28 GHz and 39 GHz bands while other US MNOs expect to increase their mmWave holdings in order to complement their spectrum portfolios.[216]

A8.132 Given the propagation characteristics of mmWave, its deployment for mobile use is expected to be different to that of low and mid frequency bands, using small cells and street furniture, for example, rather than it being widely deployed in macrocells.[217] We note that mmWave is being used on some macrocell sites in suburban areas for FWA in the US and may be used in the UK to provide similar services in the future.

A8.133 Given the characteristics of this spectrum and the uncertainty about how and when it will be used in mobile networks, at this stage we do not consider this spectrum to be a substitute for low and mid-frequency spectrum for mobile use.

A8.134 Further, although chipsets have already been developed, it is not clear when mobile devices will widely support the different mmWave bands, including those that will be awarded in future.

A8.135 Therefore, for the purpose of this auction, we do not consider mmWave spectrum to be useable.

---

[214] The 2X252 MHz block was licenced to EE while the 2X126 MHz block was licensed to BT PLC.
[215] https://www.qualcomm.com/news/releases/2018/07/23/qualcomm-delivers-breakthrough-5g-nr-mmwave-and-sub-6-ghz-rf-modules-mobile
[216] https://venturebeat.com/2018/05/03/verizon-pegs-2019-for-mobile-5g-as-sprint-seeks-millimeter-wave-spectrum/
[217] We understand from some MNOs that mmWave deployments in macrocells are possible, but these would not provide a comparable footprint or coverage to spectrum below 6 GHz and, therefore, would only be deployed in such a way in specific circumstances.

We propose to exclude some other potential future mobile spectrum

A8.136 In our November 2016 consultation and July 2017 Statement we mentioned that there were a number of other frequencies that may become useful for mobile access in the future. We published an update to our mobile data strategy in June 2016.[218] This described some changes to our priorities for future mobile spectrum release, including making the release of spectrum at 1427-1452 and 1492-1518 MHz a high priority, as well as spectrum at 5725-5850 MHz[219] and the mmWave bands.[220]

A8.137 We noted that the award of the 2.3 and 3.4 GHz bands is part of the Government's Public Sector Spectrum Release (PSSR) programme. In April 2016, the Central Management Unit ('CMU') (part of UK Government Investments) proposed a new target (reported in the March 2016 Budget): "750MHz of valuable public sector spectrum in bands under 10GHz will be made available by 2022, of which 500MHz will be made available by 2020."[221]

A8.138 We also mentioned that in addition to the current release of cleared spectrum, the PSSR programme involves plans to make further public sector spectrum available for civil users. The lower 2.3 GHz band (2300–2350 MHz) was noted as a priority band for investigation as part of the CMU update. We are working with MOD and other government departments to explore the potential to make available additional spectrum for civil users in the lower 2.3 GHz range. This may be on a time limited basis and/or in limited geographic areas. In our July 2017 Statement we said that such opportunities remain uncertain at this stage and in any case will not be available for some years.

A8.139 Following the European Commission Decision 2018/661 of 26 April 2018 harmonising the 1492-1517 MHz band for downlink-only mobile services on a EU wide basis, Ofcom has started the process to make the band available for mobile by announcing in our 5 July 2018 statement[222] that the band will close for new fixed links on 5 January 2019. We are currently considering the existing use of fixed links and technical variations in this band and in terms of how and when to take the necessary clearance action in order to support the EU harmonisation measures and make the band available for mobile.

---

[218] *Mobile Data Strategy, Update on our strategy for mobile spectrum*, Ofcom, 30 June 2016, http://stakeholders.ofcom.org.uk/binaries/consultations/mobile-data-strategy/statement/update-strategy-mobile-spectrum.pdf

[219] In November 2017 we decided to remove restrictions on Broadband Fixed Wireless Access (BFWA) in the 5.8 GHz band. See https://www.ofcom.org.uk/__data/assets/pdf_file/0019/108235/5.8GHz-statement.pdf

[220] In our February 2017 Update on 5G spectrum in the UK we noted that "Strictly speaking, mmWave is the band of spectrum between 30 GHz and 300 GHz – wavelengths at these frequencies are between 1mm and 1cm long. The term is commonly used refer to frequencies above 24 GHz and this is how we use it here".

[221] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/518303/enabling_uk_growth_pssr_programme_annual_report.pdf also confirmed in the August 2017 CMU annual report https://www.gov.uk/government/publications/public-sector-spectrum-release-programme

[222] https://www.ofcom.org.uk/__data/assets/pdf_file/0017/115631/statement-fixed-wireless-spectrum-strategy.pdf

A8.140 At this stage there are no concrete plans for the award of any of these bands and, therefore, the bands cannot be considered useable spectrum in the context of the competition assessment for this auction.

A8.141 With regards to the 1900 MHz band, our position as outlined in the July 2017 statement is unchanged, i.e. that we do not consider the unpaired 1900 MHz spectrum to be relevant to our analysis of competition in mobile services. Whilst this band licenced to three of the four MNOs for 3rd Generation mobile use, it is currently unused for mobile access and is unlikely to be able to be used for high power macro sites in practice due to the compatibility with the adjacent uplink band of the 2.1 GHz paired spectrum. Of this spectrum, BT/EE has 10 MHz, O2 has 5 MHz and H3G has 5 MHz.

A8.142 In the July 2017 Statement, we mentioned that BT/EE had requested a licence variation to allow it to use its 1900 MHz spectrum for LTE in support of delivery of the emergency services network. In January 2017 we published a statement[223] setting out our decision to grant the request to permit TD-LTE technologies in the 1899.9 to 1909.9 MHz spectrum. Our decision was predicated on the basis that additional technical conditions were included in BT/EE's licence to prevent interference to other users of adjacent spectrum. These additional technical conditions limit the power available for TD-LTE use to a level typical of small cells and lower than would normally be considered necessary for macro sites.[224] We have not varied the licences for unpaired 1900 MHz spectrum held by O2 and H3G to allow TD-LTE use, however, if we were asked to do so it is likely that similar technical conditions would need to be applied with tight constraints on the permissible transmit power levels.

A8.143 In line with our framework, we do not believe that the 1900 MHz should be considered useable for the purposes of our competition analysis for this award as there are major constraints in the use of the band. Therefore, our view that this spectrum is not relevant for our analysis remains unchanged.

A8.144 As set out in annex 5, alongside this publication, we have also published our proposals to support innovative services by enabling localised access to spectrum bands supporting mobile technology. We propose to open three bands supported by mobile technology for shared access (these are the 3.8-4.2 GHz, 1781.7-1785 MHz paired with 1876.7-1880 MHz and 2390-2400 MHz).[225]

A8.145 The 3.8-4.2 GHz band could be used for private industrial networks and provide additional spectrum for FWA to complement existing spectrum solutions. Both applications use bespoke equipment as opposed to mass market consumer devices (such as mobile handsets) where use of internationally harmonized bands would be required. Both the 1800 MHz and 2300 MHz are already supported by mobile networks and handsets,

[223] See https://www.ofcom.org.uk/__data/assets/pdf_file/0032/96566/Statement-EE-application-for-licence-variations-in-support-of-enhanced-mobile-communications-for-the-emergency-services.pdf

[224] 43 dBm/5 MHz EIRP for the frequency range 1899.9 – 1904.9 MHz and 30 dBm/5 MHz EIRP for the frequency range 1904.9 – 1909.9 MHz

[225] See https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation

meaning it can be used immediately, for example by mobile coverage improvement scheme providers in rural areas and in-building, or to provide private localised mobile networks.

A8.146 These bands have not been awarded yet. In addition, our proposal to license them on a localised basis means that they are unlikely to be used to offer nationwide mobile services such as those considered relevant for this assessment. We expect them to be used by providers to offer local services to rural communities, e.g. by extending mobile coverage in rural areas or providing fixed wireless access, to increase indoor coverage or offer private mobile and fixed networks (see annex 5 for more information on alternative uses for these bands). We therefore do not consider them relevant for the purposes of the competition assessment for this auction.

A9. Current performance of UK mobile networks

A9.1 In this annex, we provide an overview of the current performance of the UK mobile networks and how the MNOs are using their spectrum to deliver services to consumers. In conjunction with the analysis presented in other annexes, this analysis informs us on whether competition is working well for UK consumers and whether UK MNOs are delivering a good service, which forms the starting point for our competition assessment for this spectrum award.

A9.2 For this analysis, we have used data from the MNOs, as well as the results of independent third-party surveys and analysis.

Current UK spectrum deployment

A9.3 The MNOs each hold varying amounts of spectrum across different frequency bands and they use this spectrum to deliver 2G, 3G and 4G services to consumers. Below, we consider how they have deployed their spectrum, including the evolution in site numbers and spectrum deployment over the past few years.

A9.4 We think it is still too early to assess the full impact that the 2.3 and 3.4 GHz award may have on MNOs' deployment strategies and network capacity. However, we have noted any initial steps that they have already started to take in relation to that spectrum.

A9.5 BT/EE initially started delivering a 2G service using 1800 MHz spectrum, and then used 2100 MHz spectrum to build its 3G network. BT/EE is authorised to use 800 MHz and 2600 MHz spectrum to deliver a 4G service, as well as some 1800 MHz spectrum which is being 'refarmed' (i.e. repurposed) from 2G to 4G.

A9.6 O2 originally launched its 2G network using 900 MHz spectrum, before also deploying 1800 MHz spectrum to deliver a 2G service. It then built its 3G network using 900 MHz and 2100 MHz spectrum and its 4G network using its 800 MHz spectrum. O2 has started to refarm some of its 1800 MHz 2G spectrum and 2100 MHz 3G spectrum to 4G. It has also started to deploy the 2300 MHz spectrum it won in the latest spectrum auction to increase the capacity of its 4G network.

A9.7 H3G's 3G network is delivered by its 2100 MHz spectrum and its 4G network is delivered by its 800 MHz and 1800 MHz spectrum. H3G also holds some 1400 MHz spectrum which it acquired in 2015.

A9.8 Vodafone originally launched its 2G network using its 900 MHz spectrum, before also deploying 1800 MHz spectrum to deliver a 2G service. It then built its 3G network using 900 MHz and 2100 MHz spectrum. Vodafone is authorised to use 800 MHz and 2600 MHz spectrum to deliver a 4G service. Vodafone has started refarming some of its 1800 MHz 2G spectrum and 2100 MHz 3G spectrum to 4G. Vodafone also holds some 1400 MHz spectrum which it acquired in 2015.

A9.9 BT/EE and H3G entered into the MBNL agreement in 2007 to share a number of their physical sites and to combine their 3G networks. This agreement was then extended to cover their 4G networks. In 2012, O2 and Vodafone also entered into a site-sharing agreement and consolidated their individual networks of sites into a single grid.

A9.10 Table A9.1 below shows the overall number of sites aggregated across MNOs and the proportion of these sites which are used to offer 2G, 3G and 4G services. The number of sites with 4G deployed has [✂ REDACTED] between 2017 and 2018.

Table A9.1: Site numbers by technology (2G, 3G, 4G)

	2017	2018
Total sites across MNOs	[✂ REDACTED]	
Sites with 2G	[✂ REDACTED]	
% total sites	[✂ REDACTED]	
Sites with 3G	[✂ REDACTED]	
% total sites	[✂ REDACTED]	
Sites with 4G	[✂ REDACTED]	
% total sites	[✂ REDACTED]	

Source: Ofcom analysis of MNO data from June 2017 and May 2018

A9.11 Table A9.2 below shows the overall number of sites held by each MNO.

Table A9.2: Site numbers by MNO

	BT/EE	O2	H3G	Vodafone
2017 total sites	[✂ REDACTED]			
2018 total sites	[✂ REDACTED]			

Source: Ofcom analysis of MNO data from June 2017 and May 2018

A9.12 [✂ REDACTED]

A9.13 Table A9.3 below shows the number of sites with each frequency deployed in 2017 and 2018:

Table A9.3: Site numbers by MNO and by frequency

	BT/EE					O2							
	2G	3G	4G			2G		3G		4G			
Frequency	1800	2100	800	1800	2600	900	1800	900	2100	800	1800	2100	2300
2017 sites	[✂ REDACTED][226]												
% of sites	[✂ REDACTED]												
2018 sites	[✂ REDACTED]												
% of sites	[✂ REDACTED]												

	H3G					Vodafone							
	3G	4G				2G		3G		4G			
Frequency	2100	800	1400	1800	2100	900	1800	900	2100	800	1800	2100	260
2017 sites	[✂ REDACTED]												
% of sites	[✂ REDACTED]												
2018 sites	[✂ REDACTED]												
% of sites	[✂ REDACTED]												

Source: Ofcom analysis of MNO data from June 2017 and May 2018

226 [✂ REDACTED]

A9.14 Table A9.3 shows [✂ REDACTED].

Comparison of UK mobile networks

A9.15 In annex 6, we explained that network quality is one of the most important factors for consumers when selecting a mobile network provider. Here, we consider in more detail how MNOs perform across three key aspects of network quality: reliability, coverage and speed.

Reliability

A9.16 A number of factors contribute to the concept of network reliability. These include being able to make uninterrupted calls and texts, accessing data when required and experiencing stable data rates.

A9.17 For this analysis, we have considered the following sources of evidence: (i) the reports published by Rootmetrics and P3, which conduct various UK-wide tests to assess a number of factors related to network reliability; (ii) our Consumer Mobile Experience report, which outlines the results of a number of tests conducted to assess network performance, including reliability; and (iii) the report published by Global Wireless Solutions, which also performs reliability testing across 32 UK towns and cities.

A9.18 The latest **Rootmetrics**[227] research, published in August 2018, rates MNOs across six categories: overall performance, reliability, speed, data, call and text performance in the first half of 2018. The tests carried out by Rootmetrics looked at performance across the whole of the UK, including cities, villages, roads and indoor locations.

Table A9.4: Rootmetrics' assessment of mobile performance

Category	BT/EE	O2	H3G	Vodafone
Overall	96.0	86.6	93.0	90.1
Reliability	97.6	91.6	96.5	92.2
Speed	91.8	73.1	82.9	86.9
Data	96.0	86.4	92.1	92.5
Call	95.6	85.6	93.8	86.0
Text	99.1	96.6	96.8	96.6

Source: Rootmetrics, August 2018

A9.19 According to Rootmetrics, BT/EE outperforms the other MNOs in each of the six test categories and has won the UK Overall RootScore Award for the tenth consecutive time

[227] http://rootmetrics.com/en-GB/content/mobile-performance-in-the-uk-part-1-performance-across-the-entire-uk-1h

since testing started in 2013. It has also come first in every category for the second consecutive test period. H3G displayed strong results and came second place in four categories. Vodafone came second in three categories and O2 came fourth in most categories. The results remain largely consistent and relatively similar to previous test results from the second half of 2017.

A9.20 Specifically looking at network reliability, Rootmetrics defined this as a holistic look at reliability performance across mobile internet, call, and text testing. BT/EE holds the highest Rootmetrics score in this area, with H3G not far behind.

A9.21 Rootmetrics commented that although O2 came last in most categories, its performance has improved compared to the previous test period due to an increase in its 4G footprint and investment in additional spectrum.

A9.22 **P3** conducts independent network tests on an annual basis, assessing performance in large cities, smaller towns and on roads, while walking and while driving. According to P3's most recent report from 2017[228], which is based on tests conducted in September 2017, BT/EE was its 'overall winner', graded as 'very good' and showing a distinct lead in voice and data rankings, as well as achieving a high grade in what P3 calls 'operational excellence'. Vodafone came second in its report, graded as 'good', with H3G in third place, also graded 'good', and O2 in fourth, graded as 'satisfactory'.

A9.23 Regarding voice services, P3 analysed call success ratios, call setup times and speech quality. According to P3's 2017 report, BT/EE delivered the best voice performance, though Vodafone was comparable in larger cities but not in smaller towns and on roads. O2 also showed good performance in larger cities but fell substantially behind in smaller towns and on roads. H3G generally came third in voice tests but had comparatively long call setup times.

A9.24 In regard to data services, P3 conducted a number of tests relating to the speed and success ratios of file uploading/downloading and page loading and the success ratios, uninterrupted viewing and resolution while watching YouTube videos. According to P3's 2017 report, BT/EE outperformed the other MNOs in almost all tests, with O2 coming last in all scenarios.

A9.25 P3's 2017 report also contains an 'Operational Excellence' category which uses a crowdsourcing approach to collect data on network availability over a period of three months. Its conclusion is that each of the MNOs has a very stable and reliable network, with only two isolated instances of MNOs' networks being unavailable during the period considered in the report.

A9.26 Ofcom's latest **Consumer Mobile Experience report**[229]**,** published in May 2018, outlines key findings from tests conducted between September and December 2017 to assess the network availability and performance experienced by over 5,000 people. With regards to

[228] http://www.p3-networkanalytics.com/wp-content/uploads/2017/10/171024_P3-connect-Mobile-Benchmark-UK-2017-FV.pdf

[229] https://www.ofcom.org.uk/__data/assets/pdf_file/0028/113689/consumer-mobile-experience-2018.pdf

reliability, the report states that tests showed no significant differences across MNOs in either the failure rates of 3G or 4G connections or dropped call rates due to lack of service.

A9.27 Between November 2017 and February 2018, **Global Wireless Solutions**[230] conducted a nationwide test of mobile network performance to assess network reliability. This involved voice and mobile internet network performance testing in 32 major towns and cities, as well as focus groups and consumer polling. The results of its testing show that O2 was the most reliable network in 17 of the towns and cities tested, H3G was the most reliable in 12, and BT/EE in three. Vodafone was the most reliable network in none of the towns or cities tested.

Coverage[231]

A9.28 In this section we consider the overall voice and data coverage performance of the MNOs, including the coverage they provide by using different types of technology.

A9.29 We have applied a different power threshold for each coverage category to ensure a minimum level of satisfactory quality of service (QoS).[232]

A9.30 The three types of coverage that we discuss in this section are landmass, outdoor premises and indoor premises. 'Landmass' refers to the entirety of UK locations and it is assumed that the user is located outdoors. 'Outdoor premises' refers to locations in which premises exist and it is assumed that the user is located outdoors. 'Indoor premises' refers to locations in which premises exist and it is assumed that the user is located inside, but close to a window. This is consequently translated into an expected penetration loss in signal strength, which is assumed to be 10dBm.

Voice coverage

A9.31 Table A9.5 presents the voice coverage of the four MNOs in September 2018, across landmass, outdoor premises and indoor premises, based on Connected Nations data provided by the four MNOs.

A9.32 O2 and Vodafone outperform BT/EE and H3G by approximately 5% in landmass and 3% in indoor coverage. All MNOs have an outdoor premises voice coverage of more than 99%.

---

[230] http://news.gwsolutions.com/most-reliable-operators-in-uk/

[231] The mobile coverage figures provided in this annex include corrections to EE's 3G and Vodafone's 4G coverage due to errors in the data they had previously submitted. These corrections reduce EE's predicted 3G coverage calculation and increase Vodafone's predicted 4G coverage calculation. The accuracy of the data provided to us under our formal powers is a matter that Ofcom takes very seriously and in light of these corrections we have decided to investigate this matter formally.

[232] The coverage thresholds that we have applied are: 2G outdoor (-81dBm), 3G outdoor (-100dBm) and 4G services outdoor (-105dBm). The indoor coverage figures take into account the effects of walls, doors, roofs etc. which will reduce or block mobile signals as they pass through. We have assumed that all buildings block mobile signals in the same way (by reducing signal strength by 10dB). In reality, some buildings will block signals more than others and we will reflect this in subsequent updates of our Connected Nations report.

Table A9.5: Voice coverage

	Landmass	Outdoor	Indoor
BT/EE	85.0%	99.4%	95.8%
O2	90.4%	99.8%	99.1%
H3G	84.8%	99.5%	95.9%
Vodafone	90.4%	99.8%	98.6%

Source: Ofcom analysis of MNO data from September 2018

Data coverage

A9.33 We present below the MNOs' landmass, outdoor and indoor premises coverage when offering data services as estimated in September 2018. We focus on two different scenarios:

- Basic data services offered using 3G and 4G technology[233]: this is shown in Table A9.6 below and considers a power threshold for each technology of -100dBm for 3G and -115dBm for 4G. We have used these thresholds in order to reflect the minimum signal strength required by each technology to offer a 200 kbit/s service. The reason for choosing a 200 kbit/s data speed for this coverage metric which comprises both 3G and 4G is that 3G technologies offer lower speeds compared to 4G. Such speeds however are unlikely to be sufficient for certain services, especially in the future.
- Good quality data services offered using 4G technology only: this is shown in Table A9.7 and considers a minimum data speed of 2 Mbit/s, corresponding to a power threshold of -105dBm. We have moved to this approach for measuring 4G coverage because smartphones require stronger signals than older, simpler phones to function effectively. Therefore, we only consider an area to be covered if it receives a strong enough signal for a smartphone user to get a good voice and data service.

A9.34 As shown in Table A9.6, BT/EE and H3G are ahead of O2 and Vodafone in landmass coverage. Outdoor coverage is close to 100% for each MNO, and indoor coverage is around 99% for each MNO.

[233] Low data rates are also achievable with 2G technologies, but we set the power threshold to consider speeds of at least 200 kbit/s which are unlikely to be achieved with 2G technologies

Table A9.6: 3G or 4G data coverage with download speed of 200 Kbit/s[234]

	Landmass	Outdoor	Indoor
BT/EE	91.8%	99.9%	99.2%
O2	88.5%	99.8%	99.2%
H3G	89.7%	99.9%	99.2%
Vodafone	89.2%	99.8%	99.0%

Source: Ofcom analysis of MNO data from September 2018

A9.35 It can be observed that voice coverage percentages are slightly lower than their equivalent basic data coverage percentages. This is due to the different thresholds applied to derive the percentages. Basic data coverage is associated with a minimum expected service of 200 kbit/s, corresponding to a received signal threshold of at least -115dBm, whereas acceptable voice coverage on 4G is associated with a received signal threshold of -105dBm. The higher required signal threshold for 4G voice therefore results in lower voice coverage percentages.

A9.36 In Table A9.7 below, we present MNOs' coverage of landmass, outdoor premises and indoor premises using **4G technology**, based on our approach to measuring good quality 4G coverage (i.e. an expected minimum QoS for 4G coverage of a single-user download speed of 2 Mbit/s). BT/EE is ahead by a significant margin in landmass coverage. All MNOs have similar outdoor coverage of approximately 99%, and O2 and Vodafone are ahead in indoor coverage.

Table A9.7: Landmass, outdoor and indoor 4G coverage with download speed of 2 Mbit/s

	Landmass	Outdoor	Indoor
BT/EE	84.4%	99.1%	88.4%
O2	74.4%	98.9%	94.8%
H3G	78.4%	98.6%	89.4%
Vodafone	78.6%	99.0%	93.7%

Source: Ofcom analysis of MNO data from September 2018

A9.37 We have also looked at how 4G landmass coverage has evolved over time (from June 2014 to September 2018) for all MNOs based on our new approach to measuring good quality 4G coverage. [✂ REDACTED].

[234] In Table A9.6 we have adjusted the coverage threshold for 4G to -115dBm to make it comparable with 3G coverage which is based on download speed of 200 kbit/s.

Figure A9.1: 4G landmass coverage over time

[✂ REDACTED]

A9.38 In Table A9.8 below we present MNOs' coverage across frequency bands for landmass, outdoor premises and indoor premises. The analysis below is available for March 2018, differently from the above which provides more recent information about coverage in September 2018.

Table A9.8: Coverage by frequency band[235]

	Frequency	Landmass	Outdoor	Indoor
BT/EE	GSM1800	[✂ REDACTED]		
	UMTS2100	[✂ REDACTED]		
	LTE800	[✂ REDACTED]		
	LTE1800	[✂ REDACTED]		
O2	GSM900	[✂ REDACTED]		
	UMTS900	[✂ REDACTED]		
	UMTS2100	[✂ REDACTED]		
	LTE800	[✂ REDACTED]		
H3G	UMTS2100	[✂ REDACTED]		
	LTE800	[✂ REDACTED]		
	LTE1800	[✂ REDACTED]		
Vodafone	GSM900	[✂ REDACTED]		
	UMTS900	[✂ REDACTED]		
	UMTS2100	[✂ REDACTED]		
	LTE800	[✂ REDACTED]		

Source: Ofcom analysis of MNO data from March 2018

A9.39 BT/EE relies on [✂ REDACTED] to provide 3G coverage. However, [✂ REDACTED] to provide 4G coverage. We observe that [✂ REDACTED]. This is the result of [✂ REDACTED].

A9.40 O2 relies on [✂ REDACTED] to provide 3G coverage, [✂ REDACTED]. However, [✂ REDACTED]. Even though O2's [✂ REDACTED]. Additionally, [[✂ REDACTED].

A9.41 H3G is the only MNO that does not have a 2G network and it relies on [✂ REDACTED] to provide 3G coverage. It utilises [✂ REDACTED] to provide 4G coverage, [✂ REDACTED]. In contrast, [✂ REDACTED].

A9.42 Vodafone [✂ REDACTED].

[235] Note, that different technologies have different speed thresholds, this is reflected in the coverage figures.

A9.43 We next look at [✂ REDACTED] coverage from the 1800 MHz and 800 MHz frequency layers. We observe that [✂ REDACTED].

Figure A9.2: Coverage achieved through different spectrum layers

[✂ REDACTED]

A9.44 The two maps below show parts of [✂ REDACTED] networks in rural Wales; the colour coding used for coverage by [✂ REDACTED] is the same as in the above graph in order to provide a visual representation of the key insights derived from the data analysis.

Figure A9.3: Map of [✂ REDACTED] network in rural Wales

[✂ REDACTED]

Figure A9.4: Map of [✂ REDACTED] network in rural Wales

[✂ REDACTED]

Source: Ofcom analysis of MNO data from March 2018

Speed

A9.45 Several independent tests measure the speed of the UK's mobile networks. These include the aforementioned Rootmetrics report, Ofcom's Smartphone Cities study, Ofcom's Consumer Mobile Experience report, Speedtest assessments, OpenSignal speed tests and video speed analysis and Tutela speed assessments.

A9.46 These speed tests consistently show BT/EE achieving the highest average data download speeds and outperforming the other MNOs. O2 displays the lowest speeds across most tests. However, as previously mentioned, speed is only one of the factors which influences customers' overall experience.

A9.47 It is worth noting that there does not seem to be a predetermined download speed below which a service is deemed as inadequate; instead it depends on the type of service consumers are requesting from the network and what speed the network can supply to support that service.

A9.48 Ofcom's **Smartphone Cities**[236] report published in December 2016 tested the 4G mobile network performance of the four MNOs between July and October 2016 in seven cities across the UK: Belfast, Birmingham, Cardiff, Edinburgh, London, Sheffield and Southampton.

A9.49 The overall performance of the MNOs is shown in Table A9.9 below. BT/EE achieved the fastest average download speeds of 32 Mbit/s across the seven cities compared to H3G and Vodafone on 18Mbit/s and O2 on 13 Mbit/s. BT/EE also offered speeds of over 2 Mbit/s 99% of the time, compared to Vodafone on 95%, H3G on 93% and O2 on 90%. There were only marginal differences in relation to average web browsing speeds and successful loading of web pages across the MNOs.

[236] https://www.ofcom.org.uk/__data/assets/pdf_file/0027/95904/Smartphone-Cities-Dec16.pdf

Table A9.9: Smartphone Cities 4G browsing speeds and download speeds

	4G Web browsing speed						4G Download speed	
	Average speed			Successful loading			Average speed	Speed over 2Mbit/s
	BBC	Amazon	YouTube	BBC	Amazon	YouTube		
BT/EE	4 seconds	2 seconds	1 second	99%	99%	100%	32 Mbit/s	99%
O2	5 seconds	2 seconds	1 second	97%	98%	99%	13 Mbit/s	90%
H3G	4 seconds	2 seconds	1 second	98%	98%	99%	18 Mbit/s	93%
Vodafone	4 seconds	2 seconds	1 second	98%	98%	99%	18 Mbit/s	95%

Source: Smartphone Cities, December 2016

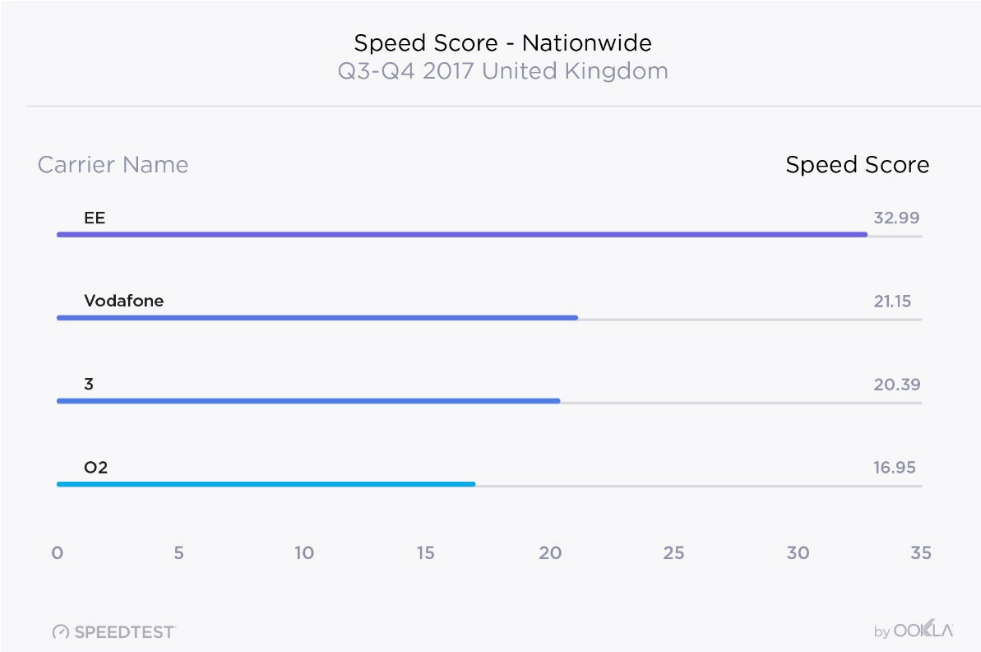
A9.50 The report also analysed latency, or response time, in milliseconds, which is important for activities that require minimal delay like Skype and FaceTime. BT/EE had the quickest response time across all cities at 33ms, followed by Vodafone (41ms), H3G (42ms) and O2 (43ms).

A9.51 **Ofcom's Consumer Mobile Experience report**[237] found that in tests conducted between September and December 2017, the average download speeds (3G and 4G combined) for the specific websites YouTube and Chrome on the O2 mobile network were significantly slower than for the other MNOs.

A9.52 Figure A9.5 shows speed test scores from the **Speedtest**[238] website. Speedtest used its own methodology to calculate an independent speed score for each MNO, based on MNOs' download and upload speeds. Results from its analysis carried out in Q3-Q4 2017 show that BT/EE was the fastest mobile carrier with a score of 32.99. Vodafone was second fastest with 21.15, closely followed by H3G which scored 20.39. O2 came last with a score of 16.95.

[237] https://www.ofcom.org.uk/__data/assets/pdf_file/0028/113689/consumer-mobile-experience-2018.pdf
[238] http://www.speedtest.net/reports/united-kingdom/

Figure A9.5: Speedtest scores



Source: Speedtest, Q3-Q4 2017

A9.53 Speedtest also analysed median peak speeds from each MNO. Each MNO displayed a lower median speed in peak hours due to network crowding, but BT/EE continued to deliver the fastest peak speeds compared to other MNOs. In peak hours, BT/EE's median download speed was lower by 5.2%, Vodafone by 5.0%, H3G by 4.9%, and O2 saw the largest drop at 8.1%.

Table A9.10: Speedtest download and upload speeds (based on median speed for modern devices)

Category	BT/EE	O2	H3G	Vodafone
Peak Hours Download (Mbit/s)	27.29	12.97	13.86	16.40
Peak Hours Upload (Mbit/s)	8.84	6.83	7.10	7.98
All Hours Download (Mbit/s)	28.80	14.11	14.58	17.26
All Hours Upload (Mbit/s)	9.29	7.13	7.35	8.16

Source: Speedtest, Q3-Q4 2017

A9.54 **OpenSignal**[239] named BT/EE as the fastest overall network in its UK Mobile Networks report published in October 2018, which was based on tests carried out between June and August 2018. BT/EE registered an overall average speed of 25.92 Mbit/s, ahead of Vodafone on 18.41 Mbit/s, H3G on 15.55 Mbit/s, and O2 on 12.79 Mbit/s. BT/EE was also the fastest network when assessing 4G download speeds.

[239] https://opensignal.com/reports/2018/10/uk/mobile-networks-update

A9.55 H3G recorded the fastest 3G download speeds, having increased its speeds significantly compared to those recorded in OpenSignal's previous report published in April 2018 where BT/EE was the fastest. OpenSignal noted that BT/EE's 3G speeds remain fairly static compared to the previous report, stating that it may be due to reallocation of network resources and capacity to 4G.

Table A9.11: OpenSignal download speeds

Category	BT/EE	O2	H3G	Vodafone
Download Speed – Overall (Mbit/s)	25.92	12.79	15.55	18.41
Download Speed - 4G (Mbit/s)	28.90	14.61	18.78	21.92
Download Speed - 3G (Mbit/s)	7.17	4.58	7.82	4.58

Source: OpenSignal, October 2018

A9.56 The report also looked at 3G and 4G latency in milliseconds. BT/EE and Vodafone showed the lowest latency for both their 3G and 4G networks.

Table A9.12: OpenSignal latency

Category	BT/EE	O2	H3G	Vodafone
Latency - 4G	39.77	42.38	48.15	40.78
Latency - 3G	60.98	73.76	64.11	62.52

Source: OpenSignal, October 2018

A9.57 **OpenSignal** also published a State of Mobile Video report[240] in September 2018, which analysed how consumers experience video over mobile networks in 69 countries around the world, awarding each country a video experience score. These scores accounted for performance in picture quality, video loading time and stall rate.

A9.58 In the UK, each MNO achieved a score within OpenSignal's 'Good' category.[241] Interestingly, the results of the analysis showed that high speeds did not necessarily equate to a good video experience at a country level. For example, South Korea had the highest overall download speed which was over 5 Mbit/s ahead of its closest rival, but it only achieved 16th place in the overall video experience analysis, whereas Czech Republic

[240] OpenSignal The State of Mobile Video report, https://opensignal.com/reports/2018/09/state-of-mobile-video. Measurements took place from May – August 2018.
[241] Vodafone achieved the highest score of 62.21 out of 100, followed by EE on 62.15, O2 on 58.45 and Three on 56.31. 'Good' and 'Fair' categories are characterised by sluggish video load times, stops and stutters mid-stream being common to varying degrees, and connections often having trouble coping with higher-resolution formats. https://opensignal.com/blog/2018/10/23/europe-shone-in-our-mobile-video-experience-analysis-but-the-winner-wasnt-who-youd-expect/

was rated as the top country for video experience but was not in the top ten countries for overall download speed.

A9.59 **Tutela**[242] speed test results from August 2018 showed BT/EE as having the fastest network, with an average 4G download speed of 23.84 Mbit/s. Vodafone registered an average 4G download speed of 20.26 Mbit/s, O2 of 14.72 Mbit/s and H3G of 9.83 Mbit/s. These findings were based on over 600,000 speed tests conducted in August 2018.

Table A9.13: Tutela download speeds

Category	BT/EE	O2	H3G	Vodafone
Download Speed - 4G (Mbit/s)	23.84	14.72	9.83	20.26
Download Speed - 3G (Mbit/s)	7.27	5.41	6.67	5.51

Source: Tutela, August 2018

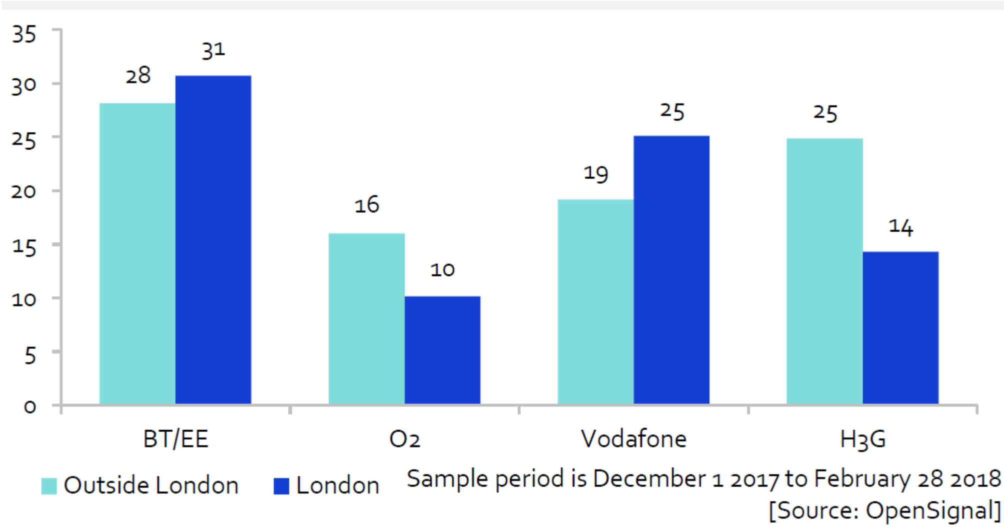
A9.60 Tutela reported that O2 has deployed the 2300 MHz spectrum it won in the most recent auction to six cities around the UK, with plans to extend this to a further four cities by the end of 2018. The average download speed recorded by Tutela on the 2300 MHz spectrum was 26.9 Mbit/s, which was 80% faster than O2's average 4G download speed of 14.7 Mbit/s. However, Tutela noted that O2's overall standing compared to the other operators still remained the same due to the limited deployment of the 2300 MHz spectrum.

Speeds in London

A9.61 Enders Analysis presented some OpenSignal data regarding download speeds in London compared to the rest of the UK in its report entitled 'Covert growth in UK mobile' published on 8 May 2018.[243] It stated that London may have been expected to have faster speeds than the rest of the country given the density of base stations in London, however only Vodafone showed a substantially higher speed in London, and O2 and H3G displayed far lower speeds due to having less spectrum available.

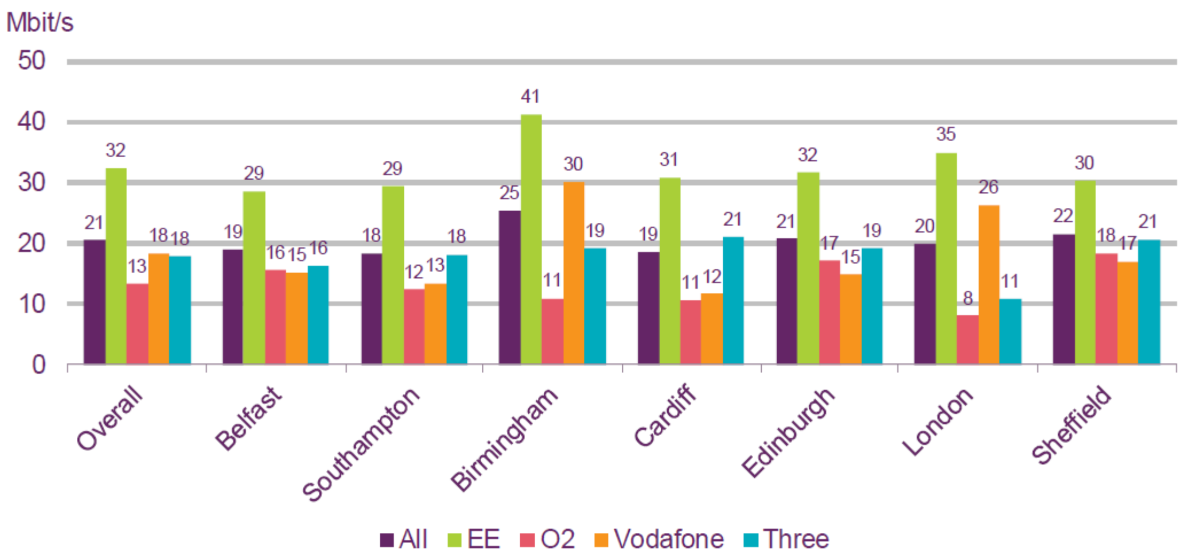
[242] https://www.tutela.com/blog/the-impact-so-far-of-o2s-uk-spectrum-investment
[243] http://www.endersanalysis.com/content/publication/covert-growth-uk-mobile

Figure A9.6: Enders Analysis download speeds – London and outside London



A9.62 Ofcom's **Smartphone Cities** report also analysed 4G speed across a few cities including London, using tests carried out from July to October 2016. The results were similar to the OpenSignal data; namely that Vodafone showed a substantially higher speed in London compared to its overall UK speed, and O2 and H3G showed much lower speeds in London compared to their overall figures.

Figure A9.7: Smartphone Cities 4G speeds



Source: Ofcom mobile broadband measurements, fieldwork July to October 2016.

A10. Indoor coverage modelling

A10.1 In section 5, we explain that low frequency spectrum is useful to provide coverage, particularly in indoor and deep indoor locations. This is a consequence of the favourable propagation characteristics of the low frequency bands.

A10.2 Currently, the MNOs' holdings of low frequency spectrum are asymmetric. This might mean that an operator with a relatively large quantity of low frequency spectrum could have an advantage in providing indoor coverage, as well as in providing other services that might also benefit from low-frequency spectrum (e.g. those requiring high network reliability). A significant asymmetry in low frequency spectrum holdings would be a cause for concern if that meant that certain operators could not provide, or could only provide with an inferior quality, certain services as a result of not having enough low frequency spectrum available.

A10.3 To inform the competition assessment, we have modelled the indoor coverage that, in theory, could be achievable by mobile networks with different carrier bandwidths and frequencies (i.e. 700 MHz and 1800 MHz). The networks we have modelled are intended to be representative of current UK LTE networks, in terms of carrier frequency, bandwidth and site count. We have assessed the ability of the networks modelled to offer the speed required for a basic mobile data service, like web browsing or email access, and other more data intensive services like full HD video streaming.

A10.4 This model generates the distribution of downlink Single User Throughput (SUT) versus cumulative population from different macro-cell networks with base station parameters taken from current 4G mobile networks operating in the 800 and 1800 MHz bands.[244] Downlink SUT is used as a proxy for the quality of coverage that a user might experience, as it is a measure of the data rate that could theoretically be delivered to a single user if the entire resources of the cell site were available to that user at any instant in time.

A10.5 The model is similar to the one we used in our 2012 Statement on the assessment of future mobile competition and award of 800 MHz and 2.6 GHz.[245] Then, we explained that it is not realistic to develop a technical model that could capture every possible dynamic variation with enough certainty on which we could base our policy. In our 2012 Statement we set out a number of caveats regarding the modelling we undertook then (see, in particular, paragraphs A7.7 to A7.10 of annex 7 of that statement). These caveats also apply to our current modelling.

A10.6 Our model allows a comparison between networks (which are representative of current, typical, LTE deployments) operating at different frequencies and bandwidths as well as a different number of sites. The number of sites is sourced from deployments of UK MNOs for those, or similar, frequency bands so that the model is calibrated to represent a typical

[244] Data extracted from Q4 and Q5 from Ofcom's section 135 information request to MNOs, June 2018
[245] See https://www.ofcom.org.uk/__data/assets/pdf_file/0022/46912/annexes7-12.pdf

mobile national deployment in the UK. Specifically, the network configurations we have compared are:

- 2 x 20 MHz at 1800 MHz and 18,000 sites nationally;
- 2 x 10 MHz at 700 MHz and 16,000 sites nationally; and
- 2 x 5 MHz at 700 MHz and 16,000 sites nationally.

A10.7 We believe that the model is useful in comparing the relative variation in performance between macro-cell networks operating at different frequencies and bandwidths. It is less useful in providing information on absolute performance. This is because the model is a simplified representation of a mobile network (see A10.31 to A10.53 for a detailed explanation of the modelling methodology). Thus, the results we present here should not be taken as a definitive prediction of macro-cell network performance.

Brief summary of results

A10.8 Notwithstanding the caveats mentioned above our modelling shows that, due to its more favourable propagation characteristics, low frequency spectrum (e.g. 700 MH or 800 MHz), when compared to spectrum at higher frequencies (e.g. 1800 MHz), has an advantage in providing services to harder to reach locations such as indoors (both shallow and deep). This advantage can be offset to a certain extent by deploying a denser network (more sites) and wider carriers. For instance, our analysis shows that a network with 2 x 20 MHz of 1800 MHz and with approximately 10% more sites can provide service to more indoor locations than a network with 2 x 5 MHz of 700 MHz. However, the same 2 x 20 MHz of 1800 MHz network is not quite able to match the performance of a 700 MHz network with a 10 MHz carrier (despite having a denser site grid and twice the carrier bandwidth). More specifically:

- lower frequency spectrum (2 x 10 MHz of 700 MHz) allows operators to provide a given level of customer experience (proxied by single user throughput (SUT)) to a larger share of indoor locations than a network based on 1800 MHz (2 x 20 MHz of 1800 MHz), particularly in deep indoor locations;
- when comparing a network based on 2 x 5 MHz of 700 MHz with a network based on 2 x 20 MHz of 1800 MHz the advantage of low frequency spectrum is less evident for some indoor locations (especially for basic connectivity, characterized by SUT ≥ 2 Mbps);
- in the case of deep indoor locations, a network based on 2 x 10 MHz of 700 MHz can outperform a network with 2 x 20 of 1800 MHz (i.e. with twice the bandwidth), though a network based on only 2 x 5 MHz of 700 MHz may not have sufficient bandwidth for more data intensive services characterized by a SUT ≥ 10 Mbps.

Results

Format of the results and summary of the modelling approach

A10.9 We present the results from our modelling in two formats:

- **Bar graphs**: where each bar represents the percentage of cumulative population[246] within an area that would receive a minimum downlink SUT of either 2 Mbps (representative a basic mobile data service[247]) or 10 Mbps (representative of a data-intensive service).[248]
- **Line graphs**: where the X-axis represents the cumulative population within a given analysis area and the Y-axis represents the downlink SUT. We use this approach as a proxy to quantify the distribution of downlink SUT achievable within an area and to estimate what would be the advantages or disadvantages of using mobile networks based on different spectrum bands and number of sites.

A10.10 We have carried out our analysis for indoor locations. We have defined two indoor scenarios, intended to represent:

- **Shallow indoors**, relatively easy to serve areas such as those fairly close to windows or external sides of buildings, and further into buildings with relatively low entry losses, and
- **Deep indoors**, harder to serve areas such as within enclosed rooms away from external walls or in basements, and into buildings with relatively high entry losses.

A10.11 We have considered three different 'analysis areas' based on their density of population in order to understand how network performances might vary in different environments (e.g. cities as compared to less densely populated rural areas). These are indicated as 'most densely' and 'least densely' areas (see paragraph A.10.37-A10.38 for further explanation on hoe we clarify these areas). We consider that splitting our analysis into areas based on their population density is a better way to understand the implications of our conclusions in the context of a competition assessment.

A10.12 Our model is based on a signal to interference plus noise ratio (SINR)[249] approach. When a mobile cell site or handset is experiencing high levels of interference or noise, the SINR ratio drops. SUT can be calculated from SINR using a suitable mapping function (see paragraphs A10.41 to A10.43 below).

---

[246] By 'cumulative population' we mean the population within the area analysed (within the 'sample') that our model predicts could receive a downlink SUT of at least the corresponding value on the opposite graph axis

[247] As defined in Page 2 in our 700 MHz coverage obligations consultation, 2 Mbps represents a connection fast enough for browsing the internet and watch glitch-free video. See https://www.ofcom.org.uk/__data/assets/pdf_file/0022/111937/consultation-700mhz-coverage-obligations.pdf

[248] Such as streaming high-quality video (HD or Ultra HD). To note, the recommended speed needed to stream HD video from services such as Netflix, Amazon TV, Apple TV, Hulu, BBC iPlayer, etc. is typically 3-5 Mbps and for Ultra HD is typically 15-25 Mbps.

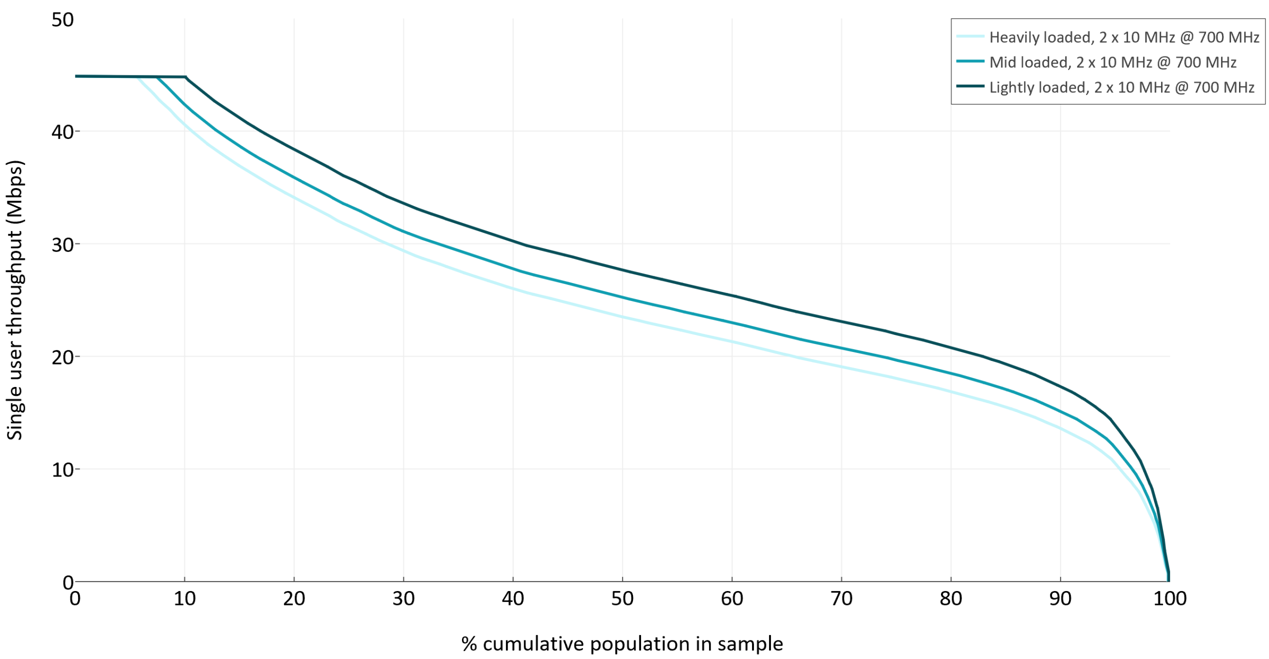
[249] Signal to Interference and Noise Ratio is a metric used in mobile network to estimate the upper bounds of the channel capacity or traffic.

A10.13 To quantify the impact of a site experiencing high levels of interference, we have considered different network loadings in the nearby sites. By network loading we mean the likelihood of nearby sites transmitting data to a certain number of users. In practical terms, this will require the use of additional resource blocks and an increased power. Figure A10.1 shows the impact on the SUT distribution of the same network when nearby sites are lightly, mid or heavily loaded. We explain these three categories later in this annex.

A10.14 As expected, SUT perfomance decreases when the loading of nearby sites increases. Although Figure A10.1 only shows the results from a 2 x 10 MHz network, the effect of higher loadings in the nearby sites has a similar impact on both 2 x 5 MHz and 2 x 20 MHz networks.

A10.15 As we are interested in the relative difference between network performance rather than absolute values, we present the SUT distribution curves for only mid loaded networks in the following sub-sections.

Figure A10.1: SUT distribution in shallow indoor environments, different traffic loadings in a 2 x 10 MHz of 700 MHz network



Detailed results

A10.16 In the following sub-sections we present the results of our modelling.

Lower frequency spectrum (2 x 10 MHz of 700 MHz) allows operators to provide a given level of customer experience (proxied by single user throughput (SUT)) to a larger share of indoor locations (both shallow and deep indoors) than a network based on 1800 MHz (2 x 20 MHz of 1800 MHz), particularly in deep indoors locations

A10.17 Figure A10.2, Figure A10.3 and Figure A10.4 illustrate the percentage of population that our model shows could receive a SUT of at least 2 Mbps (basic connectivity) or at least 10

Mbps (data intensive services) within the most, mid and least densely populated areas analysed, for the 2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz networks.

Figure A10.2: Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in the most densely populated area (2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)

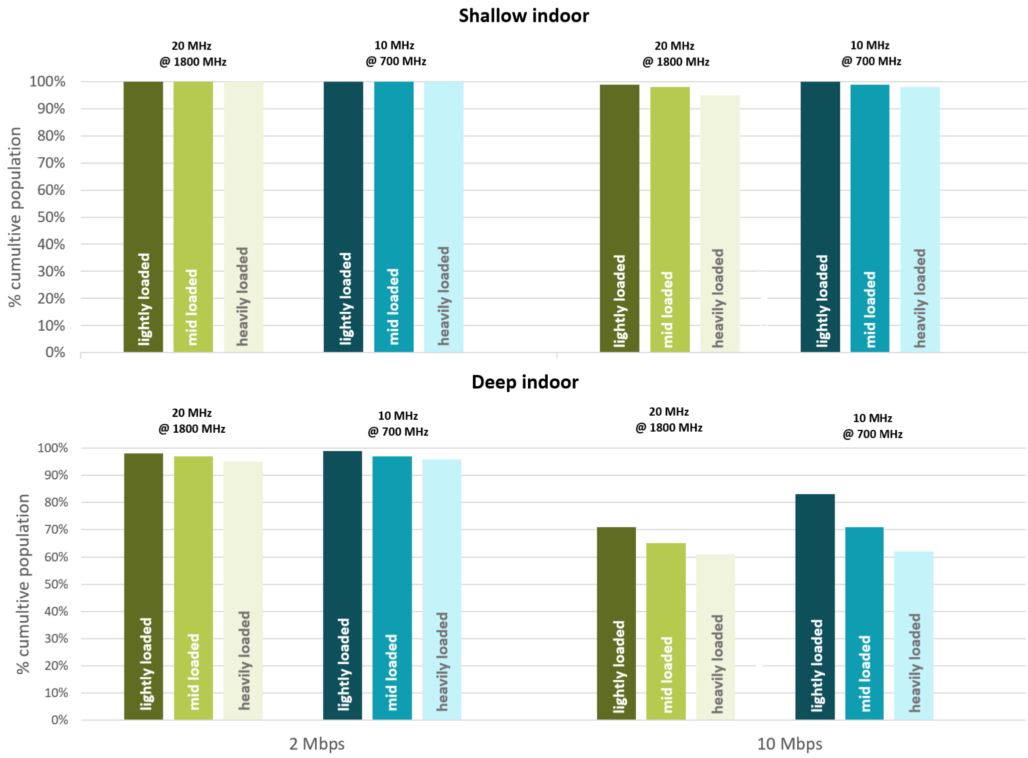


Figure A10.3: Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in the mid densely populated area (2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)

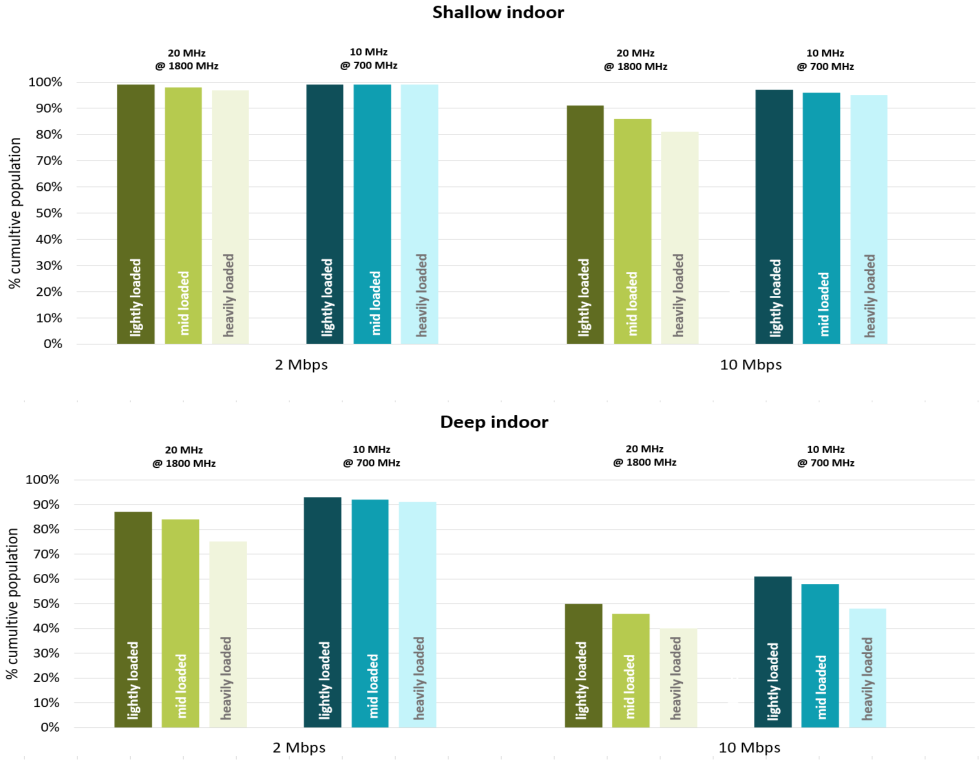
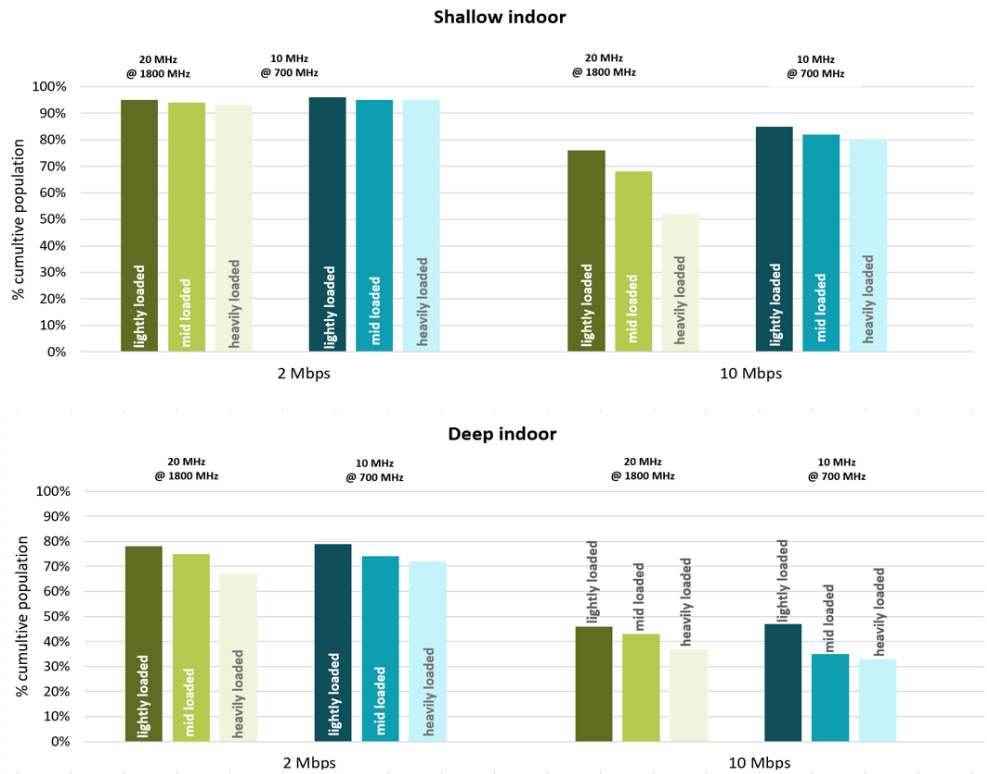


Figure A10.4: Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in the least densely populated area (2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A10.18 As shown in Figure A10.2, Figure A10.3 and Figure A10.4, in general, our model shows that the 2 x 10 MHz at 700 MHz network configuration outperforms the 2 x 20 MHz at 1800 MHz network in almost all scenarios. This is most evident for deep indoor environments and for data-intensive services. The exception being for the least densely populated area for data intensive services (10 Mbps) in deep indoor environments (see paragraph A10.22 below for a possible explanation).

A10.19 Figure A10.5 and Figure A10.6 present the SUT distribution in the most and mid densely populated areas, both in shallow indoor and deep indoor environments, for the 2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz networks. The black dots in the figures represent the point on the distribution where the SUT a 2 x 20 MHz of 1800 MHz network configuration falls below that for a 2 x 10 MHz of 700 MHz network configuration. So, for example, 2 x 20 MHz of 1800 MHz can provide better SUT performance than 2 x 10 MHz of 700 MHz for up to approximately 37% of the cumulative population shallow indoors. However beyond 37% of the cumulative population 2 x 10 MHz of 700 MHz performs better. For deep indoors, the point at which 2 x 10 of 700 MHz starts out-performing 2 x 20 MHz of 1800 MHz is approximately 55% of the cumulative population.

Figure A10.5: SUT distribution curves, shallow and deep indoor locations in the most densely populated areas (2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)

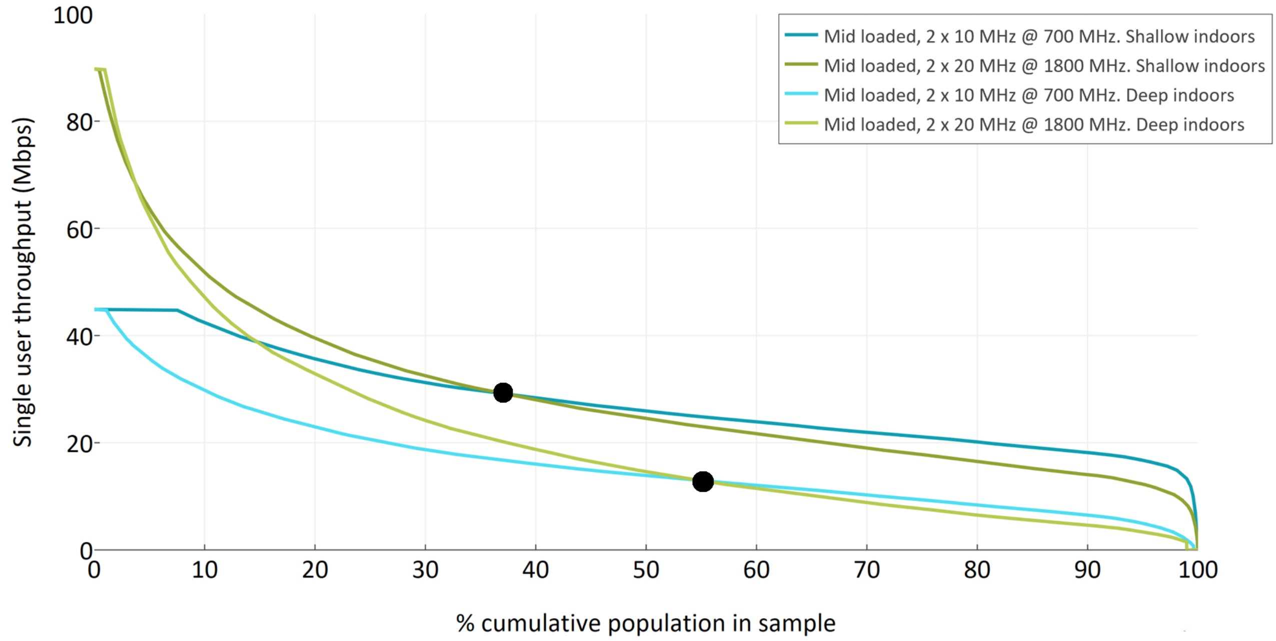
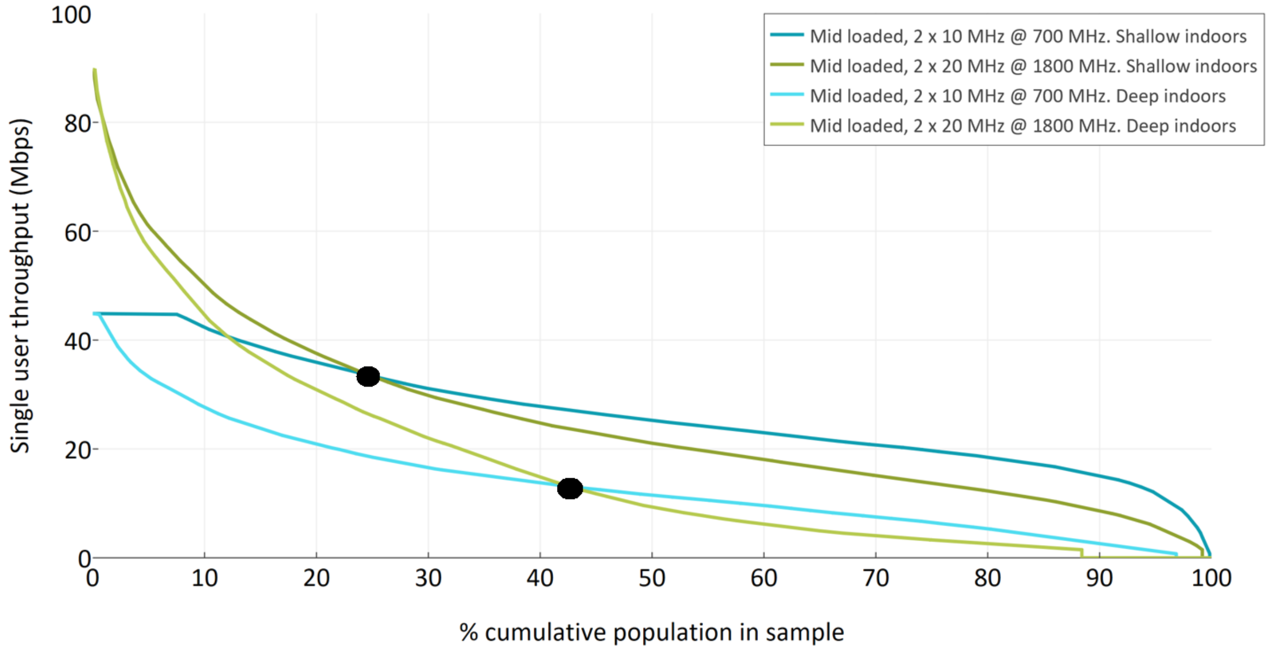


Figure A10.6: SUT distribution curves, shallow and deep indoor locations in the mid densely populated area (2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A10.20 The SUT distributions in Figure A10.5 and Figure A10.6 show that 2 x 20 MHz of 1800 MHz gives higher SUT performance for the lower values of cumulative population. This is the result of using a wider bandwidth (20 MHz available for downlink); therefore, this advantage could not be matched by either 2 x 5 MHz or 2 x 10 MHz of 700 MHz.

A10.21 In deep indoor environments, all network configurations considered perform less well than they do in shallow indoor environments, due to the higher building penetration losses (See Figure A10.21 for building penetration losses details), even though the relative difference between performance of the three networks continues to be evident (Figure A10.5 and Figure A10.6).

A10.22 We note the relatively poor performance of all network configurations in the results for the least densely populated area. This may be a reflection of the relatively low number of cell sites within this area, less than 1k for both 700 MHz and 1800 MHz networks (see Figure A10.22). Furthermore, this might mean that these results are not as statistically robust as those of most and mid densely populated areas, which have significantly more cell sites.

When comparing a network based on 2 x 5 MHz of 700 MHz with a network based on 2 x 20 MHz of 1800 MHz the difference in performance is narrower for shallow indoor locations (especially for basic connectivity characterized by SUT ≥ 2 Mbps)

A10.23 Figure A10.7, Figure A10.8 and Figure A10.9 illustrate the percentage of population that our model shows could receive an SUT of at least 2 Mbps (basic connectivity) or at least 10 Mbps (data intensive services) within the most, mid and least densely populated areas analysed, for the 2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz network configurations.

Figure A10.7: Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in most densely populated areas (2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)

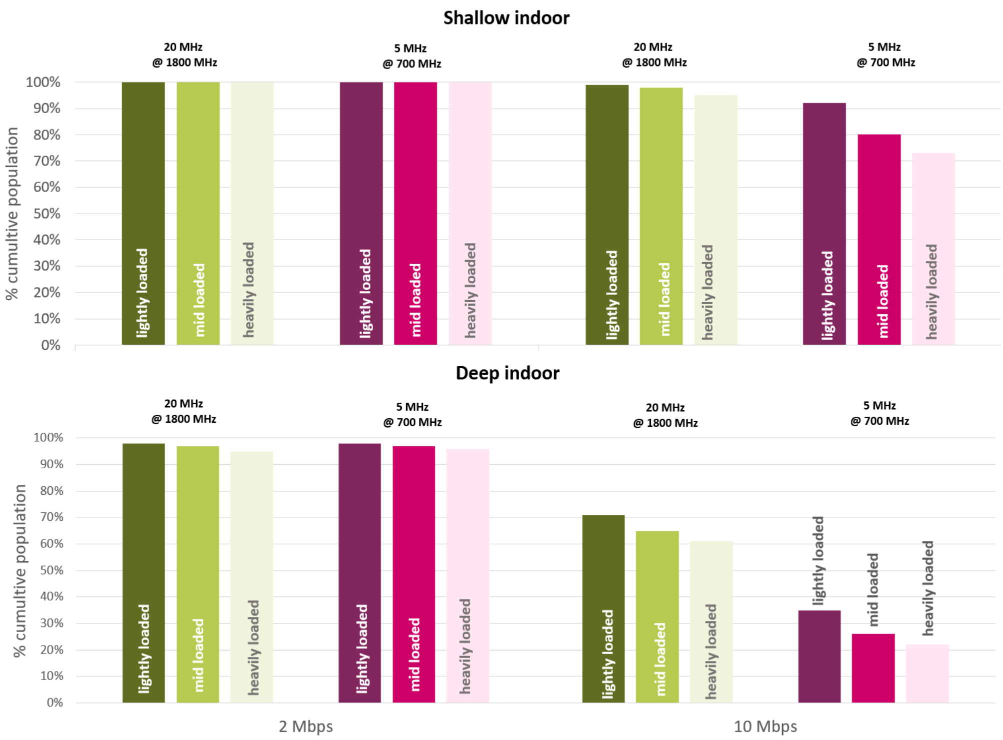


Figure A10.8: Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in mid densely populated areas (2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)

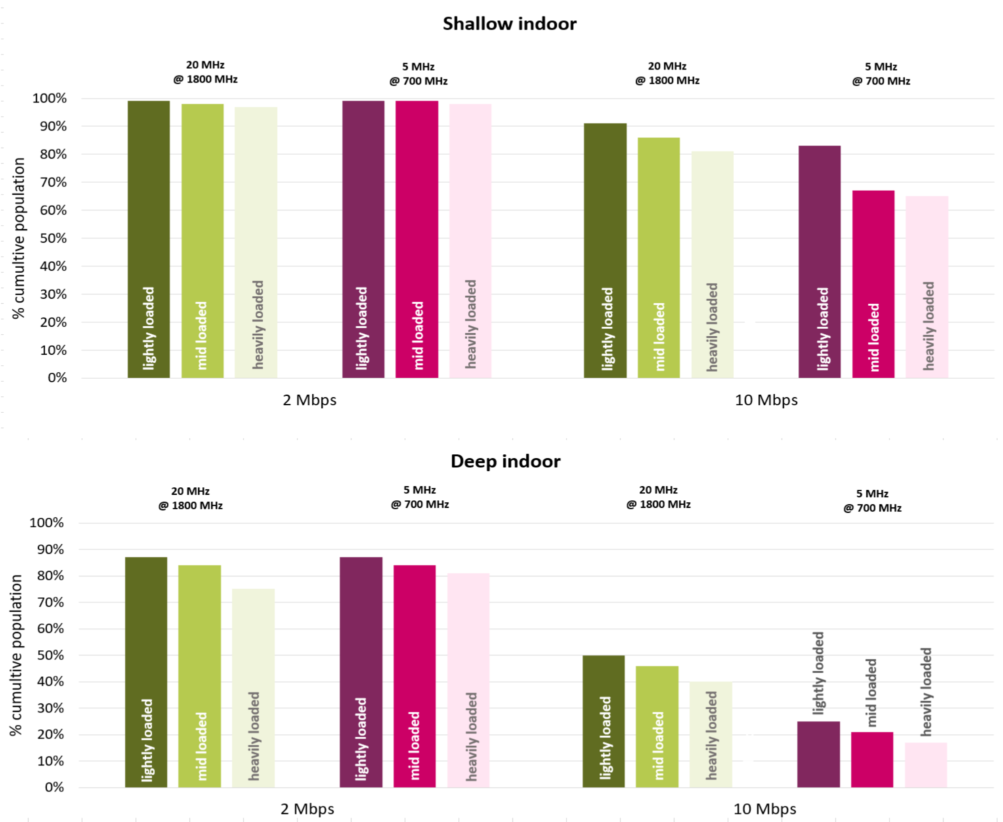
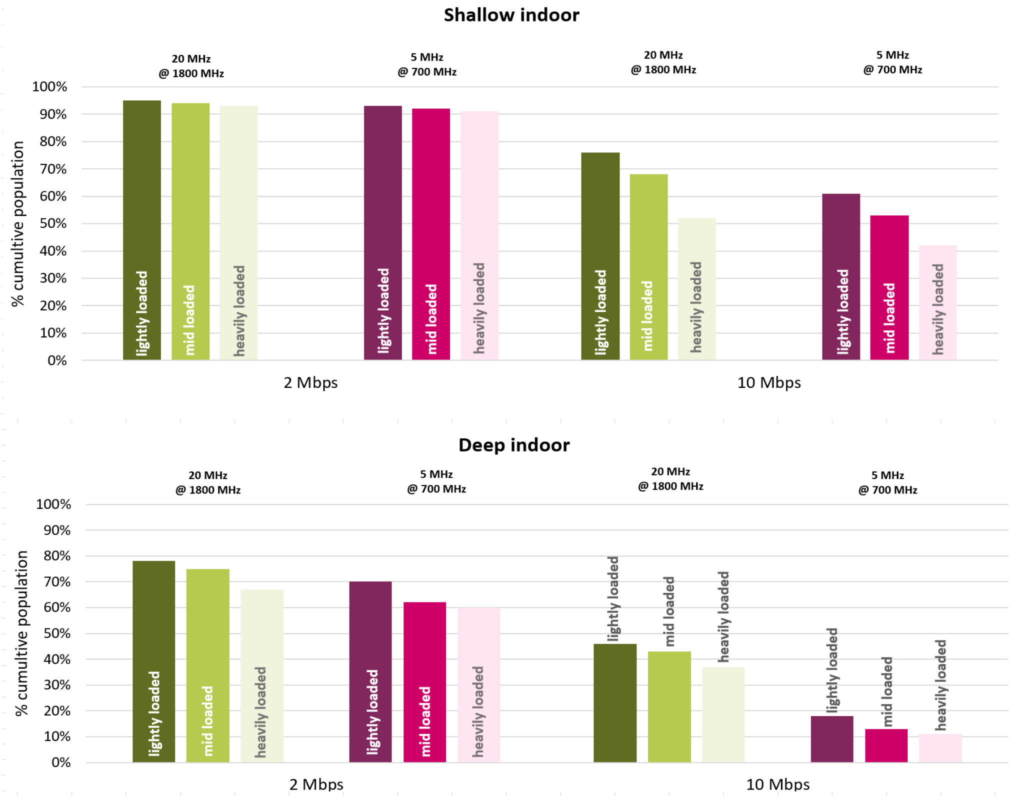


Figure A10.9: Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in least densely populated areas (2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A10.24 Figure A10.7, Figure A10.8 and Figure A10.9 show that 2 x 20 MHz of 1800 MHz outperforms 2 x 5 MHz of 700 MHz, both in shallow and deep indoor environments. For all of the scenarios analysed the percentage of cumulative population achieving 2 Mbps or 10 Mbps is higher for 2 x 20 MHz of 1800 MHz.

A10.25 Figure A10.10 and Figure A10.11 present the distribution of the SUT in the most and mid densely populated areas, both in shallow and deep environments, for the 2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz networks.

Figure A10.10: SUT distribution curves, shallow and deep indoor locations in most densely populated areas (2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)

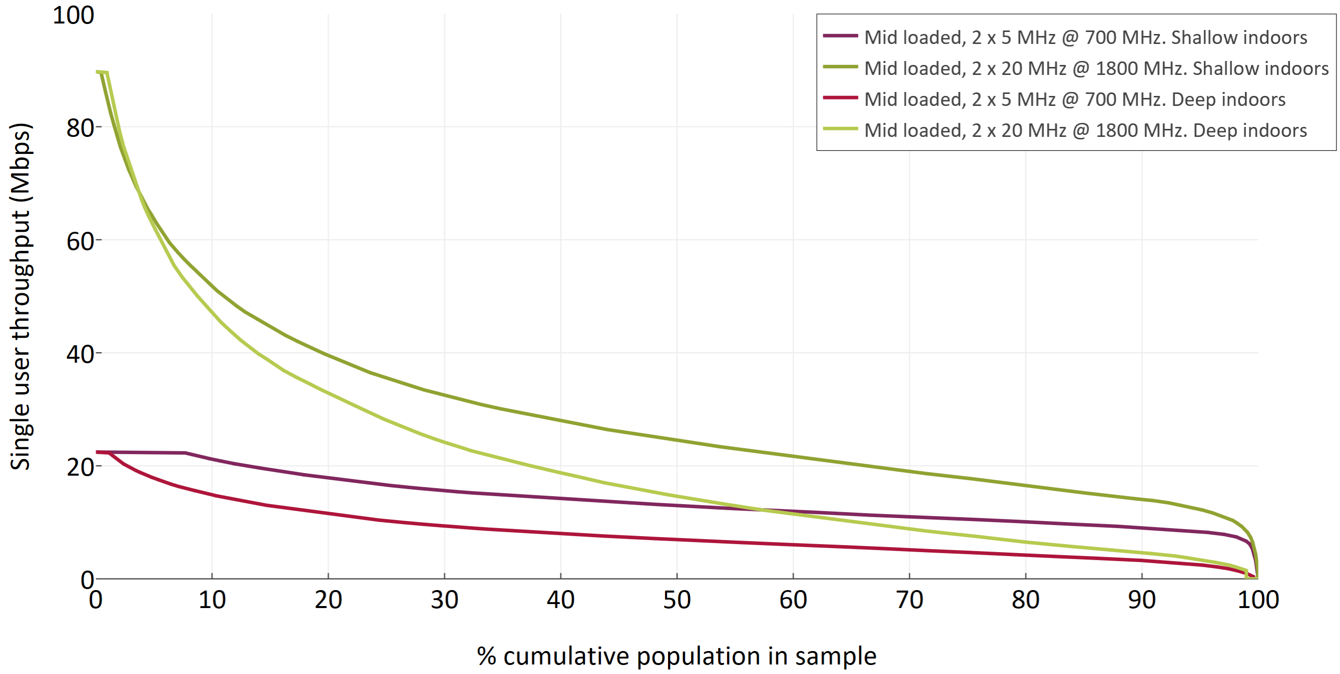
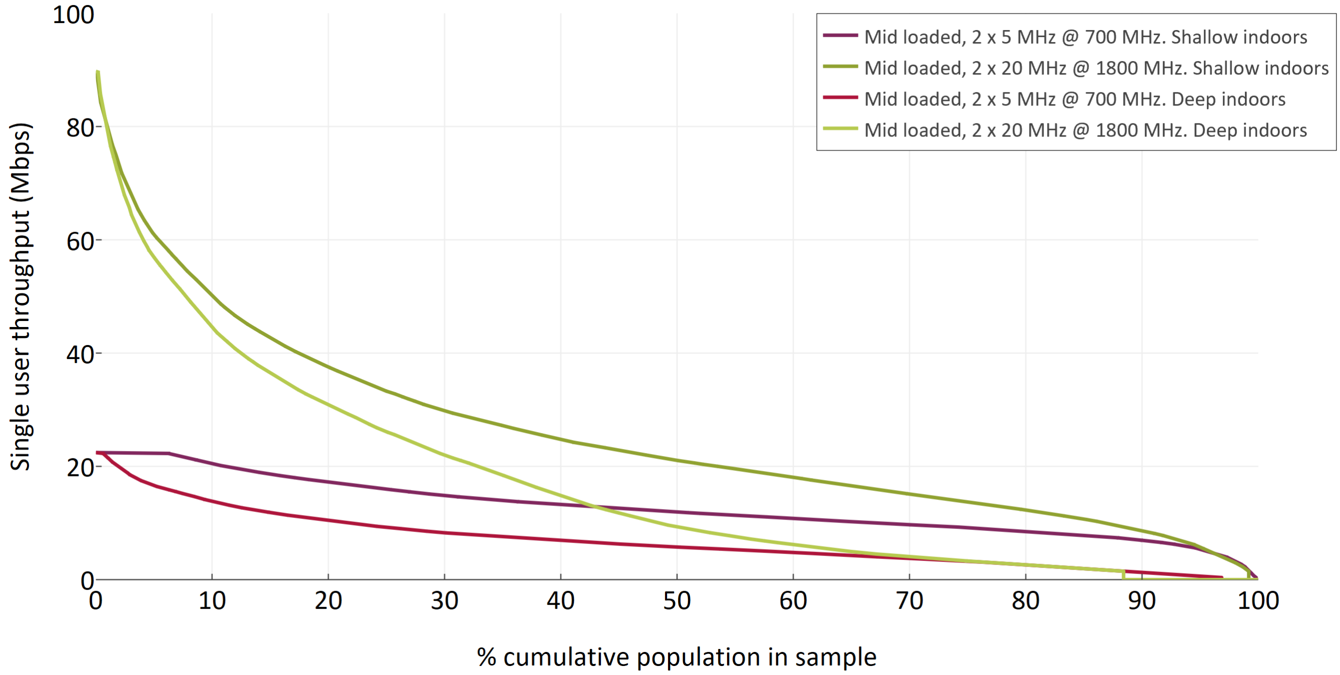


Figure A10.11: SUT distribution curves, shallow and deep indoor locations in mid densely populated areas (2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A10.26 2 x 20 MHz of 1800 MHz provides higher SUT than 2 x 5 MHz of 700 MHz due to the bandwidth available being four times greater. In this case the difference gap is bigger than that when comparing with 2 x 10 MHz of 700 MHz, which leads to fewer locations getting the same levels of SUT.

In the case of deep indoor locations, a network based on 2 x 10 MHz of 700 MHz can outperform a network with 2 x 20 of 1800 MHz (i.e. with twice the bandwidth), though a network based on only 2 x 5 MHz of 700 MHz may not have sufficient bandwidth to for more data-intensive services characterized by a SUT≥ 10 Mbps. Hence an operator with only 2 x 5 MHz of low frequency spectrum may want to acquire more.

A10.27 Figure A10.7, Figure A10.8 and Figure A10.9 show that 2 x 5 MHz of 700 MHz has the poorest SUT performance, especially for data intensive applications (i.e. am SUT of 10 Mbps). Nonetheless, the same charts show that this network can provide an SUT sufficient for basic connectivity (2 Mbps) to a greater proportion of shallow indoor and deep indoor locations.

A10.28 Figure A10.12 and Figure A10.13 show the SUT distribution in deep indoor environments for all networks analysed. The black dots in these figures represent the percentage of cumulative population that could achieve an SUT of at least 10 Mbps.

Figure A10.12: SUT distribution curves, deep indoor locations in mid densely populated areas (2 x 5 MHz of 700 MHz, 2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)

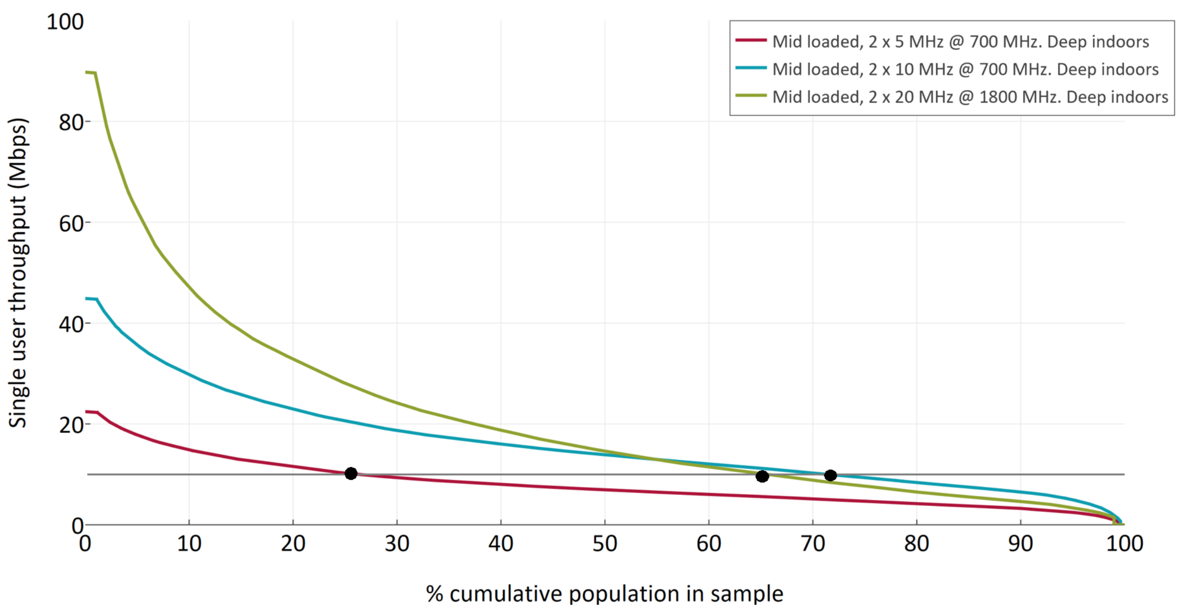
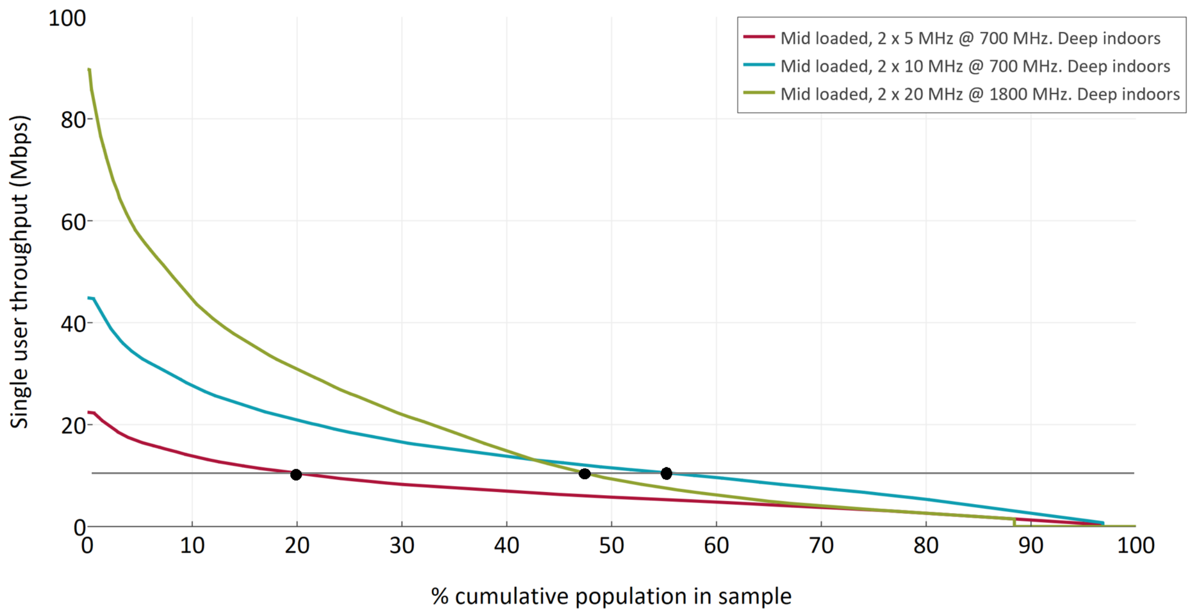


Figure A10.13: SUT distribution curves, deep indoor locations in mid densely populated areas (2 x 5 MHz of 700 MHz, 2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A10.29 Although limited in bandwidth, a network of 2 x 5 MHz of 700 MHz could be used to provide basic connectivity and some data-intensive services to a large proportion of population in the areas analysed. Figure A10.12 and Figure A10.13 show that the achievable SUT of 2 x 5 MHz of 700 MHz is steady at around 5 Mbps across the majority of the population in the areas analysed.

Supporting tables

A10.30 Figure A10.14 and Figure A10.15 show the percentage of cumulative population that can receive a minimum SUT of 2 Mbps and 10 Mbps in each of the analysis areas.

Figure A10.14: Percentage of cumulative population with a minimum 2 Mbps, all analysis areas, networks and network loadings

	Network analyzed	Lightly loaded		Mid loaded		Heavily loaded	
		Shallow indoor	Deep indoor	Shallow indoor	Deep indoor	Shallow indoor	Deep indoor
Most densly populated	20MHz @ 1800MHz	100%	98%	100%	97%	100%	95%
	10MHz @ 700MHz	100%	99%	100%	97%	100%	96%
	5MHz @ 700MHz	100%	98%	100%	97%	100%	96%
Mid densly populated	20MHz @ 1800MHz	99%	87%	98%	84%	97%	75%
	10MHz @ 700MHz	99%	93%	99%	92%	99%	91%
	5MHz @ 700MHz	99%	87%	99%	84%	98%	81%
Least densly populated	20MHz @ 1800MHz	95%	78%	94%	75%	93%	67%
	10MHz @ 700MHz	96%	79%	95%	74%	95%	72%
	5MHz @ 700MHz	93%	70%	92%	62%	91%	60%

Figure A10.15: Percentage of cumulative population with a minimum 10 Mbps, all analysis areas, networks and network loadings

	Network analyzed	Lightly loaded		Mid loaded		Heavily loaded	
		Shallow indoor	Deep indoor	Shallow indoor	Deep indoor	Shallow indoor	Deep indoor
Most densly populated	20MHz @ 1800MHz	99%	71%	98%	65%	95%	61%
	10MHz @ 700MHz	100%	83%	99%	71%	98%	62%
	5MHz @ 700MHz	92%	35%	80%	26%	73%	22%
Mid densly populated	20MHz @ 1800MHz	91%	50%	86%	46%	81%	40%
	10MHz @ 700MHz	97%	61%	96%	58%	95%	48%
	5MHz @ 700MHz	83%	25%	67%	21%	65%	17%
Least densly populated	20MHz @ 1800MHz	76%	46%	68%	43%	52%	37%
	10MHz @ 700MHz	85%	47%	82%	35%	80%	33%
	5MHz @ 700MHz	61%	18%	53%	13%	42%	11%

Methodology

Model overview

A10.31 In this sub-section we present an overview of our modelling of the performance of macro-cell LTE networks operating in the 700 MHz and the 1800 MHz frequency bands.

A10.32 The approach to analysing the results is similar to the one used in our 2012 Statement.The model itself is an evolution of one used in 2012 and has been derived from our 4G coverage obligation model.[250]

A10.33 This model only analyses the downlink performance of a network in indoor locations, it does not include an assessment of uplink performance, nor does it include an assessment of other means providing indoor coverage.

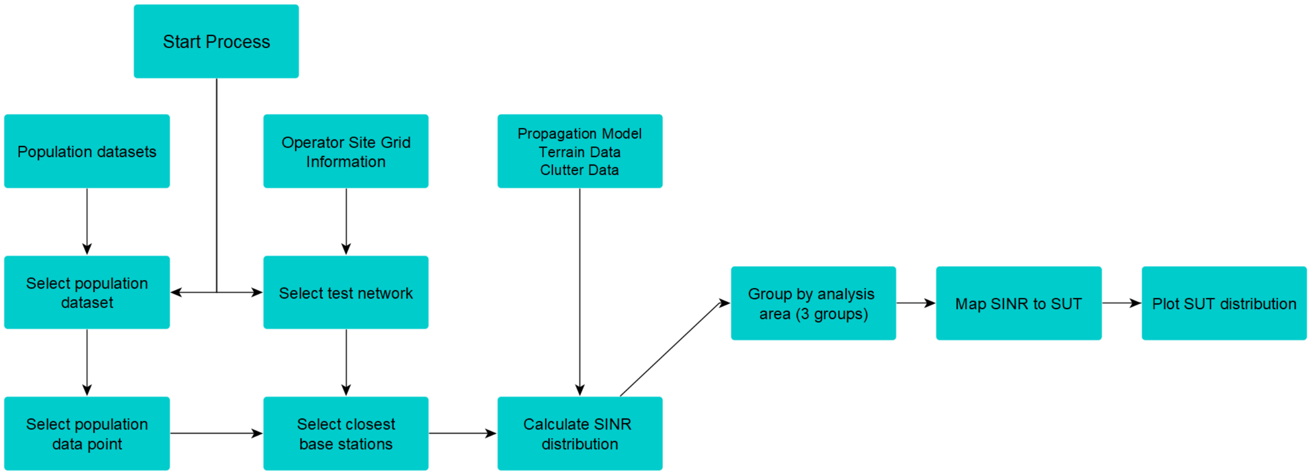
A10.34 To assess downlink performance, the model calculates the SINR (DL-SCH[251]) distribution for a hypothetical test terminal located at a reference indoor location at various population

[250] See Ofcom 4G Coverage verification https://www.ofcom.org.uk/__data/assets/pdf_file/0026/58292/4gcov-verification.pdf

[251] Downlink Shared Channel

points within the area analysed, taking into account signals from the 20 closest base sites. Using the resulting SINR distribution and the bandwidth for each scenario, we calculate the SUT distribution for each of the networks analysed (see paragraphs A10.41 to 0). We consider the networks used in our modelling to be representative of reasonably mature roll-outs in these two bands. Figure A10.16 shows the model process flow.

Figure A10.16: Model process flowchart



A10.35 The macro-cell site grids[252] for each network are used to calculate the wanted downlink signal strength and SINR at a number of locations points within each analysis as follows (see paragraph 10.36 for further detail on the location points):

- The nearest 20 base stations to the population data point are identified;
- For each sector of the nearest base stations identified in step a), the median downlink power that would be received by a terminal 1.5 metres above ground level at each location point is calculated (taking into account a theoretical antenna radiation pattern tuned to the beam widths relevant to each sector);
- The base station sector providing the highest received signal strength at each iteration of the subsequent calculation is designated as the serving sector;
- Non-serving sectors are assumed to be transmitting at each of three different loadings, equivalent to them transmitting at 22%, 47% and 87% of their maximum power (see paragraph A10.52 for details). The serving sector is assumed to be transmitting at its maximum power.

[252] This site grid includes information of each site containing: unique Site ID, location, height above ground, channel bandwidth and number of sectors. For each sector, information relevant to the carrier frequency is included on: boresight direction, horizontal and vertical antenna beamwidths, antenna downtilt and E.I.R.P.

- A downlink SINR distribution[253] (for the DL-SCH) is generated using a Monte Carlo process and by assuming 0.5 location variability cross-correlation between the serving and non-serving sites;
- Using the SINR distribution generated in step e) together with an appropriate mapping function (taken from the function in Annex A.1 of 3GPP TR 36.942), the average downlink single-user throughput distribution for the analysis area is generated.

Analysis areas and population points

A10.36 As with our modelling approach to the 2012 Competition assessment for the 800 MHz and 2.6 GHz spectrum award, underpinning all the technical results presented in this annex are downlink SINR distributions generated across three different analysis areas. Within each analysis area we have calculated the downlink SINR for location points taken from the residential delivery point data at a postcode unit level from the Ordinance Survey's Geopoint Plus R63 dataset. For each location point we have assigned a population value (representing the population contained within the area covered by the corresponding postcode unit) using 2011 UK census data.

A10.37 We have defined three representative analysis areas based on population density as follows:

- **Most densely** populated area: the area within which 50% of the population lives that is most densely populated;
- **Mid densely** populated area: the area within which a further 30% of the population lives that is the next most densely populated relative to the most densely populated area; and
- **Least densely** populated area: the area within which 10% of the population lives that is the next most densely populated relative to the most and mid densely populated areas.

A10.38 The analysis areas are defined on the basis of local authority district boundaries. They exclude Northern Ireland due to lack of data. Hence the most densely populated area is comprised of the most densely populated local authority districts in England, Scotland and Wales where 50% of the population live (from the 2011 UK Census).[254] We have not modelled the area where the last 10% of the population live (i.e. the area of the country with the lowest population density) because we do not consider this area to be relevant for our competition assessment. It should be noted that the analysis areas, though they have a similar definition, are not identical to the ones we used in 2012 Competition Assessment as they have been updated to reflect the latest Census data (our previous 2012 analysis areas

[253] DL_SCH refers to the Downlink Shared Channel, where information about user data, dedicated control and user information are transmitted in LTE.
[254] We are not including Northern Ireland in this model, due to lack of the appropriate data.

were based on census data from 2001).

Figure A10.17: Analysis areas used in this assessment in 2018

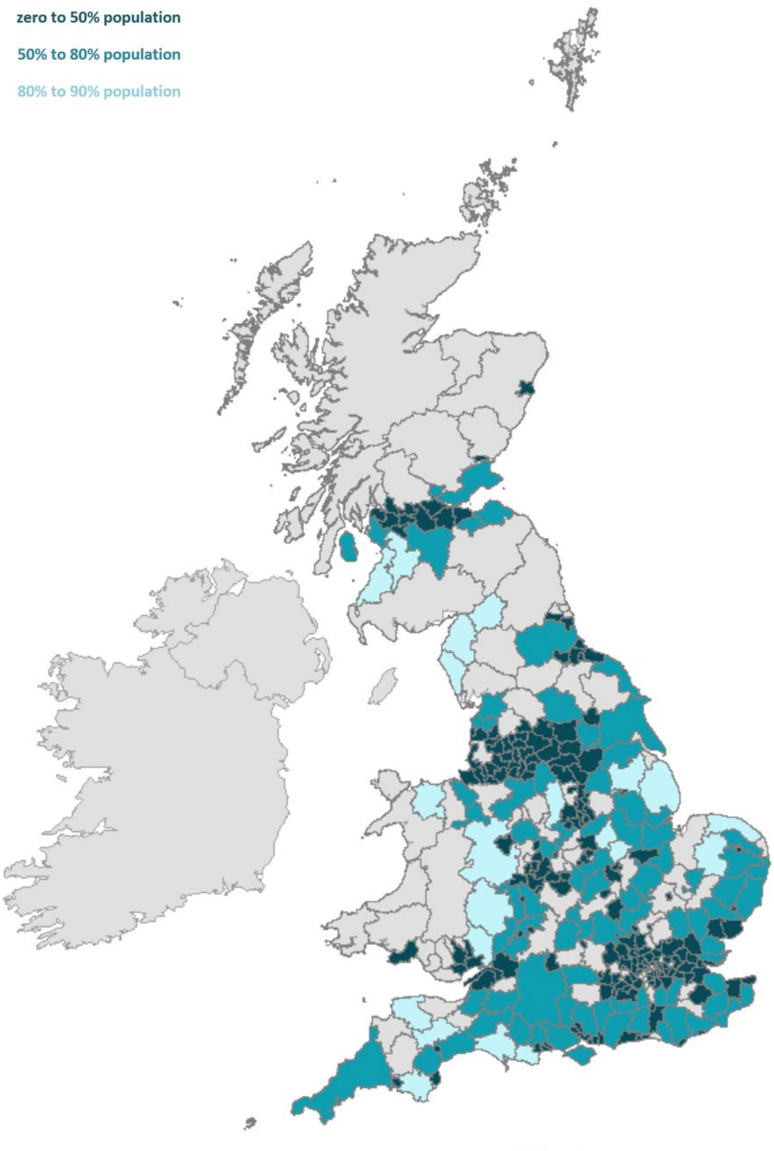


Figure A10. 18 Population and population per household for each analysis area

Analysis area	Population	Population per household
Most densely populated	30,685,657	2.47
Mid densely populated	19,097,052	2.43
Least densely populated	6,137,131	2.42

Propagation model

A10.39 Our model estimates path losses according to the latest version of Recommendation ITU-R P.1812. This Recommendation describes a propagation prediction method suitable for terrestrial point-to-area services in the frequency range 30 MHz to 3 GHz.

A10.40 We have implemented a modified version of Recommendation ITU-R P.1812[255] where one of the sub models dealing with the end terminal corrections has been excluded. This modification may be more suitable for the UK environment based on the preliminary benchmarking results of the ongoing propagation measurement campaign by Ofcom. For the purposes of this analysis there is an almost negligible difference with the throughput values obtained in the two cases. Nevertheless, this variation should be noted.

Estimation of Single User Throughput (SUT) values

A10.41 We have derived SUT from SINR (Signal to Interference plus Noise Ratio) using the mapping function defined by 3GPP in Annex 1 of 3GPP TR 36.942. This document provides details of how the throughput of a modem with link adaptation can be approximated by an attenuated and truncated form of the Shannon bound as follows:

Equation A10.1: Throughput calculation using Shannon truncated bounds

$$Throughput, Thr, \frac{bps}{Hz} = \mathrm{BW} * \left\{ \begin{matrix} 0 \; for \; SINR < SINR_{min} \\ \alpha * S(SINR) \; for \; SINR_{min} < SINR < \; SINR_{max} \\ Thr_{max} \; for \; SINR > \; SINR_{max} \end{matrix} \right\}$$

Where: *S(SINR)* is the Shannon bound: $S(SINR) = \log_2(1+SINR)$ (bps/Hz) and:

α	is the attenuation factor, representing implementation losses
$SINR_{min}$	is the minimum SINR of the codeset (dB)
Thr_{max}	is the maximum throughput of the codeset (bps/Hz)
$SINR_{max}$	SINR at which max throughput is reached $S^{-1}(Thr_{max})$ (dB)

A10.42 The parameters α, $SINR_{min}$ and Thr_{max} can be chosen to represent different modem implementations and link conditions. The parameters proposed in Figure 10.19 represent a baseline case, which assumes:

1:2 antenna configuration

Typical Urban fast fading channel model (10 kmph in the downlink, 3 kmph in the uplink)

Link Adaptation

Channel prediction and HARQ

[255] See ITU-R 1812.2 recommendation https://www.itu.int/rec/R-REC-P.1812/en

Figure A10.19: SINR to SUT mapping function parameters

Parameter	DL	UL	Notes
α	0.6	0.4	Represents implementation losses
$SINR_{min}$ (dB)	-10	-10	Based on QPSK, 1/8 rate (DL) & 1/5 rate (UL)
$Thru_{max}$ (bps/Hz)	4.4	2.0	Based on 64QAM 4/5 (DL) & 16QAM 3/4 (UL)

A10.43 For the purposes of this analysis, we have chosen to use the values of $SINR_{min}$, $Thru_{max}$ (and hence $SINR_{max}$) taken directly from Annex 1 of 3GPP TR 36.942 with no further modification. We consider them to be adequate for the purposes of this analysis given the caveats outlined above (see A10.5 and A10.7).

Building entry loss assumptions

A10.44 As explained earlier, we are focusing the analysis on indoor locations only. There is a need to define the entry losses that an RF signal would suffer on its way inside a building. In the context of this model, we assume that all buildings present the same entry loss.

A10.45 We have used the building entry loss from Recommendation ITU-R P.2109.[256] The output of this Recommendation is in the form of a cumulative distribution function of the probability that a given loss will not be exceeded, and does not differentiate between the loss suffered by a signal penetrating the exterior wall and the attenuation suffered in the path through the building. This is derived from a statistical model derived from empirical measurements taken in various environments and types of buildings.

A10.46 ITU-R P.2109 includes estimations for two types of buildings: traditional and thermally efficient (TEF). Modern TEF buildings usually present significantly higher building entry losses than traditional buildings, due to their construction materials. For the purposes of this analysis we have assumed buildings are of a traditional type. We do not hold detailed information about the UK stock of TEF dwellings, though it is our understanding that these represent a small fraction of the overall UK housing stock. We are therefore content that basing results on losses for traditional buildings is reasonable. On the other hand, we would expect lower levels of coverage in modern TEF buildings.

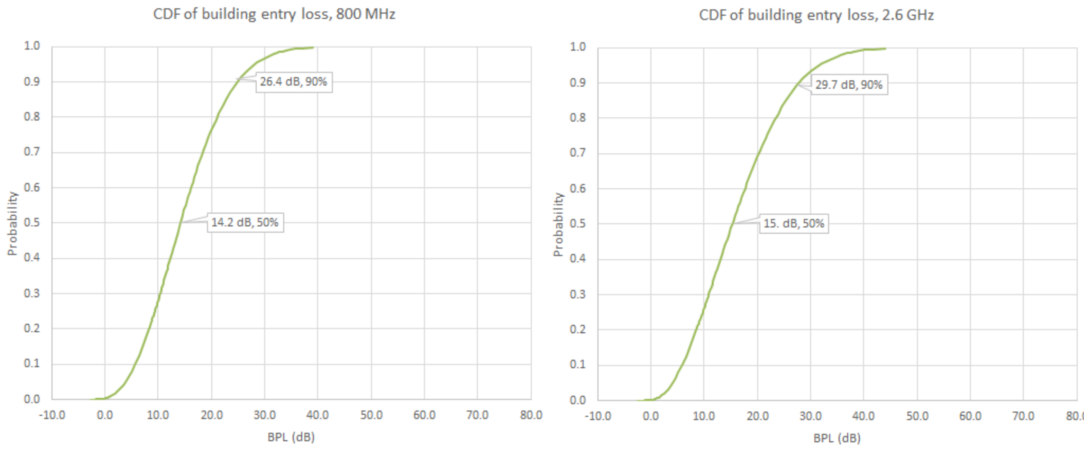
A10.47 We define two different indoor environments, shallow and deep, as follows:

- **Shallow indoor**, derived from the 50th percentile of the CDF from ITU-R P.2109 for traditional buildings, i.e. a 50% probability that the loss is not exceeded. This is intended to represent relatively easy to serve areas such as those fairly close to windows or external sides of buildings, or further into buildings with relatively low penetration losses.

[256] See P.2109: Prediction of Building Entry Loss – ITU https://www.itu.int/rec/R-REC-P.2109/en

- **Deep indoor**, derived from the 90th percentile of the CDF from ITU-R P.2109 for traditional buildings, i.e. a 90% probability that the loss is not exceeded. This is intended to represent harder-to-serve locations, such as enclosed rooms away from external walls or in basements, or into buildings with relatively high penetration losses.

Figure A10.20: Example of the CDF curves of the building entry losses for 800 MHz and 2.6 GHz



A10.48 During the 2012 Competition Assessment we also defined two types of indoor locations called ‘shallow’ and ‘deep’, with associated building entry loss assumptions. Since 2012, significant further work has been undertaken to improve knowledge of building entry losses. This has led to the publication in 2017 of Recommendation ITU-R P.2109 which gives an internationally recognized method for the estimation of building entry loss.

A10.49 It should be noted that, though broadly comparable, our current definition of what constitutes shallow and deep within a building are not identical to the definition we used in 2012. Figure A10.21 compares the building entry losses used in our 2012 assessment and those we are using in this analysis for frequencies at 800 MHz and 1800 MHz.

Figure A10.21: BEL values used in the 2012 and 2018 Competition Assessments

	Building Entry Loss (dB) 2012 Assessment		Building Entry Loss (dB) 2018 Assessment based on ITU-R P.2109	
Frequency (MHz)	Shallow Indoor	Deep Indoor	Shallow Indoor	Deep Indoor
700	10.5	25.2	14.2	26.5
1800	13.7	28.9	14.9	28.6

The macro-cell networks modelled

A10.50 We have modelled two macro-cell base station networks with parameters taken from actual mobile networks operating at 800 MHz and 1800 MHz. The 700 MHz network we used is based on site data from Vodafone's 800 MHz LTE network and the 1800 MHz network is based on site data from BT/EE's 1800 MHz LTE network. For the purposes of this analysis, we consider these networks to be representative of reasonably mature LTE roll-outs. They are taken from MNO responses to information requests from June 2018. The parameters we have used include bases station locations, and information per sector on transmit power (E.I.R.P), antenna height, downtilt, azimuth, and horizontal and vertical beam width.

A10.51 Figure A10.22 shows the number of sites in each of the analysis areas.[257] This table shows that the 1800 MHz is cell site grid is denser than the 800 MHz grid in all analysis areas (most, mid and least densely populated).

Figure A10. 22: Sites per analysis area

Analysis area	1800 MHz site grid	700 MHz site grid	Difference
Most densely populated	~ 8,700	~ 8,000	~ 700
Mid densely populated	~ 3,900	~ 3,300	~ 600
Least densely populated	~ 850	~ 750	~ 100
Total UK sites	~ 18,000	~ 16,000	~ 2,000

[257] Note these cell sites are located in England, Scotland and Wales, as we do not currently hold the necessary information to perform this analysis for Northern Ireland. Therefore, the cell sites not included in the analysis will include those located in the least densely populated areas in England, Scotland and Wales (the remaining 10% percent) plus those located in Northern Ireland.

Effects of nearby sites

A10.52 One of the main sources or interference in a mobile network is inter-cell interference from other cells in the network serving other users (on the same frequency). To understand the effect on SUT we have modelled three different loadings of the surrounding cells:

- **lightly loaded:** the surrounding cells will be only using the resources necessary for signalling and other overheads (i.e. 22% signalling etc + 0% traffic = 22% overall loading);
- **mid loaded**: the surrounding cells are 25% loaded with user traffic in addition to signalling and other overheads (i.e. 22% signalling etc + 25% traffic = 47% overall loading); and
- **heavily loaded**: the surrounding cells are 65% loaded with user traffic in addition to signalling and other overheads (i.e. 22% etc + 65% traffic = 87% overall loading)

A10.53 For all three loadings, the serving cell is assumed to have all available downlink resources (i.e. all resources minus signalling and other overheads) available to serve a single user. whereas the surrounding sites will have a resource block allocation depending on how much demand we consider.

A11. The benefits of improving coverage

Summary

A11.1 This annex sets out the benefits we consider will be generated by improving rural 4G coverage through geographic coverage obligations (with a premises requirement and a minimum of 500 new wide-area coverage sites).

A11.2 In this annex, we set out the current extent of good quality 4G coverage and note that many rural areas do not experience good quality coverage, or only experience good quality coverage from a subset of operators. We explain why we consider that the market is unlikely to deliver the desired level of coverage. We describe the benefits that we would expect to arise from the additional coverage resulting from our proposed obligations and the nature of the improved experience.

A11.3 The beneficiaries would include homes and businesses located in areas of improved coverage, in addition to people that visit or travel through the areas on a frequent or occasional basis.

A11.4 Finally, we consider whether the social benefits from improved coverage will vary according to which operators deliver the coverage obligations. We provisionally conclude that the social benefits will be broadly similar regardless of which operators win the obligations.

Current coverage is not adequate

A11.5 As we explained in our 2017 Connected Nations report, we have changed the way in which we measure coverage. We consider that today's consumers are likely to be satisfied with coverage when:

- *Voice calls*: nearly all mobile calls which last for at least 90 seconds can be made and successfully completed without interruption; and
- *Data services*: nearly all connections deliver a speed of at least 2 Mbps. This is fast enough to allow users to browse the internet and watch glitch-free mobile video.

A11.6 We refer to this as 'good quality' coverage. Indoor and outdoor mobile coverage in the UK has improved significantly in recent years. However, in our view coverage is still not good enough. As we set out in section 4, many consumers still experience poor coverage, especially in rural areas.

A11.7 It is also useful to define at the outset what we mean by total and partial not-spots in this context, as these terms are used below:

- *Total not-spot*: By total not-spot areas, we mean areas where no operator provides good quality 4G coverage. One or more operators may provide poorer quality coverage (i.e. voice coverage, or data coverage at a lower signal strength).

- *Partial not-spot*: By partial not-spot area, we mean an area where one, two or three operators provide good quality coverage, i.e. at least one operator does provide good quality 4G coverage, and at least one does not (though they may also offer coverage at a lower quality).

A11.8 We usually measure coverage by considering the number of UK premises where each operator provides good quality voice and data coverage (‘**premises coverage**’) and the extent of the UK landmass where each operator provides good quality voice and data coverage (‘**geographic coverage**’).

A11.9 As to the premises coverage, while there are relatively high levels of voice coverage outside people’s homes, each operator falls some hundreds of thousands of premises short of providing this service throughout the UK. Indoor voice coverage is slightly worse than outdoor. Once signal loss for penetrating inside a building is accounted for, indoor 4G data coverage is considerably worse. Geographic coverage, which includes the places people move around in for business and leisure, is lower than premises coverage. Figure A11.1 below summarizes the current levels of good quality and data coverage in the UK.

Figure A11.1: Current levels of good quality voice and data coverage, September 2018

	Voice Coverage			4G Data Coverage		
	Landmass	Outdoor premises	Indoor premises	Landmass	Outdoor premises	Indoor premises
BT/EE	85.0%	99.4%	95.8%	84.4%	99.1%	88.4%
O2	90.4%	99.8%	99.1%	74.4%	98.9%	94.8%
H3G	84.8%	99.5%	95.9%	78.4%	98.6%	89.4%
Vodafone	90.4%	99.8%	98.6%	78.6%	99.0%	93.7%

Source: Ofcom Connected Nations 2018

Coverage is particularly poor in rural areas, and in Scotland and Wales

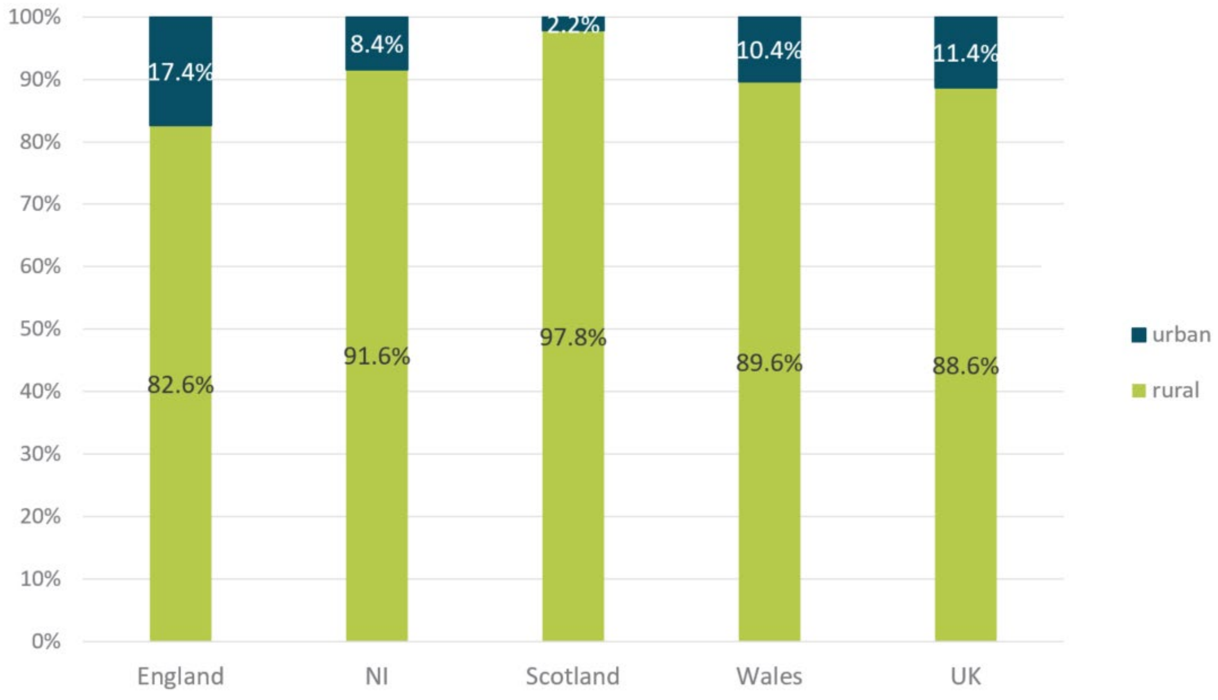
A11.10 A larger proportion of premises in rural areas (compared with urban and suburban ones) will experience coverage of a poorer quality (i.e. where the signal falls below the strength necessary to achieve good quality coverage).

A11.11 Individual operators all have more than half a million premises in rural areas which they do not provide good indoor coverage to, while only 18% of rural premises have good indoor coverage from all operators. In these areas, consumers are unlikely to be able to access data-intensive applications indoors and may experience delays and buffering with basic internet applications. In some cases, data sessions may not be possible at all.

A11.12 Outdoor coverage is also poor for the most rural areas, with between 10% and 20% of premises located in this area being without even good outdoor coverage from individual operators.[258] This trend extends into landmass coverage, with individual operators expected to serve between 52% and 69% of the most rural landmass.

A11.13 Rural territory represents a significant part of the UK as a whole and lack of mobile coverage in these areas impacts on many consumers' experience. For Figure A11.2 below, the UK landmass has been divided into equal sized pixels, with each pixel classified according to whether it is urban or rural.[259] It shows the vast majority of pixels (i.e. landmass) are rural. The proportion of the landmass that is rural is higher in Northern Ireland, Wales and Scotland compared to England.

Figure A11.2: Rural and urban landmass of UK and the UK nations



Source: Ofcom

A11.14 As we showed in section 4, a patchwork quilt of coverage from operators spreads across much of the UK (with more than 90% of the UK served with good outdoor coverage by the combined coverage footprints of all operators). However, good quality outdoor coverage provided by each individual operator, and therefore the coverage that individual consumers actually experience, is significantly lower. This means that, in rural areas in

---

[258] This reflects Ofcom's analysis of information provided to us by operators on the levels and locations of good 4G coverage they expect to provide by June 2019, compared against our classification of the most rural landmass. In our 2017 Connected Nations, we explained that we used a 'Locale' classification to identify premises as being in an urban or rural area. Locale is a third-party data source based on the analysis of 2011 census output areas (OAs). We assign the Locale classifications to either urban or rural based on the following. Urban: Codes A to C which relate to settlements with populations over 10,000 and codes D to E which relate to settlements with populations over 2,000. Rural: F to G which relate to settlements with populations under 2,000. See paragraphs A1.32 to A1.33 in Connected Nations. https://www.ofcom.org.uk/__data/assets/pdf_file/0016/108511/connected-nations-2017.pdf

[259] Each pixel is 100m x 100m.

particular, consumers are likely to find many areas where they cannot get good quality outdoor coverage as they move around.

A11.15 Coverage levels in the more rural parts of the UK, including particular nations, lag far behind comprehensive coverage. 4G coverage is worse in some UK nations than in others. Figure A11.3 below presents the current levels of coverage for each nation.

Figure A11.3: Voice and data coverage across UK Nations by all four operators, September 2018

	Geographic Coverage	Outdoor Premises Coverage	Indoor Premises Coverage
England	88-94%	99%	89-95%
Northern Ireland	86-94%	94-99%	67-93%
Scotland	51-68%	97-99%	87-94%
Wales	67-83%	96-98%	87-89%

Source: Ofcom: Connected Nations 2018

A11.16 We have undertaken work to understand the key drivers for the presence of one, or more than one, operator in a given area.[260] Our analysis shows that the key determinant for good coverage is the population density of an area (though other local factors, including terrain, may contribute). The lower current levels of coverage in Scotland, Wales and Northern Ireland (compared to England) reflects that these nations have a greater proportion of rural landmass (see Figure A11.2 above), with a lower population density.

A11.17 As we said in our March 2018 consultation, we want to ensure that the benefits of the proposed obligations are fairly distributed throughout the nations, by ensuring the greatest uplift in the nations that have the lowest coverage today. We discuss the various benefits that stem from increasing rural coverage from paragraph A11.29 below.

Why does the market fail in delivering comprehensive mobile coverage?

A11.18 As we noted in section 4, we believe there are limits to the extent to which competition is likely to drive the expansion of mobile coverage to address the coverage issues that exist today. There are several possible reasons for this market failure:

- Indirect benefits from mobile coverage;

[260] See Economic Geography https://www.ofcom.org.uk/research-and-data/multi-sector-research/availability-of-communication-services/economic-geography-2017

- Informational and behavioural biases; and
- Difficulty of geographic price differentiation.

A11.19 We expand below on these potential reasons for market failure.

Indirect benefits from mobile coverage

A11.20 There are indirect benefits from providing mobile coverage such as private external value and broader social value (e.g. increased social capital) which we discuss in paragraph A11.44 to A11.49 and A11.57 to A11.72 below. Absent coverage obligations, we expect that operators will make decisions on providing additional coverage based on profitability.[261] To the extent there are benefits from coverage that the operators cannot capture (i.e. monetise), then coverage may be insufficient from the perspective of society as a whole. The larger the size of these values, the greater the likely under-provision.

Informational and behavioural factors

A11.21 For some consumers, the difference in mobile coverage provided by different networks may be very clear. For example, this might be the case for consumers where only one operator provides coverage in the areas where they frequently use their phone.

A11.22 However, consumers who have good coverage from all operators most of the time may not have adequate information to determine which operator provides the best coverage in the places where they go only occasionally. This is particularly the case when consumers spend time in many different locations.

A11.23 Consumers may also exhibit behavioural biases that mean they put less than optimum weight on coverage when choosing their mobile provider. For example, consumers' choices may be driven by product characteristics which are easily understood and certain, such as the headline price of a mobile contract, rather than some aspects of quality, such as coverage.[262] These behavioural biases may be particularly pronounced because of the complexity and uncertainty involved in consumers assessing the benefits of greater coverage.[263]

---

[261] A commercial (profitable) level of roll-out does not necessarily mean that the traffic over every site generates revenues greater than the costs of providing that site. Operators can have a financial incentive to provide sites that generate relatively little traffic, if consumers value having wide area coverage and take that into account when choosing a provider.

[262] There can be many different factors to consider when choosing a mobile package, including various different dimensions of price, contract duration, handsets and other aspects of quality. Our Digital Communications Review noted that communications '*products can be more diverse and complex, with more options for consumers, than many other networked services (e.g. energy, water)*'. Ofcom, Initial conclusions from the Strategic Review of Digital Communications, February 2016 paragraph 7.33, p.84, https://www.ofcom.org.uk/__data/assets/pdf_file/0016/50416/dcr-statement.pdf

[263] A fuller discussion of behavioural biases is set out in *Applying behavioural insights to regulated markets*, The Behavioural Insights Team for Citizens Advice, 26 May 2016, https://www.citizensadvice.org.uk/Global/CitizensAdvice/Consumer%20publications/Applying-behavioural-insights-to-regulated-markets.pdf

A11.24 These informational and behavioural factors could mean that operators have insufficient incentives to compete by providing marginal improvements in coverage, and that coverage is below the level that would best meet consumers' needs.

Difficulty of geographic price differentiation

A11.25 Even if some consumers (such as those in rural areas) are willing to pay to cover the costs of greater coverage, it may not be profitable for operators to provide this. This could be because operators cannot profitably increase prices when providing better coverage because prices are set nationally and some other consumers (such as those in urban areas) are not interested in paying for the additional coverage. In addition, it may be the case that some rural consumers would be prepared to pay extra for improved coverage, and others would not.

A11.26 An issue is therefore whether prices can be set in some way that differentiates by geography. In its response to the March 2018 consultation, Vodafone said that mobile pricing *"inherently must be national'* and described the market failure that would result from geographic price differentiation.[264]

A11.27 There is no explicit geographic price discrimination currently.[265] In principle, there are different ways operators could try to price discriminate to capture the higher costs of providing coverage in rural areas, such as through different prices depending on the consumer's address or by offering more expensive services with a greater geographic coverage (for example, an 'add-on' for geographic coverage in the hardest to reach areas). However, we accept that there may be challenges in introducing geographic charges of this nature. The informational challenges and behavioural biases described above may contribute to this. For example, consumers may not like different geographic pricing, partly because of the extra complexity in understanding when it applies.

A11.28 In conclusion, the factors set out above suggest that the operators are unlikely to make the commercial decision to increase coverage beyond a certain point because the benefits of increased coverage will not necessarily be reflected in their profits.

The benefits of increasing coverage

A11.29 In this section, we consider the potential social benefits of increased good quality 4G mobile coverage, and the harm suffered by consumers and businesses from a lack of mobile coverage.

[264] Vodafone's response to the March 2018 consultation, page 6
https://www.ofcom.org.uk/__data/assets/pdf_file/0012/115401/Vodafone.pdf
[265] This is despite there being very considerable price discrimination within the retail mobile industry on a range of other characteristics, e.g. contract and pay-as-you-go, handset prices, size of any monthly call and data allowance and the bundling of mobile services with other services.

Consumers and business customers would benefit from coverage improvements

A11.30 Consumers consider that reliability and coverage constitute a key part of the quality of a mobile network. Ofcom research in 2018 found that 9% of mobile users are currently fairly or very dissatisfied with their reception or signal strength, and 4% are very dissatisfied.[266] Dissatisfaction is significantly higher in rural areas: 20% of mobile users in rural areas were dissatisfied with their mobile reception or signal strength compared to 7% of urban users.[267] Poor mobile reception or coverage is the most common reason for dissatisfaction with a mobile service.[268]

A11.31 There is evidence that some consumers currently place a higher priority on a reliable voice service than on data services. However, over time, consumers are likely to increasingly expect a fuller set of services to be available requiring a good quality data service.

A11.32 Research carried out by Jigsaw for Ofcom sets out some of the ways consumers would benefit from improved mobile coverage:[269]

a) **Increased social connectedness**: those in areas of poor coverage often find themselves disconnected and as a result can miss out on social activities. By contrast good coverage means that consumers communicate to react as things develop and 'plan on the go' as new information is received.

b) **Finding travel details**: the ability to access information on-the-go includes being able to check the opening times of local businesses and being able to check timetables, maps and travel details.

c) **Finding services**: visitors and tourists can benefit from the ability to find services as they travel through an area.

A11.33 The Jigsaw research also highlights how improvements in mobile coverage can benefit businesses:

a) **Increased ease of navigation**: navigation is an increasingly vital mobile data service which many SME consumers now rely on, particularly map-based services.

b) **Improvements in marketing:** businesses could improve their quality of service, for example by having active social media pages.

c) **Access to documents:** employees can improve communication on-the-go by accessing information and documents when out and about.

---

[266] Ofcom Customer Satisfaction Tracker: Summary of Research Findings, Ofcom, 2018, slide 12 https://www.ofcom.org.uk/__data/assets/pdf_file/0021/113628/customer-satisfaction-tracker-2018.pdf

[267] Ofcom, Customer Service Tracker Survey 2018, Question M4. And how satisfied are you overall with the reception or signal strength that you get on your mobile phone service. Available at https://www.ofcom.org.uk/__data/assets/pdf_file/0021/112287/Customer-service-tracker-2018-data-tables.pdf Table 25.

[268] Ofcom Customer Satisfaction Tracker: Summary of Research Findings, Ofcom, 2018, slide 11

[269] See pages 15 to 22, Jigsaw, *Mobile coverage: Qualitative research,* 2017; https://www.ofcom.org.uk/__data/assets/pdf_file/0021/108129/jigsaw-mobile-coverage-qualitative-research.pdf

A11.34 Responses to our March 2018 consultation highlighted that lack of mobile coverage can be problematic for businesses. For example, the National Farmers Union (NFU) said: "Quality mobile voice connections are essential, but so is the access to applications to enable online only regulatory services that have to be complied with".[270]

A11.35 There are other sources of evidence which suggest that improved coverage is important for businesses. For example, a recent report by the Scottish Affairs Select Committee states that "mobile coverage on roads is pivotal for businesses".[271]

A11.36 A survey commissioned by Amazon businesses flagged the importance of having good mobile phone coverage alongside fixed broadband coverage.[272] According to this survey, for many businesses the two go together, with their mobile smartphone effectively serving as a back-up when a fixed connection is not available for e-mails and internet access. In particular, businesses said that:

- if a mobile signal is weak, businesses must rely on the landline for internet which ties business people to the office, reducing the scope to work flexibly or remotely;
- a poor mobile signal can result in lost business sales, for example when a business cannot communicate with a potential client at the right time or they miss calls or messages from clients;[273]
- there can be a time penalty if business people have to visit a client or another branch of their business in person rather than using the phone;
- a weak mobile signal can mean not being able to accept electronic payments, which is a growing consideration when fewer payments are made by cash; and
- for employees, a poor mobile phone signal has potential to add risk, if they are travelling or working alone.

A11.37 In areas without good quality data and voice coverage, consumers are likely to experience frustrations, which will depend on the quality of coverage in the area they are moving through. In some cases, this may be capable of supporting a basic data service, while in other cases a voice call may not connect or may be of poor quality. There may be workarounds available to the consumer, such as communicating via text messaging. However, these workarounds are best suited to situations where the consumer in the poor coverage area is initiating a communication. They do not fulfil the broad expectation expressed by many consumers that their mobile service should seamlessly allow them to

[270] NFU's response to the March 2018 consultation, page 4 https://www.ofcom.org.uk/__data/assets/pdf_file/0011/115013/National-Farmers-Union.pdf

[271] *Digital Connectivity in Scotland*, July 2018, Scottish Affairs Select Committee, https://publications.parliament.uk/pa/cm201719/cmselect/cmscotaf/654/65408.htm#_idTextAnchor053 This conclusion was partly based on a study by Rural England CIC, SRUC and Amazon (2018), Unlocking the digital potential of rural areas across the UK, available at https://ruralengland.org/unlocking-the-digital-potential-of-rural-areas-research/.

[272] Rural England CIC, SRUC and Amazon (2018), Unlocking the digital potential of rural areas across the UK, p. 46-47, available at https://ruralengland.org/unlocking-the-digital-potential-of-rural-areas-research/.

[273] There may be other negative impacts on businesses due to poor mobile signal, such as damage to the reputation or presenting an unprofessional image if they cannot participate in a video call due to an intermittent connection.

be generally contactable, regardless of the means of communication chosen by others in better coverage areas.

Types of benefit from improved coverage

A11.38 Improved coverage will benefit individual mobile users in the ways we have outlined above, but there are also wider benefits to society. We consider below a number of ways that improved coverage may deliver benefits:[274]

- private user value (additional consumer surplus);[275]
- private external value;
- macroeconomic benefits; and
- broader social value.

A11.39 We use the term 'social benefit' to encompass all the benefits discussed above.[276]

Private user value/additional consumer surplus

A11.40 Private user value is the benefit enjoyed by individuals from their own use of the service. As noted above, subscribers to an operator with improved 4G outdoor coverage would benefit if they live, visit or travel through the improved coverage area. Subscribers of other providers may also benefit if they switch to the operator that has improved its coverage.

A11.41 Studies suggest that mobile data services deliver significant consumer benefits, so coverage improvements are likely to increase these benefits. For example, Analysys Mason (2012) suggested that a very pessimistic estimate of the consumer surplus from use of mobile data services in the UK in 2011 was approximately £5.5 billion.[277]

A11.42 Since 2013, the average amount of mobile data consumption has increased five-fold, while the weighted average monthly price of the average mobile use baskets (excluding handsets) has fallen by 11.5%.[278] Also, the number of 4G subscriptions increased from 2.7

---

[274] In the 2014 Statement on Spectrum Management Strategy we identified two components of value to society from spectrum use: private value and wider social value. See paragraphs 4.6 to 4.8 https://www.ofcom.org.uk/__data/assets/pdf_file/0021/71436/statement.pdf . In this context we have split private value into private user value and private external value. We use the term broader social value in place of wider social value. We have also included a separate discussion of macroeconomic benefits. We would expect that higher macroeconomic output is as a result of private use value, private external value and broader social value. However, we discuss the macroeconomic benefits separately for convenience as there are various studies that consider it.

[275] Consumer surplus is the difference between the amount that consumers are willing to pay for a good and the actual amount they pay.

[276] As noted in footnote 271 above, in the 2014 Statement on Spectrum Management Strategy we used the term total social value to refer to the combined benefits from using spectrum for mobile services. In this consultation we have used the term social benefits. Similarly, the term social value and the categories of private use value, private external value and broader social value are used in the independent report to DCMS in November 2015, *Incorporating Social Value into Spectrum Allocation Decisions*, https://www.gov.uk/government/publications/incorporating-social-value-into-spectrum-allocation-decisions.

[277] Analysys Mason (2012), *Impact of radio spectrum on the UK economy and factors influencing future spectrum demand*, p. B-18, http://www.fcs.org.uk/image_upload/pdf/Impact_of_radio_spectrum_on_the_UK_economy.pdf.

[278] See Figure A6.1, Figure A6.15 and paragraph A6.52.

million in 2013 to 58.4 million in 2017.[279] This demonstrates the growing importance of mobile data, and the increasing importance of 4G coverage as a means to access this.

A11.43 In 2014, RAND produced a report on the value consumers place on extended mobile coverage.[280] RAND estimated the willingness of residents, businesses and visitors to pay for the extension of mobile coverage to areas without any mobile signal (i.e. without a usable 2G, 3G or 4G connection). The report found that local residents, businesses, visitors and tourists to the area were willing to pay a significant amount for improved 2G and 3G/4G coverage.[281] For example, local residents, businesses and visitors were willing to pay £22, £33.20 and £24.70 per month respectively for a better quality 3G/4G signal than was available nearby (this is in addition to what they were already paying to use mobile services). Further information from the 2014 RAND report is discussed in annex 12.

Private external value

A11.44 Private external value captures indirect benefits for mobile users from improved mobile coverage. It covers benefits that accrue to people and businesses because others experience an improvement in coverage. One type of private external value from better 4G coverage relates to better two-way communication. For example, if better coverage enables additional interactions including through social media, it could provide not only private user value for those consumers in the area of improved coverage, but also private external value for others who would be able to communicate with them, even if their own coverage has not improved.

A11.45 Another type of private external value relates to the scope for mobile data connectivity to have wider indirect effects, including efficiencies through easier access to information and enabling transactions that would not otherwise have happened. Examples might include businesses benefiting from mobile consumers getting better real time access to information about their services, having a wider availability of different ways to pay (e.g. mobile wallet apps), and looking further forward to other emerging future use cases such as connected and autonomous vehicles.[282]

---

[279] Ofcom (August 2018), https://www.ofcom.org.uk/__data/assets/pdf_file/0022/117256/CMR-2018-narrative-report.pdf, Figure 4.1.

[280] *Estimating the value of mobile telephony in mobile network not-spots*, RAND Europe, 2014, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/412201/Mobile_network_not_spots_final_report.pdf

[281] These categories of people were defined as follows in the 2014 RAND report:

- Residents are located within not-spot areas in England; cannot obtain a mobile network signal when inside their home (self-reported); may run a business from home.
- Business premises are located within not-spot areas in England, cannot obtain a mobile network signal when inside business premises (self-reported).
- Local visitors live near, but not in, a not-spot area in England; regularly/occasionally travels through or visits places in their local area where there is no mobile phone signal; can obtain a mobile network signal when inside their home (self-reported); may run a business from home.
- Tourists have travelled to a not-spot area in England, outside of their local area, within the past 12 months either for business or leisure purposes, can obtain a mobile network signal when inside their home (self-reported).

[282] To illustrate how these new applications enabled by mobile data could potentially add considerable private external value, we note the forecasts in a KPMG report about the economic benefit of connected and autonomous vehicles. KPMG

A11.46 Because these external effects do not directly benefit the individual that is purchasing a mobile service, consumers are unlikely to value them and hence are unlikely to be willing to pay for them. We are not aware of any studies that we can use directly to estimate the level of the private external value of improved 4G coverage. However, various studies have argued that the impact of greater mobile broadband coverage may be very significant, and a significant part of this might be expected to be through the private external value.

A11.47 The macroeconomic benefits of increased mobile broadband coverage, on which there are various studies (see Figure A11.4 below) is likely to be an important component of the private external benefits.

A11.48 As well as private external benefits, there can also be private external costs. For example, improving 4G coverage is likely to involve extending coverage in rural areas which could have a negative visual impact due to additional mobile infrastructure.[283] This potential harm is mitigated by planning rules, which balance the need for development and the visual impact. For this reason, we consider these costs are likely to be small. This is consistent with the 2014 RAND study, which found that the potential visual impact of additional mobile phone masts was not a major concern.[284]

A11.49 In summary, our provisional view is that the private external value from extending good outdoor 4G coverage is likely to be considerable.

Macroeconomic effects

A11.50 Extending good outdoor 4G coverage is likely to generate macroeconomic benefits such as an increase in the UK GDP and the respective growth rate. This may be related, for example, to a multiplier effect from the investment required to extend 4G coverage (e.g. the firms that deploy 4G coverage may hire more workers and more money will be spent in the economy), or it might be by virtue of firms being able to improve their efficiency and expand their sales (e.g. firms can reduce some of their costs and expand their customer base).

A11.51 Below we summarise the main conclusions from studies that attempt to quantify the impact of improvements in telecommunications services on GDP – see the left column of Figure A11.4 below. However, the applicability and relevance of these studies is limited because we are interested specifically in the value of incremental 4G coverage in the UK for the 20 years after the auction date, while the existing studies consider the value of connectivity (i.e. fixed and mobile), or the value of 4G technology as a whole, or consider a different time frame, or refer to other geographical areas. For example, the macroeconomic multipliers relevant to investment in areas of low population density could

forecasts the annual economic benefits to grow to £51 billion by 2030. While the majority of this relates to the benefits for the consumers affected (which is relevant to the private use value), £16 billion of this annual benefit relates to wider effects that we might classify as private external value. Page 11, *Connected and autonomous vehicles – the UK economic opportunity*, KPMG, 2015, https://assets.kpmg.com/content/dam/kpmg/images/2015/05/connected-and-autonomous-vehicles.pdf

[283] In England, Wales and Scotland 9.3%, 19.9% and 7.2% of the land area are covered by national parks respectively. See http://www.nationalparks.gov.uk/students/whatisanationalpark/factsandfigures

[284] See RAND report (2014) page 28.

be different from the average multipliers estimated in the studies. However, we have not identified a sound basis to apply any adjustments to these estimated multipliers.

A11.52 There are also potential technical issues in some of these macroeconomic studies, e.g. establishing the direction of cause and effect, suggesting that the results need to be interpreted with caution. Additionally, some of these studies have been commissioned by operators and, thus, may be positioned towards demonstrating the benefits of 4G, e.g. some assumptions might be on the optimistic side.

A11.53 For illustrative purposes, we have broadly adapted (when possible) the study findings (see the left column of Figure A11.4) as if they applied equally to the proposed coverage obligations (see the middle column of Figure A11.4 below) and so show the potential magnitude of the macroeconomic value from extending 4G coverage if this approach was valid. The illustrative resulting estimates (when available) are set out in the right column of Figure A11.4 below. For the reasons noted above, we do not treat these as reliable estimates of the macroeconomic value of extending 4G coverage, so Figure A11.4 is illustrative only.

Figure A11.4: Literature review on the macroeconomic impact from telecommunications

Study finding	If applied to our 4G coverage improvement	Resulting illustrative estimate for 4G coverage improvement
Investment multiplier approach[285]		
ONS output multiplier for 'telecommunication services' was 1.41 while its output multiplier for construction was 1.859 in 2014.[286]	If improving 4G coverage led to an increase in investment of £300m,[287] then, if we apply an unadjusted multiplier, that would equate to an increase in GDP of between £423m and £558m, i.e. between £123m and £258m of additional benefit above the actual investment.	Increase in GDP between £423m and £558m with an unadjusted multiplier.
Bottom-up approach[288]		
A study by Rural England CIC, SRUC and Amazon (2018) based on a survey of firms based in rural areas estimated that there is a digital potential across rural areas of the UK in the range £12-26 billion of Gross Value Added (GVA)[289] per year.[290]	This is a study on digital connectivity, rather than 4G. It is difficult to disentangle what is specific to 4G, hence difficult to apply to our proposed coverage improvement.	We have not generated an estimate as it is difficult to derive a meaningful number focused on the benefits specific to 4G coverage.

[285] The investment multiplier approach refers to the concept that any increase in investment spending has a more than proportionate positive impact on the general economy. The multiplier attempts to quantify the additional effects beyond those immediately measurable by the investment. Another example that falls within this type of approach is: Deloitte (2011), *The impact of 4G technology on commercial interactions, economic growth, and U.S. competitiveness*, available at https://www2.deloitte.com/content/dam/Deloitte/us/Documents/technology-media-telecommunications/us-tmt-impactof-4g-060612.pdf (accessed on 6 December 2018).
[286] https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/ukinputoutputanalyticaltablesdetailed (accessed on 6 December 2018).
[287] As set out at Figure 4.3 in section 4, £300m is the midpoint for our estimate of the costs of meeting a 90% geographic coverage obligation.
[288] Another example that falls within this type of approach is from O2 (2018) available at https://news.o2.co.uk/press-release/o2-backs-rural-britain/ (accessed on 6 December 2018).
[289] GVA is the value of goods and services produced, minus the value of materials and inputs used in their production.
[290] https://ruralengland.org/wp-content/uploads/2018/03/Unlocking-digital-potential-website-version-final.pdf, p. 8 (accessed on 6 December 2018).

Study finding	If applied to our 4G coverage improvement	Resulting illustrative estimate for 4G coverage improvement
Top-down approach[291]		
Edquist et al. (2017) suggested that a 10% increase in mobile broadband adoption (including both 3G and 4G) leads to an increase in GDP of between 0.6% and 2.8%.[292]	We do not have an estimate of the percentage increase in mobile broadband adoption due to improved 4G coverage.	Increase in GDP of between £1.2bn and £5.6bn per 1% increase in mobile broadband adoption.

A11.54 Figure A11.4 above suggests that wider provision of good quality 4G services could lead to an increase in GDP. Some of the literature implies that improved 4G coverage could have a very significant impact on GDP, but it is difficult to infer how large this effect might be for extending 4G coverage from current levels in the UK.

A11.55 We do not regard the macroeconomic effects as additional to the other categories of social benefits. In particular, we would expect that the greater coverage of good 4G services would lead to an increase in GDP as a result of the private use value (e.g. via the consumption of additional telecommunications services), private external value (e.g. businesses benefiting from mobile consumers being better informed about their services, being able to locate them more easily) and broader social value (e.g. via the consumption of services with social goals as described in the section further below).

A11.56 We acknowledge that an argument could be made that the coverage obligations may have some impact on the deployment of services in more commercially attractive areas (e.g., deployment of 5G). For example, an MNO might find it more difficult to finance the expenditure required for 5G if it is spending on additional coverage, and additionally an MNO may face operational practicalities in rolling out new coverage and 5G at a similar time. However, we expect operators would have an incentive to undertake profitable investment and be able to invest in commercial areas alongside coverage obligations areas, particularly as we are proposing to offer a discount on their spectrum package to support additional coverage costs.

[291] Other examples that fall within this type of approach are: Williams et al. (2012) *What is the impact of mobile telephony on economic growth*? https://www.gsma.com/publicpolicy/wp-content/uploads/2012/11/gsma-deloitte-impact-mobile-telephony-economic-growth.pdf (accessed on 6 December 2018); and Capital Economics (2014) available at http://newsroom.ee.co.uk/download/230212/capitaleconomicsreport-improvingconnectivitynov2014.pdf (accessed on 6 December 2018).

[292] Edquist et al. (2017) *How important are mobile broadband networks for the global economic development?*, available at https://spiral.imperial.ac.uk/bitstream/10044/1/46208/2/Goodridge%202017-05.pdf (accessed on 6 December 2018).

Broader social value

A11.57 Broader social value captures the benefit to citizens and society due to social goods that are enjoyed by most or all people in society, typically irrespective of income. Social goods that give rise to broader social value potentially include democratic freedoms, equality, tolerance of minorities, and other aspects of social capital and physical security.

A11.58 We anticipate that improving 4G coverage would create considerable broader social value in various ways. Below we discuss this under the following headings, while recognising there may be some overlap between them:

- Providing health and safety assurances;
- Increasing social capital;
- Reducing the Digital Divide – promoting the sustainability of rural communities; and
- Supporting the improved provision of services that benefit society.

Providing health and safety assurances

A11.59 Mobile coverage provides a crucial safety net that enables people to deal with emergency situations.[293] This could include situations such as a car breakdown[294] or a medical emergency while in the countryside.[295]

A11.60 A large part of this safety net comes from the ability to contact and be contacted. These functions require a basic level of voice connectivity, and so new coverage would have the greatest additional benefits where it is provided in areas which currently have patchy or no voice coverage.

A11.61 However, dealing with these situations may also require more than basic voice connectivity, including identifying geographic location and navigation, and being able to draw upon health information and treatment advice (for example, being able to find first aid information online, in both written and audio-visual format). Furthermore, as noted above, consumers increasingly expect that they can contact, or be contacted by, others in a number of ways.

Increasing social capital

A11.62 The Office of National Statistics (ONS) has described social capital as follows:

> *"In general terms, social capital represents social connections and all the benefits they generate. Social capital is also associated with civic participation, civic-minded*

[293] Jigsaw 2017, Mobile Coverage: Qualitative research, p 2.
https://www.ofcom.org.uk/__data/assets/pdf_file/0021/108129/jigsaw-mobile-coverage-qualitative-research.pdf
[294] Noted in our Jigsaw 2017, Mobile Coverage: Qualitative research, p.14
[295] Longsleddale Parish in its response to our March 2018 consultation noted that individuals are regularly stranded on the surrounding fells without contact being possible. (p.3)
https://www.ofcom.org.uk/__data/assets/pdf_file/0010/115012/Longsleddale-Parish.pdf

attitudes and values which are important for people to cooperate, such as tolerance or trust."[296]

A11.63 We anticipate that improved 4G coverage would aid the development of local social capital and could reduce social isolation experienced in rural communities, for example by:

- Increasing the ability to foster and maintain personal relationships, such as arranging to meet up and keeping in touch. This is particularly relevant as data-based forms of communication, such as instant messaging and social media, are now the primary way in which many consumers use their mobile phone.[297]
- Helping the community to share ideas, discuss issues or problems.[298]
- Aiding the formation of, organisation of and participation in local clubs and societies.
- Aiding the development of smart transport systems, such as on demand shuttle services.[299]
- Supporting charities such as Age UK and RNIB which are increasingly using internet technology to communicate with and link together elderly people in networks.[300]

Reducing the Digital Divide – promoting the sustainability of rural communities

A11.64 Take-up of faster mobile data services is extending people's choice over how, where and when they communicate with others, watch or listen to content services, seek information, shop and participate in the digital world. However, there is a persistent digital divide between those who have access to the latest technologies, and those who do not. As the world goes increasingly online, those left behind risk social and economic exclusion – and digital exclusion often disproportionately affects vulnerable citizens and consumers.[301]

A11.65 The Government's Digital Strategy for 2017 stated that "broadband and mobile must be treated as the fourth utility, with everyone benefiting from improved connectivity. This will play a crucial role in ensuring that everyone, wherever they live and however they connect,

---

[296] Measuring national well-being: An analysis of social capital in the UK, ONS, January 2015, https://www.ons.gov.uk/peoplepopulationandcommunity/wellbeing/articles/measuringnationalwellbeing/2015-01-29
[297] For example, the 2017 Jigsaw qualitative research (p.18) found that poor quality mobile coverage "made it particularly difficult for consumers to enjoy the benefits of 'live' communication and prevented them from being able to take part in things 'in the moment' when they happen. In the shorter-term this created ongoing feelings of missing out on social plans and conversations. For some consumers, this had a strong impact on one's immediate and wider social networks in the longer-term." The importance of mobile for maintaining relationships is also illustrated by 67% of participants in Tinder Foundation's Mobile Devices project reporting better quality and more regular communication with friends and family, helping people to overcome loneliness and isolation. See Tinder Foundation, March 2015, Mobile: Helping to close the Digital Divide, p.7, https://www.tinderfoundation.org/sites/default/files/research-publications/mobile-helping-to-close-the-digital-divide_final.pdf.
[298] Skerratt, S. (2018) Recharging Rural, Report to The Prince's Countryside Fund, London: The Prince's Countryside Fund, p.55, http://www.princescountrysidefund.org.uk/research/recharging-rural
[299] Skerratt, S. (2018) Recharging Rural, Report to The Prince's Countryside Fund, London: The Prince's Countryside Fund, p.55
[300] Local Government Association and Public Health England (2017), Health and Wellbeing in Rural Areas, p.22, https://www.local.gov.uk/sites/default/files/documents/1.39_Health%20in%20rural%20areas_WEB.pdf
[301] Ofcom Digital Communications Review, p.2.

can make full use of digital services and benefit from participation in the digital economy”.[302]

A11.66 There is some evidence that mobile specifically has a role to play in addressing digital exclusion, as vulnerable consumers may find mobile to be lower cost and more flexible than alternative forms of internet access.[303] Therefore, reducing inequality in mobile coverage has a role in reducing social and economic exclusion, and developing the local economies in poorer areas of the UK.

A11.67 The Recharging Rural report found that mobile coverage was a fundamental necessity for businesses and communities.[304] Rural residents cite poor broadband and mobile phone coverage as the top barrier facing their communities, and one of the top three changes required to help rural communities increase their own sustainability,[305] ensuring that they remain attractive places for residents to live,[306] tourists to visit[307] and businesses to base themselves in.

A11.68 Furthermore, there is evidence that UK citizens value the ability for everyone in society to have access to similar core services and experiences, and that individuals should not be disadvantaged due to their geographic location.[308]

Supporting the improved provision of services that benefit society

A11.69 Improved mobile coverage would also support the improved provision of services that benefit society, allowing citizens living in rural areas to take advantage of technology-driven solutions. For example, a 2016 National Infrastructure Commission report said that: “*Over the next decade, widespread and high quality mobile coverage could enable transformational change to sectors such as connected health, education, transport and the*

---

[302] DCMS, 2017. *UK Digital Strategy*. https://www.gov.uk/government/publications/uk-digital-strategy/uk-digital-strategy .
[303] Mobile is more flexible as it can provide connectivity without requiring contracts (through pay-as-you-go) and may be more suited to those in shared accommodation or who regularly move between different accommodation. In addition, research has found that many users find smartphones more intuitive, easier to use and simpler to understand than PCs and laptops. See Tinder Foundation, *Mobile: Helping to close the digital divide? A qualitative evaluation of the Vodafone mobile devices project,* March 2015*.* The Communications Consumer Panel and ACOD noted in its consultation response that this flexibility was especially beneficial to microbusinesses and vulnerable consumers (p.2).
[304] Skerratt, S. (2018), Recharging Rural, Report to The Prince’s Countryside Fund, London: The Prince’s Countryside Fund, for example, pages 17, 54 and 64.
[305] The other two changes were a reduction in the closure of key services such as banks, post offices and pubs; and fairer funding for rural areas that compensates for the higher costs of improvements. Skerratt, S. (2018) Recharging Rural, Report to The Prince’s Countryside Fund, London: The Prince’s Countryside Fund, p.26 and 59.
[306] Our research noted participants’ concerns that poor mobile coverage could risk the gradual depopulation of these areas, particularly younger generations, hampering the long-term social and economic potential of the area. See Jigsaw, *Mobile coverage: Qualitative research,* 2017, page 10.
[307] Our research noted that some participants, particularly SME consumers, feared that poor coverage may be enough to put tourists off from visiting at all (if they are aware in advance of a lack of coverage) or from visiting again (having experienced the lack of coverage). See Jigsaw, *Mobile coverage: Qualitative research,* 2017, page 10. This may be heightened by the fact that tourists may have experiences of good coverage in the places that they live, and so may have higher expectations of the quality of mobile coverage.
[308] The Ofcom Digital Dividend Review identified the importance of the principles of universal coverage and universal access. See para 2.17, p.8, https://www.ofcom.org.uk/__data/assets/pdf_file/0021/19416/researchrpt.pdf

internet of things. It could also put the UK in a leading position to enable our digitised industries and the digital services sector to flourish."[309]

A11.70 While there might be some private use value for these, there is also likely to be significant broader social value from the improved provision of these services for more of society, and also cost and resource savings to the public sector. The importance of this is likely to grow significantly over the long period of time we are considering.

A11.71 The National Infrastructure Commission particularly noted the importance of mobile coverage in enabling healthcare technologies: "*UK wide coverage is already becoming increasingly necessary in order to avoid regional inequalities in the use of current and future healthcare technologies relying on mobile connectivity, at least in part. Over the next decade or so, as new technologies emerge, the ability to achieve fast and reliable connectivity when on the move could become very significant for a range of 'smart' health devices.*"[310]

A11.72 Various studies have identified the benefits of health-related mobile applications.[311] While it may be possible to access these applications at home using fixed Wi-Fi, mobile coverage ensures that these can be used at all times as people go about their daily lives:

- Mobile applications can provide monitoring or treatment of long-term conditions, such as diabetes, asthma or other respiratory conditions.[312] Mobile applications can also be used to deliver support for mental health conditions and counselling.[313] Continuous connectivity is likely to be particularly important to ensure that these function at all times as people go about their daily lives.
- Smartphone records may save medical professionals time when performing home visits, compared to using paper equivalents, potentially allowing two extra visits per day.[314] Mobile connectivity will avoid the need to gain access to the patient's fixed Wi-Fi to use these.

---

[309] National Infrastructure Commission, (2016) *Connected Future*, p.69. https://www.nic.org.uk/wp-content/uploads/Connected-Future-Report.pdf
[310] National Infrastructure Commission, (2016) *Connected Future*, p.44.
[311] For example see BCG (2012), *The socio-economic impact of mobile health,* https://www.telenor.com/wp-content/uploads/2012/05/BCG-Telenor-Mobile-Health-Report-May-20121.pdf
[312] Other examples include apps that can be used to guide patients through daily exercise routines in orthopaedics and stimulate nerves to control chronic pain. See NHS England (2014), National Pathology Programme Digital First, p.42-43, https://www.england.nhs.uk/wp-content/uploads/2014/02/pathol-dig-first.pdf, and Deloitte (2017), *The future awakens: Life sciences and health care predictions 2022,* https://www2.deloitte.com/content/dam/Deloitte/tr/Documents/life-sciences-health-care/deloitte-life-sciences-health-care-predictions-2022.PDF, p.10 and 26.
[313] For example, Cumbria Rural Health Forum has piloted web- and app- based counselling. Local Government Association and Public Health England (2017), Health and Wellbeing in Rural Areas, p.22, https://www.local.gov.uk/sites/default/files/documents/1.39_Health%20in%20rural%20areas_WEB.pdf
[314] Deloitte (2015), Connected Health: How digital technology is transforming health and social care, page 3, https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/life-sciences-health-care/deloitte-uk-connected-health.pdf.

- Mobile connectivity will help to support the launch of an NHS smartphone application in England from December 2018.[315]
- Rural communities have identified mobile applications as a tool for booking emergency travel to a local GP and accessing emergency home visit carers and district nurses.[316]
- Greater mobile connectivity may also lead to public sector cost savings, to the extent that the increased use of mhealth in rural areas directly substitutes for GP and hospital visits.[317] More generally, mobile connectivity will allow citizens to access government services and complete application forms (such as for benefits or licences) on-the-go, which will result in public sector cost savings as a result of a reduction in face-to-face or phone contacts.[318]

What improvements in coverage would result from our proposed obligations?

A11.73 The coverage obligations we are proposing would require the operator who wins them to:

- deliver good quality 4G mobile coverage outdoors to at least 90% of the UK landmass;
- deploy a minimum of 500 new wide-area coverage sites (the 'new sites requirement'); and
- provide new coverage in areas where at least 140,000 premises are located[319] (the 'premises requirement').

A11.74 In line with our current approach to measuring coverage, we consider that it is necessary to meet the following performance targets in order to ensure a good quality consumer experience: (i) more than 95% of 90 second voice calls can be made without interruption; and (ii) a connection speed of at least 2Mbps is available to provide the throughput needed for more demanding data services such as video streaming. We currently expect that an

[315] The app will give patients safe and secure access to their GP record, and can be used to make GP appointments, order repeat prescriptions and access 111 for urgent medical queries. See https://www.gov.uk/government/news/new-nhs-app-will-make-it-quicker-and-easier-to-access-health-services , and https://digital.nhs.uk/services/nhs-app. (accessed 7 December 2018).

[316] See Skerratt, S. (2018) Recharging Rural, Report to The Prince's Countryside Fund, London: The Prince's Countryside Fund, p.55.

[317] Examples of quantified cost savings of specific applications of mobile health apps can be found in Deloitte (2015), Connected Health: How digital technology is transforming health and social care, case example 4, p.20, https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/life-sciences-health-care/deloitte-uk-connected-health.pdf. The average cost of a GP consultation is £45. See CEBR (2015), The economic impact of Basic Digital Skills and inclusion in the UK, page 6, https://doteveryone-prod.s3-eu-west-1.amazonaws.com/uploads/The%20economic%20impact%20of%20digital%20skills%20and%20inclusion%20in%20the%20UK_Final_23_11_15.pdf.

[318] 66% of UK adult smartphone users have completed a form or application on a smartphone; 15% weekly. Ofcom Adults Media Use and Attitudes Report 2018, Figure 7, p.29 https://www.ofcom.org.uk/__data/assets/pdf_file/0011/113222/Adults-Media-Use-and-Attitudes-Report-2018.pdf

[319] We consider that this premises requirement will help to ensure that the social benefits we envisage from the obligations are delivered, and are broadly similar, irrespective of which operators deliver the coverage obligations. We set out in annex 14 the modelling work we have undertaken to demonstrate that the premises requirement is achievable.

average 4G signal strength of -105 dBm would be needed to meet our proposed coverage obligations through 4G technology. [320]

A11.75 The aim of these obligations is to provide, as a minimum, good quality 4G outdoor coverage over the majority of all populated and regularly visited areas of the UK, with some wider benefits delivered as a result. In particular, we expect there will be some improvements in in-building and in-vehicle coverage in rural areas, in line with the benefits we would typically expect from the deployment of new infrastructure. We expect the mobile experience to improve for residents in the areas, and for people who visit or travel through them. We consider that this would provide a significantly more comprehensive and seamless mobile experience as people travel around in their daily lives.

Most additional coverage is likely to be in partial not-spots in rural areas

A11.76 Many of the additional areas to be covered as a result of the proposed obligations are likely to already receive good outdoor 4G coverage from at least one operator ('partial not-spots'). For those living in these areas, we must therefore account for the possibility that in some cases, consumers will already be experiencing a good service. However, in many of these areas, consumers are unlikely to have a seamless experience of good quality coverage because there is a 'patchwork quilt' of partial coverage from different operators, as discussed above (paragraph A11.14). We consider there is likely to be significant consumer benefit from an intervention that would bring a more comprehensive and consistent level of coverage from one operator across a wider area.

A11.77 We note that customers of the obligation holder who do not live in the areas directly affected by the obligation are likely to also benefit from this addition of seamless coverage if they move through the area. When deciding where to roll-out coverage to meet the obligation, operators are likely to consider the footfall or traffic through a potential site, the costs of providing power and site access, and whether the potential site makes a reasonable contribution to increasing geographic coverage. Therefore:

- We consider it likely that much (though not necessarily all) of the roll-out may take place in partial not-spots. This is because these areas are likely to have higher footfall than total not-spots and better access to infrastructure (and another operator may consider that it is profitable to roll-out in that area).[321] We estimate that any one operator could achieve 91% geographic coverage by just rolling out in existing partial not-spots.

[320] A lower signal strength would lead to a lowered call success rate. For data services, lower signal strength would lead to either a lowered minimum download speed for the same confidence level or a lowered the confidence level for the same minimum download speed.
[321] Albeit that the decision of the original operator to roll-out in the area may in part have been based on having limited competition in those areas.

- We also therefore expect that operators may be attracted to site locations serving larger sections of the unserved road network, and so this provision of additional good quality outdoor coverage would have some impact on improving the road coverage of the operator with the coverage obligation. Although the coverage obligations that we are proposing would be primarily focussed on good outdoor coverage, we anticipate that in these circumstances a substantial part of the footprint of any new site would provide in-vehicle coverage.[322]

A11.78 We expect the additional coverage as a result of the proposed obligation to be primarily in rural areas. As Scotland, Wales and Northern Ireland tend to be more rural (see Figure A11.2) we might expect them to see a significant benefit from our proposed coverage obligations (although we expect that our 'premises requirement' will also see coverage improvements in rural England too).

Nature of improved coverage

A11.79 To meet the proposed obligations, operators will need to deploy new base stations. In these areas, we expect that much of the additional coverage will include good indoor coverage and good in-vehicle coverage on most of the roads. The obligated operator would be required to provide good outdoor coverage for 140,000 premises which they currently do not cover. We expect around half these premises could receive a signal that provides good indoor coverage.

A11.80 We also expect that where new base stations are deployed there will be some overspill benefit, improving the coverage levels in neighbouring areas that may already have outdoor coverage, to a level that supports improved indoor coverage.[323] We consider that around 100,000 to 300,000 premises could benefit in this way (see paragraph A11.92 below).

A11.81 The benefits of good indoor coverage tend to be reduced by most homes, businesses and other premises already having Wi-Fi for data and potentially for voice.[324] But we consider there is still a material value from having indoor mobile coverage:

- Not all consumers use Voice over Wi-Fi (although this may become more integrated and widespread in the future) meaning that people will receive voice calls to their mobile devices when inside when they may not otherwise;

[322] However, we also recognise that around 5-10% of in-vehicle not-spots on the major road network consist of very short stretches where coverage dips below -95 dBm but remains above -105 dBm. In these circumstances, a more localised small cell solution would be needed and is unlikely to be delivered through the proposed obligations.
[323] While we anticipate that there would be some ancillary improvements in indoor coverage in parts of the covered area footprint, this is not the focus of the obligation.
[324] 92% of those with access to the internet at home have a fixed broadband connection. Ofcom Technology Tracker H1 2018: QE12: *Which of these methods does your household use to connect to the internet at home*?, Table 62 https://www.ofcom.org.uk/__data/assets/pdf_file/0021/113169/Technology-Tracker-H1-2018-data-tables.pdf

- A minority of residential and business consumers do not have (or, given the choice, would not wish to have) a fixed connection and so may benefit significantly from having good indoor mobile coverage.[325] This may have a particular benefit in terms of the social inclusion, as these consumers may be more likely to be on low incomes.[326]
- Some people choose to or need to access the internet over their mobile network even when consumers have a fixed line.[327]
- Mobile can also be useful as a backup if there is a problem with fixed access.[328]

A11.82 In relation to in-vehicle coverage we expect this to be beneficial for drivers because it can enable more consistent use of navigation tools and it would allow passengers to use a range of mobile services and applications.

A11.83 We provide an illustration below of the kinds of locations where new outdoor coverage could be brought to fulfil the obligation, and the nearby areas with poor in-home and in-vehicle coverage that could also benefit.

[325] A small proportion of households (7%) with internet access only access the internet at home through a mobile connection, and 5% of households with internet access are smartphone-only internet households. Ofcom Technology Tracker, H1 2018: QE12: *Which of these methods does your household use to connect to the internet at home*?, Table 62 https://www.ofcom.org.uk/__data/assets/pdf_file/0021/113169/Technology-Tracker-H1-2018-data-tables.pdf
Our Jigsaw qualitative research, p. 3, found that a minority of consumers would have preferred to rely totally on their mobile phone and dispense with their fixed line broadband contract. These people had a feeling of umbrage that poor mobile coverage forced them to retain fixed broadband.

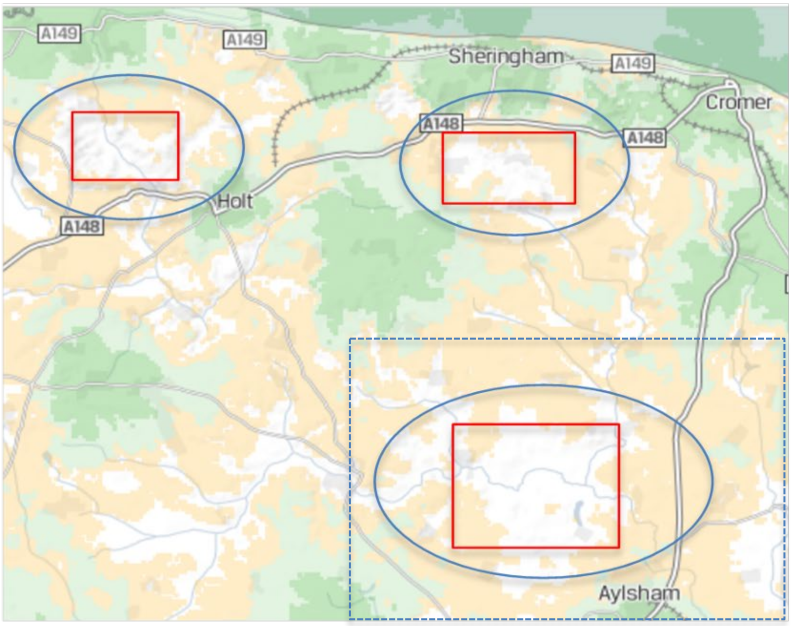
[326] Research has found that almost all of those who are 'smartphone by circumstance' (those who were using their smartphones because their situations (often financial) meant they were unable to access other devices) were 'smartphone by default' (conducting the vast majority of their online activities through their smartphone) because they couldn't afford, or couldn't access, other devices. Few had broadband at home. Ofcom, 2016, '*Smartphone by default' internet users: A qualitative research report"*, p.11-12 available at https://www.ofcom.org.uk/__data/assets/pdf_file/0028/62929/smarphone_by_default_2016.pdf

[327] 38% of those with internet access at home have accessed the internet using a mobile phone or smartphone via their phone's 3G or 4G network while at home. Ofcom Technology Tracker H1 2018: QE12: *Which of these methods does your household use to connect to the internet at home*?, Table 62

[328] Study by Rural England CIC, SRUC and Amazon (2018), p. 46, available at https://ruralengland.org/wp-content/uploads/2018/03/Unlocking-digital-potential-website-version-final.pdf

Figure A11.5: Illustration of potential intervention areas and benefits

Key	
Indoor 4G coverage very likely	
Indoor 4G coverage likely	
Good 4G outdoor coverage	
Poor 4G coverage/No coverage	
Possible Intervention area	
Illustration of spillover benefit	



Source: Ofcom

Beneficiaries from an intervention in the selected area could include a number of quite small communities with poor coverage, a larger community that may have some outdoor service but not indoors, an A road and a significant tourist attraction.

Some of these areas would receive coverage from the obligation holder for the first time, whilst some would receive improvements that would mean better coverage as people move around.

Source: Ofcom and Google Earth

Consumer experience of improved coverage

A11.84 Over the long timescales we are considering (to 2039), we expect that many people would directly benefit to some extent from improved coverage. Some may benefit a great deal (for example, those who reside in, work or regularly visit any area with poor coverage), whereas others may benefit only to a very small extent (for example if they only occasionally find themselves in an area of existing poor coverage). We have grouped the potential direct beneficiaries into three broad categories which we discuss below: ‘rural residents’, ‘other rural consumers and business customers’ and ‘urban consumers and business customers’. This categorisation is principally based on how long each group would be expected to spend in areas that experience improved coverage. It is intended to capture both residential and business customers, especially the 760,000 businesses in rural areas.[329]

A11.85 Our initial assumption is that the beneficiaries are the customers of the obligated operators (either existing customers or those who switch to an obligated operator). We recognise this could significantly understate the number of beneficiaries for several reasons. These include:

- There is a substantial degree of network sharing between operators in two well-established arrangements (between EE/H3G and O2/Vodafone). We expect an obligated operator to build new masts to improve its coverage to meet the obligation. Depending on the identity of the obligated operators, there could be some sharing of new masts across operators that would expand the pool of beneficiaries. For example, if one operator in a network sharing pair wins an obligation in the auction and the other does not, the network sharing partners could reach an agreement making it commercially attractive for the non-obligated operator to share some of the new masts (with the obligated operator benefiting from some sharing of its costs). If so, the pool of beneficiaries would extend to some customers of the non-obligated operator within that network sharing arrangement.
- Mobile consumers who purchase services from other operators may still benefit from private external value and broader social value, as we discuss previously.

A11.86 Below, we summarise the broad categories of people we expect to benefit directly from improved coverage.

Rural residents

A11.87 Our first category captures those residential and business customers whose premises would have a significant increase in signal quality. For simplicity, we refer to these customers as ‘rural residents’ as we have assumed that these premises will be predominantly in rural areas.

A11.88 Some of those living in the areas where coverage would be improved may already be enjoying good coverage from another operator. For the customers of the obligated operator that would experience an improvement in coverage, the nature of such improvement will depend on the level of coverage that is currently provided, and the efficacy of any workaround they may have in place. In general, we would expect these customers to start from a situation where any coverage is patchy, perhaps limited to voice calls, with some areas where voice is not available at all or call quality is poor, and with only a basic and intermittent data experience. Whilst the impacts of building penetration losses will vary, these customers are unlikely to have good indoor coverage.

---

[329] This figure relates to 2016 and uses the ONS’s measure of businesses that includes the ‘local units’ of multi-sited businesses. See section 2.1 https://ruralengland.org/wp-content/uploads/2018/03/Unlocking-digital-potential-website-version-final.pdf (accessed on 6 December 2018).

A11.89 We have identified ways that premises are likely to benefit:

- premises that currently have poor 4G coverage from the obligated operator, but will gain good quality 4G *outdoor* coverage (and a proportion will also gain good 4G indoor coverage); and
- premises that currently have good 4G outdoor coverage from the obligated operator, but will gain good quality 4G *indoor* coverage.

A11.90 The coverage obligation would result in (at least) 140,000 premises in the first category gaining good outdoor coverage from the obligated operator. We expect the improvement in coverage to enable this group of consumers to enjoy consistent, good quality voice calls and access to a reliable data connection capable of supporting services from email, WhatsApp and smooth internet browsing (while outside). It should also enable reliable access to online maps and video services. The customers of the obligated operator would also benefit from improved indoor and in-vehicle coverage in many premises and roads in the local area, due to overspill effects. We estimate for around half of the premises the signal strength could be sufficient to attain good indoor coverage.

A11.91 For the second category, we expect many other premises and locations to gain good indoor coverage from the additional masts. For individual operators, there are currently somewhere between one and three million premises which we estimate receive poor indoor coverage. Whilst some of these are in dense urban areas unlikely to benefit from the obligation, we consider that many locations in rural settings will benefit as a result of the coverage obligation.

A11.92 We consider that a reduction of around 10% of the premises where the operator currently provides poor indoor coverage could be a reasonable estimate. This is informed by our analysis of the significant number of rural premises (where our intervention is focused) that do not have coverage (as set out in section 4). It has also been informed by our analysis of the outputs of network dimensioning work described in annex 14. In light of this we estimate that a further 100,000 to 300,000 premises that already have good outdoor 4G coverage could gain good indoor 4G coverage.

A11.93 We recognise that for those premises that already have good outdoor 4G coverage but gain good *indoor* 4G coverage the gain in social benefits will not be as large as if the premises had gone from no coverage at all to indoor coverage.

Other rural consumers and business customers

A11.94 This category of beneficiaries includes consumers who regularly visit areas where coverage would be improved as a result of the obligation, but do not live there. We expect this group of consumers to receive a large benefit from the increased coverage.

A11.95 We consider that these are likely to be mainly consumers who live in neighbouring communities. They may be regular visitors to the areas of improved coverage because they work there, or travel through these areas on route to work. Sometimes their work may require them to go there, but only occasionally (e.g. local plumbers or builders).

A11.96 Other people may visit these areas as part of their daily routines to see friends or family, or to perform daily tasks from shopping to visiting a local post office, schools or other community centres. People may also visit these areas for more leisure-oriented activities, such as walking. The National Travel Survey statistics published by the Department for Transport suggest that people living in rural areas of England made on average around 2.8 daily trips in 2016/17.[330] The distances travelled also tend to be larger in rural areas.[331] This suggests the pool of beneficiaries within this category could be quite large.

A11.97 This group also could include people from larger urban areas who travel through or work in these poor coverage areas on a more regular basis.

A11.98 The increase in coverage from the obligation will mean that more roads are covered. This coverage improvement is particularly important.[332,333] Using mobile devices inside vehicles often requires good indoor signal strength to have a good service, so the obligation may not deliver a good service inside vehicles on all the roads covered, but a significant proportion of the roads are likely to be close enough to the new masts to gain coverage inside vehicles.

A11.99 There will also be considerable benefits to businesses from improved mobile coverage. As discussed from paragraph A11.29, businesses are currently affected by poor mobile signal strength, including because it impacts the ability to work flexibly and on-the-move.

A11.100 As the importance of mobile services continues to grow in the future, we expect use outside the home to also become more important.

Urban consumers and business customers

A11.101 This category of beneficiaries reflects a wider group of consumers who would receive an occasional benefit from the increased coverage. We refer to this group as 'urban' consumers for simplicity even if not all such consumers will necessarily live in urban areas.

A11.102 This group includes those who visit the rural areas with improved coverage for business or leisure, including short visits such as walking, shopping or socialising, or for more extended visits such as holidays. When these urban consumers visit these areas, they would benefit from an improved service. Currently they may have some chance of a voice call (possibly with areas of patchy or intermittent experience) and very little access to data coverage. If

[330] Average number of trips for the classifications i) *rural town and fringe* and ii) *rural village, hamlet and isolated dwelling* were 1,057 and 1,028 respectively in 2016/17 across all modes of transport (including walking). See the statistical dataset on "How people travel (mode of transport). Data about mode by region: Average number of trips", published by Department for Transport on 30 July 2013 and last updated on 26 July 2018; https://www.gov.uk/government/statistical-data-sets/nts03-modal-comparisons#history .

[331] See the statistical dataset on "How people travel (mode of transport). Mode by region: Average distance travelled", published by Department for Transport on 30 July 2013 and last updated on 26 July 2018; https://www.gov.uk/government/statistical-data-sets/nts03-modal-comparisons#history

[332] *Digital Connectivity in Scotland*, July 2018, Scottish Affairs Select Committee, https://publications.parliament.uk/pa/cm201719/cmselect/cmscotaf/654/65408.htm#_idTextAnchor053

[333] The 2017 Jigsaw qualitative research consumer research also highlighted the importance consumers place on coverage on roads https://www.ofcom.org.uk/__data/assets/pdf_file/0021/108129/jigsaw-mobile-coverage-qualitative-research.pdf

coverage improves as a result of the obligations they would be able to access a full range of data services, and more reliable and widespread voice coverage.

Nature of improvement for roads

A11.103 Our research has indicated that coverage on roads is particularly important.[334] In order to better understand the additional benefits delivered by our proposed coverage obligations, we have carried out an exercise to map the total additional kilometres of coverage of A-road and B-roads which a typical operator starting at 82%[335] would achieve if it rolled out to 90% geographic coverage.[336] We have used an 82% coverage starting point as our counterfactual for three of the MNOs, as discussed in section 4.

A11.104 In order to calculate an approximate 90% coverage footprint, we assumed that a typical operator will first roll-out into partial not-spot areas that have the highest signal strength from another operator.[337] We then counted the number of pixels per road type in each nation, and calculated the average number of pixels per km of road for each road type in each nation.[338] The total length of roads contained within the 82-90% coverage area was then calculated, assuming the km per pixel ratio was also valid within this area.

Figure A11.6: Approximate total kilometres of roads gaining good quality outdoor coverage as a result of coverage increasing 82% to 90% (Incremental coverage as a percent of total road category in brackets)

	UK-wide	England	Scotland	Northern Ireland	Wales
A roads*	1684 km (3%)	430 km (1%)	910 km (9%)	20 km (1%)	324 km (8%)
B roads	2219 km (7%)	761 km (4%)	915 km (13%)	123 km (4%)	420 km (14%)

**excluding A roads considered motorway*

Source: Ofcom analysis using DfT Road length Statistics (RDL02)

[334] See footnotes 333 and 331.
[335] As a proxy for the geographic coverage of a 'typical operator' at 82% [✂ REDACTED]. We used our formal powers to request information from each operator on the levels of coverage they expect to provide by June 2019. These figures are set out in Figure 14.1 (redacted).
[336] Motorways generally already have good outdoor coverage, so we have not included them in this exercise
[337] We recognise that in the real world different operators will have different deployment strategies and might choose to target a complete not-spot area before covering all partial not-spots. We receive median signal level to the nearest dBm for a grid of 100m pixels from operators. The signal in the road itself could be worse than the pixel median due to earthworks.
[338] Using DfT data on length of road for that type in the region: https://www.gov.uk/government/statistical-data-sets/road-length-statistics-rdl. The pixels per km vary by up to 10% across the regions and nations. Signal quantisation results in an error up to 15% of the length of road benefiting from incremental coverage for A roads in Northern Ireland, and 1-7% for the other road types and other regions.

A11.105 This indicates that 3% of the UK's A-roads, and 7% of B-roads, could receive good outdoor quality from that operator as a result of the obligation (assuming that a typical operator rolls out to 90% coverage by prioritising partial not-spot areas).

A11.106 In addition to this outdoor coverage, there will likely be an overspill effect, resulting in more of the road network receiving good in-vehicle coverage.[339] Although we cannot estimate the exact overspill effect in terms of km for future deployments, based on existing deployments, we would expect that around 87% of the additional km of A-roads covered would also receive good in-vehicle coverage, and around 72% of all additional B roads (using typical operator data).

A11.107 In Northern Ireland, Scotland, and Wales, a higher proportion of non-motorway trunk roads (A- and B-roads which connect population centres) pass through rural areas than in England. Improving coverage on these kinds of roads is therefore likely to magnify the beneficial effects for people living and working in those population centres.

Summary – improvement to consumer experience resulting from proposed coverage obligations

A11.108 To summarise, the aim of our proposed coverage obligations is to achieve good quality outdoor 4G coverage from two operators over the majority of all populated and regularly visited areas of the UK. We consider that this would provide a significantly more comprehensive and seamless mobile experience as people travel around in their daily lives.

A11.109 The premises requirement will ensure that each obligated operator provides additional coverage in the areas where people live and work. In addition to providing good outdoor coverage to 140,000 premises, we consider that around half of these premises will achieve a signal strength sufficient for good indoor coverage. There could also be an overspill benefit for another 100,000 to 300,000 premises that currently have good outdoor coverage being able to receive good indoor coverage.

A11.110 We would expect that around 1,600 km of A-roads and 2,200 km of B-roads would receive good coverage from each obligated operator as a result of the obligations, with a large majority of these roads also receiving good in-vehicle coverage.

A11.111 We consider that this would lead to a better mobile experience for both residents in the areas of improved coverage, and for people who visit or travel through those areas.

A11.112 We expect the improved coverage to mainly be in areas that are currently partial not-spots, but this could depend on which operators win the obligations (see from paragraphs A11.119 below).

[339] At -95dBm signal strength.

The social benefit would be broadly similar whichever operators delivered greater coverage

A11.113 In the sub-section above, we describe how improving coverage would result in social benefits. In this sub-section we consider whether the social benefit would vary according to which operators delivered greater coverage as a result of a coverage obligation.

A11.114 As set out in chapter 4, the operators are likely to have different levels of geographic coverage prior to the auction. We estimate that (absent any coverage obligations) Vodafone, O2 and H3G's geographic coverage levels may be around 82% in long run, while BT/EE may have a higher level of coverage of around 84%.

A11.115 This comparison implies that, if BT/EE won one of the proposed obligations, it would deliver a smaller incremental increase in geographic coverage compared to other operators. This could suggest it would deliver a lower social benefit in comparison to the other operators, as the smaller incremental increase in coverage would benefit a smaller number of additional consumers in total.

A11.116 However, the proposed 'premises requirement' would also require the obligated operator to provide outdoor coverage to at least 140,000 premises where it does not currently provide a good outdoor 4G service.[340] We believe that this would have an equalising effect across operators, such that the level of social benefit delivered by any of the four mobile operators would be broadly similar in practice.

A11.117 The equalising effect of the premises requirement would be two-fold:

- It would ensure that the minimum incremental increase in outdoor premises coverage delivered is the same regardless of which operator delivers the obligation; and
- While BT/EE would deliver a smaller incremental increase in geographic coverage in getting to 90%, BT/EE is more likely than the other operators to cover at least some premises in total not-spots in order to meet the premises requirement, where the benefits of extending coverage are higher per direct beneficiary (although the total number of beneficiaries may be smaller)

A11.118 We explain the reasons for this below.

How would operators meet the premises requirements?

A11.119 The additional premises that the obligated operator would be required to extend coverage to could be in partial or total not-spots. In order to meet the premises requirement, we assume that operators would, where possible, roll-out in partial not-spots rather than total not-spots. This is because the presence of at least one operator in partial not-spots suggests that the economic case for providing coverage in these areas is stronger than in areas where there are no operators present.

[340] We note that the proposed 'new sites requirement' (which will require the obligated operator to deploy a minimum of 500 new wide-area coverage sites) may also have an equalising effect.

A11.120 Our modelling suggests that Vodafone, O2 and H3G could potentially meet the premises requirement by rolling out solely to premises in partial not-spots. BT/EE could also do this, but we consider it is more likely to provide coverage to both partial and total not-spots premises, due to its larger geographic coverage footprint (i.e. because it already provides a higher level of geographic coverage than the other operators, there are fewer partial not-spots where it does not already provide coverage available for it to deploy in).

A11.121 The coverage data we have collected from operators indicates that, at the time of the auction, around [✂ REDACTED] of UK landmass will be partial not-spots for Vodafone, H3G and O2, which corresponds to, on average, around 276,000 premises (when measured at the -105 dBm threshold). By comparison, BT/EE would have only [✂ REDACTED] of UK landmass available to deploy in as partial not-spots (approximately [✂ REDACTED] premises). Total not-spots account for around 9% of UK landmass, within which we expect there will be approximately [✂ REDACTED] premises by the time of the auction.

A11.122 The direct beneficiaries of coverage improvements in total not-spots would mostly be 'rural residents' as described above. While there is a relatively small number of 'rural resident' consumers who live in total not-spots, we expect these consumers to have a greater incremental value for the service, compared to those located in partial not-spots. This is because these consumers, who spend most of their time in total not-spots, cannot get a good 4G signal from any operator, while those in partial not-spots have the option of getting coverage from at least one operator already.

A11.123 Any operator with a coverage obligation would have to meet the same minimum premises requirements. But BT/EE is more likely to cover a number of premises in total not-spots in order to meet the proposed requirements (and, for the reasons set out above, we expect coverage of total not-spots to bring more social benefit per direct beneficiary than coverage of partial not-spots). Therefore, we expect the social benefits delivered by the coverage obligation to be broadly similar, regardless of which operator wins it.

A12. Our assessment of the appropriate level of geographic coverage obligations

Identifying an appropriate level for the proposed coverage obligations

A12.1 We identified in annex 11 the market failures and consumer harm arising from the current level of 4G coverage, and the benefits that we would expect from improved coverage. We now consider the appropriate level of the coverage requirements for our proposed obligations.

A12.2 There are three requirements in the obligation: geographic coverage level (as a percentage of landmass); premises requirement (additional premises not currently covered by the obligated operator); and new sites requirement (additional sites to be added by the obligated operator).

A12.3 Below we focus the discussion on two alternative levels of geographic coverage – 90% and 92%. We provisionally conclude that 90% is the appropriate level of geographic coverage for the coverage obligations. The levels that we propose for the premises and new sites requirements are informed by this proposed level of geographic coverage, as set out in chapter 4 and annex 14.

A12.4 To assess the potential benefits and costs associated with increasing coverage, we have assumed that in the counterfactual (i.e. absent the obligations over the next 20 years) H3G, O2 and Vodafone would have approximately 82% coverage, and BT/EE would have approximately 84% coverage. Our reasons for this are set out in more detail in section 4.

Analytical framework for assessing the appropriate level for coverage obligations

A12.5 To assess whether a particular level of coverage obligation is appropriate to award in the auction, we have considered both the total social benefits and the incremental social benefits of the increased coverage:

- **Total benefits** (from 82% to the proposed coverage level) – we have considered whether the total benefits of moving from 82% coverage to the proposed coverage level are at least as large as the underlying costs. This is to help us consider whether the expected social benefits of meeting a coverage obligation set at this level could be said to exceed the costs; and

- **Incremental benefits** (from 88% to 90%, and from 90% to 92%)[341] – we have also considered whether the incremental benefits of the final two percentage points of coverage are at least as large as the underlying incremental costs. This is to help us consider whether a coverage obligation at 90% would be likely to add net social benefits compared to a coverage obligation at 88%, and whether a coverage obligation at 92% would be likely to add net social benefits compared to a coverage obligation at 90%.

A12.6 We anticipate that the incremental social benefits from coverage will decline as coverage levels increase. This is because operators are already likely to have deployed in areas where it is clearly profitable (i.e. incremental revenues exceed incremental costs). The areas likely to generate the highest profits are those that the most people live in or visit and are therefore also likely to be the areas where coverage brings the most benefits. The remaining areas are likely to generate lower incremental revenues (i.e. because they have fewer inhabitants/visitors) and/or the incremental costs of increasing coverage are likely to be relatively high. Consistent with our analysis of costs, this also suggests that the incremental costs of providing additional coverage will increase as coverage levels increase.

A12.7 Given declining incremental benefits and increasing incremental costs, where incremental benefits exceed incremental costs, the total benefits will always be greater than the total costs. Therefore, the incremental cost-benefit test is the binding constraint.

Estimating the incremental benefits of improved coverage

A12.8 In annex 11 we set out our assessment that improving mobile coverage would deliver significant benefits. As we explain below, quantifying such benefits in £m is inherently difficult, and quantifying the benefits that would be delivered by any particular percentage point of increased coverage is particularly challenging.

A12.9 Therefore, in order to determine whether the incremental benefits of increasing coverage are likely to be greater than the incremental costs of doing so, we have considered what the level of total social benefit from the coverage obligations would need to be in order for the incremental benefits of increased coverage to be greater than the incremental costs. We have then considered a wide range of evidence to judge whether the total social benefit is likely to be at least as great as this value.

A12.10 To identify the level of total social benefit from the coverage obligations that is needed for the incremental benefits to be at least as large as the incremental costs, we need to make an assumption about the rate of decline in benefits as the level of coverage increases. A zero rate of decline (or 0% per percentage point of geographic coverage) means that the incremental benefit, for example, from 91% to 92% geographic coverage is the same as, for

[341] We have considered coverage in two percentage point increments, as we believe that smaller increments (such as one percentage point) are at risk of being too granular to allow us to estimate meaningful incremental costs of coverage improvements.

example, from 88% to 89%. However, a rate of decline greater than zero means that the incremental benefit from 91% to 92% is smaller than from 88% to 89%.

A12.11 Given the particular challenges in quantifying incremental benefits, identifying a reasonable assumption for the rate of decline is not straightforward and requires regulatory judgement:

a) As we explain in A12.6 above, we anticipate the incremental social benefits of increased coverage decline as the level of coverage increases. As such, this rate of decline should be greater than zero.

b) However, we consider that the rate of decline is unlikely to be high:

i) There is no rate of decline in the proportion of landmass covered (by definition, each percentage point increase in the level of geographic coverage means that coverage would be added to the same additional landmass);

ii) While the exact coverage of premises and roads at each percentage point of geographic coverage will depend on specific geographic roll-out choices of operators, it could be expected that the coverage of these features might decline at a rate higher than 5%.[342]

c) Social benefit is a function of the landmass and places that are covered, the number of times people use and visit those areas and the value they, and society, place on that coverage. As such, we expect the rate of decline in incremental benefits to be between the rate of decline in landmass coverage (0% per percentage point) and the rate of decline in coverage of premises and roads (which might be higher than 5% per percentage point).

A12.12 We have therefore adopted a reasonable stylised assumption that the incremental social benefit declines by 5% for each additional percentage point of geographic coverage beyond 82%.

A12.13 We now explain how we have applied this framework to a 90% and 92% geographic coverage obligation.

The total benefit likely to be necessary to justify 90% coverage obligations

A12.14 We estimate that it would cost approximately £85m to £107m for an operator to increase geographic coverage from 88% to 90% (in a conservative scenario where the obligation was delivered solely with new sites).[343]

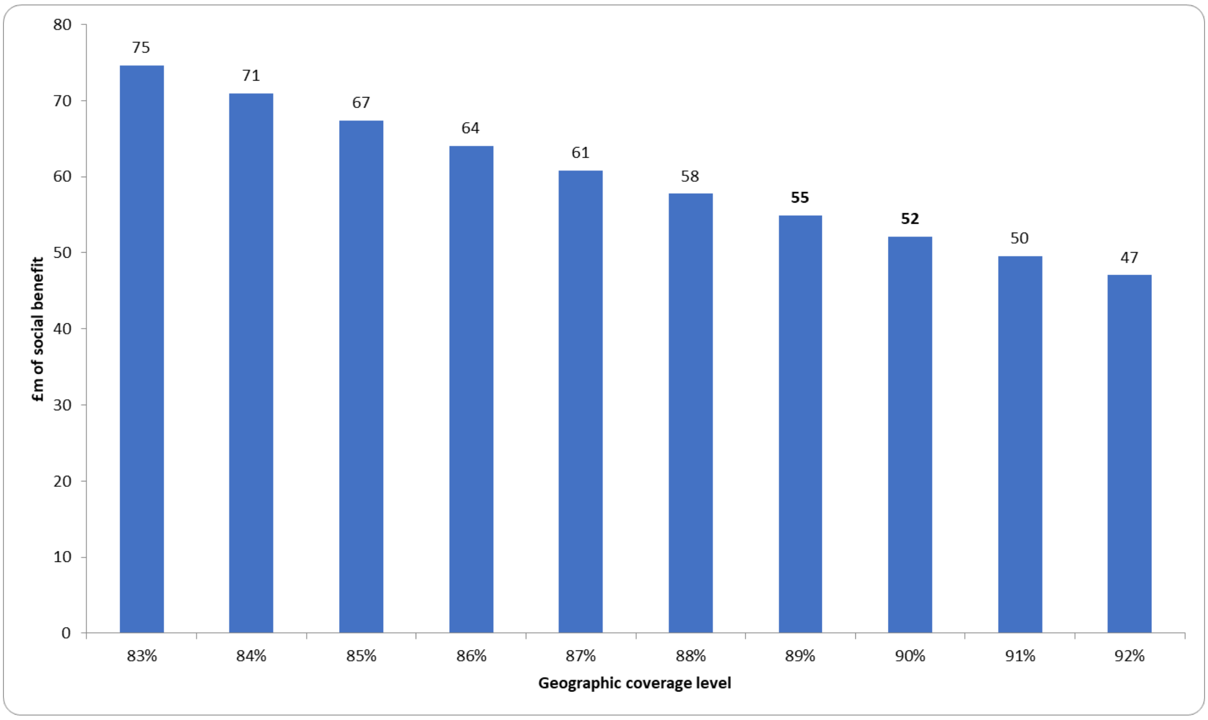
A12.15 We have therefore calculated the incremental benefits from each percentage point of coverage that would likely be necessary for the incremental benefit of increasing coverage from 88% to 90% to be £85 to £107m (assuming a stylised 5% decline in benefits for every

[342] The rate of decline is generally lower for B-road and minor road coverage than for premises and A-roads coverage. These rates of decline exclude overspill benefits to indoor coverage and in-vehicle coverage.

[343] Based on an assumption that 215 to 272 sites would be required to deliver this increment of coverage. This has been derived using the same methodology for estimating the number of sites for a particular level of coverage as in annex 14.

additional percentage point of coverage after 82%). For example, the implied amounts for the incremental benefit of increasing coverage from 88% to 90% to be £107m are shown in Figure A12.1 below.

Figure A12.1: Incremental benefits by percentage point for the incremental benefit of extending coverage from 88% to 90% to be £107m (assuming 5% rate of decline)



Source: Ofcom

A12.16 We can calculate the total benefit of increasing coverage from 82% to 90% that would be implied by an incremental cost (of going from 88% to 90%) of £85m to £107m by summing the individual incremental benefits for each percentage point of coverage. This means that the total benefit of expanding coverage from 82% to 90% would need to be at least £400m to £500m[344] to ensure that the incremental benefits of providing coverage from 88% to 90% are at least £85m to £107m.[345]

[344] This figure is rounded to the nearest £10m. Before rounding this range is £399m to £502m.

[345] We have also considered the implications of different assumptions for the rate of decline in incremental benefits, compared to the required range of £400m to £500m. Assuming a zero rate of decline would imply that the required benefits are £340m to £430m (i.e. lower by £60m to £70m). Assuming a 10% rate of decline would increase the required benefits to approximately £480m to £600m (i.e. higher by £80m to £100m). These calculations all assume that the rate of decline begins at 82%. If instead the incremental benefit was to remain constant for some percentage points beyond 82%, before declining, this would imply that the level of required benefit would be lower. Although the assumption on the rate of decline has a greater impact than the assumption on when that rate of decline begins, these two assumptions to some extent offset each other. For example, assuming that the incremental benefit declines by 5% for each percentage point of coverage beyond 82% is equivalent to assuming that the rate of decline is zero up to 88%, and then declines by 13% for each percentage point of coverage beyond that.

The total benefit likely to be necessary to justify 92% coverage obligations

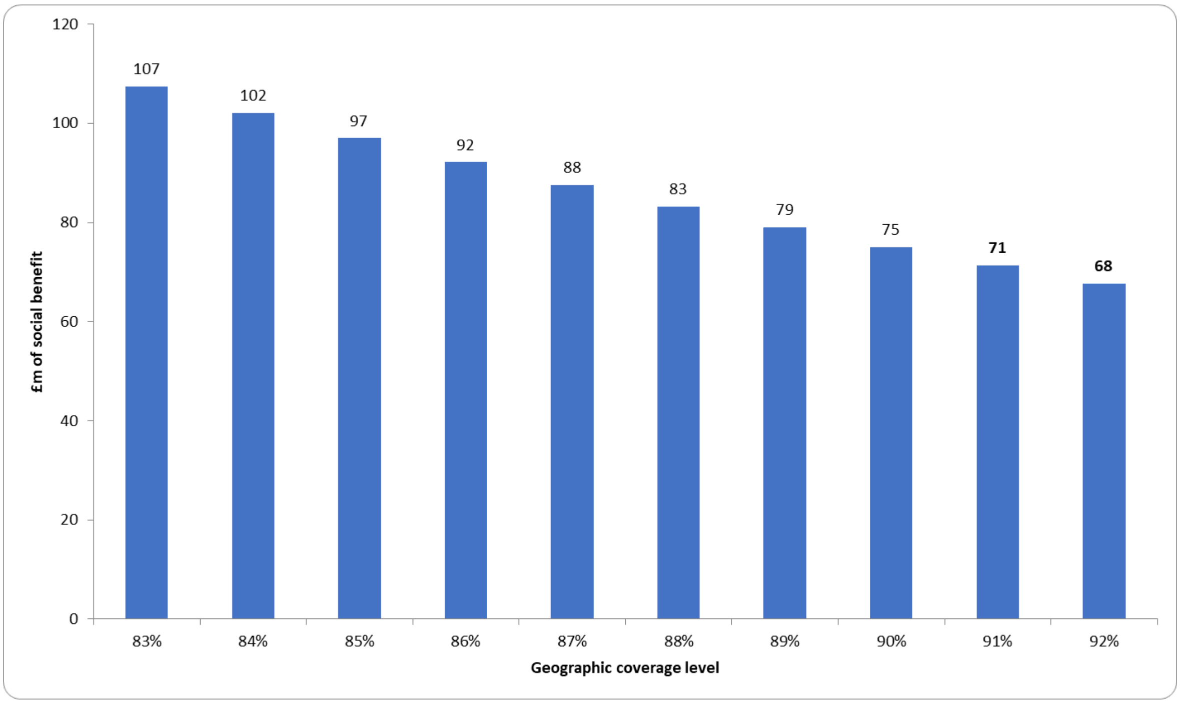
A12.17 We have also assessed the level of benefits necessary to satisfy the tests set out above for a 92% coverage level (which is the level of geographic coverage that we proposed in our March 2018 consultation).

A12.18 As for 90%, we have first considered the cost of the final increment of coverage (which in this case is the increase in coverage from 90% to 92%). We have then estimated the level of total social benefit from increasing coverage to 92% that is likely to be necessary for the incremental social benefit of increasing coverage from 90% to 92% to be at least as large as the incremental cost.

A12.19 We estimate that the incremental cost of increasing coverage from 90% to 92% would be £108m to £139m.[346]

A12.20 Again, assuming a 5% decrease in the benefit of each additional percentage point of geographical coverage, we have calculated the incremental benefits, at each percentage point of coverage, that would be necessary for the incremental benefit of increasing coverage from 90% to 92% to be at least £108m to £139m. For example, the implied figures for the incremental benefit of increasing coverage from 90% to 92% to be £139m are shown in Figure A12.2 below.

Figure A12.2: Incremental benefits by percentage point for the incremental benefit of extending coverage from 90% to 92% to be £139m (assuming 5% rate of decline)



[346] Based on an assumption that 273 to 352 sites would be required to deliver this increment of coverage. This has been derived using the same methodology for estimating the number of sites for a particular level of coverage as in annex 14.

Source: Ofcom

A12.21 We can calculate the implied total benefit of increasing coverage from 82% to 92% by summing the individual incremental benefits of coverage. This means that the total benefit of expanding coverage from 82% to 92% would need to be at least £670m to £860m[347] to ensure that the incremental benefits of providing coverage from 90% to 92% are at least £108m to £139m.[348]

A12.22 For ease of comparison with the range for a 90% obligation, this range of required benefits for a 92% obligation can also be presented as £562m to £723m for 82% to 90% (which we round to £560m to £720m) plus £108m to £139m for 90% to 92%.

There is significant uncertainty in estimating the level of benefits from coverage obligations

A12.23 There is significant uncertainty about the level of both the total benefits that a coverage obligation would provide, and the level of incremental benefits of increasing coverage. This is because there is substantial uncertainty about both the number of beneficiaries and the size of the average benefit per beneficiary. For example:

- It is unclear how often consumers who do not live in the areas where new coverage is being provided would visit these areas.
- Consumers may have different understanding of what the coverage obligations would deliver (in terms of improved quality of service) and how this would impact on them, which may make quantified evidence on willingness to pay for coverage improvements an unreliable indicator of the true private value of the specific coverage improvements we expect from the coverage obligations we are proposing.
- It is hard to attribute a monetary value to the broader social benefits from improved coverage (such as improving social capital), as it cannot be easily quantified using market values.

A12.24 Furthermore, much of the available evidence (for example, on willingness to pay and on macroeconomic effects) is not focused on the specific improvement in mobile coverage whose benefits we are seeking to quantify.

A12.25 We therefore consider that there is an unavoidable uncertainty about the level of benefits, and a substantial risk of spurious precision in quantified estimates of the benefits of improvements in mobile coverage. We therefore do not seek to derive a specific figure as

[347] This is rounded to the nearest £10m – the exact figures are £670m to £862m.

[348] It is possible that the incremental benefit of increased coverage would decline more sharply at higher levels of coverage, as significantly fewer premises, roads and places people visit may gain coverage, and therefore fewer people would benefit from improved coverage. On the other hand, at higher levels of coverage, it may be more likely that total not-spots are covered. A sharper rate of decline in the incremental benefit of increased coverage would imply a higher total benefit of increasing from 82% to 92% would likely be necessary to justify a 92% obligation, and it would also increase the difference between the benefit level likely to be needed to justify a 90% obligation and the required benefit to justify a 92% obligation.

the right estimate of benefits. We instead focus on the threshold question of whether benefits are likely to be large enough to satisfy the tests outlined above.

The total benefits from 90% coverage are likely to be at least £400m to £500m

A12.26 Our provisional view is that a geographic coverage obligation set at 90% of the UK landmass is likely to deliver social benefits which would be at least £400m to £500m, which is the level of benefit we estimate would be necessary to justify the costs of a 90% obligation. We have reached this view having considered a wide range of evidence, with particular regard to the following considerations.

A12.27 Firstly, the coverage obligations would make a material difference to the degree of mobile coverage, especially in rural areas. The obligations would help to meet our duty to ensure the widespread availability of mobile voice and data services throughout the UK, and to have regard to the different interests of people living in the UK, including those living in rural areas. The obligated operators would be required to provide an additional 140,000 premises with good outdoor 4G coverage and a significant proportion of these are likely to see an improvement in signal strength that means they will have good indoor coverage.[349]

A12.28 In addition, for each obligation many other premises (perhaps 100,000 to 300,000) that already have good outdoor 4G coverage will gain good *indoor* 4G coverage. We expect that most of these premises would be in rural areas, meaning that for each obligation around 6 to 11%[350] of rural premises are likely to see significant improvement in signal strength, with better coverage on many roads and over a wider geographic area, providing benefits to many consumers who may travel through or spend time in the areas of greater coverage.

A12.29 Secondly, as set out above, we consider that there will be considerable social benefits from each obligation from additional consumer surplus, private external value and broader social value.

A12.30 Thirdly, an obligation set at 90% of geographic area is consistent with extending to data coverage the policy intention underlying the 2014 voice coverage agreement between operators and the Government.[351]

---

[349] We expect that these premises would predominantly already have coverage from another operator, rather than being in total not-spots.

[350] We estimate that 240,000 to 440,000 premises will gain a significant improvement in signal strength, and there are a total of 4,039,561 premises in the UK in rural areas. Source: Ordnance Survey AddressBase® Premium, Epoch 57.

[351] In 2014, the MNOs agreed with the Government to extend geographic voice coverage to 90% by 2017. While the MNOs committed collectively to spending a very large amount (£5 billion) on mobile infrastructure by 2017, this expenditure did not all relate to expanding voice coverage to 90%. Large parts of this investment may have related to maintaining or improving quality within areas that already had voice coverage. https://www.gov.uk/government/news/government-secures-landmark-deal-for-uk-mobile-phone-users
The full text of the agreement is set out in an Annex A of *Tackling Partial Not-Spots in Mobile Phone Coverage Government Response to Consultation*, DCMS, 12 March 2015, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/412618/Government_Response_FINAL__1_.pdf

A12.31 Fourthly, we note that various Government bodies and consumer groups have broadly argued for coverage obligations greater than the 92% we initially proposed in the March 2018 consultation. This is consistent with there being sufficient benefits to justify a 90% coverage obligation – for example:

a) Through '4G For All', the Country Land and Business Association (CLA) campaigns for action that delivers better mobile coverage for landowners, farmers and rural businesses across England and Wales.[352] In the CLA's view, coverage in rural areas should be improved by imposing a legally binding 95% 4G geographic coverage target.[353]

b) The Communications Consumer Panel has welcomed initiatives to improve mobile quality of service, such as the 4G coverage obligation in the 2013 auction of 98% indoor coverage UK wide, and 95% in each nation by the end of 2017. The Panel believes that there should be much greater (and ideally 100%) mobile coverage for all consumers – including indoor, road and rail coverage.[354]

c) A group of cross-party MPs urged former digital secretary Matt Hancock to implement a legal obligation on the UK's four mobile operators to provide 4G coverage to 95% of the UK's landmass by 2022.[355]

A12.32 Finally, we set out above that we consider the market will under-provide coverage. We note that the scale of intervention implied by an obligation to 90% is modest relative to the size of the market. We estimate the cost of meeting such an obligation to be around £255m (with a range of £170m to £340m) from an operator's perspective, equivalent to annualized costs of £25m per year[356] over the period we are considering. This can be contrasted with total mobile retail sales of over £15 billion in 2017.[357]

A12.33 Based on this evidence in the round, and applying our regulatory judgement, we provisionally conclude that a geographic coverage obligation set at 90% of the UK landmass is likely to deliver social benefits which would be at least £400m to £500m.

The total benefits from 92% coverage are unlikely to be as large as £670m to £860m

A12.34 We acknowledge that there is some qualitative evidence (for example, the views of various Government bodies and consumer groups expressed above) that the benefits may be sufficiently large to justify a 92% coverage obligation.

---

[352] The CLA is the membership organisation for owners of land, property and businesses in rural England and Wales.
[353] https://www.cla.org.uk/4GForAll# (accessed on 25 October 2018).
[354] https://www.communicationsconsumerpanel.org.uk/current-work/mobile-and-broadband-coverage-and-quality-of-service (accessed 25 October 2018).
[355] https://www.theregister.co.uk/2018/05/14/mps_call_for_legally_binding_4g_target_in_rural_areas/ published on 14 May 2018 (accessed on 25 October 2018).
[356] £25.2m per year over 20 years, discounted at the mobile operator nominal pre-tax weighted average cost of capital of 7.6%.
[357] Retail mobile voice & data revenues were £15.6 bn in 2017. See Figure 4.1 of Ofcom's 2018 Communications Market Report, https://www.ofcom.org.uk/__data/assets/pdf_file/0022/117256/CMR-2018-narrative-report.pdf

A12.35 However, we note the following:

a) The scale of intervention required, while still relatively small in the market context, would be larger than that of a 90% obligation.

b) A 92% obligation goes beyond just extending to data coverage the 2014 voice coverage agreement between operators and the Government.

c) The total benefit from increasing coverage from 82% to 92% implies that the total benefit of extending coverage from 82% to 90% needs to be at least £560m to £720m. This is approximately 40% larger than the benefit for this increment of coverage that supports a 90% coverage level.

A12.36 Whilst recognising the unavoidable uncertainty about the level of benefits, our regulatory judgement is that that the total benefits from 92% geographic coverage are unlikely to be as large as £670m to £860m, which is the level of benefit we estimate would likely be necessary to justify the costs of a 92% obligation.

We have undertaken quantitative sense-checks on our provisional conclusion that the benefits of a 90% obligation exceed the costs

A12.37 While we have noted above the difficulties in producing a robust quantified estimate of the benefits of such a coverage obligation, we have undertaken two high-level quantitative sense checks on this provisional conclusion:

a) First, we have developed illustrations of the assumptions that would support social benefits of a 90% coverage obligation within the range of £400m to £500m and considered the plausibility of assumptions at least as large.

b) Second, we have also considered whether the total social benefits of mobile services implied by social benefits of a 90% coverage obligation of £400m to £500m is consistent with estimates of the private use value of mobile services.

A12.38 We set out both of these high-level sense checks below. In both cases, we consider that the assumptions that justify a 90% obligation fall within the plausible range. For example, the assumptions on consumer willingness to pay and the level of switching to the obligation holder are relatively low, and broadly consistent with existing survey evidence.[358] However, we acknowledge that there may be other reasonable sets of assumptions which may lead to a higher or lower quantified level of benefits.

[358] 2014 RAND study (available at https://www.rand.org/pubs/research_reports/RR641.html) on consumer willingness to pay for improved coverage; 2017 ComReg study (available at https://www.comreg.ie/publication-download/mobile-consumer-experience-survey) on whether consumers would switch to a (hypothetical) new operator which offered a reliable quality of signal / coverage; and The GB Tourist, 2017 Annual Report, Kantar TNS, https://gov.wales/docs/statistics/2018/180823-gb-tourist-statistics-2017-en.pdf.

Illustrative calculation of social benefits from an obligation at 90%

A12.39 Below we set out illustrative calculations of the potential scale of the social benefits for a single coverage obligation at 90% of geographic landmass. Thereafter we consider the benefits of a second obligation relative to a single obligation.

Direct and indirect beneficiaries

A12.40 We derive the illustrations of total social benefits by considering the benefits on a 'per consumer' basis, relating to the direct beneficiaries. The relevant benefits include all of the categories of social benefits discussed above, namely:

- private use value;
- private external value;
- macroeconomic benefits; and
- broader social value.

A12.41 Private external value and broader social value (and some macroeconomic benefits) accrue to indirect beneficiaries of the coverage obligation. However, for simplicity, we include them in the benefit-per-direct-beneficiary (noting that it is the use and availability of mobile services for individual consumers that stimulates these wider benefits for society).

A12.42 Our calculations below rely on making various assumptions about the range of social benefit per consumer. While we consider these assumptions to be within the plausible range, there is limited evidence to benchmark the particular assumptions we have made. Our calculations are therefore illustrative.

Categorisation of direct beneficiaries

A12.43 We build up the total social benefits using the three broad categories of direct beneficiaries we described in annex 11 (from paragraph A11.87):

- Rural residents – residential and business customers whose premises would have a significant increase in signal quality;
- Other rural consumers and business customers – consumers who regularly visit areas where coverage would be improved as a result of the obligation, but do not live there; and
- Urban consumers and business customers – a wider group of consumers who would receive an occasional benefit from the increased coverage.

A12.44 For each of the three categories of consumer above we discuss below:

- Information we can use to inform our view of the level of the expected benefit, drawing on a 2014 RAND report which considered the willingness to pay for voice and data coverage in areas without a mobile signal from any operators;[359] and
- Illustrative assumptions regarding the number of direct beneficiaries and the scale of the benefit per consumer and an illustration of the potential size of the total benefit.

Rural residents – consumers who live in areas with a significant increase in signal

Information from the 2014 RAND report

A12.45 One source of information on the value consumers place on extended coverage is the 2014 RAND report commissioned by the UK Department for Environment, Food & Rural Affairs (DEFRA) and the Department for Digital, Culture Media & Sport (DCMS). This report estimated the willingness of residents, businesses and visitors to pay for the extension of mobile coverage to areas without any mobile signal (i.e. without a usable 2G, 3G or 4G connection).

A12.46 Figure A12.3 below shows residents' and businesses' willingness to pay (WTP) for coverage in the area without mobile signal (when the survey was undertaken, which was between late November 2013 and early January 2014). This is in addition to what they pay to use mobile phone services. The 'same signal quality' row shows what they were willing to pay for mobile coverage of similar quality to that available in nearby areas where there was coverage, and the 'better signal quality' row shows what they were willing to pay for better coverage than that available in nearby areas.

A12.47 For example, residents were prepared to pay £23.40 per month more than they were paying at the time to have better 2G signal quality (compared to the signal available nearby) and £24.70 per month more to have better 3G/4G signal quality. Figure A12.3 below also shows that the willingness to pay just to improve the quality of 3G/4G signal was £11.30 per month (=£24.70 - £13.40) for residents and £3.60 for businesses (per phone).

[359] In the 2014 RAND report, not-spots are defined as areas without signal. See p. xi in the 2014 RAND report available at https://www.rand.org/content/dam/rand/pubs/research_reports/RR600/RR641/RAND_RR641.pdf (accessed on 6 December 2018).

Figure A12.3: Additional willingness to pay *per month* for not-spot residents and businesses

	Residents[360]		Businesses (per phone)	
	2G	3G/4G	2G	3G/4G
Same signal quality	£12.00	£13.40	£21.00	£29.60
Better signal quality	£23.40	£24.70	£24.50	£33.20
Increment for better quality	£11.40	£11.30	£3.50	£3.60

Source: Rand (2014), Table D.6 and Table D.8[361]

Note: Same (better) signal quality is compared to those available nearby.

A12.48 For rural residents, our coverage obligation involves providing a significant increase in signal strength for premises that would generally otherwise have some weaker service provision by the operator concerned.

A12.49 Whilst we consider the 2014 RAND study results provide a useful reference point, it is not straightforward to relate the gain from the obligation we propose to the WTP results in Figure A12.3 above. This is partly because it is not clear what individuals surveyed meant when they said they would be prepared to pay, for example, £12 a month more for the same signal quality 2G service as in nearby areas where there was coverage.

A12.50 There is no clear line between an area having coverage and not having any coverage. Rather, coverage may be weaker in some areas than others, meaning the quality of the consumer experience may involve a decline (for example, in terms of more patchy coverage, more dropped calls and very slow data rates). It is unclear whether or not the nearby areas that were used as the comparator would have similar signal strength to our obligation. Similarly, it is unclear exactly what survey respondents were envisaging with regard to 'better signal strength' (i.e. what their benchmark for a 'better signal strength' was).

Assumptions about scale of benefit for this category of consumers and illustrative total benefit

A12.51 We described in annex 11 (from paragraph A11.88) two ways rural resident premises could benefit from the coverage obligation:

---

[360] Residents are located within not-spot areas in England; cannot obtain a mobile network signal when inside their home (self-reported); and may run a business from home. Business premises are located within not-spot areas in England and cannot obtain a mobile network signal when inside business premises (self-reported).
[361] Available at https://www.rand.org/content/dam/rand/pubs/research_reports/RR600/RR641/RAND_RR641.appendices.pdf (accessed on 6 December 2018).

a) Premises that currently have poor 4G coverage from the obligated operator, but gain good quality 4G *outdoor* coverage (a proportion of which will also gain good 4G indoor coverage); and

b) Premises that currently have good 4G outdoor coverage from the obligated operator but will gain good quality 4G *indoor* coverage.

A12.52 There would be (at least) 140,000 premises in the first category due to the premises requirement. In paragraph A11.92 we estimated that there would be 100,000 to 300,000 premises in the second category. Therefore, in total we expect 240,000 to 440,000 premises (i.e. 140,000 that gain good outdoor 4G coverage plus 100,000 to 300,000 that move from good outdoor to good indoor 4G coverage) to gain from a significant increase in signal strength. We have assumed an average of 340,000 premises for this illustration.

A12.53 We also make assumptions about the obligated operator's market share. While we recognise that the market shares of the mobile operators currently differ, over the forward-looking period that we are considering for our social benefit assessment, market shares can change. Given there are four mobile operators, we have made the neutral assumption that each operator would have a 25% market share in the counterfactual.

A12.54 However, as we would expect a selection of other operators to initially have better coverage than the operator with the obligation (at least in some areas, i.e. partial not spots where the obligated operator does not current provide good quality coverage), we consider it appropriate to make a downward adjustment to reflect the market share across this group of consumers. We assume its market share across rural resident premises is somewhat lower at 20%. As it would have significantly improved coverage with the obligation, we would expect its market share to rise somewhat, but the extent of this increase is uncertain. In the illustration below we have assumed the market share increases by 10 percentage points to 30%. In Figure A12.9 below we have also considered a scenario where the market share for the obligation holder increases by 15 percentage points to 35%.[362]

A12.55 Considering the 2014 RAND study as a reference point, Figure A12.3 above shows that the willingness to pay to improve the quality of 2G or 3G/4G signal was £11.40 and £11.30 per month, respectively, for residents. For businesses (per phone), the increments for better quality were £3.50 and £3.60, for 2G and 3G/4G, respectively.

A12.56 We recognise there are differences in the improved mobile coverage that the 2014 RAND study was capturing versus that of our obligation. Consumers may value the mobile

---

[362] ComReg (2017) considered the question: "If a new (hypothetical) national mobile phone network was established, offering a reliable quality of signal / coverage (i.e. where calls and texts were not dropped), would you switch to this new network if the costs were the same as your current package?". Responses were: 9% "Yes definitely"; 12% "Yes probably"; 17% "Unsure"; 19% "Probably not"; 38% "Definitely not"; and 5% don't know or can't say (as employer mobile). See slide 75 at https://www.comreg.ie/publication-download/mobile-consumer-experience-survey (accessed on 6 December 2018). The switching assumptions we considered in Figure A12.9 (5%, 10% and 15%) are less than the 21% of responses in the "Yes definitely" and "Yes probably" categories. This is a conservative approach because survey respondents may overstate their willingness to act in practice or may be unaware of a minimum contract period attached to their current subscription.

coverage envisaged by our obligation less than the willingness to pay reported in the 2014 RAND study because:

c) Our coverage obligation aims to achieve improved 4G coverage in areas where consumers are likely already to have some voice and data services (albeit lower quality). By contrast, the 2014 RAND study was measuring willingness to pay in areas where there was no useable 2G, 3G or 4G service.

d) In the areas where we would expect an operator to deploy under our obligation, the obligated operator may already provide a poorer quality service and other operators may also be present in the area. By contrast, the 2014 RAND study was measuring the willingness to pay in areas where there was no useful signal from any operator.

A12.57 On the other hand, we are considering benefits over a forward-looking period of 20 years, during which time we expect the benefits from mobile services to grow, particularly as more consumers experience 4G, and there may continue to be rapid growth in data consumption. We consider that in the future there is likely to be material additional value for users from a good 4G service compared to a service offering lower speeds such as 3G.

A12.58 The 2014 RAND study found that the incremental WTP per month for better signal quality 3G/4G compared to better signal quality 2G is £1.30 (= £24.70 - £23.40) for residents, and £8.70 (=£33.20 - £24.50) for businesses (per phone), i.e. the premia for better signal quality data services seems relatively small for consumers that already have access to better signal quality voice services.

A12.59 However, some residents and businesses in rural areas may also benefit with our coverage obligation in terms of improving the signal quality for voice. In particular, for consumers that are only concerned about mobile voice (and not mobile data), our coverage obligation may imply a better 2G signal quality, for which the 2014 RAND study reference points would be an incremental value per month of £11.40 for residents, and £3.50 for businesses (per phone).

A12.60 The 2014 RAND study did not find 4G services to be valued more highly than 3G services. However, we consider that this finding may no longer be true. In 2013/14, when the study was undertaken, most people (especially in rural areas) had not yet experienced 4G services and had yet to see the value of such services. Since 2014, access to and use of mobile data services have quadrupled (see Figure A6.1), and the value of 4G is likely to be significantly higher today.

A12.61 In addition, the 2014 RAND study only captures one part of the value of mobile coverage, i.e. the private use value (additional consumer surplus measured by WTP). We are interested in the total social benefit per consumer, including all aspects of social benefits, not only private use value but also private external value and broader social value (including macroeconomic gains as well), as previously discussed.

A12.62 Given these differences, it is difficult to use the 2014 RAND WTP to estimate the benefits from our coverage obligation. For our illustrative calculation set out in Figure A12.4 below, we assume benefits per consumer of £5 per month, i.e. between the RAND average WTP of

£11.30 for improved 3G/4G signal for residents and £3.50 for businesses (per phone).[363] This £5 per month is an average per resident in premises benefiting from improved coverage by being (or becoming) a customer of the obligated operator – for some consumers it might be higher whereas for others it might be lower or zero.[364] However, we note that £5 per month is a relatively small proportion (27%) of the current average monthly price consumers face, which itself is likely to underestimate consumer willingness to pay, and will not capture external benefits.[365]

A12.63 For the purposes of this estimation, we have assumed two residents per premises as if all premises were residential.[366] We have also assumed that each resident will have a smartphone in the relevant 20-year period.[367]

Figure A12.4: Illustrative calculation of social benefits relating to consumers in premises with significant signal gains

	Illustrative calculation
Number of premises	340,000
Market share pre-obligation	20%
Market share post-obligation	30%
Residents per premises	2
Number of beneficiaries	204,000
Benefit per consumer per month	£5
Total benefit (present value)	**£129m**

363 See paragraphs A12.58 and A12.59 above on the incremental willingness to pay of consumers that already have better signal quality for 2G, and consumers that are only concerned about mobile voice but may also benefit with the implementation of our coverage obligation.
364 In illustration 2 in Figure A12.9 below we consider the more conservative case of an average benefit of £3.60 per month per consumer (rather than £5.00).
365 Based on a weighted average monthly price for average mobile use baskets (excluding handsets) of £18.36 per month. See Figure A6.15.
366 We have based this assumption on the information used for the Mobile Infrastructure Project (MIP), which similarly covered rural areas of the UK. The MIP provided a mobile signal to 7,199 premises which roughly equated to 14,100 residents (i.e. 1.96 residents per premises). See p. 5 at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/651008/MIP_Impact_and_Benefits_Report.pdf (accessed on 6 December 2018).
367 The proportion of adults who personally use a smartphone increased from 27% in 2011 to 78% in 2018 (CMR 2018, p. 53, https://www.ofcom.org.uk/__data/assets/pdf_file/0022/117256/CMR-2018-narrative-report.pdf) (accessed on 6 December 2018). We expect therefore that smartphone use will continue to rise over the 20-year period we are considering.

A12.64 This illustrative calculation results in social benefits relating to consumers in premises with significant signal gains of £129m in present value terms over the period we are considering.[368]

Other rural consumers – consumers who regularly visit areas of improved coverage

Information from the 2014 RAND study

A12.65 The 2014 RAND study reported WTP for local visitors to areas without a mobile signal (see Figure A12.5 below). In the RAND study local visitors were defined as people that lived near but not in a not-spot area, who regularly or occasionally travelled through or visited places in their local area where there was no mobile phone signal.[369]

Figure A12.5: WTP *per month* for local visitors visiting not-spots

	2G	3G/4G (age <45)
Same signal quality	£6.30	£13.20
Better signal quality	£15.10	£22.00
Increment for better quality	£8.80	£8.80

Source: Rand (2014), Table D.7[370]

Note: Same (better) signal quality is compared to those available nearby.

A12.66 The 2014 RAND study suggests local visitors were prepared to pay £15.10 per month more than they were paying at the time to have a better 2G signal quality (compared to the signal available nearby) in the not-spots that they visited, and local visitors aged below 45 were prepared to pay £22.00 per month more to have 3G/4G signal with a better quality (compared to the signal available nearby). These amounts above represent the average amount local visitors were prepared to pay each month for coverage with different types of services (2G, 3G, 4G) and signal qualities in a not-spot that they visit regularly. For those aged 45 and older, the value for 3G services was not significantly different than for 2G services.

[368] We have considered the social benefits over the 20-year initial licence term assuming zero benefits in the first 4 years (roll-out period to meet the obligation), using a 3.5% social discount rate in real terms. Source: HMT Green Book social time preference rate, paragraph A6.3 at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/685903/The_Green_Book.pdf (accessed on 6 December 2018).
[369] 2014 RAND study Table 2.3.
[370] Available at https://www.rand.org/content/dam/rand/pubs/research_reports/RR600/RR641/RAND_RR641.appendices.pdf (accessed on 6 December 2018).

Assumptions about scale of benefit for this category of consumers and illustrative total benefit

A12.67 The number of 'other rural consumers' who benefit will be much larger than the number of residents of the premises that have a significant signal improvement. This is because (as described in paragraph A11.97) people use mobiles in many premises other than their homes (such as workplaces, shops, visiting friends, pubs, etc) and when they travel between these locations.

A12.68 93% of adults in the UK who use their mobile to access the internet say they use it outside their home.[371] Moreover, 64% of those adults in the UK who use their mobile to access the internet say they access mobile services equally in the home and outside the home and 8% say they use their mobile phones mainly outside the home.[372] These people use their mobiles outside their homes in variety of places:[373]

- 76% when travelling (e.g. on a train or in a car);
- 69% in indoor public spaces (e.g. pub/restaurant/theatre/shopping centre);
- 68% outdoors;
- 67% in other people's homes (e.g. friends/ family); and
- 57% at their workplace.

A12.69 We estimate that, on average, there will be around 9.8 million people (aged 12 and older)[374] in UK rural areas that will be using smartphones in the 20 years after the auction.[375,376] We have assumed that half of other rural consumers that are customers of the obligation holder have some benefit.[377] This implies over 1 million consumers will

---

[371] Ofcom Technology Tracker H1 2018, *QD15 Which one of these best describes where you use your mobile phone to access the internet,* Table 47 https://www.ofcom.org.uk/__data/assets/pdf_file/0021/113169/Technology-Tracker-H1-2018-data-tables.pdf

[372] Ofcom Technology Tracker H1 2018, *QD15 Which one of these best describes where you use your mobile phone to access the internet,* Table 47.

[373] Ofcom Technology Tracker H1 2018, QD16 *In which of these places do you use your mobile phone to access the internet outside of the home,* Table 48

[374] In Ofcom (2017) *Children and Parents: Media Use and Attitudes* we reported that 86% of children aged 12-15 owned a mobile phone and 93% had access to a mobile phone. See Figure 9, p.39 https://www.ofcom.org.uk/__data/assets/pdf_file/0020/108182/children-parents-media-use-attitudes-2017.pdf. We therefore consider that the vast majority of children aged over 12 are likely to use a mobile phone.

[375] World Bank estimated that the rural population in the UK was 17% of the total population in 2016 (reported in Trading Economics see https://tradingeconomics.com/united-kingdom/rural-population-wb-data.html, accessed on 6 December 2018). 96% of UK adults used a mobile phone in 2018, see Ofcom (2018), Communications Market Report, Figure 1.3 https://www.ofcom.org.uk/__data/assets/pdf_file/0022/117256/CMR-2018-narrative-report.pdf. The average number of people in the UK aged 12 and older between 2016 (actuals) and 2041 (ONS's projections) is 59.8m. ONS's national population projections can be found at https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2016basedstatisticalbulletin (accessed on 6 December 2018). We have again assumed that all mobile phone users in the UK will have a smartphone during that period. See footnote 363.

[376] Our estimate was calculated as follows: 59.8m people (aged 12 and older) x 17% (rural) x 96% (mobile phone users).

[377] We assumed 50% because it is the midpoint between 0% and 100% (i.e. no one benefits, and all consumers benefit). In illustration 3 in Figure A12.9 below we considered a more conservative assumption that only 35% (rather than 50%) of other rural consumers receive a benefit from the coverage obligation.

benefit to some extent from the obligation.[378] This assumption is based on the additional premises covered, as well as the increase in landmass and a material proportion of roads in rural areas which will also receive significantly better coverage.

A12.70 In terms of premises, as noted above, around 240,000-440,000 would have significantly improved signal strength, which accounts for around 6 to 11% of total rural premises, some of which will be public premises, such as shops, pubs and restaurants.[379]

A12.71 In terms of the benefit per consumer, we consider the amount that local visitors were willing to pay to improve 2G or 3G/4G signal from the RAND study (£8.80 per month) provides a useful reference point. However, the RAND definition of local visitors is different to the 'other rural consumers' we have identified above. The RAND study was aimed at local visitors to areas without a mobile signal on a regular or occasional basis. Some 'other rural consumers' may visit areas of poor 4G coverage with a similar frequency to the RAND local visitors, however, others may encounter poor 4G coverage less frequently.

A12.72 On average, we expect 'other rural consumers' to encounter poor coverage with lower frequency than the RAND local visitors. This suggests that across all 'other rural consumers' the average value derived from improved 4G coverage under our obligation is likely to be lower than the WTP suggested by the 2014 RAND study.

A12.73 Some consumers may value the mobile coverage envisaged by our obligation less than indicated by the RAND WTP for reasons described previously, i.e. the areas under consideration in the RAND study had no mobile signal from any operators.

A12.74 On the other hand, as set out in paragraph A12.57, the RAND study results may understate the benefits in the 20-year period we are considering. In addition, the RAND study only captures one part of the value of mobile coverage, i.e. the additional consumer surplus measured by WTP.

A12.75 For the illustrative example in Figure A12.6 below we have assumed that the benefit relating to other rural consumers is £2 per month per consumer (less than a quarter of the RAND private value figure (£8.80) for local visitors). In practice, some may gain less from the additional coverage and some may gain more, with the assumed benefit per consumer being an average.

A12.76 In our assessment it is ultimately the proportion of consumers that benefit multiplied by how much each consumer benefits that matters, so it is equivalent to considering that more rural consumers receive some smaller benefit.[380] Some examples of the sorts of benefits that individuals may receive when they travel around areas with patchy coverage are described in paragraphs A11.32 and A11.33.

[378] That is 9.8m rural mobile users x 25% (assumed market share of obligated operator) x 50% (assumed proportion of obligated operator's customers that benefit).

[379] Ordnance Survey AddressBase® Premium, Epoch 57. Of the total 29,272,964 UK premises, 4,039,561 are in rural areas.

[380] In illustration 3 in Figure A12.9 below we considered a more conservative assumption that only 35% (rather than 50%) of other rural consumers receive a benefit from the coverage obligation. Illustration 3 is equivalent to fixing the proportion of other rural consumers that will benefit from the coverage obligation at 50% and considering a benefit per other rural consumer at £1.40 (rather than £2.00), keeping everything else constant.

Figure A12.6: Illustrative calculations of social benefits relating to other rural consumers

	Illustrative calculation
Total number of rural consumers	9.8m
Consumers living in premises with large increase in signal strength	680,000
Market share of obligation holder across rural consumers	25%
Proportion of other rural consumers assumed to benefit	50%
Number of beneficiaries[381]	1.13m
Benefit per other rural consumer per month	£2
Total benefit (present value)	**£287m**

A12.77 This illustrative calculation results in social benefits to other rural consumers of £287m in present value terms over the period we are considering.

Urban consumers – wider group of consumers with small benefit

Information from the 2014 RAND report

A12.78 The 2014 RAND report explored the WTP for 'tourists' visiting not-spots – see Figure A12.7 below. By tourists, the RAND study means people that have travelled to a not-spot area in England outside of their local area within the past 12 months.

[381] The number of other rural beneficiaries is calculated as (9.8m-680,000)x25%x50%=1.13m. The 680,000 consumers living in rural areas with large increase in signal strength were subtracted to avoid double counting of benefits.

Figure A12.7: WTP *per day* for tourists visiting not-spots

	2G (<65 years)	2G (>65 years)	3G (<45 years)	4G (<45 years)
Same signal quality	£0.20	£0.50	£1.90	£2.30
Better signal quality	£2.70	£3.00	£4.40	£4.90
Increment for better quality	£2.50	£2.50	£2.50	£2.60

Source: Rand (2014), Table D.9[382]

Note: Same (better) signal quality is compared to those available nearby.

A12.79 Figure A12.7 above indicates that:

- tourists had significant willingness to pay for improvements in the mobile signal. With the exception of those younger than 45, the study did not find 4G services to be valued more highly than 3G services. However, we consider that this finding may no longer be true for the reasons set out in paragraph A12.60 above;
- tourists aged less than 65 were prepared to pay £2.70 per day more than they were paying at the time to have better 2G signal quality (compared to the signal available nearby) in the not-spots that they visited; and
- tourists aged less than 45 were prepared to pay £4.90 per day more than they were paying to have better 4G signal quality (compared to the signal available nearby) in the not-spots that they visited.

Assumptions about scale of benefit for this category of consumers and illustrative benefits estimation

A12.80 In our illustration in Figure A12.8 below we have assumed that there are 48 million urban mobile phone users,[383] on average, over the period we are considering, and that half[384] of

[382] Available at https://www.rand.org/content/dam/rand/pubs/research_reports/RR600/RR641/RAND_RR641.appendices.pdf (accessed on 6 December 2018).

[383] This is estimated as the average population aged 12 and older between 2016 (actual) and 2041 (ONS's projections) multiplied by 96% (proportion of UK population with mobile phones in 2018) multiplied by 83% (proportion of urban population in the UK). ONS's projections available at https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2016basedstatisticalbulletin (accessed on 6 December 2018). Proportion of the UK population with mobile phones available at CMR 2018, p. 11, available at https://www.ofcom.org.uk/__data/assets/pdf_file/0022/117256/CMR-2018-narrative-report.pdf (accessed on 6 December 2018). Proportion of urban population in the UK in 2016 reported at https://tradingeconomics.com/united-kingdom/rural-population-wb-data.html (accessed on 6 December 2018).

[384] Given the uncertainty on the proportion of urban consumers that will benefit from extended 4G coverage, we assumed the mid-point between 0% and 100% for our base case, i.e. 50%. In illustration 4 in Figure A12.9 below we considered the more conservative assumption of 35% (rather than 50%).

them will have a small benefit from the additional coverage which we believe will mostly be in rural areas.

A12.81 The 2014 RAND study suggests that tourists below 45 had an incremental willingness to pay of £0.50 per day for good 4G compared to good 3G coverage (£4.90 for better signal quality 4G compared to £4.40 for better signal quality 3G). Also, the RAND study suggests that the same tourists were willing to pay a premium of £3.00 per day when 4G additionally entails an improvement in signal quality (i.e. £4.90 for better signal quality 4G compared to £1.90 for same signal quality 3G).

A12.82 On the other hand, as discussed in paragraph A12.60 above, the willingness to pay for 4G services is likely to have increased since the time of the 2014 RAND study and is likely to grow further over the 20-year period we are considering. In addition, as noted in paragraph A12.61 above, the RAND study only captures one part of the value of mobile coverage i.e. the additional consumer surplus measured by WTP.

A12.83 We have assumed that better 4G coverage would lead to a benefit of 10 pence per consumer per month, equivalent to £1.20 per consumer per year.[385] As noted above, the RAND study suggests tourists under 45 would be willing to pay £0.50 or £3 to gain better quality 4G (compared to better or lower quality 3G, respectively). This suggests that a consumer would need to spend less than half a day to 3 days per year (depending on the gain of mobile signal strength with the obligation) in the areas where our obligation improved the mobile signal from 3G to good 4G coverage to achieve a benefit of at least £1.20.

Figure A12.8: Illustrative calculations of social benefits relating to urban consumers

	Illustrative calculation
Total urban consumers	48m
Market share of obligation holder across urban consumers	25%
Proportion of urban consumer to benefit	50%
Number of beneficiaries	6m
Benefit per urban consumer per month	£0.10
Total benefit (present value)	**£75m**

A12.84 The illustrative calculation above implies a total benefit for urban consumers of £75m in present value terms over the period we are considering.

[385] In illustration 4 in Figure A12.9 below we considered the more conservative assumption of a benefit per urban consumer at £0.01 per month (rather than £0.10 per month).

A12.85 Another way of reviewing the reasonableness of the gain for this group of consumers is to consider it in terms of evidence on the number of trips to the countryside and the amount of value that would be implied per visit. There were estimated to be 413 million day-trips[386] and 17 million overnight trips to the countryside or small villages in Great Britain in 2017.[387] We assume that:

- 83% of these visits may be from urban consumers who may benefit from the coverage obligation, as 83% of the population in the UK was in urban areas in 2016;[388]
- 8% of rural premises receive a large increase in signal quality (as noted in paragraph A12.70 above we expect 6 to 11% of premises to benefit); and
- 25% of consumers are with the obligated operator.

A12.86 The assumptions above imply that there are around 7 million trips[389] per year where urban consumers will benefit from the mobile coverage improvements in rural areas. If we further assume that all of these trips have the same benefit, then to achieve benefits of £75m would require a value of coverage improvement of slightly more than £0.65 per trip.[390] This is broadly consistent with the willingness to pay premium in the range £0.50 to £3.00 per day for 4G compared to 3G (see paragraph A12.81 above) given that we are considering a significant increase in the quality of the mobile service with the obligation, but are not assuming there would otherwise be no mobile service.

Our illustrative calculations imply a total social benefit above £400m over 20 years

A12.87 If we sum the benefits illustrated above for the three categories of consumer, the total benefit is £488m over 20 years. Figure A12.9 below summarises the total benefits, for other more conservative sets of assumptions, for each category of consumers in turn.[391] In each case (by construction) the total benefits are in the range £400-500 million. Other, less conservative sets of assumptions would yield larger benefits in excess of about £500 million.

---

[386] Slides 26 and 85, *The Great Britain Day Visitor 2017 Annual Report*, Kantar TNS, https://gov.wales/docs/statistics/2018/180823-great-britain-day-visits-survey-2017-en.pdf (accessed on 6 December 2018). The largest single reasons for visits to the countryside are to visit friends or family and to undertake outdoor activities.

[387] Slide 53, *The GB Tourist, 2017 Annual Report*, Kantar TNS, https://gov.wales/docs/statistics/2018/180823-gb-tourist-statistics-2017-en.pdf (accessed on 6 December 2018).

[388] https://tradingeconomics.com/united-kingdom/rural-population-wb-data.html (accessed on 6 December 2018).

[389] This can be calculated as (413m+17m)x83%x8%x25% = 7.1m.

[390] This can be calculated as £75m/[(413m+17m)x83%x8%x25%x16years] = £0.66 per trip.

[391] For simplicity, we have not taken account of two sources of benefits, which means that the illustrative calculations may underestimate benefits. We have assumed that the coverage obligation would not generate any benefits before the end of the 4th year after the auction (roll-out period), while in practice consumers are likely to enjoy the benefits of additional coverage as masts are deployed over the implementation period (and in our estimates of the costs of the obligation we have assumed that some sites will be built before the end of the roll-out period). In addition, we did not account for the benefits to urban businesses customers or international visitors travelling through the area of improved coverage.

Figure A12.9: Summary of the illustrative calculations of total social benefits (in present value terms)

	Illustrative calculation 1[392]	Illustrative calculation 2[393]	Illustrative calculation 3[394]	Illustrative calculation 4[395]
Rural consumers with signal gain	£129m	£108m[396]	£129m	£129m
Other rural consumers	£287m	£287m	£201m	£287m
Urban consumers	£75m	£75m	£75m	£5m
Total social benefit	**£491m**	**£470m**	**£405m**	**£421m**

Impact of a second geographic obligation

A12.88 The illustrations in the previous sub-section are for a single geographic coverage obligation. We have considered how the overall benefits would change with two coverage obligations. We would expect all the existing customers for both obligated operators to benefit from the additional coverage provided as described for the three categories of consumers above. This means the overall benefits for the 'other rural consumers' and the 'wider group of urban' consumers would effectively double (as we are assuming each operator has a 25% market share of these customers, meaning 50% rather than 25% of these customers benefit if there are two rather than one coverage obligations).

A12.89 With respect to the consumers in premises with a direct improvement in signal strength, again, existing customers of each operator would benefit in the same way described above. However, we might expect some differences in customer switching to the obligated operators. As the additional coverage is likely to be provided in partial not-spots, there is likely to already be at least one operator with good coverage of the area. If the two obligated operators rolled out additional coverage to the same partial not-spots, then this would result in three (or potentially four) operators providing good coverage. In this scenario most consumers in the area would already have or gain good coverage, so there would be less incentive to switch.

[392] Assumptions used to generate illustration 1 are set out in Figure A12.4, Figure A12.6 and Figure A12.8 above.
[393] Difference in assumptions compared to illustration 1: final market share for obligation holder in premises with significant signal gains at 25% (rather than 30%).
[394] Difference in assumptions compared to illustration 1: share of other rural consumers assumed to benefit at 35% (rather than 50%).
[395] Difference in assumptions compared to illustration 1: proportion of urban consumer assumed to benefit at 35% (rather than 50%); and the benefit per urban consumer at £0.01 per month (rather than £0.1 per month).
[396] Equivalently, this value can also be obtained by considering the following different assumptions compared to illustration 1: final market share for obligation holder in premises with significant signal gains at 35% (rather than 30%); and benefit per consumer with significant signal gains at £3.60 per month (rather than £5.00 per month).

A12.90 It is possible that each of the obligated operators would roll-out to different partial not-spots, but it is likely there would be at least some overlap. Overall this means that the obligated operators would be likely to win fewer additional customers as a result of the coverage improvement.

A12.91 In illustrative calculation 1 above (see Figure A12.9 above) we assumed that in the areas where the coverage obligation directly increases the signal strength the obligation holder increased its market share from 20% to 30% as a result of switching. If two operators improve coverage then there could be less switching, such as an increase from 20% to only 25% for each operator (this reflects an assumption that both obligated operators will pick some of the same poor coverage areas to roll-out to, and some different areas). We covered this case of lower switching in illustrative calculation 2.

A12.92 This implies that where two coverage obligations are awarded the benefits generated by each obligation holder to consumers in premises that directly benefit from improved signal strength might be slightly lower. For example, in the illustrative calculation 2 we take a switching assumption of 5 percentage points (i.e. market share for an obligation holder increases from 20% to 25%) and the benefit is £108m for each operator. This compares to £129m in the illustrative calculation 1 when there is a single coverage obligation and switching is 10 percentage points (i.e. market share for the obligation holder increases from 20% to 30%). Given the modest size of this illustrative difference and the overall uncertainty about the size of benefits, we do not propose to reach a materially different view about the benefits of each obligation if two obligations are awarded compared to one obligation being awarded.

Using estimates of the private use value of all mobile services to sense-check the plausibility of the benefits likely to be necessary for a 90% coverage obligation

A12.93 We have also considered whether the social benefits likely to be necessary to justify a 90% coverage obligation imply a plausible value for the total social benefits of all mobile services.

A12.94 To assess this, we have considered the potential percentage gain in total mobile social benefits from the extra mobile coverage provided by the obligation. We have considered a range of possible percentage gains of 0.25% to 1%, using as a simple reference point the percentage of premises that we expect to gain a significant improvement in 4G coverage.

A12.95 We expect around 1% of premises to gain a significant improvement in 4G coverage, and so use this as our upper bound.[397] However, we recognise that some of these premises will already have good outdoor 4G coverage (and are only gaining good indoor coverage as a result of the obligation) while others may currently have a patchy 4G service, and so the

[397] We expect 240,000 to 440,000 premises to gain a significant improvement in signal strength (see paragraph A12.52). The total number of premises in the UK is 29,272,964 (Source: Ordnance Survey AddressBase® Premium, Epoch 57). Therefore the percentage of premises expected to see improved signal strength as a result of the obligation is 0.8% to 1.5%.

incremental gain in coverage for these areas may be lower than in areas without outdoor 4G. As such we have also considered a range of gains below 1% in the total social benefits of mobile services.

A12.96 Figure A12.10 below shows what we would need to believe about the social benefit per operator and across all operators to justify total benefits of £450m from a single coverage obligation for this range of percentage gains in mobile social benefits. We have used £450m for simplicity as this is the mid-point of the likely required range of benefits for a 90% obligation of £400m to £500m. The final column shows what we would need to believe about the mobile industry social benefit per year.

A12.97 The top row considers the case of an assumed gain of 0.25% in total benefits for all its mobile services from the obligated operator due to a 90% geographic coverage obligation (column B). If the benefits from the obligation were £450 million over a 20-year period (column A), this implies the total benefits from all services of that operator would be £180 billion over 20 years (column C). If we assume the obligated operator has a 25% market share, this implies total mobile benefits across the whole market (all operators) of £720 billion over 20 years (column D). In the final column we convert this 20-year value into an equivalent figure per year of £68bn.[398] A higher assumed percentage gain in column B would imply that the coverage obligation benefit figure of £450 million would be consistent with a lower whole market benefit per year, such as £17 billion per year for a 1% gain.

[398] Based on a discount rate of 3.5% in real terms. Source: HMT Green Book social time preference rate, paragraph A6.3 at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/685903/The_Green_Book.pdf (accessed on 6 December 2018).

Figure A12.10: Implied total social benefits of all mobile services for different percentage gains in benefits from an obligation

Assumption of total benefit of 90% (£m) (A)	Assumed gain in mobile social benefits from MNO due to extra coverage (B)	To justify total benefits of £450m, total social benefit from MNO is C=A/B (£m)	To justify total benefits of £450m, total social benefit from 4 MNOs is D=Cx4 MNOs (£m)	To justify total benefits of £450m, total social benefit from 4 MNOs per year (£m)
450	0.25%	180,000	720,000	68,316
450	0.50%	90,000	360,000	34,158
450	0.75%	60,000	240,000	22,772
450	1.00%	45,000	180,000	17,079

Note: The incremental total benefit of £450m is gross of costs. Thus, for comparability, the total social benefit (columns C and D) and the total social benefit from 4 MNOs per year are gross of costs.

A12.98 We can use estimates of the total private value of all mobile services to test these implications, while acknowledging that they do not capture the total social benefits of increased mobile coverage, as they do not include private external value, macroeconomic effects and broader social value. Analysys Mason (2012) forecasted that consumer surplus from mobile voice services alone would be around £40 billion to £55 billion by 2021 and is likely to continue to grow significantly after that.[399] Therefore, if the obligation delivered a 0.5% or larger increase in social benefits, it would provide benefits of more than £450m on the basis of consumer surplus from mobile voice services alone.

A12.99 In the previous paragraph above, we have taken into account only the consumer surplus for mobile voice services alone. In addition, there are significant benefits from data services, which we expect would have grown very significantly since 2012.

A12.100 Once we consider the anticipated future growth in mobile use, as well as the external and macroeconomic benefits, and the broader social value arising from the increased coverage, an increase in social benefits as small as 0.25% as a result of increased coverage could also be broadly consistent with a total benefit of £450m or even higher.

[399] Analysys Mason (November 2012), *Impact of radio spectrum on the UK economy and factors influencing future spectrum demand*, Figure 4.1, pages 16-17 https://www.gov.uk/government/publications/impact-of-radio-spectrum-on-the-uk-economy-and-factors-influencing-future-spectrum-demand.

A13. Maximum discount for the coverage obligations

A13.1 As set out in section 7, we are proposing a CCA award where the coverage obligations would not be attached to any specific block(s) of spectrum. Bidders would be encouraged to bid for a coverage obligation in return for an explicit discount on any spectrum on which they are bidding.

A13.2 We are proposing to offer two coverage obligations in the award, each set at a minimum of 90% of the UK landmass (with a 'premises requirement' and a 'new sites requirement'). In this annex, we explain why we consider it is appropriate to set the maximum discount for each obligation in the range of £300m-£400m, with a central case of **£350m**.

A13.3 We consider it appropriate to set the same maximum discount for all bidders. As discussed in section 4 (from paragraph 4.67) and Annex 11 (from paragraph A11.113), we consider that the social benefits delivered by the obligation are likely to be broadly similar across different operators.

Our approach to setting the maximum discount for the obligations

A13.4 The maximum discount has two functions in our proposed auction design, both of which have informed our provisional approach to setting the maximum discount:

it provides an incentive for bidders to bid for a coverage obligation; and

even where there are bids for a coverage obligation, it limits when an obligation is awarded to reflect the balance between costs and benefits.

A13.5 Given the first of these two functions, we consider that a reasonable starting point is to set the maximum discount at a conservatively high estimate of the costs of meeting the proposed obligations, where we are confident benefits are greater. The conservative nature of this starting point is intended to provide an incentive to bid for the coverage obligations, as we would expect bidders' actual costs of meeting the obligations may be lower.

A13.6 The level of the discount would be bid down in the auction if there is competition for the coverage obligations leading to excess demand. We also note that any bidder who faces lower costs of meeting the obligation might get a net profit from taking on the coverage obligation.[400]

A13.7 Based on our range of cost estimates for operators to meet the coverage obligation, and recognising that the maximum discount is a reserve price, we consider that a reasonable starting point is a range of £300m-£400m, with a central case of **£350m**. For simplicity, in the discussion below we generally refer to this central case.

[400] This is analogous to the profit a bidder might get from winning spectrum if it has a higher valuation than other bidders.

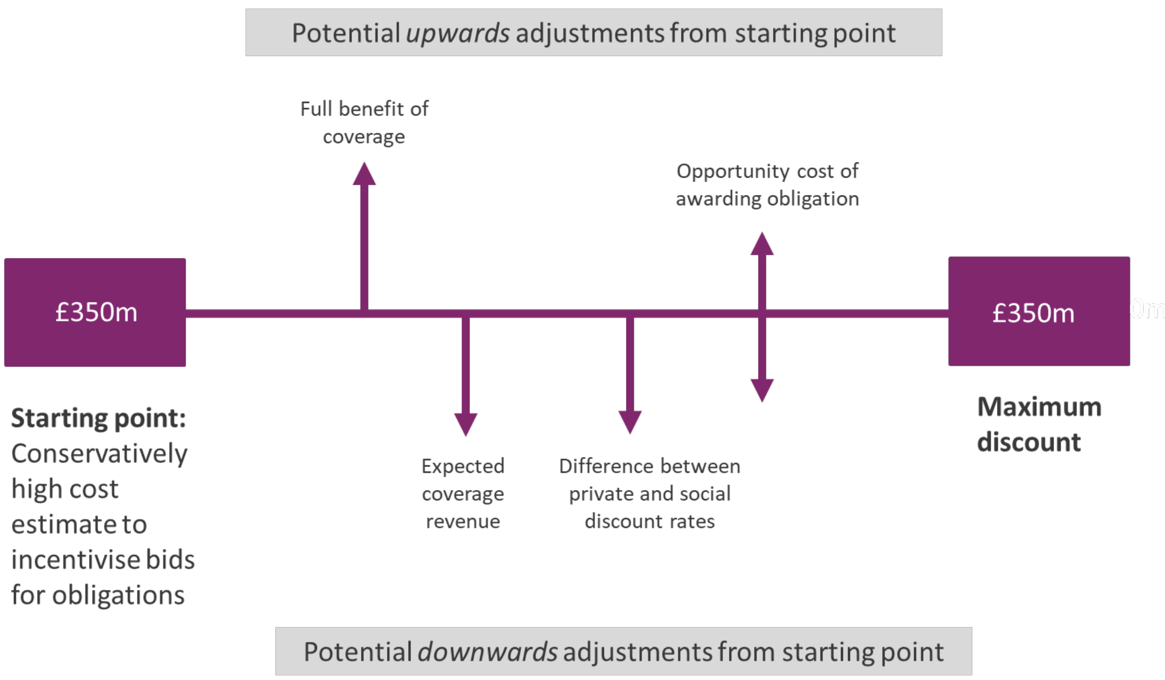
A13.8 In order to fulfil the second of these two functions (balancing the costs and benefits of awarding the coverage obligations), there are a number of considerations to take into account. These, in theory, suggest different directions of adjustment from the starting point of **£350m**:

- an upward adjustment to reflect the full benefits of the coverage obligation;
- a downward adjustment to subtract revenue that the bidder acquiring the coverage obligation might expect to receive from increasing its coverage (and so reflects in its bids);
- a downward adjustment to reflect the difference between private discount rates, which we expect operators to take into account in their auction bids, and the social discount rate appropriate for the purposes of comparing costs and benefits; and
- a possible adjustment in either direction for the loss in total bid value to reflect accurately the opportunity cost of awarding the coverage obligation.

A13.9 However, the size of each adjustment and the relative size of upward and downward adjustments are inherently uncertain. Given the offsetting effects and the uncertainty, we consider it would be reasonable to set the maximum discount in the range of £300m-£400m, with a central case of **£350m**.

A13.10 This is summarised in the diagram below, using the central case for illustration.

Figure A13.1: Summary of derivation of maximum discount



A13.11 We elaborate on the two functions of the maximum discount below.

Incentive to bid for a coverage obligation

A13.12 Offering a discount in the award for taking on a coverage obligation provides bidders with an incentive to bid for the obligation. We expect a bidder would be prepared to bid for (and acquire) a coverage obligation where its overall costs of meeting the obligation minus any additional revenue that the obligation would provide are outweighed by the maximum discount.

A13.13 The maximum discount is the reserve price for the coverage obligation lots in the auction. We generally adopt a conservative approach in setting reserve prices, for spectrum (see section 7) as well as coverage obligations. For spectrum, we prefer to set the level of reserve prices materially below benchmarks for possible market value, to avoid dissuading bidders from bidding for lots in the auction. This implies analogously for coverage obligations that a reasonable starting point for our maximum discount should be materially higher than our estimates for possible costs of meeting the obligation, to avoid dissuading bidders from bidding for coverage obligations in the auction (and noting that some stakeholders suggested that costs could exceed our estimates). For convenience, we refer to this as a conservatively high estimate of the costs of meeting the obligation.

A13.14 In annex 14 we identify a range for our cost estimates of £170m – £340m.[401] Although we consider that this range may already be conservative, for the purpose of setting a reserve price we consider that we should go well above the bottom end of this cost estimate range. Also taking into account the risk of spurious precision, we therefore consider that the maximum discount should be at least £300m, which is in the upper part of our cost estimate range. However, this figure is below the top end of our cost estimate range so there is still a risk that a maximum discount at this level might not be sufficiently high to incentivise bids for the coverage obligations.

A13.15 We would prefer to set a reserve price for coverage obligations materially higher than our estimates for possible costs of meeting the obligation, noting also the inevitable degree of uncertainty in our cost estimates. There may therefore be a case for setting the maximum discount for coverage above the top end of this cost estimate range. This suggests the potential for a maximum discount up to £400m to increase the chances of incentivising bids for the coverage obligations. The central case in this range for the starting point for the maximum discount of £300m to £400m is £350m.

A13.16 However, we consider that bidders' *net* costs may be lower than our starting point due to the revenue bidders may expect to receive from meeting the coverage obligation. For example, a bidder who wins a coverage obligation may gain subscribers in the areas of extended coverage due to consumers switching to it as a result of the improvement in the extent and quality of its coverage. In addition, an operator may be able to sell higher value

[401] As set out in annex 14, this is our estimate of operators' costs of meeting the coverage obligation, using a weighted average cost of capital (WACC) for mobile operators as the discount rate. This use of a private sector discount rate, reflecting operators' perspective on costs, is relevant when considering the first function of the maximum discount rate to incentivise bids for coverage obligations from bidders.

packages (such as larger data allowances) to customers who will experience higher quality data coverage as a result of the obligation.

A13.17 There would be an incentive to bid for a coverage obligation as long as the discount covered the bidder's costs of meeting the obligation minus any additional revenue[402] that the obligation would provide (which we refer to as the "net cost").

A13.18 We note, then, that there may be a case to reduce the maximum discount below a conservatively high estimate of obligation costs, to take account of obligation revenues. The potential revenue could vary within a wide range: it could be small or much more material, depending on the extent of consumer switching due to the coverage obligation.[403] The size of any downward adjustment to take account of obligation revenues is therefore very uncertain.

Balancing the full costs and benefits of awarding an obligation

A13.19 The second function of the maximum discount in the award is to limit the circumstances in which a coverage obligation is awarded, to seek to ensure that an obligation is only awarded where we consider that the benefits it will deliver are likely to exceed the opportunity costs. The opportunity cost would consist of both the resource cost of an obligation, and any change in the allocation of spectrum that could result from awarding it. We have set out examples of how the maximum discount limits the opportunity cost associated with awarding a coverage obligation at the end of this annex.

A13.20 For this second function, the role of the maximum discount is to take account of the benefits of a coverage obligation. By contrast, the opportunity cost of awarding an obligation would be reflected in the bids in the auction from bidders through the loss in total bid value, i.e. the difference in the value of bids with and without the obligation.[404]

A13.21 Taking account of the costs and benefits of awarding an obligation suggests both upwards and downwards adjustments from our starting point of a conservatively high estimate of costs for the maximum discount. We discuss these theoretical adjustments below.

Full benefits from a coverage obligation suggest an *upward* adjustment to the maximum discount

A13.22 In section 4 and annex 11, we discuss the various ways in which increasing coverage through an obligation might deliver social benefits. In our view the benefits of our proposed obligations are at least as high as £400m to £500m, which is above our starting point for the maximum discount.[405] For example, for the central case of £350m, the full benefits would be at least £50m to £150m larger than the maximum discount.

[402] Although we refer to 'revenue' for simplicity, we expect the bidder's incentive to bid for a coverage obligation to reflect the expected profits associated with any additional revenue (i.e. after accounting for any relevant costs).
[403] We discuss the level of consumer switching to the obligation holder in annex 12.
[404] We define 'total bid value' as the value of the bids in the candidate winning combination of bids (which includes at most one bid from each bidder) excluding Ofcom's reserve bids for spectrum and coverage lots that would not be allocated to a bidder in that bid combination. 'Total auction value', by contrast, includes Ofcom's reserve bids for any unallocated spectrum and coverage lots in the bid combination.
[405] See annex 12 for illustrative calculations of these social benefits.

A13.23 This suggests that, in principle, the maximum discount could potentially be at least as large as £400m-£500m if it is to reflect the full potential benefits of our proposed obligations, and so should be increased beyond our starting point. Otherwise we might not award an obligation even where we expect the benefits it would deliver would exceed the opportunity costs.

Coverage obligation revenue suggests a *downward* adjustment to the maximum discount

A13.24 As set out above, bidders may expect to gain some revenue from the coverage obligations. There is therefore a case to reduce the maximum discount below the starting point, since it reflects a conservatively high estimate of costs before any expected revenue from an obligation is taken into account. We would expect bidders to reflect the expected net cost of an obligation in their bids, which in turn would be reflected in the loss in total bid value (i.e. the larger the expected revenue, the smaller the loss in total bid value). Therefore, to maintain an appropriate balance between the benefits and costs of an obligation, the maximum discount should correspondingly be reduced.

A13.25 This downward adjustment would be relevant to both functions of the maximum discount: (i) the incentive to bid for a coverage obligation as discussed above; and (ii) for the maximum discount to balance benefits and costs of an obligation.

A13.26 As we have said, it is very difficult to estimate the revenues (and therefore, the extent of any downward adjustment), which could be small or much more material.

The difference between private and social discount rates suggests a *downward* adjustment to maximum discount

A13.27 When valuing spectrum and assessing the costs of meeting coverage obligations, operators would expect to receive revenues and incur expenditures on capital and operating costs at various times over a forward-looking 20-year period. Auction bids for spectrum and coverage obligations are expressed in terms of an upfront lump-sum (or present value) figure.

A13.28 To formulate such values for the purpose of auction bids, we would expect operators to take account of a private discount rate that they consider suitable for that purpose. For example, when we estimate operators' costs of meeting the coverage obligation in annex 14, we use a weighted average cost of capital (WACC) for mobile operators as the discount rate. This is reflected in the cost estimates reported above, from which we derived the starting point for the maximum discount. Using a private sector discount rate is an appropriate approach when considering the first function of the maximum discount to provide an incentive for bidders to bid for a coverage obligation.

A13.29 However, the second function of the maximum discount is to reflect the balance between costs and benefits. As explained in annex 14, we consider it appropriate to use a social discount rate when comparing costs and benefits - specifically, the social time preference rate (STPR). For example, we use the STPR as the discount rate for the illustrative calculations of benefits in annex 12.

A13.30 There may therefore be a mismatch between the private discount rate(s) reflected in auction bids, and so also in the loss in total bid value, and the social discount rate which is appropriate to reflect the balance between costs and benefits.

A13.31 In general, we expect the STPR to be lower than the private discount rate(s) used by operators when formulating their values and bids. For example, the STPR is 5.6%, whereas the WACC for mobile operators is 7.6% (both expressed in nominal terms). Discounting the same future cash flows at a lower discount rate would imply a higher present value figure. In theory, therefore, the difference between private and social discount rates suggests a case for an upward adjustment to the loss in bid value (e.g. adding a pre-specified £m amount to the observed loss in bid value from auction bids), or equivalently a downward adjustment to the maximum discount.

A13.32 An indication of the order of magnitude of the possible adjustment can be provided using our estimated costs of an obligation, comparing the difference between the ranges of:

- £170m-£340m with a private discount rate (the WACC); and
- £200m-£400m with the social discount rate (the STPR).

A13.33 The difference between these two ranges is £30m-£60m.

A13.34 However, the appropriate size of the adjustment is uncertain. For example, it would depend on the pattern of bidders' expected future cash flows reflected in their relevant auction bids and the difference between the STPR and the relevant private discount rates that bidders use (which underpin the loss in bid value). In the auction we will not observe either the pattern of cash flows or the private discount rates used by bidders, only the resulting bids that they make.

The opportunity cost of a change in the allocation of spectrum suggests a possible adjustment in either direction

A13.35 Our general approach to awarding spectrum in circumstances where demand is likely to be greater than the amount of spectrum available is to allow the market to determine the best allocation. In most circumstances, we believe an auction is the most appropriate way of allowing the market to determine the most efficient allocation because we design our spectrum auctions to seek to ensure that each spectrum lot is allocated to the bidder who has the highest intrinsic value for it (subject to competition measures).

A13.36 We recognise in section 7 that including coverage obligations may result in a change to the allocation of spectrum that would otherwise be achieved, absent any obligations. There would be an opportunity cost associated with this, which we would expect to be reflected in loss in total bid value. This is because a change in the allocation of spectrum would involve some of the spectrum being allocated to a coverage bidder, displacing a higher-value bidder for that spectrum.

A13.37 The maximum discount imposes a limit to the loss in total bid value resulting from a coverage obligation being awarded and, in doing so, seeks to balance the benefits of awarding coverage obligations with the opportunity costs of doing so. As such, it therefore acts as a limit on the possible change in allocation of spectrum.

A13.38 In other words, the obligation will only be awarded if the loss in total bid value is less than the maximum discount. The larger the change in the allocation of spectrum, the greater the loss in bid value and so the less likely it is that an obligation would be awarded. See example 3 at the end of this annex for an illustration of how this works in practice.

A13.39 However, there may be circumstances where loss in total bid value is not equivalent to the true opportunity cost of awarding a coverage obligation. This would suggest we should adjust the maximum discount in order to maintain an appropriate balance between costs and benefits in the winner determination.

- If the loss in total bid value understates the full opportunity cost of changing the spectrum allocation, this would suggest we should *decrease* the maximum discount. An example of how opportunity cost may be understated is if this loss in bid value does not capture any potential lost consumer surplus as a result of a bidder not being awarded spectrum despite having the highest intrinsic value for it e.g. if that bidder goes on to provide lower-quality or slower roll-out of new services. There is therefore a risk that a higher maximum discount could lead to a coverage obligation being awarded when the full opportunity costs exceed the benefits of improving coverage.
- If the loss in total bid value overstates the full opportunity costs, this would suggest we should *increase* the maximum discount. An example of this potential overstatement is if, despite a bidder winning more spectrum as a result of winning the coverage obligation, the efficient allocation may still be achieved through a post-auction trade between the coverage bidder and the bidder that has the highest intrinsic value. The result of any such trade would be that the spectrum still ends up with the bidder who has the highest intrinsic value for it. This would mean that the eventual opportunity cost of awarding a coverage obligation (i.e. after the post-auction trade) would be less than the loss in total bid value in the auction. A lower maximum discount may therefore lead to a coverage obligation not being awarded, despite the benefits exceeding the true opportunity costs.

A13.40 There may also be circumstances when, in principle, we would not wish to adjust the maximum discount to align the loss in total bid value and the opportunity cost for awarding a coverage obligation. For example, the allocation of spectrum might not change as a result of awarding an obligation or, even if there is a change in the allocation of spectrum, there might be no loss in consumer benefits as a result.

A13.41 An example of why there might be no loss in consumer benefits is if a bidder incurs a higher network cost due to winning less spectrum, but decides to nevertheless provide the same network and services as it would have if it had won the spectrum (e.g. by building more sites or re-farming other spectrum). In this case, there would be no loss in consumer benefits from the change in the allocation of spectrum and the loss in bid value in the auction would provide the appropriate measure of opportunity cost for the cost-benefit balance. This situation would imply no adjustment to the maximum discount.

A13.42 It is therefore unclear: (i) whether we should make an adjustment to the maximum discount to take account of the opportunity costs associated with potentially changing the allocation of spectrum; (ii) whether any such adjustment should be upwards or downwards; and (iii) the size of any upward or downward adjustment.

We propose to set the maximum discount for each 90% obligation within the range of £300m-£400m, with a central case of £350m

A13.43 In summary, we consider that £300m to £400m with a central case of £350m – reflecting conservatively high estimates of costs of meeting an obligation – would be a reasonable starting point for the maximum discount for the coverage obligations.

A13.44 The effects discussed above imply different directions for possible adjustments to the maximum discount from this starting point. In addition, there is a great deal of uncertainty over the size of any such net adjustment. We therefore consider that it would be reasonable to set the maximum discount within the range of £300m-£400m, with a central case of £350m.

A13.45 We think this would allow the maximum discount to perform both of its functions in the auction. First, it would provide bidders with incentives to bid for the coverage obligations. Since the proposed discount is based on a conservatively high estimate of the costs of meeting the proposed obligations (before subtracting potential revenue from an obligation), there may be competition for the coverage lots leading to excess demand, which would bid down the discount. Second, the maximum discount at this level would assist in achieving a reasonable balance between the opportunity costs of awarding an obligation and the benefits.

Example of how the maximum discount limits the opportunity cost associated with awarding a coverage obligation

A13.46 As set out above, the second role of the maximum discount is to balance the costs and benefits of awarding a coverage obligation.

A13.47 To illustrate how the maximum discount performs this role in practice, we have set out three examples below. Each of these examples considers three scenarios that have different bid values. For each scenario, we have shown possible winning combinations of bids, which respectively include and do not include bids on coverage. For simplicity, these examples show only one obligation, with a maximum discount of 50. The outcome of the winner determination for each scenario is as follows:

- **Scenarios 1 and 2: the obligation is sold –** The opportunity cost of awarding the coverage obligation is lower than the maximum discount. The allocation of spectrum does not change, or changes by a small amount which is allowed within the limit set by the level of maximum discount.

- **Scenario 3: the obligation is unsold –** The opportunity cost of awarding the coverage obligation is higher than the maximum discount. In this case the obligation is bid for but not awarded, because this would have required the allocation of spectrum to change by too much relative to the maximum discount.

A13.48 The first two examples describe two equivalent methods of deriving the auction outcome, and how the maximum discount features in both. In the first example, we set out how the maximum discount imposes a limit on the overall opportunity cost associated with the coverage obligation, and therefore limits the circumstances under which we would award the obligation. The second example shows how the auction outcome can equivalently be determined by seeking the combination that maximises total auction value. Finally, the third example shows how the maximum discount limits the opportunity cost associated specifically with a change in the allocation of spectrum.

Example 1: maximum discount limits overall opportunity cost associated with awarding coverage obligation

A13.49 One way to determine the outcome is to compare the opportunity cost of awarding the obligation in auction bids against the maximum discount (set at 50). Where the opportunity cost is larger than the maximum discount, the obligation will remain unsold. The opportunity cost in the auction of awarding the coverage obligation is reflected in the loss in total bid value. As shown in the table below, the loss in total bid value is difference between bid combinations B and A, i.e. between combinations with the highest bid values for spectrum (without a coverage bid) and the highest bid values that include a bid for the coverage obligation. The table below sets out the bid values and outcomes for the three scenarios.

Figure A13.2: Total bid values from bidders for stylised combinations of bids for spectrum and coverage obligation

	Scenario 1	Scenario 2	Scenario 3
Highest bid value for combination that **includes** bid for coverage obligation (A)[406]	70	70	70
Highest bid value for combination that **does not include** bid for coverage obligation (B)[407]	100	110	125
Opportunity cost of awarding coverage obligation (B – A)	30 (=100 – 70)	40 (=110 – 70)	55 (=125 – 70)
Outcome	Opportunity cost is less than max discount (30 < 50) A is winning combination, coverage is awarded	Opportunity cost is less than max discount (40 < 50) A is winning combination, coverage is awarded	Opportunity cost is greater than max discount (55 > 50) B is winning combination, coverage is not awarded

A13.50 As the table above shows, for scenarios 1 and 2, the opportunity cost of awarding the coverage obligation is 30 and 40 respectively. These are both lower than the maximum discount. Therefore for both scenarios the winning outcome is combination A, and the coverage obligation is sold.

A13.51 In scenario 3, the opportunity cost of awarding the coverage obligation is 55. This is higher than the maximum discount, resulting in the coverage obligation not being sold, and combination B being the winning outcome.

Example 2: outcome is determined by finding the combination that maximises auction value

A13.52 The winner determination can be described in two equivalent ways. In example 1, we describe that a bid for a coverage obligation would win as long as the maximum discount is at least as large as the loss in 'total bid value'. In this second example, we set out an

[406] To generate combination A, we maximise total bid value, subject to the constraint that the coverage obligation is allocated to one of the bidders.
[407] To generate combination B, we maximise total bid value, excluding any bids that include the coverage obligation.

equivalent way to derive the outcomes, which is to examine which combination had the higher 'total auction value' in each scenario.[408] This is because the auction outcome is determined by the combination that achieves the highest total auction value.

A13.53 For combinations that include bids from bidders on the coverage obligation, the total auction value would be the same as the total bid value from bidders. For combinations that do not include bids on the coverage obligation, the total auction value would be the total bid value from bidders less the maximum discount (since if this were the winning combination, the benefits of the coverage obligation not be obtained).[409] To illustrate this, the table below shows the total auction value for the same scenarios and bid combinations A and B as in example 1 above (which, respectively, include a bid on coverage and do not include a bid on coverage).

Figure A13.3: Total auction value for stylised combinations of bids for spectrum and coverage obligation

	Scenario 1	Scenario 2	Scenario 3
Total **auction value** for combination A (total bid value for A)	70	70	70
Total **bid value** for combination B	100	110	125
Total **auction value** for B (total bid value for B less the maximum discount)	50 (=100-50)	60 (=110-50)	75 (=125-50)
Outcome	Highest total auction value is A (50 < 70) A is winning combination, coverage is awarded	Highest total auction value is A (60 < 70) A is winning combination, coverage is awarded	Highest total auction value is B (75 > 70) B is winning combination, coverage is not awarded

A13.54 The table shows the total auction value for combination B includes Ofcom's reserve bid of 50, as there are no bids from bidders on the coverage obligation in that combination. In the first two scenarios, we can see that combination A has a total auction value of 70, which is higher than combination B for scenario 1 (50) and scenario 2 (60). Therefore, A is the winning combination and the coverage obligation is awarded to a bidder in both of these scenarios. This is reversed in scenario 3, where combination A has a value of 70,

[408] "Total auction value" includes both the value of the bids in the combination from bidders and reserve bids from Ofcom for any unallocated spectrum or coverage lots in that bid combination. This is different to "total bid value", which excludes reserve bids from Ofcom for spectrum and coverage lots.
[409] Since Ofcom's reserve bid for the coverage obligation is a negative amount, i.e. the maximum discount on the price of spectrum, this can equivalently be expressed as the sum of total bid value and the negative reserve bid for the obligation.

which is lower than combination B's value of 75. We can therefore see that the obligation remains unsold in scenario 3, as the combination with the highest total value is combination B (which does not include a bid from a bidder on coverage). Example 2 is therefore the same as example 1, just showing the two equivalent ways to derive the auction outcome.

Example 3: maximum discount limits opportunity cost associated with a change in the allocation of spectrum

A13.55 As set out previously in this annex, we would expect the opportunity cost associated with awarding coverage obligations to reflect both of the following components: (1) the net cost of the obligation to bidders; and (2) the opportunity costs associated with any change in the allocation of spectrum. We would expect both of these to be reflected in loss in bid value. The maximum discount imposes a limit to the sum of these components of opportunity cost, enabling the auction to determine whether a bid including the coverage obligation is a winning bid.

A13.56 To illustrate this, in this third example we have expanded on the scenarios in examples 1 and 2 by including the bid values for a third possible combination (C) in addition to the same combinations A and B as above. While combination A is the highest bid value that includes a bid for the coverage obligation, combination C includes the same allocation of spectrum between bidders as combination A but without a bid on the coverage obligation.[410] Combination C therefore allows us to decompose the difference between combinations A and B in terms of the two components of opportunity cost.

A13.57 The outcome of these scenarios, with regards to whether there is a change in the allocation, is:

- **Scenario 1 – the obligation is sold with no change in spectrum allocation:** There is no opportunity cost associated with the change in the allocation of spectrum.
- **Scenario 2 – the obligation is sold, which results in a change in spectrum allocation:** There is a smaller opportunity cost associated with changing the allocation of spectrum. This means that there has been a change in allocation, as a result of awarding the coverage obligation.
- **Scenario 3 – the obligation is not sold, as it this would require too large a change in the allocation of spectrum:** There is a larger opportunity cost associated with changing the allocation of spectrum. This means that too significant a change in the allocation would have been required in order to award the coverage obligation.

[410] This combination C assumes that the coverage bidder in combination A also bid for a package that includes the same amount of spectrum as its bid in combination A, but without the coverage obligation.

Figure A13.4: Components of opportunity cost associated with awarding a coverage obligation

	Scenario 1	Scenario 2	Scenario 3
Highest bid value for combination that **includes** bid for coverage obligation (A)	70	70	70
Highest bid value for combination that **does not include** bid for coverage obligation (B)	100	110	125
Bid value for combination **with same spectrum allocation** as A**,** but does not include bid for coverage obligation (C)	100	100	100
Net cost to bidder of the coverage obligation (C – A)	30 (=100 – 70)	30 (=100 – 70)	30 (=100 – 70)
Opportunity cost of changing the allocation of spectrum (B – C)	0 (=100–100)	10 (=110–100)	25 (=12 –100)
Overall opportunity cost of awarding coverage obligation (net costs + opportunity costs of changing spectrum allocation) [411]	30 (=30 + 0)	40 (=30 + 10)	55 (=30 + 25)
Outcome	Coverage is awarded There is no change in the allocation	Coverage is awarded There is a change in the allocation, with an associated opportunity cost of 10	Coverage is not awarded The opportunity cost associated with awarding the obligation is 25

A13.58 Combinations A and C include the same allocation of spectrum, with the only difference being the coverage obligation. As such, we would expect the difference in bid value between these combinations to reflect the net cost of the obligation to the coverage bidder. The difference between combinations C and B is only the change in the allocation of spectrum if B was to be the winning combination. This therefore allows us to isolate the opportunity cost in auction bids of the change in the allocation of spectrum.

[411] As shown in table 13.1, an equivalent way of deriving the total opportunity cost would be (B – A).

A13.59 For scenario 1, the bid value of combination B is the same as combination C. From this, we can ascertain that there is no opportunity cost associated with changing the allocation, which means there was no change in the allocation of spectrum as a result of awarding the obligation.

A13.60 However in scenario 2, we can see that there is an opportunity cost associated with changing the allocation of 10. This means that, in order for the coverage obligation to be awarded, a change in the allocation of spectrum is necessary.

A13.61 For both scenarios 1 and 2, the overall opportunity cost associated with awarding the coverage obligation is less than the maximum discount (50), resulting in the obligation being awarded. This means that, although scenario 2 requires a change in the allocation in order to award the coverage obligation, the opportunity cost associated with this change in allocation is justified by the benefits reflected in the maximum discount.

A13.62 By contrast, in scenario 3 the overall opportunity cost (55) is greater than the maximum discount (50), and so the obligation remains unsold. This is due to the larger opportunity cost associated with the change in allocation (25), compared to scenarios 1 and 2. In other words, in order for the obligation to sell in scenario 3, this would require a greater change in the allocation and larger costs than would be justified.

A14. The cost of meeting our proposed coverage obligations

A14.1 In section 4 of this consultation document, we set out our proposal for including two coverage obligations in the auction and our estimate of the likely costs of meeting these obligations. Each of these obligations would require the operator who wins it to provide (i) at least 90% geographic coverage; (ii) good outdoor 4G coverage at a minimum of 140,000 premises to which the licensee does not provide such coverage on the date of the auction and (iii) build at least 500 new sites.

A14.2 In this annex, we explain our basis for the minimum quality at which we expect the proposed obligations to be delivered and set out in more detail the technical analysis we have done to estimate the costs of meeting them.

Summary of our approach to estimating the cost of the proposed obligations

The mobile coverage metrics required to deliver a good mobile user experience

A14.3 Consumers and businesses increasingly rely on good quality mobile voice and data service. Our analysis, informed by real-world consumers reporting dissatisfaction with their service, has led us to conclude that a good service is likely to be characterised as:

- more than 95% of voice calls can be made without interruption; and
- a connection speed of at least 2Mbps is available with a more than 95% probability to provide the throughput needed for more demanding data services such as video streaming.

A14.4 On the basis of our drive testing measurements, we consider that this level of service requires an average signal level of at least -105dBm. Our costs estimates are based on this minimum signal level.

Estimating the number of additional sites for extending coverage and their approximate cost

A14.5 To estimate how much it is likely to cost operators to fulfil the proposed obligations, we had to first reach a preliminary view on the level of coverage each operator is likely to provide at the date of the auction. To do this, we used our formal powers to request information from each operator on the levels of coverage they expect to provide by June 2019. Our results are set out in Figure 14.1 below[412].

[412] Responses to this request were in the format of signal strength provided by each operator in 100m x 100m pixels across the UK (of which there are 24 million). We then checked each pixel, and where there was a signal strength over -105 dBm (which is our measure of good 4G outdoor coverage), we assigned coverage to that pixel. We then counted the number of 100m x 100m pixels with “good coverage” and took that number as a percentage of all 24 million pixels to come up with a percentage figure for outdoor coverage for each operator.

Figure 14.1: Operators' 4G landmass coverage (June 2019 projections)

[✂ REDACTED]

A14.6 As set out in section 4, we expect that a typical operator will reach around 82% geographic coverage over the 20-year period we are considering, absent the coverage obligations we are proposing, and that one operator (BT/EE) is likely to provide more coverage (84%). To ensure that our proposed obligations would be achievable for all operators, the starting point for our analysis is the costs that a typical operator would face in our counterfactual (i.e. starting from 82%), although our analysis also gives us a view of the costs that EE might face.

A14.7 However, starting our cost analysis from the counterfactual for a typical operator would require us to predict the locations where a typical operator is likely to add coverage. Since this would introduce additional uncertainty, we have initially modelled the network roll-out of a typical operator starting from the coverage levels and locations operators have told us they will soon reach (around 80%) and deducted the additional sites that we consider they will add themselves under our counterfactual at the end of our analysis (see step "d" below).[413]

A14.8 For this analysis we have used a commercial cellular planning tool capable of undertaking a network dimensioning exercise, with the aim of filling in the coverage gaps in footprints given to us by operators. This involved four steps:

- Establishing the number of new sites needed to fill in all of these coverage gaps, up to a level close to 100% of the UK landmass. Our analysis suggests that this would require approximately 6,000 sites;
- Establishing the number of sites needed to reach different geographic coverage levels between the positions operators have told us they expect to reach shortly, up to the 92% level we originally proposed in our March 2018 consultation;
- We then looked in particular at the 90% level we are now proposing. Our analysis[414] suggests that approximately 600-1100 sites could be needed;

[413] To support our March 2018 consultation, we undertook a network modelling exercise from the coverage level of 80% that one operator had told us they expected to reach. We have subsequently supplemented that work with further modelling based on another operator's predictions for June 2019, and present both pieces of analysis here.
[414] In summary, we have estimated which of the additional sites required to cover almost all of the UK would be most efficient to deliver good 4G coverage over 90% of the UK.

- We then took account of our expected counterfactual for operators in the absence of obligations. We estimated that, in our counterfactual, a typical operator would start with the equivalent of approximately 100 additional sites, compared with coverage they have told us they will achieve in June 2019. On this basis, we estimated that a typical operator is likely to require in the order of 500-1000 sites to deliver 90% coverage. We also observed that an operator starting with more coverage (e.g. if BT/EE remained around the 84% level we think plausible in our long-run counterfactual) this requirement could fall to between 300-700 new sites (some of which might be sites covering small areas).

A14.9 As part of our proposals, we want to ensure operators provide improvements in coverage that can be noticed by consumers. To achieve this, we are proposing that each operator must deploy a minimum of number of new sites ('the new sites requirement') and bring good outdoor coverage to a minimum number of homes and businesses that did not previously have it from the obligated operator ('the premises requirement'). Based on the above analysis, we concluded that a requirement to build 500 new sites would be at the conservative end of the range for what we have estimated that a typical operator is likely to deploy to deliver the benefits we are seeking. We then carried out additional analysis of the number of premises that could be brought into coverage by adding 500 - 1000 new sites. We determined that bringing 140,000 new premises into outdoor coverage was a reasonable target for all operators within this 500 - 1000 site range.

A14.10 We then estimated the approximate cost of building 500 - 1,000 new sites. Our revised estimate of the average total site costs we expect operators to consider is in the region of £340,000, over 20 years (i.e. present value, taking into account both the initial cost of a site and the ongoing costs).[415] We derived this estimate by analysing the data provided by the operators under our formal powers in relation to the 100 - 1000 most expensive total site costs for sites operators have deployed in the last four years.

[415] Note that this is based on a Weighted Average Capital Cost discount rate of 7.6%, and that for the purposes of making a comparison with the benefits we have assessed, we use an STPR of 5.6%, equivalent to a higher cost per site of £395,000

The mobile coverage metrics required to deliver a good consumer experience

A14.11 As we explained in our 2017 Connected Nations report, and in line with a recommendation from the National Infrastructure Commission (NIC), we have changed the way in which we measure coverage. This is because smartphones require stronger signals than older, simpler phones in order to function effectively. Therefore, we only consider an area to be covered if it receives a strong enough signal for a smartphone user to get a good voice and data service. In our March 2018 consultation, we said that, in practice, this level of service implies that a mobile operator is required to deliver a 4G signal strength of **-105 dBm** to achieve outdoor geographic mobile coverage in any given 100m^2 area (“pixel”) of the UK’s landmass. As discussed in Section [4], EE and Vodafone argued that this could lead to disproportionate costs and suggested that a lower signal strength would be appropriate in rural areas.

A14.12 In this section we describe the approach we have taken to establish the signal level thresholds needed to deliver a good consumer voice and data 4G (LTE) experience according to our current approach to measuring coverage. This analysis supports our view, which we set out in Section [4], that our current approach to measuring good mobile coverage remains appropriate for the coverage that we seeking to achieve through the proposed obligations.

A14.13 We consider that it is necessary to meet the following performance targets in order to ensure a good quality consumer experience:

- more than 95% of 90 second voice calls can be made without interruption; and
- a connection speed of at least 2Mbps is available with a more than 95% confidence to provide the throughput needed for more demanding data services such as video streaming. We recognise that demand for higher throughputs is likely to increase with time. However, measurements of mobile data service performance suggest that a reliable connection speed of at least 2Mbps meets most consumer connection requirements today and into the foreseeable future.

A14.14 Generally, the actual signal level within a 100m-by-100m pixel (area) varies around the average signal across the pixel. This is due to shadow fading caused, for example, by localised signal blockages by trees and buildings. This means that if an operator plans for a particular average signal level within a 100m-by-100m pixel, this planned signal strength or better will only be achieved over 50% of the area of each pixel. Thus, to meet a particular quality of experience (QoE) target, the average signal level within a 100m-by-100m pixel needs to be adjusted accordingly.

A14.15 Based on our drive and handset testing results, we have found that for outdoor use an *average* LTE Reference Signal Received Power (RSRP) signal level of -105dBm is needed to meet the performance targets set out above with at least 95% confidence. This signal level relates to the average signal available over a 100m-by-100m pixel as discussed above.

A14.16 More significantly from a consumer experience perspective, this average signal level of -105dBm ensures that voice and data services operate reliably over the area of the pixel. Thus, this average signal level of -105dBm ensures more calls can be completed without interruption and that a reliable data connection rate of at least 2 Mbps is available to consumers.

Coverage metrics should relate to delivering a good consumer experience

A14.17 Consumers increasingly expect to be able to achieve a good quality, reliable mobile connection experience wherever they are – be it indoors, outdoors or on the move. There is increasing use of smartphones and tablets amongst consumers, which are providing wider access to online mobile services but generally require stronger signals than older, simpler phones.

A14.18 Ofcom's research found consumers value the availability of reliable services[416]. More recent Ofcom research[417] showed that in areas with good signal coverage (i.e. those with a higher mobile signal strength), consumers used their phones to access a wide range of services almost wherever and whenever they want. Consumers valued access to services beyond basic calls and text messages, in particular access to: online maps, video and online information services.

A14.19 In contrast, in areas of poor signal coverage (i.e. those with a lower mobile signal strength) where less reliable lower speed connections are available, consumers only had access to more basic voice calls and text messaging, where calls are often dropped, and text messages not sent.

A14.20 Given the additional value of the services that can be provided to consumers and businesses with access to good signal coverage, we have chosen to use a signal strength metric that corresponds to being able to support a wide range of mobile services with high level of confidence.

A14.21 We are aware that factors beyond low signal level can also reduce the performance of mobile connections including interference from other base stations and handsets and network congestion. However, due to the practical difficulties associated with accurately measuring and assessing the effect of these additional factors, which typically affect various places to differing extents at different times of the day, we propose to use only received signal level to specify the minimum thresholds for the proposed coverage obligations. We also believe that the operators face strong commercial incentives to address issues such as network congestion over time.

---

[416] Ofcom 2016: Quality of service in telecoms. https://www.ofcom.org.uk/__data/assets/pdf_file/0025/78370/jigsaw_quality_of_service_in_telecoms.pdf.

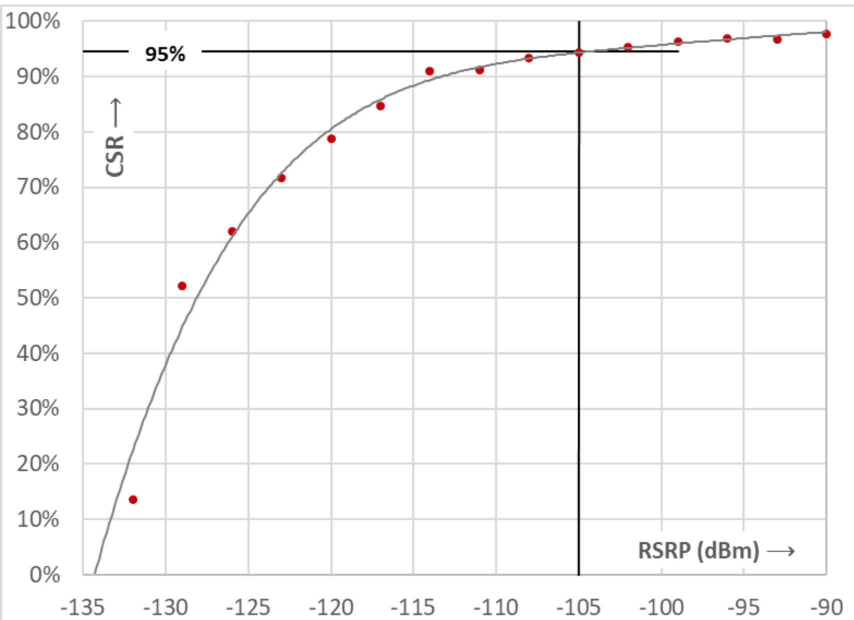
Voice call coverage performance metrics

A14.22 From a consumer perspective, the likelihood of being able to successfully make a telephone call without it being dropped has a direct impact on the experience of using mobile services. Because of this, it is a key performance indicator used by network operators. One way in which this can be specified is a call success rate (CSR). This is the probability that a call can be made and maintained for a given time. For example, a target CSR of 95% for 90 second calls would ensure that most consumers will have a good voice call experience for most of their calls.

A14.23 We have used a target CSR of 95% for 90 second calls to provide a high likelihood of a good experience for consumers. We have carried out drive testing to determine the average signal level needed to provide this level of CSR: we used smartphone handsets to make repeated voice over LTE (VoLTE) calls to a landline, and recorded the number of successful and unsuccessful calls for different measured average signal strengths during the calls[418]. The measurements were made on an in-service commercial LTE mobile network operating in a 5 MHz channel in the 800 MHz band. The test route was a few thousand miles long.

A14.24 We took accurate measurements of the average RSRP using calibrated industry-grade high accuracy radio frequency (RF) scanners[419]. The results from the tests are shown in Figure 14.2. This shows that the CSR reduces with reducing average signal strength. It also shows that an average signal level of -105 dBm is needed for 4G services to deliver a call success rate of at least 95%.

Figure 14.2: VoLTE CSR vs RSRP (Source: Analysis of Ofcom's field measurements)



[418] We used Ofcom's commissioned research to avoid the use of handsets with either superior or inferior sensitivity, https://www.ofcom.org.uk/research-and-data/technology/telecoms/mobile-handset-testing.
[419] We did not use the values for received signal power reported by the test handsets.

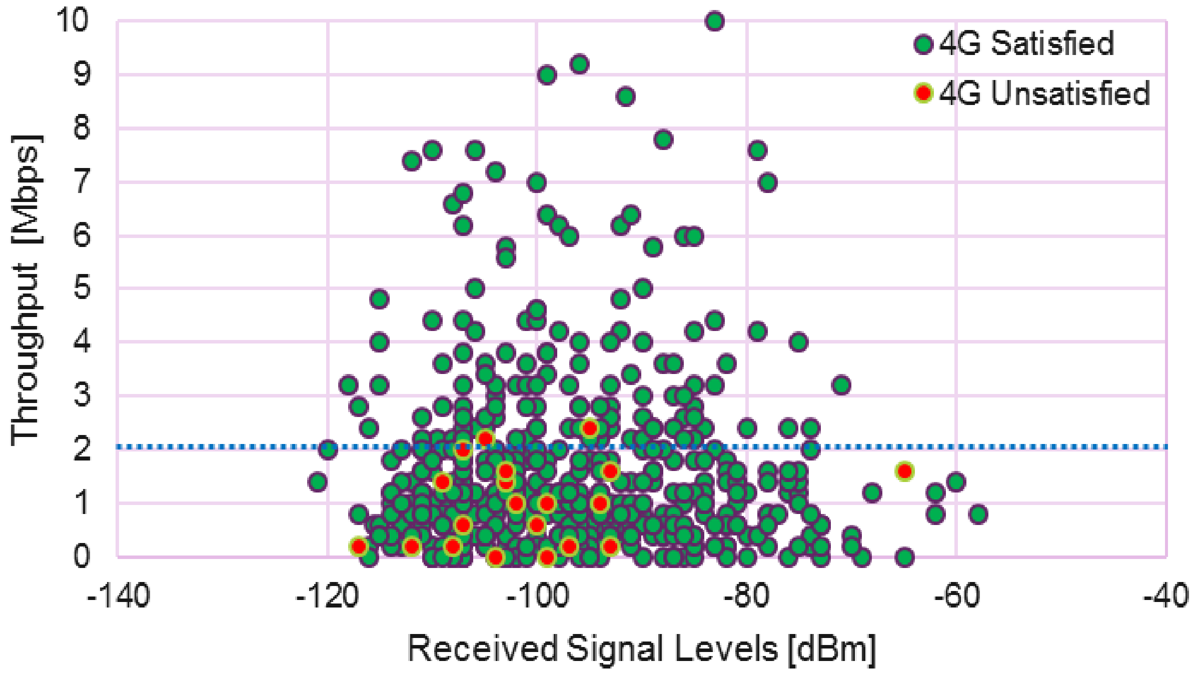
Data service metrics

A14.25 In 2016, Ofcom launched a mobile research app[420]. Once installed, the app ran a series of passive tests on the mobile phones. These measured network availability and performance, including connection speed. The app also allowed consumers to report whether they were satisfied with the quality of mobile services they were receiving. A total of 6,632 people downloaded the app and of these, 4,288 people retained the app on their phones for at least a week. Once collated, this set of anonymised data enabled us to record the mobile connection experience of the app users over time.

A14.26 We used the data collected from the research app to establish the correlation between consumer satisfaction and download throughput, which is shown in Figure 14.3. This plot shows that most reports of dissatisfaction occur when the download speed falls below 2Mbps. We have therefore set 2Mbps as the minimum download speed target to provide a high likelihood of a good experience for consumers, noting that 4G networks are capable of delivering much higher average and peak download speeds than this.

A14.27 A 2Mbps connection speed is also compatible with the highest download speed typically required to deliver standard definition video including more demanding content such as sports event coverage[421].

Figure 14.3: The correlation between consumer satisfaction and download throughput (Source: Ofcom's consumer research)



[420]Reports summarising the data obtained from the app are available from https://www.ofcom.org.uk/research-and-data/telecoms-research/mobile-smartphones/consumer-mobile-experience
[421]https://www.bbc.co.uk/iplayer/help/speed_checker_online

A14.28 We used drive testing to determine the average signal level needed to provide a high likelihood of providing a minimum of 2 Mbps data connection speed. We used Amazon Web Services to host a site from which handsets downloaded test files. The data connection speed measurements were made on a commercial LTE mobile network operating in a 5 MHz channel in the 800 MHz band. We measured and recorded the average signal strength for each of these downloads.

A14.29 Our testing showed that at higher signal levels there is a greater chance of achieving a given minimum connection speed. It showed that an average LTE RSRP of -105 dBm delivered a better than 95% chance of having a 2 Mbps service for outdoor use.

Signal strength for our proposed coverage obligations

A14.30 Based on our analysis of measurement campaigns, we have found that an average signal level of at least -105dBm is needed to provide a 95% VoLTE call success rate and a 95% or better chance of a 2Mbps connection speed being achieved. Therefore, we currently expect that an average 4G signal strength of -105 dBm would be needed to meet our proposed coverage obligations through 4G technology.

Estimate of the costs of meeting our proposed obligations

A14.31 In the remainder of this annex, we explain the analysis we have undertaken to inform our estimates of how much it would cost to meet our proposed obligations. We begin by setting out in more detail our approach to the network dimensioning exercise which has informed our view of the appropriate coverage obligation thresholds.

Overview of our network dimensioning study

A14.32 Mobile network planning plays a key part in rolling-out and maintaining services that address consumers' needs. Planning approaches have evolved significantly since the first and second-generation mobile networks deployed in 1990s. Nonetheless, the main aim remains the same: to deliver the most coverage and capacity to support services with the minimum amount of infrastructure, thereby minimising capital and operational expenditure.

A14.33 Mobile network planning can be split into three main stages: initial dimensioning, detailed-planning and optimisation:

a) Initial dimensioning provides a broad view of how many cell sites are needed and their associated roll-out costs.

b) Detailed-planning addresses the real-world deployment challenges by selecting locations where sites can realistically be deployed. The associated cost implications can deviate significantly from the initial estimates at this stage.

c) In the pre- and post-deployment optimisation, network performance is continuously monitored and optimised with reference to a range of factors: antenna orientation, tilts, sectorisation, power, resources, traffic or interference management.

A14.34 The approach we have followed for our cost estimates is akin to an advanced dimensioning exercise, such as is carried out in the first stage of network planning. We began by using operators' coverage prediction maps to identify areas of poor or no coverage in the UK.

A14.35 We then generated estimates of the number of new sites that would be required to provide coverage to these areas using a network dimensioning feature of a commercial cellular planning tool[422] to model a network design that would target uncovered areas with the minimum number of sites.

A14.36 We have applied constraints to the site deployment strategy that we modelled and used parameter ranges to ensure that dimensioned network remains reflective of the existing base station portfolio in the UK. Figure 14.4 provides the key settings used in this study.

A14.37 We have used detailed terrain and land usage (clutter) map datasets alongside an appropriate semi-deterministic propagation model[423] to capture the diverse topography of the UK. We have focused on the provision of downlink coverage and consider that

[422] ATDI, ICS Telecom EV, advanced radio planning and spectrum engineering.

[423] Recommendation ITU-R P.1812-4: A path-specific propagation prediction method for point-to-area terrestrial

moderate to good uplink performance would be achievable at the coverage levels we suggest due to our relatively high downlink RSRP threshold requirement (-105 dBm). We also note that there are technical solutions available to operators to balance both sides of the link.

A14.38 We recognise that building new sites is not the only way operators could improve their coverage. Other methods of increasing coverage which may be less expensive than building a new site include making amendments to their existing infrastructure and/or accessing other operators' infrastructure and sites. Hence, the results of our dimensioning study presented here are conservative in terms of estimating the overall level of costs required for coverage expansion.

Figure 14.4: Network dimensioning parameters

	Setting	Value
Base station	Minimum inter-site distance (ISD)	200 m
	Carrier frequency[424]	800 MHz
	LTE carrier bandwidth	10 MHz
	Radiated power (EIRP[425])	60 dBm
	Antenna height (above ground level)	20 m
	No of sectors \Antenna pattern	1\Omnidirectional
Receiver	Antenna height (above ground level)	2 m
	RSRP[426] coverage threshold	-105 dBm

Identification of areas of poor coverage for our network dimensioning study

A14.39 [✂ REDACTED]. We have selected two operaters [✂ REDACTED] and applied our good quality coverage threshold (-105 dBm) to their 4G predicted coverage[427] for the identification of operator specific areas of poor coverage.

A14.40 The selection [✂ REDACTED]. Figure 14.5 summarises the UK wide and per nation statistics of these uncovered areas with Figure 14.6 providing a visual perspective.

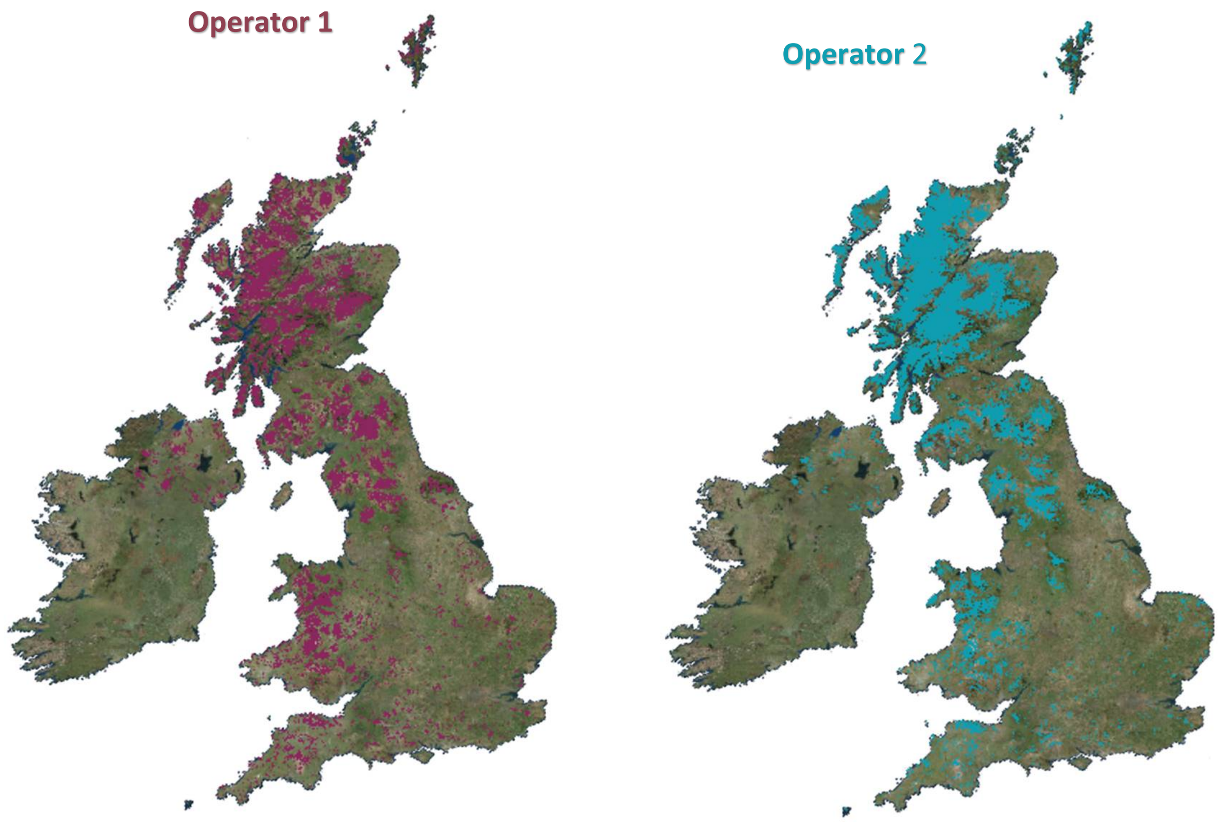
A14.41 We note that both operators provide good LTE coverage to approximately 80% of the UK landmass, however the level of coverage is quite different across nations, especially in Scotland and Wales.

[424] We have used 800 MHz for pathloss predictions noting negligible differences between 800 MHz and 700 MHz
[425] Effective Isotropic Radiated Power
[426] Reference Signal Received Power (RSRP) is defined as the linear average over the power contributions of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth.
[427] [✂ REDACTED].

Figure 14.5: Landmass statistics for areas of poor or no coverage

Nation	% of areas of poor or no coverage	
	Operator 1	Operator 2
England	[✂ REDACTED]	
Scotland	[✂ REDACTED]	
Wales	[✂ REDACTED]	
Northern Ireland	[✂ REDACTED]	
United Kingdom	[✂ REDACTED]	

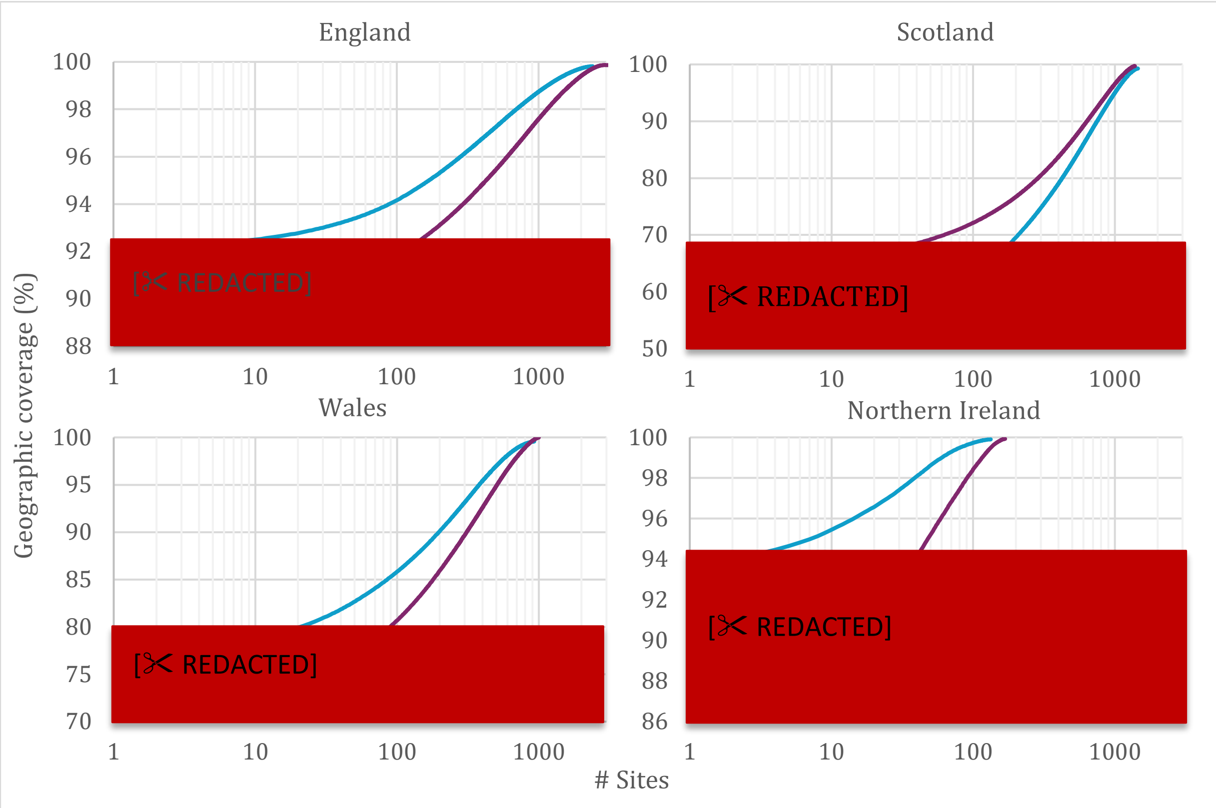
Figure 14.6: Areas of poor or no coverage included in the network dimensioning study



Results of our network dimensioning study

A14.42 Figure 14.7 presents the results of our dimensioned network for the areas of poor coverage of two operators in each Nation. The curves represent the cumulative distribution of coverage contribution from each additional site, ordered in the most to least significant contribution they make to the uncovered areas. We also provide the additional sites requirement statistics in Figure 14.8.

Figure 14.7: Additional sites required for extending coverage to ~100% of nations' landmass (– Operator 1, – Operator 2)[428]



A14.43 The results highlight that the nation which would require the highest number of new sites to reach 100% coverage is England, followed by Scotland, Wales and Northern Ireland; even though Scotland's areas of poor coverage in terms of landmass is roughly two or three times more than England's.

A14.44 The reason for this disparity is the projected level of coverage across nations. Because of lower current levels, areas of poor coverage in Scotland are generally contiguous, in contrast to England's patchy, spread out and non-continguous areas. The result of this is that in England a larger number of individual sites are required to cover small and non-contiguous areas of poor coverage, compared to Scotland, where sites can cover relatively larger proportion of uncovered landmass.

A14.45 A common trend across all nations' results is the exponential increase in additional sites required for the last few percent of the uncovered landmass where each additional site provides progressively less additional coverage. These sites are required to fill small coverage holes due to difficult terrain or non-contiguous nature of areas of poor coverage.

---

428 Note that we have redacted elements of this figure to protect confidential information on the starting points of operators used in this analysis

A14.46 Note that our proposed nations targets are set at lower levels than the ~100% end point of this modelling exercise. Taken on its own, our proposal for geographic coverage in England and Northern Ireland of at least 90% (in line with our overall requirement) might not drive significant additional coverage in these areas (though the impact of this will vary depending which operator acquires the obligation). However, our proposed requirement to bring additional premises into coverage, and deploy new mobile sites, whilst not specific to an individual nation, are likely to see additional coverage investments in these areas. As can be seen from Figure 14.7, our proposed targets for Scotland (74%) and Wales (83%) are likely to safeguard significant new investments in coverage in these Nations for a typical operator.

Figure 14.8: Area statistics for extending coverage to ~100% of the UK landmass

Operator 1	**UK Total**	**England**	**Scotland**	**Wales**	**Northern Ireland**
Area of no coverage (km^2)	[✂ REDACTED]				
% proportion of no coverage area	[✂ REDACTED]				
# of additional sites	5,793	3,242	1,383	1,000	168
% of additional sites	100 %	56 %	24 %	17 %	3 %
Operator 2	**UK Total**	**England**	**Scotland**	**Wales**	**Northern Ireland**
Area of no coverage (km^2)	[✂ REDACTED]				
% proportion of no coverage area	[✂ REDACTED]				
# of additional sites	4,923	2,401	1,453	928	133
% of additional sites	100 %	49 %	29 %	19 %	3 %

Sensitivity analysis of our dimensioning study results

A14.47 We recognise that our network dimensioning study does not cover all network planning activities required for real world deployments. We also note that any attempt to derive the site requirements using a desk-based modelling approach is inevitably going to be affected by several sources of uncertainty, especially when the areas we are attempting to cover include the most difficult terrain in the UK that can severely impact propagation and hence the site coverage.

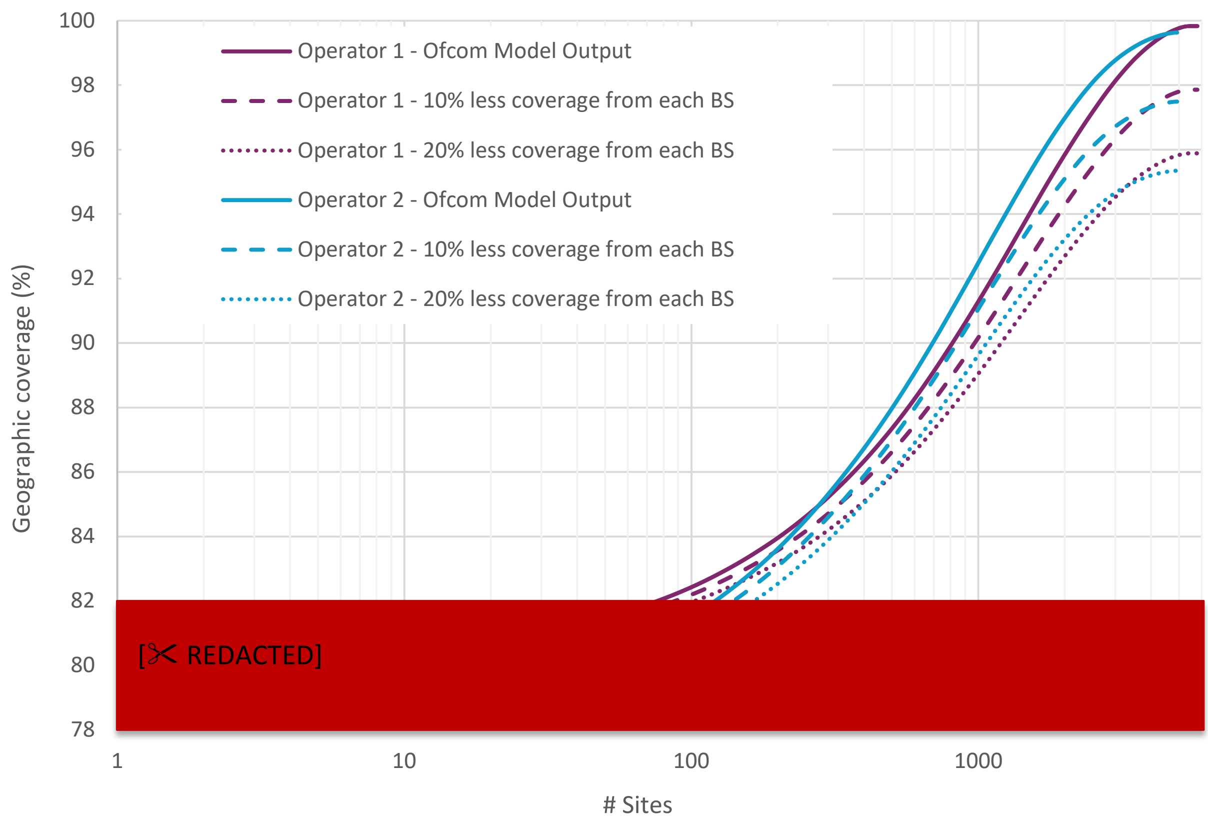
A14.48 Since we are attempting to predict the coverage of a network that has not yet been designed or deployed, the deployment strategy that we have assumed for the network roll-out may not align with operators' actual plans for extending coverage in rural and hard-to-reach areas.

A14.49 Our deployment strategy tends to select cell site locations which are optimum in terms of providing coverage (e.g. highest local terrain) and agnostic of real world deployment challenges in building a site, such as availability of backhaul, access to power, etc. In reality, some of the site locations predicted by our model may be impractical to build and real-world locations may not be optimum in terms of providing the same level of area coverage.

A14.50 Given these challenges, our network dimensioning study requires regulatory judgement. We have sought to mitigate the potential for cost deviations in two main ways: firstly, using relatively conservative modelling assumptions within our network dimensioning study; and secondly, conducting sensitivity analysis to understand the cost profile if operators are able to achieve in practice lower coverage levels from each site.

A14.51 Figure 14.9 presents the results of our dimensioned network aggregated to the UK level and the sensitivity analysis we have performed to understand the impact of locations that may be unfeasible for real world deployments. The results are presented in the form of cumulative distribution of coverage contribution from each new site and ordered in the most to least significant contribution they make to the areas of poor coverage.

Figure 14.9: Additional sites required for extending coverage to ~100% of the UK landmass[429]



A14.52 Our modelling predicts approximately 6,000 cell sites with unconstrained site placements would be required to provide nearly ~100% geographic coverage for both operators. The

[429] Note that we have redacted elements of this figure to protect confidential information on the starting points of operators used in this analysis

model first deploys sites that can provide maximum coverage uplift before moving to address smaller areas and coverage holes. This results in an exponential increase in cell site requirement with growing numbers of masts required for each additional percent of geographic coverage uplift.

A14.53 The two dashed curves for each operator in Figure 14.15 are produced by reducing the area contribution from each dimensioned cell site by 10% and 20%, respectively. This is to illustrate the impact of cell sites locations and the associated additional sites that may be required above the initial 6,000 site estimate.

A14.54 This sensitivity analysis shows that the modelling estimate of 6,000 cell sites to provide 100% landmass coverage is only sufficient to provide good quality coverage to approximately 96%–98% of landmass in these more conservative scenarios. However, the impact is minimal initially, and approximately 10% additional geographic coverage (from 80% to 90%) can still be realised with approximately 600–1,100 cell sites.

A14.55 We have not attempted to further refine our results and predict the additional cell site requirements for the remaining 2%–4% of landmass. This is because at such high geographic coverage levels, even the most sophisticated statistical approaches may not be able to provide meaningful results as the achievable coverage becomes highly dependent on specific local factors and there is likely to be significant variance between the dimensioned network and outcomes on the ground.

A14.56 We also recognise that our use of a single mast height of 20m and average radiated power (EIRP) may be quite conservative for the areas of poor coverage we have dimensioned. In practice, rural sites can achieve significantly larger footprints by use of taller masts and maximum power, if other constraints (for instance local planning restrictions and network management decisions) are not limiting factors.

A14.57 In light of the above, we recognise that the results of our network dimensioning study may not be accurate at the local level, reflecting the fact that we have not carried out a detailed network planning and optimisation exercise. However, we consider it suitable for providing high level coverage statistics and broad range cell site requirements.

A14.58 As we set out in Section 4, we expect a typical operator would achieve in the region of 82% geographic over the 20-year period that we are considering. From the analysis above, we estimate that this higher starting level could reduce the number of new sites needed by around 100 sites. Therefore, we consider that a typical operator would need to build approximately 500-1,000 new sites to provide coverage to 90%, starting from our counterfactual of 82%. We also note that an operator with a starting point between 84% and [✂ REDACTED] (over the 20-year period that we are considering) might require around 300-700 fewer sites.[430]

Comparison of our dimensioning study results with existing networks

[430] Note that for the higher end of this range we would expect some sites to be low power solutions to fill in smaller coverage gaps.

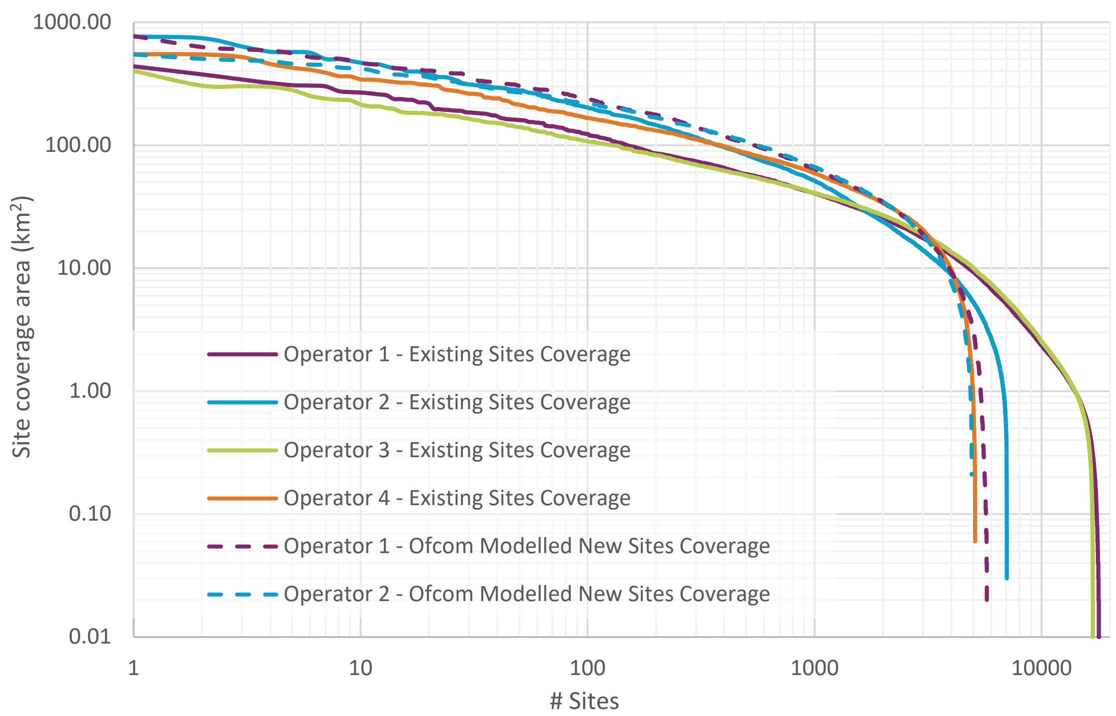
A14.59 In order to check the reasonableness of our study results, we have compared the level of coverage that we have modelled would be provided by each new site in our modelled network with the level of coverage that operators' existing 800 MHz sites (operating at our threshold of -105dBm) actually provide.

A14.60 Figure 14.10 presents this comparison where the existing sites of all operators and additional sites of our dimensioned networks are ordered in descending order of areas covered by individual sites. For this comparison, we have used operators' best server datasets[431] to extract their 4G site footprints by aggregating sector level coverage and linking it to parent sites.

A14.61 We note that there is a significant range in areas covered by existing sites across an operator's network. The coverage sites that individually provide the greatest level of coverage (~ 5000 across all operators) provide coverage footprints of more than 10 km^2 with the first ~1000 sites providing coverage in the range of ~50 km^2 to ~600 km^2.

A14.62 In comparison, the site footprints of our dimensioned networks (as preseneted by dashed curves in Figure 14.10) remain within the operators' site footprint range (~50 km^2 to ~600 km^2) and none of the modelled additional sites providing significantly more coverage than the coverage area provided by individual sites of operators.

Figure 14.10: Site coverage area comparison – existing network vs dimensioned network sites



[431] To understand the level of coverage each operator is likely to be providing at the date of the auction, we have since used our powers under s32A of the WTA to request information from each of the operators about the levels of coverage they expect to provide by June 2019, which was provided by the operators in the familiar form of coverage maps and best server maps (site footprints per technology and frequency band).

A14.63 We also note that there is a significant number of operators' existing sites which provide less than 1 km^2 of coverage. The majority of these sites represent the existing deployment in dense urban/built-up areas. We consider these urban sites are not representative of sites that will be deployed to meet the proposed coverage obligations, targeting predominantly rural areas.

A14.64 However, we recognise that a small number of such sites could be required to fill small coverage gaps. The same trend can be seen in our modelled network where a significant proportion of the additional sites which provide less than 1 km^2 of coverage are required to fill small coverage gaps of existing network or where the site coverage is severely impacted by difficult terrain.

A14.65 This comparison suggests that the results of our network dimensioning study are likely to be broadly accurate since it shows that there is no inherent over-prediction of coverage (under prediction of site requirement) in our dimensioned network and the individual coverage provided by the additional sites that we have modelled aligns well with operators' existing networks.

Analysis of the number of new sites required to meet the premises requirement

A14.66 We are proposing to include a premises requirement in our coverage obligations, which would require the winning bidder to improve its outdoor coverage for at least 140,000 premises. This sub-section sets out the work we have undertaken to test whether this requirement affects our estimate that an operator would need to build 500-1000 sites to provide at least 90% coverage in useful areas.

A14.67 Partial not-spots represent a significant part of the unserved landmass for each operator and contain the majority of unserved premises. Based on information provided to us by operators, we expect that more than 91% of the landmass will receive coverage from at least one operator by June 2019, with between around [✂ REDACTED] premises unserved in these areas (varying by operator).

A14.68 We have therefore considered what it would take to achieve geographic coverage level of 90% whilst focussing deployment on areas where these populated areas (i.e. unserved premises) are located. That is to say, providing 90% coverage by building new sites[432] mainly in the partial not-spots.

A14.69 We recognise that if operators push out their own coverage into these partial not-spot areas, there are likely to be some constraints on the level of coverage they can achieve on a site by site basis. For example, rural and difficult terrain that may limit site coverage areas or the fragmented nature of partial not-spots which means new sites are likely to be more limited in size to fit around existing networks.

[432] We make a conservative assumption that new sites may still be required to match each individual operator's network needs (rather than simple site sharing). We are relying on other operators' sites giving us a guide of coverage levels a new deployment could achieve in these areas, both in terms of landmass and premises served.

A14.70 We began by analysing the coverage areas of individual sites at our good quality threshold in the partial not-spots. We did this because we considered that these sites are likely to be most representative of the kinds of sites operators would deploy if they continued to advance their coverage in partial not-spot areas.

A14.71 Specifically, we began by identifying what could be achieved if the coverage of the new sites required by an operator is limited to the average coverage area that other operators' sites are already providing partial not-spot coverage for (i.e. the subset of a sites total coverage that would be new to an incoming operator). In Figure 14.12, we provide the average of these partial not-spot coverage areas for the top 500 and 1000 sites of other operators in the uncovered areas of the two operators for which we have presented the results of the dimensioning study in the previous section.

A14.72 Since our dimensioning study suggests that coverage levels of 90% could be delivered with around 500-1000 sites (for a typical operator starting from 82%), we considered whether the same range would be sufficient to provide coverage in partial not spots by using conservative average site coverage areas of Figure 14.11.

Figure 14.11: Average site coverage areas in partial not spots

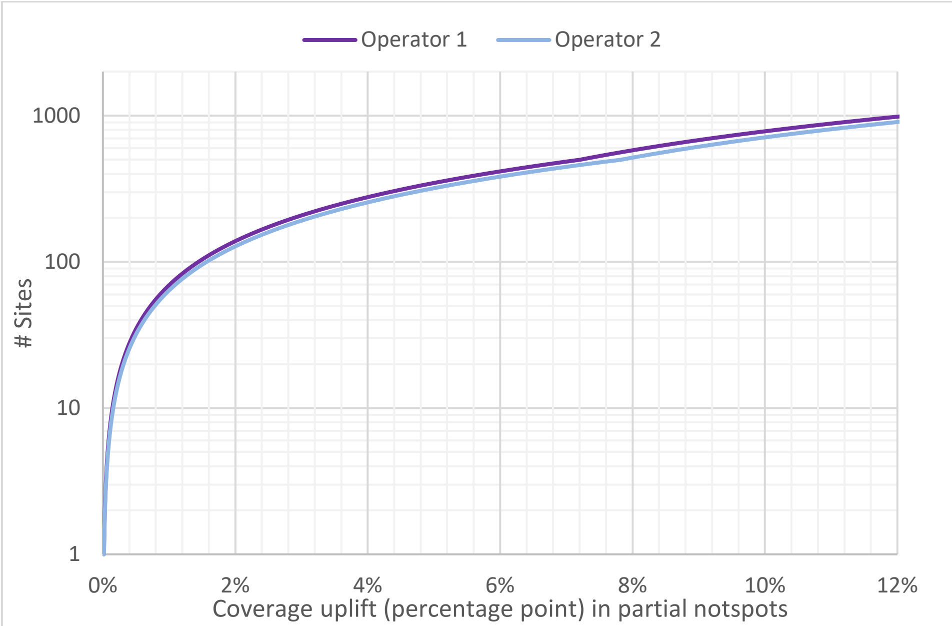
	Average site coverage areas in partial not spots (km²)	
	Top 500	Top 1000
Operator 1	35	24
Operator 2	38	25

A14.73 We present the number of additional sites required to provide good quality coverage in partial not spots for these two operators in Figure 14.12. It indicates that coverage increases of at least 10% could be delivered by less than 1,000 sites[433].

A14.74 In light of the above, we have provisionally concluded that no adjustment is required to the number of sites that we initially estimated for covering 90% of the UK landmass in order to ensure that the new sites focus on partial not spots (and therefore the number of new sites that would be required to meet our premises requirement).

[433] We consider this estimate of site requirements is likely to provide a conservative estimate of the total number of sites operators would require to provide coverage in partial not spots, since in many cases they will be able to optimise existing sites to fill small coverage gaps in partial not spot areas.

Figure 14.12: Additional sites vs coverage uplift in partial not-spots



Further analysis of the number of new masts required to meet the premises requirement

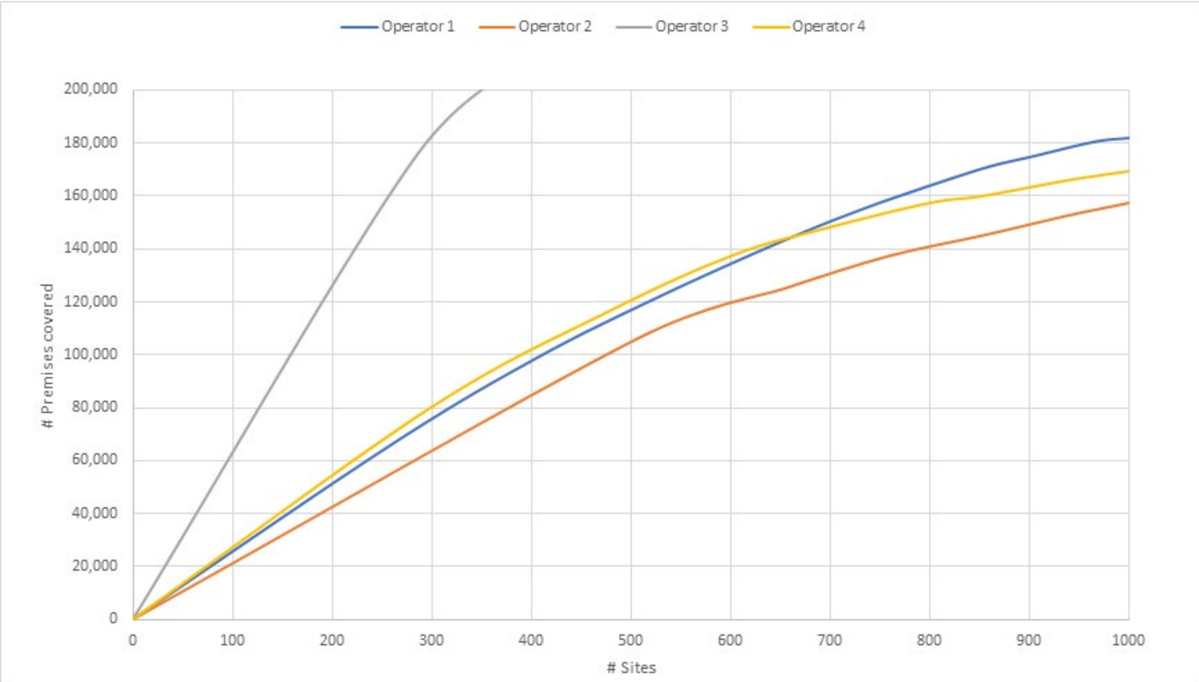
A14.75 As a further sense check to our cost analysis, and to ensure that the premises target we have proposed is achievable within our estimated range of 500-1000 sites, we have simulated a deployment strategy targeting both premises and geographic coverage focusing first on areas with significant numbers of unserved premises.

A14.76 Our analysis highlighted that for all operators, there is a significant number of premises (and therefore pockets of geographic coverage) that are close to the fringes of their existing good quality coverage. We therefore developed a process that began by deploying sites at the edges of existing networks' good quality coverage, focused on populated areas in which premises were located. We then progressively increased this site radius in a linear way as deployments moved further away from the edge of the network. We used a range of 2km – 10km radius, based on the coverage areas of individual sites we have observed in operator networks. We ran this process through to the top end of our estimated range (i.e. 1,000 sites).

A14.77 To ensure our approach remained conservative, we set this deployment algorithm an objective of covering 92% of the landmass (i.e. considerably above our proposed target) whilst delivering coverage to new premises.

A14.78 In Figure 14.13 below, we show the number of premises that our deployment algorithm predicts would see an improvement in their outdoor coverage if an operator increased its geographic coverage to 92% of the landmass.

Figure 14.13: Additional sites vs premises covered with a target of covering more than 90% UK landmass



A14.79 This analysis shows that it should be possible to bring improved outdoor coverage to a significant number of premises as part of expanding geographic coverage. It suggests that with 700-800 sites (i.e. the mid-point of our range) all operators can deliver at least around 140,000 premises into their coverage. We consider this to be a very conservative view of what an operator could achieve in practice, because it may be possible to improve coverage for many premises near the fringes of existing networks without building new sites.

A14.80 Our objective for this analysis has been to check that the levels of premises coverage we are requiring is likely to be achievable for all operators within our estimated range of 500-1000 sites. In light of the above, we estimate that bringing coverage to at least 140,000 premises would be achievable for all operators and should ensure that new sites they need to build to meet the geographic target are built in the most useful areas.

Estimate of costs of building new sites

A14.81 In the March 2018 consultation, we explained that we had taken a conservative view of the possible average costs of deploying new sites, based on the information then available to us. We thought that on this basis, a very conservative capital cost for a rural site could be up to £250,000. Our capital costings took as a benchmark the top end estimate of costs for a rural macrocell that had been estimated for us by Real Wireless in work prior to the 800

MHz award.[434] We further assumed that in a conservative approach we should account for up to 20 years operational costs using a discount rate of 9.1%. We also estimated that operational costs could be between £20-40,000 per year (although we assumed that on average costs would be towards the lower end of the range).

A14.82 We have now undertaken further work to refine our estimates of the range of costs for an average site deployed to deliver 90% geographic coverage, based on updated cost information from operators, and updated assumptions on how those costs would be incurred over the period from 2020 to 2039 (i.e. the duration of the coverage obligations).

A14.83 We have modelled the costs based on the actual costs reported by operators for sites they have deployed over the last 4 years, which we consider representative of the sites that would likely need to built in order to meet the obligation.[435] We have therefore considered only the costs of sites using 800MHz or 1800MHz[436] in rural areas with antenna heights of at least 20m. We have also only considered sites recording a positive capital cost, as we consider that it is unlikely that a site built to meet the obligation would have zero capital cost.[437]

A14.84 We recognise that the sites which would need to be built in order to meet the obligation are likely to be more expensive than the average existing site of this type, reflecting the increasing incremental costs of delivering coverage in remote areas. We have therefore focused only on the most expensive sites.

A14.85 To balance the uncertainties around where within the range of existing sites these new sites would be, including whether capital and operational expenditure is ultimately shared (as in some cases it may have been in information provided by operators on their current costs), and the remoteness of sites an operator chooses to build, we have considered the average cost of both the 1000 most expensive sites, and the 100 most expensive sites.

A14.86 We consider that the likely costs would be somewhere between these two estimates. To conclude on a reasonable point estimate between these two scenarios, we have taken the average of the following:

a) the average site cost of the 500 most expensive sites that operators have built over the last 4 years; and

b) the average of the higher end (the 100 most expensive sites) and the more balanced range (the 1000 most expensive sites).

A14.87 In order to calculate the net present value of the average cost of building a mobile site over the 20-year period 2020 to 2039, we have made the following assumptions:

[434] https://www.ofcom.org.uk/__data/assets/pdf_file/0026/71468/real-wireless-cost-analysis.pdf (Page 37).

[435] We note that a small number of sites [✂ REDACTED] have been reported by operators as being built within the last four years, but which have been coded as being built in earlier years. We have included these within our analysis.

[436] We have also included sites whose frequencies are reported as *.

[437] We further note that the [✂ REDACTED] sites which have zero capital cost but a positive operating cost were [✂ REDACTED].

a) We have assumed that an operator would meet the obligation by building an equal number of sites in each of the four years from 2020 to 2023. We therefore have created an average net present cost based on calculating the net present cost of a site built in each of those four years, noting that sites built later will have a lower net present cost.

b) We have assumed that the capital cost incurred on a site will be incurred one year before the operating costs associated with that site.

c) We have assumed that costs will remain constant in nominal terms over the period. This is equivalent to assuming that costs will decline in real terms by the rate of inflation (which, for the purposes of calculating nominal discount rates, we have assumed is 2%).[438] This is broadly consistent with our current understanding of the likely trend in backhaul costs, which is a key component of mobile site operational costs.[439]

d) We have used a standard discounting approach.

A14.88 In calculating a net present value, we need to consider the appropriate discount rate to use. We note that the discount rate will differ depending upon whose perspective is relevant for the costs being estimated:

- When comparing costs and benefits we consider it appropriate to use the social time preference rate (STPR).[440] As our cost model is nominal, we use the nominal STPR, which is 5.6%.[441]
- However, we expect mobile operators to take account of a private discount rate when discounting expected future cash flows to inform their auction bids. For this purpose, we use the weighted average cost of capital (WACC) for mobile operators. As our cost model is nominal, we use the nominal WACC, which is 7.6%.[442]

[438] We assume a long-run inflation rate of 2% as this is the target rate for CPI inflation.
[439] We note that this is consistent with the charge controls proposed in the Business Connectivity Market Review in the BT only and BT+1 markets where BT has been provisionally found to have SMP, which have been set at CPI – CPI (i.e. constant nominal prices) - see https://www.ofcom.org.uk/__data/assets/pdf_file/0022/124726/llcc-bcmr-2018-volume-2.pdf. It is likely that the majority of mobile sites required to meet the obligation would be built in these areas, as these areas are likely to be rural and/or remote. Although not directly comparable, this is also broadly consistent with the equipment unit cost trends for backhaul in Table A9.1, p.94, Ofcom, Mobile Call Termination Market Review 2018-2021 Final Statement – Annexes 1 - 15, https://www.ofcom.org.uk/__data/assets/pdf_file/0022/112459/MCT-review-statement-annexes-115.pdf.
[440] This is without a Spackman adjustment for private sector financing costs. We consider this appropriate as the obligated operators will receive a discount in the auction, so in effect receiving funds upfront from the government. This is consistent with the approach suggested in the Joint Regulator's Statement, which notes "there may be specific circumstances in which private financing costs are effectively funded upfront by the public sector and so may not need to be added" See paragraph 3.2, p.6, https://www.ofcom.org.uk/__data/assets/pdf_file/0029/37856/jrg_statement.pdf.
[441] Based on converting a real STPR of 3.5% into a nominal figure, using the Fisher equation. The real STPR of 3.5% is sourced from the HMT Green Book.
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/685903/The_Green_Book.pdf
[442] See Ofcom 2018, *Annual Licence Fees for 900 MHz and 1800 MHz frequency bands*, Annex 5, Table A5.3
https://www.ofcom.org.uk/consultations-and-statements/category-2/annual-licence-fees-900-1800-mhz

A14.89 We therefore have two different sets of costs, which reflect these different discount rates.

A14.90 Based on this methodology, we consider that a reasonable estimate across the range of possible site costs for the sites built for meeting the proposed obligations is around £395,000 based on a discount rate of 5.6%,[443] and £340,000 based on a discount rate of 7.6%. These are lower costs per site than we estimated in our March consultation, and reflect the updated information we have gathered to inform our assessment. We recognise that it is likely that some of the actual sites built to meet the obligations will cost more than this, and others will cost less.

Figure 14.14: Average cost per site[444]

Discount rate applied	**Average cost of 100 most expensive sites (A)**	**Average cost of 1000 most expensive sites (B)**	**Average cost of 500 most expensive sites (C)**	**Average of estimates A and B (D)**	**Average of estimates C & D**
5.6%	£513,000	£323,000	£373,000	£418,000	**£395,000**
7.6%	£437,000	£280,000	£322,000	£359,000	**£340,000**

Estimate of the costs of meeting the proposed obligations

A14.91 To estimate the costs of increasing coverage, we multiply the average cost per site by the number of sites we expect an operator would need to build in order to meet the obligation.

A14.92 As set out above, we estimate that a typical operator might need to build 500 – 1000 new sites to meet our proposed obligations. Our cost analysis therefore suggests that the costs for reaching 90% coverage for a typical operator starting from 82% coverage would be in the region of £200m - £400m,[445] with a central estimate of around £300m, using a 5.6% social discount rate, which is the relevant cost range for comparing costs and benefits, and £170m - £340m, based on a 7.6% private discount rate.[446]

[443] [✂ REDACTED].

[444] All figures rounded to nearest £1,000.

[445] This is a rounded figure – the specific range is £197.5m to £395m. However, we have rounded up to avoid spurious precision.

[446] We note that the later an operator would reach 82% coverage in the counterfactual, the greater is the cost of the obligation, as the operator is required to bring forward investment in the sites required to reach 82%. However, we consider that this cost would only be modest.

A15. Coexistence issues for the 3.6-3.8 GHz band

Introduction

A15.1 In this annex we present our detailed technical coexistence analysis relating to the 3.6-3.8 GHz band.

Coexistence with other services in 3.6-3.8 GHz

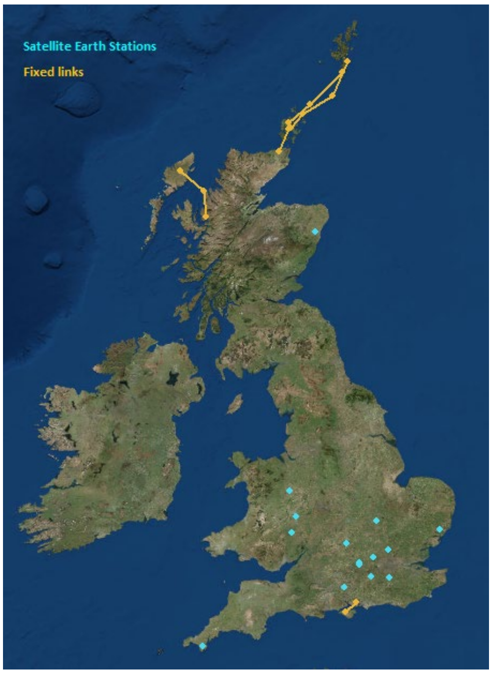
A15.2 As set out in Section 9, we have served notices of variation or revocation of existing satellite and fixed links authorisations in the band. However, there will be a period of time between the award of the spectrum in 2019 and these variations and revocations coming into effect within which we will need to maintain protection for these users. We propose to adopt a process similar to the one we have in place to coordinate new UK Broadband site deployments with other registered users in the 3.6-3.8 GHz band. This will help manage new base station deployments made by new licensees in the interim period.

A15.3 While interim protections for satellite earth stations are currently only expected to last for a few months after the spectrum award, the interim protections for fixed links may remain for a longer period[447]. We have therefore looked in more detail at the potential constraints that these interim protections may place on early base station deployments.

A15.4 Only a small number of fixed links are expected to remain in the band during the interim period and, of these, all but one will be in remote areas away from major population centres and are thus unlikely to significantly impact mobile roll-out.

[447] As noted in Section 9, we are continuing to engage with fixed links licensees with the aim of migrating fixed links operations to alternative frequencies or technologies by June 2020 where possible. This may mean that some of the proposed protections as set out in this annex may become redundant by the time of the award. We will update the list of protection requirements in the information memorandum for the award.

Figure A15.1: Locations of the remaining earth stations and fixed links during the interim period.



A15.5 There is one link operating between the Isle of Wight and Portsmouth which could potentially constrain early mobile deployments. This link operates a 30 MHz carrier centred at 3740 MHz. Below we describe the approach we have used to estimate the scale of the impact of the protection of this link on the deployment of mobile base stations in the interim period.

A15.6 We conclude that within a radius of 50 km of the Isle of Wight to Portsmouth link, roll-out of base stations is likely to be difficult, with about 80% of the sectors we analysed failing to meet the protection criteria for this fixed link. For base stations further away, roll-out is likely to be minimally affected with about 4% of sectors analysed that lie within a few kilometres either side of the extended baseline of the fixed link (out to 200 km) failing to meet the protection criteria for the link – however, in this case the failure margin is relatively small (median margin ~3 dB) implying that with reasonable mitigation (e.g. reducing powers or careful pointing) most of the sectors that failed (in our analysis) could in fact be deployed with minimal impact on network performance. The population potentially affected by this link is estimated to be c.500,000.

Analysis overview

A15.7 For the purposes of the analysis, we have assumed that an operator will roll-out a 3.6 GHz network using an existing mid-frequency cell site grid. We have derived our input assumptions based on a national macro-cell deployment.[448]

[448] Data extracted from Q4 and Q5 from Ofcom's s134 information request, June 2018

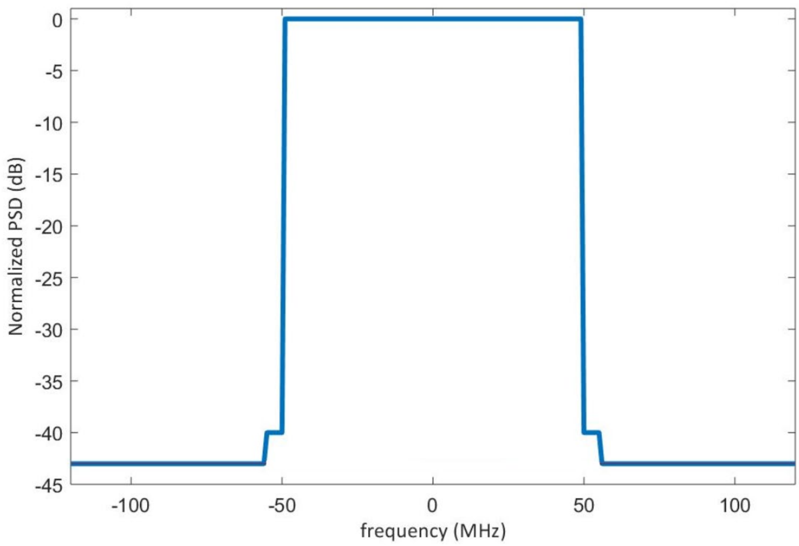
A15.8 Table A15.1 summarises the antenna and base station parameters we have assumed in our analysis:

Table A15.1: Parameters used for the coexistence in the 3.6 – 3.8 GHz band analysis

Parameter	Value
Location and height above ground of base station	From 2 GHz 3G base station grid
Down tilt and azimuth values for each base station sector	From 2 GHz 3G base station grid
Carrier frequency	3740 MHz
Carrier bandwidth	100 MHz
E.I.R.P.	44 dBW[449]
Antenna Emission mask	Same used for 3.6 – 3.8 GHz coordination, see Figure A15.2

A15.9 Figure A15.2 illustrates the emissions mask used.

Figure A15.2: Emissions mask used in our analysis



A15.10 We conducted a preliminary analysis to identify the areas where base stations are likely to cause interference to the Isle of Wight to Portsmouth fixed link. For this, we assessed a sample of base stations within 200 km of the link. This analysis showed that interference exceeding the fixed link's protection criteria only occurred when base stations were located either:

[449] We derive this value absolute based on a 200 W power amplifier and a 21 dBm antenna. The maximum power allowed by the proposed licence conditions in this band and bandwidth is 3 dB higher.

- within 50 km of the link (Area A), or
- within an area about 20 km either side of the extended boresight of the link (which cuts across parts of the South East of England including parts of London (Area B).

A15.29 We focused our detailed analysis on these two areas to get a better understanding of the likely number of base station sectors that might exceed the interference criteria of the link and the margin by which they might exceed it.

A15.30 For the analysis along the extended boresight, we subdivided Area B into three zones either side of the boresight line (±0-5 km, ±5-10 km and ±10-20 km) to understand the impact of base stations that are deployed at different distances from the line.

A15.31 In total, we analysed around 1,800 base station sectors within the two areas. This was a random sample of approximately one-third of all the base station sectors (from our national macro-cell deployment) within the two areas.

A15.32 To assess whether a base station is likely to cause interference we used the in-house tool currently used for the coordination of base stations under the UK Broadband 3.6 GHz licence. This is the tool that we are proposing to use for actual coordination in the interim period until the band is fully cleared.

A15.33 This tool estimates the impact of a mobile base station on a fixed link, based on the location, orientation and relevant technical parameters (e.g. E.I.R.P, down-tilt, etc.) for both interferer (base station sector) and victim (fixed link). This is carried out on a single-entry basis. The transmission details for the base station sectors are described in Table A15.1 and the parameters of the fixed link are derived from the ETSI SEC 5 type[450]. The power received at the fixed link from the base station sector is calculated using the ITU-R P.452.10[451] propagation model with clutter from Infoterra© 50m resolution maps. We assume a minimum signal to interference threshold (T/I) of 37 dB. This ratio is the coefficient of the power of the fixed link wanted signal and the power of any interfering signals. We have assumed a T/I of 37 dB as used in the UK Broadband coexistence tool. For every base station sector under analysis, if the calculated ratio falls below this threshold we assume it would be likely to create harmful interference to the fixed link. The failure (excess) margin is the difference between the received signal level and the interference threshold.

A15.34 The tool flags all base station sectors that, under the test assumptions, will exceed the interference criteria for the fixed link. The tool also reports the interference failure margin.

A15.35 We have used this information to inform our assessment of whether practical mitigation measures are likely to be effective in mitigating such interference. For low failure margins (up to about 6 dB) we consider that measures such as using a lower transmit power can, in

---

[450] See https://www.etsi.org/deliver/etsi_en/302200_302299/30221702/03.00.08_20/en_30221702v030008a.pdf
[451] See https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.452-10-200102-S!!PDF-E.pdf

many cases, be effective (without being overly constraining).[452] Higher failure margins (e.g. 10 dB or greater) present situations where it is likely to be difficult to mitigate, and therefore, it may not be practical to deploy those sectors without significantly affecting their performance or creating coverage holes.

A15.36 It should be noted that we have only considered single entry interference, rather than the aggregate effect of all base station sectors. This is the basis for the existing coordination process for UK Broadband.

Results

A15.37 Table A15.2 shows the number of sectors that failed to meet the interference criteria and the failure margin for both of the areas in our analysis.

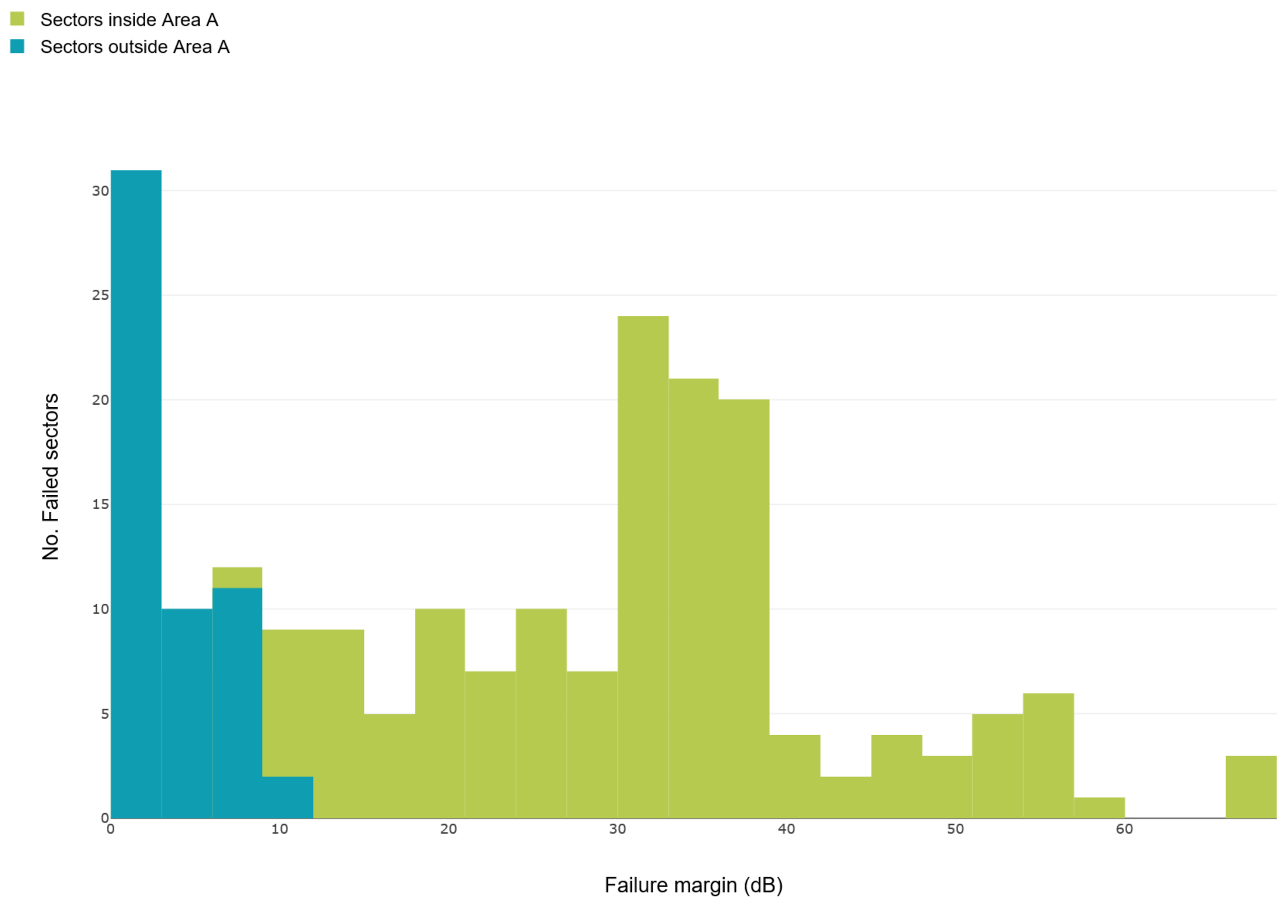
Table A15.2: Summary of results for areas A and B

Location	Total sectors analysed	Number of sectors failing	% failed sectors	failure margin, median value
Area A	224	179	80 %	~ 30 dB
Area B	1492	54	4 %	~ 3 dB

A15.38 Figure A15.4 shows the distribution of the failure margin of the sectors that failed to meet the interference criteria.

[452] Given that we believe that the 44 dBW EIRP transmit power assumption is at the upper end of that likely to be used in real life deployments (at least in the shorter term), it possible that most base station submitted for coordination will be at a lower power and therefore less likely to fail coordination in practice.

Figure A15.3: Histogram of the failure margins for areas A and B



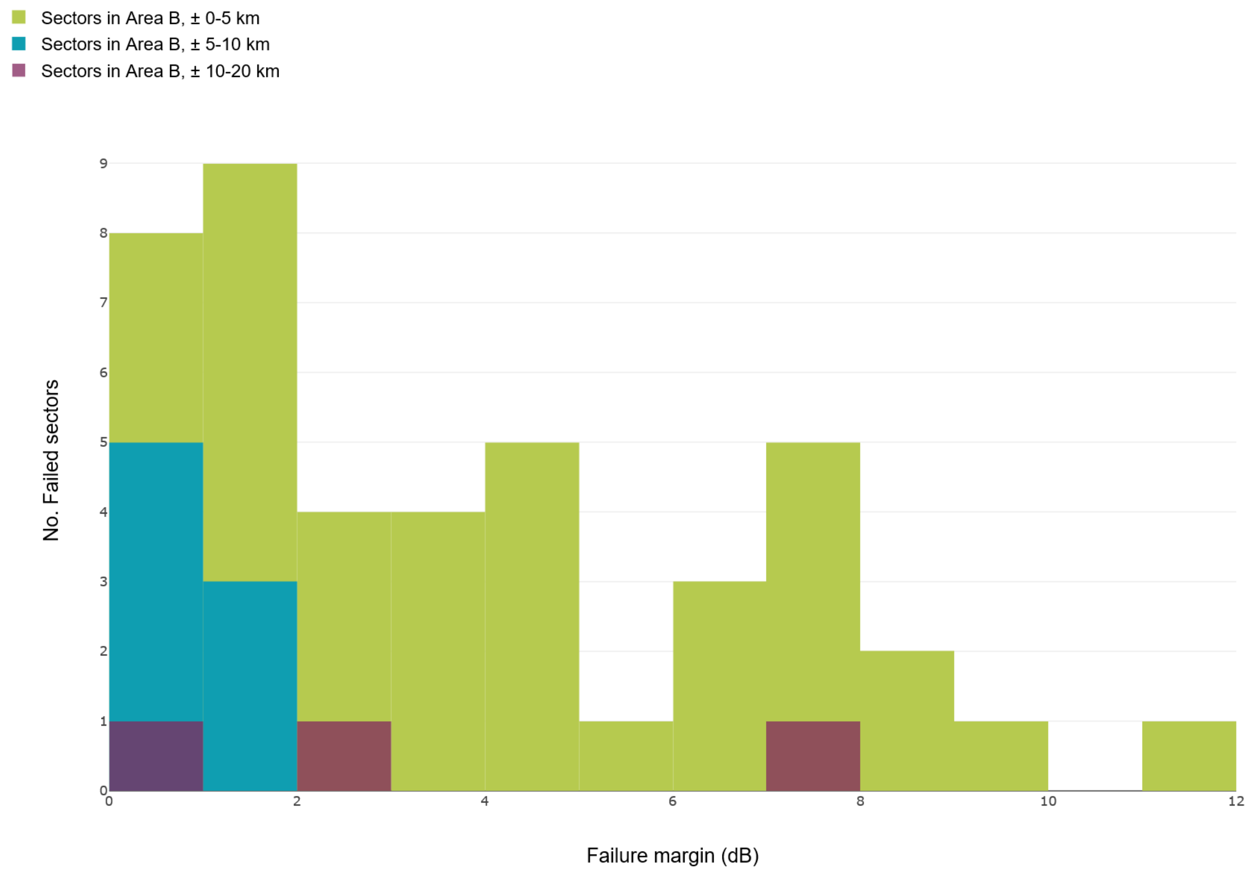
A15.39 Table A15.3 provides more details on the results for sectors located within Area B, i.e. for sectors located ±0-5 km, ±5-10 km and ±10-20 km either side of the extended boresight line. Note that sectors in Area A are not included in these results.

Table A15.3: Results of the coordination tests in Area B

Area B	Total sectors analysed	Number of sectors failing	% failed sectors	Interference margin, median value
±0-5 km	465	43	10 %	~ 3 dB
±5-10 km	412	8	7 %	~ 1 dB
±10-20 km	615	3	0.5 %	~ 3 dB

A15.40 Figure A15.5 shows the distribution of the failure margin.

Figure A15.4: Histogram of the interference margin values, Area B



A15.41 Sectors located further away from line of the extended boresight present a lower likelihood of exceeding the interference threshold.

Coexistence with services above 3.8 GHz

A15.42 We have conducted a technical analysis looking at the potential impact of new services on satellite earth stations (SES) and fixed links (FL) operating above 3.8 GHz.

A15.43 We have assessed the interference risk using two approaches as follows:

- **Area-analysis**: with this approach we assessed the interference risk from a hypothetical base station (BS) under two sets of assumptions:
    - **Worst-case:** where we assessed the area around each SES or FL over which a BS transmitting at maximum power and pointing in boresight to the SES or FL could cause interference above a specific threshold. We then determined the interference contour (i.e. the geographic boundary within which a BS could cause interference) around each SES or FL location.

  - **Realistic-case:** where we carried out a sensitivity analysis using different values for the simulation parameters. In particular, we relaxed the worst-case assumption by considering more realistic values, based on our knowledge of current mobile network deployments. This included a combination of factors that increased the overall losses towards the SES or FL, such as antenna down-tilt, azimuth pointing offsets, beamforming losses as well as a lower transmit power, which are all more in line with values we observe in real networks.

- **Example macrocell deployment analysis**: in a similar way to our previous consultations on the 3.6-3.8 GHz band, we modelled a realistic future UK-wide 5G macrocell deployment, based on our understanding of the likely characteristics of potential 5G networks in the band[453]. We then assessed the interference within a radius of 70km from each SES and FL, to produce an estimate of the number of BS sectors that could potentially cause interference to these SESs and FLs.

A15.44 For the two approaches we have conducted analysis for both active antenna systems (AAS) and non-active antenna systems (non-AAS).

Table A15.4: Assumptions: worst-case area-analysis

	Value for non-AAS 5G BS	**Values for AAS 5G BS**
Base station (BS) position and deployment	Deployed in 1km measurement steps within an area centred on each SES or FL.	Deployed in 1km measurement steps within an area centred on each SES or FL.
EIRP	65dBm/ 5MHz[454]	64dBm/ 5MHz[455]
Bandwidth	20MHz	20MHz
OOB mask	3800-3805 MHz: 21dBm/5MHz 3805-3810 MHz: 15dBm/5MHz 3810-3840 MHz: 13dBm/5MHz Above 3840 MHz: -2dBm/5MHz	3800-3805 MHz: 30dBm/5MHz 3805-3810 MHz: 27dBm/5MHz 3810-3840 MHz: 21dBm/5MHz Above 3840 MHz 6 dBm/5MHz
	The mask's values are calculated based on the generic formula specified in ECC Report 281[456], using as input for the *Pmax* parameter, the EIRP values 71dBm/20MHz for non-AAS and 70dBm/20MHz for AAS systems	

[453] See also Annex 5 in Ofcom, "Improving consumer access to mobile services at 3.6GHz to 3.8GHz", July 2017.
[454] See also Annex 19 "Award of the 700MHz and 3.6-3.8 GHz spectrum bands"
[455] See also Annex 19 "Award of the 700MHz and 3.6-3.8 GHz spectrum bands", EIRP based on assumption of an 4x8 antenna
[456] See also Table 18 ECC Report 281: https://www.ecodocdb.dk/download/5ffb56c9-9c78/ECCRep281.pdf

BS antenna	Recommendation ITU-R M.2101[457] with 8 vertical elements (separated by 0.9λ) and 4 horizontal elements (separated by 0.5λ)	Recommendation ITU-R M.2101 with 8 vertical elements (separated by 0.9λ) and 4 horizontal elements (separated by 0.5λ)
Sector pointing	To the boresight of the SES and FL antenna	To the boresight of the SES and FL antenna
Antenna tilt	-2 degrees	-2 degrees
Antenna height	20m	20m
Propagation model	ITU-R P.452-16 (short term) and ITU-R P.1812 (long term) (see discussion further below for more details)	ITU-R P.452-16 (short term) and ITU-R P.1812 (long term) (see discussion further below for more details)
Terrain and Clutter Use	Ofcom 50m terrain and land use databases[458]. When applicable, the effect of local clutter both at the Tx and the Rx as well the clutter along the link path have been considered	Ofcom 50m terrain and land use databases. When applicable, the effect of local clutter both at the Tx and the Rx as well the clutter along the link path have been considered

Table A15.5: **Assumptions: example macrocell deployment analysis**

	Value for non-AAS and AAS 5G BS
Base station (BS) position and deployment	Deployed in an area centred on each SES or FL with a radius of 70km
EIRP	A range of EIRP values was assumed based on our knowledge of existing mobile network deployments
OOB emission masks: We used 3 different masks in our analysis to model the out-of-band emissions of BS **ECC non-AAS mask:**	We generated the OOB emissions mask for each non-AAS BS based on the formula specified in ECC Report 281[459]. As input for the *Pmax* parameter of

[457] See ITU-R Recommendation M.2101-1, February 2017, https://www.itu.int/rec/R-RECM.2101/en
[458] We used a legacy terrain/clutter database developed from the Technical Computing team of the Radiocommunications Authority in 2013.
[459] See also Table 18, ECC Report 281: https://www.ecodocdb.dk/download/5ffb56c9-9c78/ECCRep281.pdf

    ECC AAS mask: **Flat 60dBc AAS mask:**	the formula, we used the EIRP value which we assumed for each BS, based on our knowledge of existing mobile network deployments. We generated the OOB emissions mask for each AAS BS based on the formula specified in ECC Report 281. As input for the *Pmax* parameter of the formula, we used the TRP value which we assumed for each BS, based on our knowledge of existing mobile network deployments. In our analysis for the potential risk of interference to FL, we used an OOB emission mask for AAS BS, based on our knowledge from discussions with equipment manufacturers. This mask's behaviour assumed a flat 60dBc attenuation above 3815 MHz.
Bandwidth	20MHz
BS antenna	Recommendation ITU-R M.2101[460] with 8 vertical elements (separated by 0.9λ) and 4 horizontal elements (separated by 0.5λ)
Number of sectors per site	A range of values was assumed, based on our knowledge of existing mobile network deployments
Sector pointing	
Antenna tilt	
Antenna height	
BS activity factor	0.4
Propagation model	ITU-R P.452-16 (short term) and ITU-R P.1812 (long term) (see discussion further below for more details)
Terrain and clutter	Ofcom 50m terrain and clutter databases. Subject to the propagation model used, the effect of local clutter both at the Tx and the Rx as well the clutter along the link path have been considered.

[460] See ITU-R Recommendation M.2101-1 (02/2017), February 2017, https://www.itu.int/rec/R-RECM.2101/en

Propagation models and interference thresholds

A15.45 As we did in our previous consultations on this band (see for example our October 2016 consultation and our July 2017 statement), we assess coexistence accounting for both 'long term'[461] interference (single-entry and aggregate) and interference during anomalous propagation periods, referred to as 'short term' interference[462] (single-entry). We use the same interference thresholds[463] that we currently use to provide benchmark spectrum quality. Being consistent with our in-band analysis for the 3.6-3.8 GHz band[464], the propagation models used are from Recommendation ITU-R P.1812-4 to assess coexistence against the long-term interference criterion and Recommendation ITU-R P.452-16 to assess coexistence against the short-term interference criterion.

A15.46 It should be noted that our main 'baseline' analysis focusses on assessing the interference risk based on the effect of out-of-band emissions from 5G base stations, without considering the impact of the receiver's selectivity performance (i.e. assuming perfect selectivity). However, to provide a more complete view of the potential impact, we also present some results that include the effect of receiver selectivity.

Satellite Earth Stations (SES)

A15.47 In the following paragraphs, we present the results of our interference assessment analysis for satellite earth stations. We analysed four of the thirteen SES in the band; we chose these four SES because they have assignments at the 3.8 GHz band edge and therefore they would most likely be affected by adjacent band coexistence issues.

A15.48 The SES parameters for the assignments we considered have been taken directly from the relevant licences and are presented in Table A15.6 below.

Table A15.6: Satellite Earth Station modelling parameters

Satellite Earth Station	SES 1	SES 2	SES 3	SES 4
Antenna Gain (dBi)	54.9	49.2	54.2	48.1
Beamwidth	0.28	0.51	0.44	0.58

[461] Long term interference thresholds are used to manage the interference conditions for a receiver that will occur most of the time.
[462] Short term interference thresholds take into account an interfering signal being enhanced for short periods of time. Short-term interference usually occurs when atmospheric conditions lead to anomalous propagation conditions.
[463] It is Ofcom policy to provide benchmark spectrum quality with respect to long-term and short-term interference for holders of fixed link licences, PES licences and grants of RSA for ROES (Recognised Spectrum Access for Receive-only earth stations). With respect to long term interference, this ensures that I/N levels for registered satellite earth stations would not normally be expected to exceed -10 dB for more than 20% of the time. The criteria for fixed link licences are detailed in OfW446. With respect to short-term interference for holders of fixed link licences and PES licences, this ensures that I/N levels for registered satellite earth stations would not normally be expected to exceed 0 dB for more than 0.005% of the time. The criteria for fixed link licences are detailed in OfW446.
[464] See also "Improving consumer access to mobile services at 3.6-3.8 GHz" https://www.ofcom.org.uk/__data/assets/pdf_file/0017/103355/3-6-3-8ghz-statement.pdf

Antenna pattern[465]	ITU-R S.580-6	ITU-R S.580-6	ITU-R S.580-6	ITU-R S.580-6
Antenna height (m)	16	5	9	2
Noise Temperature (K)	[✂ REDACTED]	[✂ REDACTED]	[✂ REDACTED]	[✂ REDACTED]
Elevation angle (º)	6	19	24	20
Azimuth (º)	110	217	218	227
Centre Frequency (MHz)	3830.5	3800.256	3801.25	3810.5
Bandwidth (MHz)	61	0.512	1.1	21

Area analysis results

A15.49 In the table below, we summarise the results obtained with a worst-case area-analysis described in A15.53 i), when assessing coexistence against long-term interference (see A15.55).

Table A15.7: SES area analysis results – worst-case – long term criteria

Satellite Earth Station	Non-AAS max interfering distance (km)	AAS max interfering distance (km)
SES 1	3.6	7.5
SES 2	1.3	1.7
SES 3	4.1	6.3
SES 4	0	0

A15.50 We also considered a more realistic scenario, where we assumed a reduction of 15 dB in received power, as a result of a combination of factors, such as increased antenna down-tilt and azimuth pointing offset, beamforming gain and reduced transmit power, as well as a more realistic performance compared to the ECC emission mask. We believe that the choice of 15dB includes also the lower end of the receiver's performance range. Based on our knowledge of the parameters of existing mobile deployments, as well as our knowledge of a likely typical 5G BEM performance from equipment vendors, we estimate that the strength of the signals from real 5G BS deployments, into SES (or FL) receivers would arrive with 20-25 dB less power compared to our worst-case assumption. The results for the analysis of the worst-case scenario are summarised in Table A15.8 below.

[465] See also Recommendation ITU-R S.580-6: Radiation diagrams for use as design objectives for antennas of earth stations operating with geostationary satellites https://www.itu.int/dms_pubrec/itu-r/rec/s/R-REC-S.580-6-200401-I!!PDF-E.pdf

Table A15.8: SES area analysis results – realistic-case – long term criteria

Satellite Earth Station	Non-AAS max interfering distance (km)	AAS max interfering distance (km)
SES 1	2.25	2.5
SES 2	0	0.4
SES 3	1.5	2.5
SES 4	0	0

A15.51 In Figures A15.6 and A15.7 we show the interference contour for SES 1 and SES 3 for AAS. On the left side of each of the two Figures we show the interference contour under worst-case assumptions (corresponding to the results in Table A15.7), whereas in the right side we consider the realistic-case scenario (corresponding to the results in Table A15.8).

Figure A15.6: SES 1 worst-case (left) and realistic-case (right) interference contour for AAS

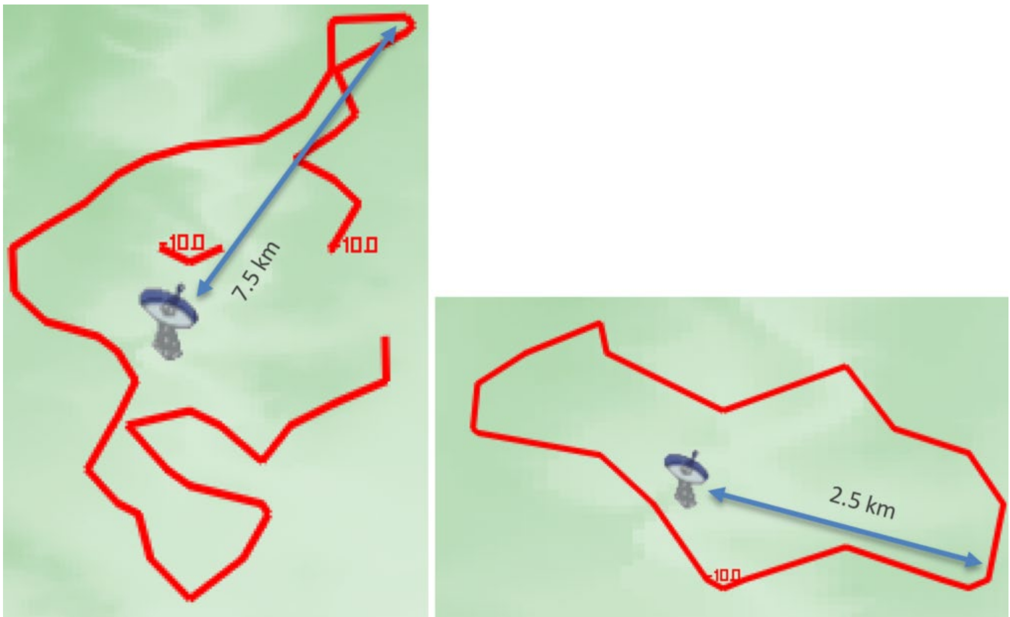
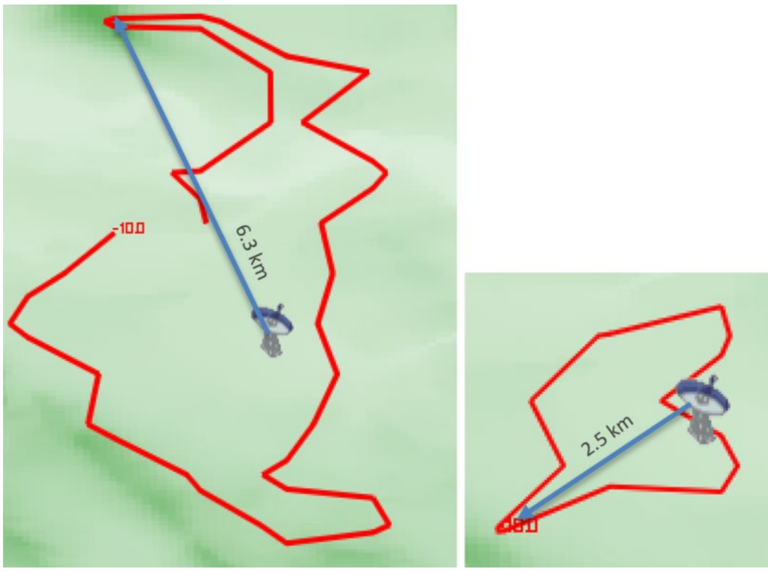


Figure A15.7: SES 3 worst case (left) and realistic case (right) interference contour for AAS



Example macrocell deployment results – baseline analysis

A15.52 We then assessed interference against our example macrocell deployment using the approach described in A15.53 ii) and the assumptions set out in Table A15.5). The results for both non-AAS and AAS are presented in Table A15.9 below, showing the number of BS sectors causing interference above the threshold.

Table A15.9: Number of interfering BS sectors within 70km of each SES

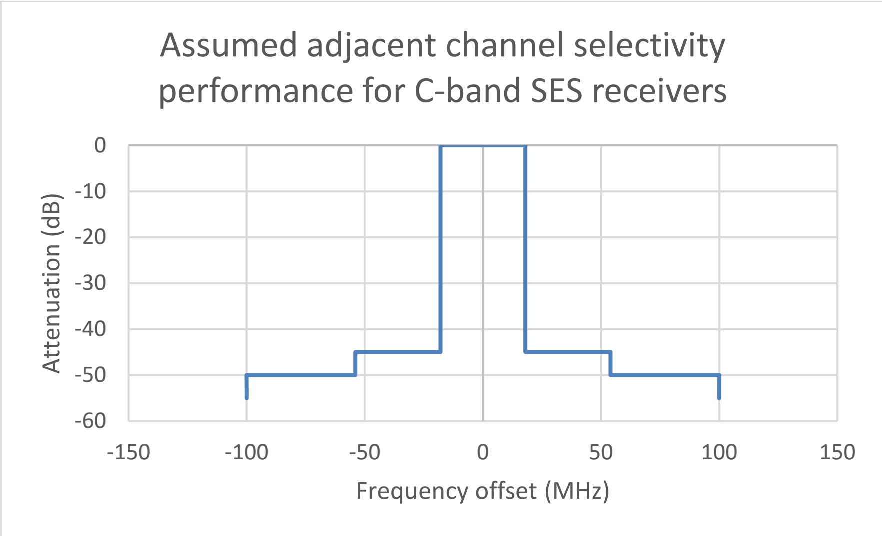
Satellite Earth Station	Long-term single entry		Short-term single entry		Long-term aggregate	
	Non-AAS	AAS	Non-AAS	AAS	Non-AAS	AAS
SES 1	1	3	1	6	1	3
SES 2	0	0	2	4	0	0
SES 3	0	0	0	0	0	0
SES 4	0	0	0	1	0	0

Sensitivity analysis including receiver selectivity

A15.53 To provide a more complete assessment of the interference risk as well as to demonstrate the potential effect of filtering, we also conducted a sensitivity analysis taking into account the effect of receiver selectivity.

A15.54 The results in Table A15.10 below illustrate the interference risk based on the combined effect of out-of-band emissions from the transmitter and the selectivity from each receiver. We have presented both area analysis and example macrocell deployment results. Upon absence of any official reference regarding the adjacent channel selectivity performance of SES receivers, we considered the mask shown in Figure A15.8 as the ACS response of C-band SES receivers. This mask is taken from ITU-R SG04 contribution 78[466] and we believe it is a reasonable approximation of what receiver masks might look in reality. All other parameters were the same as those used in the area analysis (realistic case - see paragraph A15.60 and Table A15.4) and example macrocell deployment (baseline analysis).

Figure A15.8: Assumed adjacent channel selectivity performance for C-band SES receivers.



A15.55 Comparison of the results in Table A15.10 with Tables A15.8 and A15.9 show that there is a small increase in the interference impacts when the effect of receiver selectivity is taken into account.

Table A15.10: Analysis including the effect of receiver sensitivity (for AAS systems)

Satellite Earth Station	Max interfering distance (km)	No. of interfering sectors		
		Long-term single entry	Short-term single entry	Long-term aggregate
SES 1	3	8	8	5
SES 2	0.35	0	5	0
SES 3	2.55	0	0	0
SES 4	0	1	1	0

[466] Study #10, Sharing studies between International Mobile Telecommunication-Advanced systems and geostationary satellite networks in the fixed-satellite service in the 3 400-4 200 MHz frequency band: https://www.itu.int/md/R12-SG04-C-0078/en

Blocking analysis for SES

A15.56 We did not carry out a blocking analysis, because we consider that the analysis previously carried out for the 3.6 boundary[467] also applies to the 3.8 GHz boundary.

A15.57 The analysis previously carried out for the 3.6 boundary suggested that there is some potential risk of interference to SESs above 3.6 GHz with separation distances up to about 8 km from a base station operating below 3.6 GHz. These separation distances are in line with the ones measured for out-of-band interference.

A15.58 We have identified a number of commercially available high pass filters having a 3.8 GHz pass band edge. We have also identified a number of commercially available filters having a 3.7 GHz pass band edge; these appear to be more commonly available, and all manufacturers we contacted confirmed that customising the band edge to 3.8 GHz will neither incur extra cost nor compromise performance. Such filters are generally available at a cost of around US$300~US$500.

A15.59 Therefore, we assume that SES operators can protect their receivers from blocking by retro-fitting any of those filters that better suits their protection requirements.

A15.60 Subject to system design and implementation, satellite earth stations are normally equipped with a low noise amplifier (LNA) alongside separate IF downconverter or an integrated low noise block (LNB). Both LNA and LNB may suffer front-end saturation caused by strong radio signals from nearby sites operating in adjacent frequencies, in which case a band pass filter can mitigate the interference effect. Examples of such filters are listed in the table below.

Table A15.11: Performance of commercially available pass-band filters

	Passband	Rejection at 3.65 GHz	Insertion loss
Filter A	3.8 – 4.2 GHz	Minimum 45 dB	0.3 dB
Filter B	3.7 – 4.2 GHz	Typical 30 dB	0.2 dB
Filter C	3.7 – 4.2 GHz	Typical 60 dB	0.5 dB
Filter D	3.8 – 4.2 GHz	Minimum 50 dB	1 dB
Filter E	3.7 – 4.2 GHz	Typical 40 dB	0.4 dB
Filter F	3.7 – 4.2 GHz	Minimum 45 dB	0.5 dB

Fixed Links

A15.61 In the following paragraphs, we present the results from our interference assessment analysis of four of the nine current fixed links operating in channel 8 (with a centre frequency of 3830 MHz), which is the closest fixed link channel to the 3.6-3.8 GHz band

[467] Ofcom, Public Sector Spectrum Release, Technical coexistence issues for the 2.3 and 3.4 GHz award, February 2014.

edge. We considered fixed links where the receivers were located near populated areas. The modelling parameters for the FL assignments were taken directly from the relevant licences and are presented in Table A15.12.

Table A15.12: Fixed Links modelling parameters

Fixed Link Receiver	FL 1	FL 2	FL 3	FL 4
Antenna Gain (dBi)	35.1	35.1	35.1	35.1
Beamwidth (°)	1	1	1	1
Antenna pattern[468]	ITU-R F.699	ITU-R F.699	ITU-R F.699	ITU-R F.699
Antenna height (m)	50	50	50	50
Noise Temperature (K)	1595	1595	1595	1595
Elevation angle (°)	-0.09	-0.16	0.08	-0.18
Path length (km)	37.57	7.14	7.76	35.1
Availability (%)	99.99	99.99	99.99	99.99
Fade margin (dB)	18.9	10	10	20.1
Centre Frequency (MHz)	3830	3830	3830	3830
Bandwidth (MHz)	30	30	30	30

Area analysis

A15.62 In Table A15.13 we summarise the results obtained with a worst-case area-analysis described in A15.53 i), when assessing coexistence against long-term interference (see A15.55).

Table A15.13: FL area analysis results – worst-case – long term criteria

Fixed Link	**Non-AAS** max interfering distance (km]	**AAS** max interfering distance (km)
FL 1	37.5	40
FL 2	18	18.7
FL3	33	33.3
FL4	36.9	37.1

[468] Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100MHz to 86GHz https://www.itu.int/dms_pubrec/itu-r/rec/f/R-REC-F.699-8-201801-I!!PDF-E.pdf

A15.63 Following the same approach as our analysis for satellite earth stations, we also conducted an area analysis in which we adjusted the BS parameters to represent a more realistic case. The results of the area analysis for the more realistic case are shown in Table A15.14.

Table A15.14: FL area analysis modelling results – realistic case – long term criteria

Fixed Link	Non-AAS max interfering distance (km)	AAS max interfering distance (km)
FL 1	19	37.4
FL 2	17	17.7
FL 3	13.5	14
FL 4	33.1	34.8

A15.64 The maximum interfering distances shown in Tables A15.13 and A15.14 are larger than those we observed for SESs. This is because the fixed link antennas are very directional and, unlike SES antennas, do not have a steep elevation angle. The interference contour mainly develops along the direction of the antenna boresight. We provide a summary of the results in Figures A15.9 and A15.10.

Figure A15.9: FL 1 worst-case (top) and realistic-case (bottom) interference contour for AAS

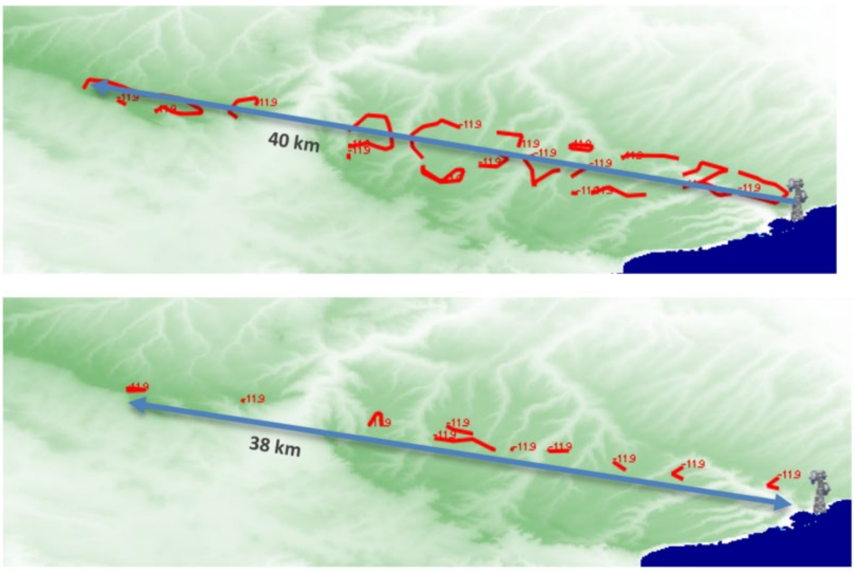
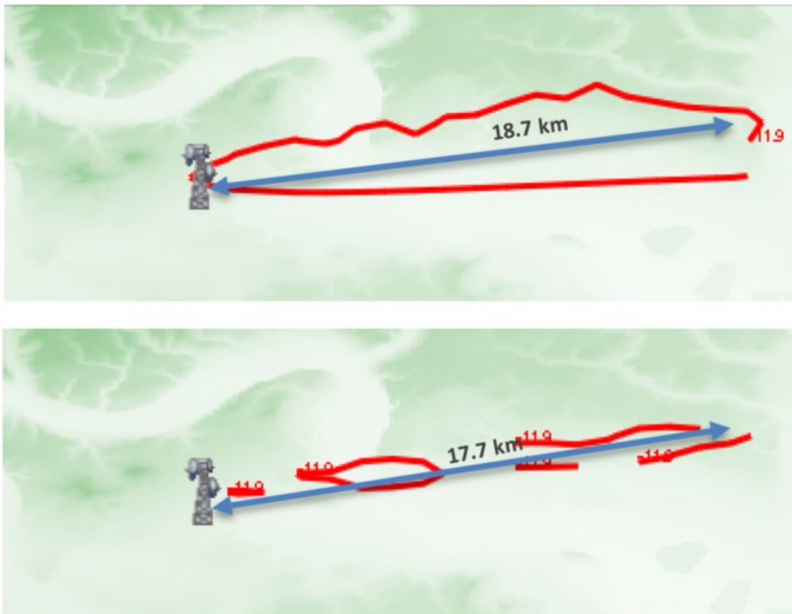


Figure A15.10: FL 2 worst-case (top) and realistic-case (bottom) interference contour for AAS



Example macrocell deployment results – baseline analysis

A15.65 We then assessed interference against our example macrocell deployment (using the approach described in A15.53 ii), and the assumptions set out in Table A15.5). A summary of the results for both non-AAS and AAS systems is presented in Table A15.15 below, showing the number of BS sectors causing interference above the threshold.

A15.66 We considered two different cases for the OOB emissions levels for AAS, as set out in Table A15.5: a conservative case based on the ECC mask and a more realistic case, using the 'flat 60dBc AAS' mask, which is a mask derived from data we received from various equipment manufacturers.

Table A15.15: Number of potentially interfering BS sectors 70km around each FL

Fixed Link	Long-term single entry			Short-term single entry			Long-term aggregate		
	ECC mask non-AAS	ECC mask AAS	Flat 60dBc AAS	ECC mask non-AAS	ECC mask AAS	Flat 60dBc AAS	ECC mask non-AAS	ECC mask AAS	Flat 60dBc AAS
FL 1	4	6	1	1	1	0	2	4	0
FL 2	20	45	7	33	76	6	28	81	5
FL 3	12	31	3	48	102	7	10	59	1
FL 4	17	32	6	4	7	1	17	44	5

Example macrocell deployment results – sensitivity analysis including receiver selectivity `

A15.67 Finally, following the same approach as for SES, we assessed the impact of receiver selectivity.

A15.68 The results in Table A15.16 illustrate the interference risk based on the combined effect of out-of-band emissions from the transmitter and the selectivity from each receiver. We have presented both area analysis and example macrocell deployment results. The receiver mask we assumed for FL receivers is based on ETSI EN 302.217[469] specifications and is also used in our frequency coordination software tool. All other parameters were the same as those used in the area analysis (realistic case) and example macrocell deployment (baseline analysis).

A15.69 Comparison of the results in Table A15.16 with Tables A15.14 and A15.15 show that there is a small increase in the interference impacts when the effect of receiver selectivity is taken into account.

Table A15.16: Analysis including the effect of receiver sensitivity for AAS systems.

Fixed Link	max interfering distance (km)	No. of potentially interfering sectors		
		Long term single entry	Short term single entry	Long term aggregate
FL 1	37.3 km	2	0	1
FL 2	17.3 km	10	12	7
FL 3	14 km	6	16	4
FL 4	36.1 km	7	4	7

A15.70 Improved receiver selectivity will help to mitigate the interference risk, including any risks related to blocking. Fixed link operators operating in channel 8 (centre frequency of 3830 MHz) will need to consider whether additional filtering is needed on a case by case basis. Filtering in fixed links systems is usually integral to the radio equipment and we therefore recommend that fixed link operators operating in channel 8 communicate with their equipment manufacturer to discuss any filtering requirements.

[469] ETSI EN 302.217 -1 v3.1.1: Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; https://www.etsi.org/deliver/etsi_en/302200_302299/30221701/03.01.01_60/en_30221701v030101p.pdf

A16. Illustrative auction procedures

A16.1 This annex sets out Ofcom's draft auction rules for the award process. The rules implement the Combinatorial Clock Auction (CCA) auction design that we have developed in collaboration with our advisers DotEcon and Auctionomics.

A16.2 Where terms are used that have specific defined meanings, they are introduced in **bold** and listed in the glossary at the end of this annex.

A16.3 This annex is not an attempt to draft auction regulations for the award. The procedures are subject to variation as a result of amendments to the auction design, to take account of responses to this consultation or as we prepare the draft regulations. We are developing the auction regulations in parallel with this consultation and we intend to consult on a draft of the proposed auction regulations in early 2019. We are publishing these illustrative procedures to help consideration of the practical implementation of the proposed auction design.

Overview of the award process

A16.4 The award process we are proposing would include spectrum lots and coverage obligations. The spectrum lot categories in the award would be:

- 2x30 MHz of paired frequencies (FDD) in the 700 MHz band (700 FDD);
- 20 MHz of unpaired frequencies (SDL) in the 700 MHz band (700 SDL); and
- 120 MHz of unpaired frequencies (TDD) in the 3.6-3.8 GHz band (3.6).

A16.5 Ofcom would also offer two coverage obligations, which bidders can include in their bids in exchange for a reduction in the price of their licence determined by the auction.

A16.6 The assignment of spectrum would be subject to a spectrum cap limiting the bandwidth that each bidder may obtain. As set out in section 5, we are proposing to apply a cap of 37% on the total amount of mobile spectrum that may be held by a single operator. Therefore, different bidders may face varying limits on the amount of spectrum that they can acquire in this auction.

A16.7 The award mechanism would consist of two distinct stages, as in other recent auctions run by Ofcom:

- the first stage (the **principal stage**), which adopts a CCA format, would determine the bandwidth that would be assigned to each bidder in each of the three lot categories of spectrum and the assignment of coverage obligations, together with a **base price** for each winner;
- the second stage (the **assignment stage**), which adopts a combinatorial sealed-bid format, would determine the specific frequencies assigned to each bidder in each of the three categories of spectrum (matching the bandwidth each has been assigned in the principal stage and ensuring that each bidder is assigned contiguous frequencies in each

category) and an **additional price** for each winner, to be paid in addition to the base price.

Participation in the auction

Qualification process

A16.8 Participation in the auction would be restricted to **qualified applicants**. In order to participate, interested parties must make an application and meet certain criteria to ensure that they are suitable to hold a spectrum licence. The provisions for qualification of applicants can be expected to be similar to those used in recent awards by Ofcom and would be specified in the Information Memorandum and auction regulations once these are published.

A16.9 As part of the application, applicants would be required to specify their current spectrum holdings, as this information would be required for the implementation of the proposed spectrum cap. Applicants may be required to lodge an initial deposit with Ofcom, which might be forfeited if the applicant breaches the rules of the award process.

A16.10 After the deadline for application, Ofcom would notify each applicant of the identity of the other applicants. Applicants would then need to ensure they meet bidder association rules. Participants in the auction may not be associated. To ensure this, one or more of a group of associated applicants may be required to withdraw their applications.

A16.11 After the deadline for withdrawal of applications, Ofcom would determine which applicants qualify to participate in the auction. In making this determination, Ofcom may require additional information from specific applicants, which would need to be provided before a deadline specified by Ofcom.

A16.12 Ofcom would publicly announce the list of bidders and return the initial deposit to any applicants who fail to qualify or have withdrawn their application in line with the auction regulations.

Financial deposit

A16.13 Prior to the start of the auction, bidders would be required to deposit a monetary amount with Ofcom (the financial deposit) to guarantee any payment they might be required to make. A bidder's **financial deposit** may be forfeited in whole or in part if the bidder breaches the award regulations.

A16.14 The **initial deposit** made by an applicant on application would, if that applicant qualifies to bid in the auction, become part of its financial deposit as a bidder. Bidders would therefore only be required to lodge the difference between their initial deposit and the financial deposit. Any interest on financial deposits would be returned to the **Consolidated Fund**.

A16.15 The amount of the financial deposit would determine the bidder's **initial eligibility**, which in turn determines the combinations of lots for which the bidder can bid for during the auction. Bidders would be required to make the financial deposit before the start of the auction, based on the starting prices of the spectrum lots for which the bidder wishes to be able to bid (see paragraph A16.49 below for details).

A16.16 Ofcom may require bidders to increase their financial deposit during the auction through a deposit notice, in order to ensure that the financial deposit is within a given range of the highest bids made by the bidder. Bidders who fail to increase their deposit as required may face restrictions for submitting further bids or be disqualified from the auction.

A16.17 A bidder's financial deposit (subject to any such forfeits) would count towards payment for awarded spectrum at the end of the auction, with the bidder making up the difference. If the price that the bidder is required to pay is less than its financial deposit, the difference would be returned to the bidder.

A16.18 Details about how and when to pay the financial deposit and arrangements for deposit notices would be provided by Ofcom at a later stage.

Running of the auction

A16.19 The auction is expected to be run over the internet using an **Electronic Auction System (EAS)**, as with previous auctions run by Ofcom. No specialist hardware or software would be required on bidders' terminals, as the EAS interface would run on a standard web browser. However, bidders would need to install authentication credentials, provided by Ofcom only to bidders, on any computer they wish to use to access the EAS.

Spectrum caps

A16.20 Ofcom is proposing to set a **spectrum cap** on the total bandwidth that any operator may hold after the auction equal to a 37% share of all relevant spectrum or 416MHz. For some operators this may set a limit on the maximum amount of spectrum they can acquire in the auction.

Principal stage

A16.21 The spectrum would be offered in **spectrum lots** in three different categories (700 MHz FDD, 700 MHz SDL and 3.6 GHz TDD). Each lot corresponds to a given bandwidth of spectrum within that category, but the specific frequencies that would correspond to the lot would only be determined subsequently in the assignment stage.

A16.22 **Coverage obligations** would be offered as a separate category. A coverage obligation corresponds to a licence condition that would be included in the award licence of any bidder that won the coverage obligation.

A16.23 A **package** is defined by indicating for each category the number of lots and whether a coverage obligation is included in the package. Bids in the principal stage are for packages. The **bid amount** indicates the maximum base price that the bidder may be required to pay if the bid is selected as a **winning bid** (in which case it would receive all the lots included in the package). The bid amount must be at least £1,000 for any package that includes at least one lot.

A16.24 Bidders may bid for spectrum unencumbered by the coverage obligation (by bidding on packages that only include spectrum lots), or for spectrum subject to the coverage obligation (by bidding on packages that include both spectrum lots and a coverage obligation). However, bidders are not allowed to bid for a coverage obligation alone.

A16.25 Bidding in the principal stage would proceed in rounds, which consist of time windows scheduled by Ofcom during which bidders are invited to submit their bids (subject to the provisions for extensions, described in the section dealing with round extensions below). Bids submitted outside this time window (applying any **extension** in force) would be rejected.

A16.26 The principal stage consists of two phases:

- the **primary bid rounds** (sometimes called a clock phase); and
- the **supplementary bids round**.

A16.27 The primary bid rounds would consist of one or more rounds. For each primary bid round, Ofcom would announce a **round price** of each lot category (i.e. a price per lot for each category). Round prices would be positive for spectrum lots. Round prices would be negative or zero for coverage obligations.

A16.28 The round prices in turn determine the **bid amount** for a package containing at least one lot.[470] This is calculated as the greater of £1,000 or the sum of round prices for all the lots contained in the package. Bidders can then make a **primary round bid** by indicating the package for which they wish to bid for and, given the prevailing round prices, this would determine the sum of round prices for all the lots contained in the package.

A16.29 At the end of each primary bid round, Ofcom would calculate the **aggregate demand** for each lot category, by summing the number of lots demanded by bidders in that round's primary bids excluding demanded lots from chain bids. There is **excess demand** for a lot category if the aggregate demand for that category is greater than the number of lots available in that category.

A16.30 The primary bid rounds would end when there is no excess demand, either for any spectrum lot category or for the coverage obligation category having a strictly negative round price. Otherwise, a further primary round is needed, for which Ofcom would increase the primary round price for:

- spectrum lot categories for which there is excess demand; and
- the coverage obligation category if there is excess demand and if the primary round price is negative;

and leave the primary round price for any other lot categories unchanged.

[470] Formally, this applies only to non-zero packages which include at least one lot. A null package is one that contains zero lots and its round price is always zero.

A16.31 The primary bid rounds are followed by a supplementary bids round, where bidders can submit in one round, multiple, mutually exclusive **supplementary bids**. Ofcom would not set prices for the supplementary bids round. Instead, bidders would be able to specify the bid amount for each of their supplementary bid packages, subject to **revealed preference constraints** that reflect bidding during the primary bid rounds. These are discussed further from paragraph A16.55 below.

A16.32 Bidding throughout the principal stage would be subject to **activity rules** to ensure that bidding is progressive and consistent with truthful bidding, discouraging bidders from withholding demand until late in the auction. In the primary bid rounds, the activity rules may limit the possibility of submitting primary bids for certain packages. In the supplementary bids round, the activity rules may cap the bid amount that a bidder can specify for a given package, depending on the bids it made in the primary rounds and on the other supplementary bids that the bidder wishes to submit.

A16.33 At the end of the supplementary bids round, all **valid bids** submitted during the principal stage would be evaluated to determine the winning bids (described from paragraph A16.120). The price that winning bidders would be required to pay for the lots they have been assigned (the base price) would be determined according to second-price principles. The second-price principle Ofcom would apply is known as the Vickrey-nearest minimum revenue core (VN-MRC) pricing rule (described from paragraph A16.126), subject to the constraint that all base prices must be at least £1,000.

A16.34 The auction would then proceed to the assignment stage.

Lots available and coverage obligations

A16.35 The available spectrum would be offered in the following lot categories:

- 700 FDD, containing six lots, each consisting of 2x5 MHz of FDD spectrum in the 700 MHz band;
- 700 SDL, containing four lots, each consisting of 5 MHz of SDL spectrum in the 700 MHz band; and
- 3.6, containing 24 lots, each consisting of 5 MHz of TDD spectrum in the 3.6 GHz band.

A16.36 The two coverage obligations would be offered in a separate category, which bidders may include in their bids. During the primary bid rounds, a bid that includes a coverage obligation would provide a discount to the prices of the spectrum lots included in the package. For the purposes of applying round prices, each coverage obligation is treated as a lot within the auction in just the same manner as a spectrum lot, with the exception that the round price of coverage obligations will be negative or zero, whereas the price of spectrum lots will always be positive.

Bids

A16.37 A bid in the principal stage consists of:

- a package, which defines the combination of spectrum lots and at most one coverage obligation that would be assigned to the bidder if that bid were selected as a winning bid; and
- a bid amount, which determines the maximum base price that the bidder may be required to pay if that bid were selected as a winning bid.

A16.38 A **non-zero package** is a package that contains at least one spectrum lot, as opposed to the **zero package** that does not contain any lot.

Implications of submitting a bid

A16.39 Submitting a bid establishes a commitment to acquire, in the event that the bid is selected as a winning bid, all of the lots (including any coverage obligation) in the package of the bid for a base price determined in accordance with the procedure described from paragraph A16.126.

A16.40 Bids submitted in the auction cannot be withdrawn.

A16.41 The bids submitted by a bidder in the principal stage are mutually-exclusive, so at most one of the various primary round and supplementary round bids submitted by a bidder can be selected as a winning bid.

Valid bids

A16.42 Bidders cannot bid for packages which:

- include more spectrum lots of a given category than there are available in that category;
- include more spectrum than the bidder would be allowed to acquire under the spectrum cap;
- include a coverage obligation, but no spectrum lots;
- include more than one coverage obligation; or
- have eligibility (as determined in accordance with paragraph A16.47) greater than that bidder's initial eligibility (as determined in accordance with paragraph A16.49).

A16.43 The **minimum bid** for a non-zero package is equal to the greater of £1,000 or the sum of the starting prices of all spectrum lots and coverage obligations included in the package.

A16.44 The bid amount must be:

- specified in a whole number of thousands of pounds; and
- at least the minimum bid for the package.

A16.45 A bid is valid only if it is submitted during a round in accordance with the auction procedures set out below.

A16.46 All bids must satisfy the activity rules.

Activity rules

Eligibility points and package eligibility

A16.47 Each lot is assigned the following **eligibility points**:

- each 700 FDD lot is assigned four eligibility points;
- each 700 SDL lot is assigned one eligibility point;
- each 3.6 lot is assigned one eligibility point; and
- each coverage obligation 'C' is assigned zero eligibility points.

A16.48 The eligibility of a package is equal to the sum of eligibility points of all the lots included in the package.

Initial eligibility

A16.49 Each bidder would have a given number of initial eligibility points at the start of the auction, which would be determined by its financial deposit. The initial eligibility of each bidder would be set to the greatest eligibility of any package of spectrum only (i.e. that excludes the coverage obligation) whose cost at starting prices does not exceed the bidder's financial deposit.

Activity of a bidder in a primary bid round

A16.50 The activity of a bidder in a primary bid round is the eligibility of the package for which it submits a primary bid in the round.

Eligibility of a bidder in a primary bid round

A16.51 The eligibility of a bidder in the first primary bid round is set to the bidder's initial eligibility and in subsequent primary bid rounds may be adjusted down by reference to its eligibility and activity in the preceding round. Specifically:

- in the first primary bid round, the bidder's eligibility is set equal to its initial eligibility; and
- in subsequent primary bid rounds, the bidder's eligibility is set equal to the smaller of its eligibility and its activity in the immediately preceding clock round.

A16.52 Therefore, if the bidder's activity is less than its eligibility, then the bidder's eligibility for the following round would be reduced (and set equal to the activity level of the primary bid just submitted). However, if the bidder's activity exceeds its eligibility in a primary bid round (which is permitted if a bidder makes a **relaxed primary round bid**, discussed below), then its eligibility for the following round would remain the same.

A16.53 The eligibility status of a bidder in a primary bid round determines which potential bids from the bidder are subject to revealed preference constraints (explained below).

Eligibility-reducing rounds

A16.54 An **eligibility-reducing round** is a primary bid round in which the bidder's activity is less than its eligibility, which leads to a reduction in the bidder's eligibility in the subsequent primary bids round. Eligibility-reducing rounds are defined with respect to each bidder independently and are made known to the bidder by the EAS before a primary bid is formally submitted.

Relative caps on package bid values (Revealed preference constraints)

A16.55 We propose that the activity rules for the CCA use revealed preference constraints arising from choices made in certain previous primary bid rounds.[471] These place relative caps on the bids a bidder can submit based on value differences implied by the bidder's earlier choices in some key rounds, as explained below.

A16.56 Suppose that a bidder chooses to bid for package X in preference to package Y when round prices are P, implying bid values P^X and P^Y respectively. A revealed preference constraint in relation to this choice constrains a subsequent bid for package Y as follows:

> Subsequent bid for package Y cannot be above the current highest bid amount for package X (which may be above P^X) plus the difference in package prices when the bidder chose to bid for package X instead of package Y (i.e. P^Y - P^X).[472]

This is a 'relative cap' on package Y; the bid value of package Y is constrained relative to a preference revealed in the last round where the bidder had sufficient eligibility to bid on both packages X and Y.

A16.57 In the relative cap, package Y is a **constrained package** and package X is a **constraining package**. Revealed preference constraints, that define relative caps, apply for the making of relaxed primary bids (discussed below), and generally in the supplementary bids round.

Relative caps in primary bid rounds

A16.58 Specifically, revealed preference constraints would apply only in primary bid rounds where a bidder wishes to submit a bid having an activity exceeding current eligibility – a relaxed primary bid. In this scenario, the revealed preference constraint would be applied with reference to the primary bid made by the bidder in the most recent primary bid round in which the bidder had eligibility at least as high as the activity proposed in the current

---

[471] In eligibility reducing rounds and the supplementary bids round. 'Package prices' is shorthand for 'round price of a package'.

[472] If the highest bid value for package X were PX, this amounts to restricting a subsequent bid value for package Y as not exceeding the bid value for package Y at round prices P, i.e. PY. If, however, a bidder has increased the bid value on package X by an amount delta, then the restriction allows a subsequent bid on package Y to be no higher than PY plus delta.

round.[473] The revealed preference constraint applying to a relaxed primary round bid is with reference to a bidder's choice made in an earlier primary bid round in which the bidder had enough eligibility to bid for the package of interest in the current round. Reduction in a bidder's eligibility and bid choices reveal information about a bidder's valuation for lots.[474]

A16.59 If round 'n' was the most recent primary bid round in which the bidder's eligibility was at least equal to the eligibility of package Y and the bidder chose to bid for package X rather than package Y in round n, the revealed preference constraint relative cap would limit a subsequent bid for package Y not to exceed the revealed preference constraint (RPC), where:

> RPC = The current highest bid amount for package X plus the difference in package prices when the bidder chose to bid for package X instead of package Y at round n prices (i.e. $P^Y_n - P^X_n$).

A16.60 If the relaxed primary bid for package Y is no greater than RPC, the relaxed primary bid is a valid bid.

A16.61 If the bid value of package Y in the current primary bid round were such that the revealed preference constraint relative cap above is not satisfied, because the value of package Y is above RPC, it may still be possible for the bidder to submit a relaxed primary bid for package Y. This possibility arises if the bidder submits one or more required chain bids.

Chain bids in primary bid rounds

A16.62 A chain bid is a revised higher bid for a constraining package such that the revealed preference constraint shown in paragraph A16.59 is satisfied. A chain bid for a constraining package in the primary bid rounds cannot be at a value above the current round price of that package.

A16.63 A chain bid is calculated as the smallest possible revised higher bid value for a constraining package X needed to ensure that a relaxed primary bid for package Y complies with the revealed preference constraint (RPC) and which is no higher than the current round price of the constraining package. Where a chain bid is calculated and meets these requirements, the relaxed primary bid for package Y is valid. In this instance, a chain bid for package X is the new bid for package X that would accompany the relaxed primary round bid for package Y.[475]

A16.64 In the case where the current package price for package Y exceeds RPC a chain bid (CB) for package X is the bid value for package X that is (i) above the current highest bid amount for package X; (ii) not higher than the current round price of package X and (iii) such that:

[473] The activity associated with any bid cannot exceed initial eligibility.
[474] Eligibility reduction is of significance during the primary bids round phase, as a bidder lowering activity knows it may foreclose the opportunity to bid on packages with activity status above current eligibility in future primary bid rounds.
[475] Chain bids would not be included in aggregate demand calculations.

The current round price of package Y = CB plus the difference in bid values when the bidder chose to bid for package X instead of package Y in round n prices (i.e. $P^Y_n - P^X_n$).

CB is the lowest bid value for the constraining package X that ensures that a bid for package Y at current round prices satisfies the revealed preference constraint. It raises the bidder's previous highest bid for package X, and with the cap RPC such that RPC just equals the current round price of package Y.

A16.65 It might not be possible to satisfy these conditions simultaneously, as the bid value for the constraining package X needed to bring RPC equal to the current round price of package Y might exceed the round price of package X. In this case, a relaxed primary bid for package Y will not be possible.

A16.66 Where a bidder is notified by the EAS that a package exceeds the bidder's eligibility in a primary bid round, the EAS would indicate whether a relaxed bid could be made for the package.

A16.67 The EAS would also inform the bidder whether the relaxed bid requires one or more chain bids. More than one chain bid may be required if the bidder's proposed current round activity is associated with a previous round which was itself followed by an eligibility reducing round that occurred before the current round. In this setting, chain bids may be required to ensure that revealed preference constraints are preserved across all pairs of bid packages that are ultimately linked through packages X and Y.

A16.68 If the submission of a bid for package Y requires a chain bid for package X, any intervening eligibility reduction between the rounds will themselves have revealed preference constraints of the form expressed above in paragraph A16.59. For example, a bidder may have submitted a bid for package W in a primary bid round after the bidder submitted a bid for package X. Eligibility reduction would have occurred if the bid for package W has lower eligibility than package X. In this case, package W would be the constraining package for package X. If a chain bid is required for package X, due to a relaxed bid for package Y, it might consequently violate the relative cap holding between packages X and W. In this situation, another chain bid in respect of package W would be required and can only be made if it preserves a revealed preference between packages X and W and does not result in a revised bid value for package W above the value of package W in the current round.[476]

A16.69 A relaxed primary round bid can only be submitted where all relative caps are preserved and this may necessitate one or more chain bids. The bidder would be made aware of this in the bid form on the EAS before confirming any relaxed primary round bid submission in the EAS. If the bidder does not confirm the submission of a relaxed primary round bid and any associated chain bid(s) required, then the EAS would not allow the bid to be submitted as a relaxed primary round bid.

[476] The number of chain bids cannot be above the number of eligibility reducing rounds that have occurred before the current round. Several chain bids may be necessary if a bidder experiences two or more eligibility reducing rounds during the primary bid rounds phase and the bidder wishes to submit a relaxed bid.

A16.70 We refer to the relative caps that result from these revealed preference constraints in the primary bid rounds as **eligibility reduction caps**.

A16.71 Revealed preference constraints would not apply for packages with eligibility less than or equal to the bidder's current eligibility level.

A16.72 Where a bidder submits a relaxed primary round bid (and it was not the final primary bid round), this would result in eligibility in the subsequent primary bid round being maintained at the same level. A relaxed primary round bid does not change a bidder's eligibility.

A16.73 A relaxed primary bid is not valid whenever the relative caps discussed above are not satisfied, either directly or indirectly via revised bid amounts for constraining packages through chain bids.

Relative caps in the supplementary bids round

A16.74 Revealed preference constraints would apply to all bids made in the supplementary bids round by reference to the bidder's choice in the final primary bid round. For these relative caps, the constraining package would be the package chosen by the bidder in the final primary bid round. For each bidder, these relative caps are called a **final price cap**.

A16.75 The final price cap would result in relative caps, which may require the bidder to raise bids on packages for which they have bid during the primary bid rounds in order to be able to submit or raise bids for other packages in the supplementary bids round.

A16.76 The relative caps would operate in a similar way as the relative cap for relaxed bids in primary bid rounds. The constraining package in the final price cap would be the bidder's package in the final primary bid round and revised bids would comprise chain bids.

A16.77 Every supplementary bid for a package with eligibility above the bidder's final primary bid round package will also be subject to a relative cap arising from eligibility reduction in a primary round, limiting the bid relative to the highest bid for the constraining package in the same way as in the primary bid rounds.

A16.78 The EAS would alert bidders to applicable relative caps and applicable associated chain bids.

Validity of primary round bids

A16.79 A bidder may only bid for one package in a primary bid round and with eligibility not exceeding the bidder's initial eligibility and may only bid for packages that comply with any applicable spectrum cap. Where a bidder raises a bid in a primary bid round with eligibility satisfying the aforementioned and is at or below the bidder's current eligibility, it shall be valid and would not be subject to any relative caps.

A16.80 Where a bidder raises a relaxed bid in a primary bid round with eligibility above the bidder's current eligibility, it shall be valid if it satisfies all applicable revealed preference relative caps. Two scenarios arise in respect of these eligibility reduction caps:

- The eligibility reduction caps on the bidder's primary round bid satisfy the revealed preference constraints and are such that the bidder could submit the bid at the round prices for the package without needing to increase its bid for any constraining package; or
- The eligibility reduction caps on the bidder's primary round bid do not satisfy the revealed preference constraints but the submission of one or more chain bids by increasing bid values for any constraining package(s) to amount(s) not exceeding the price of the constraining package at current round prices enable the revealed preference constraints to be satisfied. For this case, the revised bid amounts for the constraining packages are valid bid amounts for the constraining packages.

A16.81 The primary round bid entry form provided by the EAS would allow bidders to select a package with eligibility greater than the bidder's eligibility level. The EAS would then check whether the primary round bid would be valid given the bidder's eligibility reduction caps and the round prices in the relevant primary bid rounds, the minimum bid amounts for constraining packages that would be necessary for the bidder to be able to submit a relaxed primary round bid, and whether the bidder would be required to submit any chain bids along with this primary round bid.

A16.82 The EAS would also provide functionality to assist bidders in identifying when they may be able to submit relaxed bids. Specifically, the EAS interface would allow bidders to maintain a list of provisional supplementary bids (explained further below). The list of provisional supplementary bids would automatically include all the non-zero packages for which the bidder has already submitted a primary round bid. In addition, each bidder may enter additional packages in their list of provisional supplementary bids. When a primary bid round is in progress, the EAS interface would alert the bidder of the possibility of submitting relaxed bids for any of the packages in their list of provisional supplementary bids.

Primary bid rounds phase

Scheduling of primary bid rounds

A16.83 Ofcom would provide guidance in advance of the auction on the expected minimum notice that would be provided before the start of a primary bid round and the expected minimum round duration.

A16.84 When a round is scheduled, the following information would be made available to each bidder:

- the schedule for the round;
- the primary bid round price for each lot category and the round price for the coverage obligation for the round;
- the bidder's eligibility for the round; and
- the number of remaining extension rights the bidder has available for the primary bid rounds.

Bid submission during a primary bid round

A16.85 Each bidder may submit at most one bid in any primary bid round, using the bid form provided by the EAS.

A16.86 To submit a bid, a bidder would need to:

- specify, using the bid form provided by the EAS, the number of lots in each category that it wishes to include in the package of the bid (the bid amount would be automatically calculated by the EAS);
- send the completed bid form to the auction server, so that the bid can be checked for validity against the auction rules; and
- provided that the bid specified by the bidder is valid according to the auction rules, confirm submission of the primary round bid (along with any necessary chain bids), using the confirmation form provided by the EAS.

A16.87 Upon receipt of a valid bid submission, the EAS interface would provide a confirmation page. Conversely, if the bid submission process fails, the EAS interface would revert to the bid form. It is the responsibility of the bidder to check (through its bidder interface) that the bid has been successfully received by the auction server, and to alert Ofcom if they suspect any problems have occurred.

A16.88 The bid submission is only completed when the bidder has confirmed its submission. Bids sent to the server for validity checks but not confirmed are discarded by the EAS. Making a bid is, therefore, a two-step process.

A16.89 Once the EAS has received a confirmation of a valid submission in a round, the bidder would not be able to revise or withdraw this submission or submit any further bids in that round.

A16.90 In the first primary bid round, a bidder which does not submit a valid primary bid having activity of at least one eligibility point would be excluded from the award process and would forfeit all deposits submitted in accordance with the regulations governing the award process.

A16.91 In subsequent primary bid rounds, bidders have the option to submit a **zero bid**, i.e. a bid for an empty package containing no lots (the zero package) with a bid amount of zero. Any bidders who do not submit a primary round bid before the end of a primary bid round (taking account of any applicable extensions, as explained below) would have a zero bid automatically entered by the EAS on their behalf. A bidder who has submitted a zero bid in a primary bid round (either by actively making a zero bid or by default because of not submitting any bid at all) would not be able to submit any further primary round bids. It is important to note that any bidder who has submitted a zero bid in the primary bid round phase would be able to submit supplementary bids in the supplementary bids round.

Aggregate and excess demand

A16.92 The **aggregate demand** for a lot category in a given primary bid round is the sum of lots in that category included in the primary round bids submitted by bidders in that round, excluding any chain bids.

A16.93 At the end of each primary bid round, there is **excess demand** for a lot category if and only if aggregate demand for that lot category exceeds the number of lots available in that category.

Primary bid round prices

A16.94 For each primary bid round, Ofcom would specify the primary bid round price per lot for each lot category and coverage obligation. The primary bid round prices for spectrum lots would always be strictly positive; the price for the coverage obligation would be negative or zero.

A16.95 In the first primary bid round, the round price for each lot category and the coverage obligation would be the reserve price for that category. The reserve prices would be specified and published by Ofcom before the auction.

A16.96 For subsequent primary bid rounds:

- the round price for spectrum lot categories for which there was excess demand in the previous primary bid round would be increased;
- the round price for the coverage obligation category where it has a strictly negative price and for which there was excess demand in the previous round would be increased; and
- the round price for other lot categories would remain unchanged.

A16.97 Round prices would not decrease over the course of the primary bid rounds.

A16.98 The increase in prices of lot categories for which there is excess demand would be determined at Ofcom’s discretion and may vary across lot categories and across the rounds. We currently expects setting price increments for spectrum lots no greater than 20% of the previous price from one round to the next.

A16.99 In the case of the coverage obligations, Ofcom might set an increment in excess of 20% of the current round price. However, we do not currently expect to set an increment in excess of 10% of the reserve price.

A16.100 Throughout the primary bid rounds, prices would be specified in whole thousands of pounds.

End of the primary bid rounds phase

A16.101 The primary bid rounds phase ends after the first primary bid round in which:

- there is no excess demand for any spectrum lot categories; and

- for each coverage obligation category, either there is no excess demand for that category or the lot category price is zero.

A16.102 At this stage, the auction would progress to the supplementary bids round.

A16.103 Ofcom may exceptionally declare the end of the primary bid rounds earlier if it considers that moving directly to the supplementary bids round would be in the general interest of running an efficient award process.

Information released at the end of each primary bid round, other than the final primary bid round

A16.104 After the end of each primary bid round, other than the final primary bid round, we propose to inform bidders whether the level of excess demand for each spectrum lot category is less than or equal to the nearest higher multiple of 20 MHz (e.g. less than or equal to 20 MHz, less than or equal to 40 MHz, etc). If there were no excess demand for a spectrum lot category, we would simply inform bidders that demand is less than or equal to 20 MHz.

A16.105 We propose to reveal no aggregate demand information on the coverage obligations after each primary bid round.

Information released at the end of the final primary bid round

A16.106 We propose to reveal no aggregate demand information after the final primary bid round, both for the spectrum lots and the coverage obligations.

The supplementary bids round

A16.107 The supplementary bids round is a single round of bidding in which bidders may submit bids (supplementary bids) for alternative, mutually exclusive packages (regardless of whether the bidder has previously submitted any bids for that package in the primary bid rounds).

A16.108 Bidders can specify the bid amount for their supplementary bids, subject to the constraints set out below.

Scheduling of the supplementary bids round

A16.109 Ofcom would provide guidance in advance of the auction on the expected minimum notice period that would be provided before the start of the supplementary bids round and the expected minimum round duration.

Bid submission during the supplementary bids round

A16.110 When the supplementary bids round is in progress, bidders may submit a single list of supplementary bids using the EAS.

A16.111 To submit a list of supplementary bids using the EAS a bidder would need to:

- enter or edit a list of **provisional supplementary bids** that satisfies all constraints on supplementary bids (set out below);
- send the list of provisional supplementary bids to the EAS, so that it can be checked for validity against the auction rules; and
- provided that all the bids in the list are valid according to the auction procedures, confirm submission of the list of provisional supplementary bids using the confirmation form provided in the bidder interface of the EAS.

A16.112 The bidder would not be able to confirm the submission of a list of supplementary bids if any of the bids in the list are invalid. In such a case, none of the bids in the list would be accepted unless the bidder amends their list and completes the submission process with a valid list of supplementary bids.

A16.113 Upon receipt of a valid submission of a list of supplementary bids, the EAS interface would provide a confirmation page listing the supplementary bids received by the EAS. Conversely, if the supplementary bids submission process fails, the EAS interface would revert to the provisional supplementary bids editor. It is the responsibility of the bidder to check (through their bidder interface) that their list of supplementary bids has been successfully received by the auction server, and to alert Ofcom if they suspect any problems have occurred.

A16.114 The process of submitting a list of supplementary bids is only completed when the bidder confirms the submission. A list of supplementary bids sent to the server for validity checks but not confirmed would be discarded by the EAS.

A16.115 Once the EAS has received a confirmation of a valid submission of a list of supplementary bids in the supplementary bids round, the bidder would not be able to revise or withdraw this submission or submit any further supplementary bids.

A16.116 Any bidder who does not submit a list of supplementary bids before the end of the supplementary bids round (taking account of any applicable extensions, as explained below) would lose the opportunity to submit supplementary bids. However, any valid bids submitted by the bidder during the primary bid rounds phase remain valid and would be considered in the determination of winning bids and base prices.

Constraints on supplementary bids

A16.117 Bidders may submit at most one supplementary bid for each possible package.

A16.118 Bidders may not submit a supplementary bid for a package containing zero lots.

A16.119 Bidders may specify the bid amount for each of their supplementary bids, subject to the following restrictions:

- the bid amount must be in whole thousands of pounds;
- the bid amount must be at least the sum of the starting prices of all the lots included in the package;
- the bid amount must be at least £1,000;

- the bid amount must be at least the highest bid already submitted by the bidder for the package (which could be a primary round bid or a chain bid); and
- the bid amount cannot exceed any relative caps applicable to the bid (any eligibility reduction cap and final price cap applicable to the package, given the bidders' primary round bids in the clock phase). The relative caps apply in exactly the same manner as described above from paragraph 16.74.

Determination of winning bids

A16.120 All valid bids received in the principal stage (unless cancelled by Ofcom due to a bidder breaching the auction procedures or failing to provide the required deposit payment, as explained below) are evaluated for the determination of winning bids and base prices.

A16.121 A feasible combination of bids is a selection of bids such that:

- at most one bid is selected from each bidder;
- the selected bids do not include, in total, more lots than are available for any of the spectrum or coverage obligation categories; and

A16.122 The value of a possible winning combination of bids is defined to be the sum of:

- the bid amounts for the bids in the combination, and
- the reserve price of any spectrum or coverage obligations that would remain unassigned if the bids in the combination were the winning bids.

A16.123 The winning combination of bids is a feasible combination of bids of greatest value amongst all feasible combinations of bids.

A16.124 If there are multiple feasible combinations of equal greatest value, then a tie-break rule is used to select amongst those combinations that maximise the number of geographic coverage obligations awarded.

A16.125 If multiple feasible combinations of equal greatest value still remain after this tie-break, then Ofcom would select one of the remaining combinations at random.

Determination of base prices

A16.126 Base prices for any bidders who are not assigned any lots in the principal stage are zero. Base prices to be paid by winning bidders who are assigned a non-zero package are based on the concept of opportunity cost.

A16.127 The opportunity cost of assigning to a *subset of winners* the lots they win is calculated as the difference between:

- the highest value (as defined above) across all feasible selections of bids which do not include any bids from the winners that are included in the subset; and
- the sum of bid amounts across the winning bids from winners that are not included in the subset, plus the reserve price any spectrum lots and coverage obligations that would remain unassigned if bidders are assigned the lots specified in the bids selected.

A16.128 The standalone opportunity cost of a winner is the opportunity cost of the subset of winners that includes only that winner.

A16.129 The base prices for winning bidders must satisfy the following conditions:

a) the base price for each winning bid must be at least the sum of the reserve prices of all the lots included in the package of the winning bid;

b) the base price for each winning bid must be at least £1,000;

c) the base price for each winning bid cannot exceed bid amount of the winning bid;

d) the sum of base prices for each subset of winners (including subsets containing a single winner and the subset containing all winners) must be at least the joint opportunity cost for that subset of winners;

e) the sum of base prices must be minimised across all possible sets of prices that meet the four conditions above.

A16.130 The set of prices solving this optimisation problem are the set of prices in the **minimum revenue core**.

A16.131 If there are multiple combinations of prices (one for each winning bidder) that satisfy the conditions above (i.e. in the minimum revenue core), then the base prices would be the unique combination of prices that minimises the sum of squares of the differences between each bidder's base price and its standalone opportunity cost across all sets of prices that satisfy all four of the conditions above (i.e. the Vickrey-nearest minimum revenue core price).

The assignment stage

A16.132 The assignment of specific frequencies would be determined independently for each category of spectrum.

A16.133 Ofcom would shortlist, for each category of spectrum, the possible assignments of frequencies that assign to each bidder a contiguous frequency range that corresponds to the bandwidth determined in the principal stage.[477] Subject to the previous requirements being met, Ofcom would narrow down the selection to those assignments where unsold spectrum also forms a contiguous frequency range, if possible.

A16.134 If there is only one possible frequency assignment for a category of spectrum, then this would be the winning assignment. Then bidders would be assigned the frequencies corresponding to the spectrum they won in the relevant lot category in accordance with this assignment.

A16.135 If there are multiple possible frequency assignments for a given category of spectrum, then winners of spectrum in this category would be allowed to bid for the alternative **frequency**

[477] In the case of FDD spectrum, a contiguous duplex frequency range.

options they could be assigned across the possible frequency assignments shortlisted by Ofcom.

Scheduling a bidding round for the assignment stage

A16.136 If a bidding process for the assignment stage is needed, Ofcom would schedule a single round of bidding, in which the relevant bidders may submit bids for their preferred frequency options across all relevant categories of spectrum.

A16.137 The frequency options for each bidder are determined by Ofcom, in accordance with its determination of the possible **frequency assignment plans**. If there are multiple possible frequency assignment plans for a category of spectrum, then at least two bidders would have multiple options in that band. Any such bidders would have the opportunity to express their preferences over those options in the form of bids.

A16.138 Bidders do not have to submit assignment bids to be assigned frequencies that correspond to the spectrum they won in the principal stage. Therefore, participation in the bidding process of the assignment stage is optional. The additional price for any bidders who do not participate would be zero.

A16.139 When the assignment round is scheduled, the following information would be made available to each bidder:

- the schedule of the round;
- the frequency options for which the bidder may bid.

Assignment bids

A16.140 A bid in the assignment stage relates to a frequency option available to the bidder and specifies the maximum additional price that the bidder may be required to pay if it is assigned the corresponding option. Submitting a bid establishes a commitment to pay the corresponding additional price if the bidder is assigned the corresponding option.

Bid submission

A16.141 When the bidding round is in progress, participating bidders may submit a single list of bids using the EAS.

A16.142 The interface of the EAS would provide a bid form that lists all the options available to the bidder for all relevant categories of spectrum.

A16.143 To submit its list of bids, a bidder would need to:

- enter the bid for each one of the options its wishes to bid for in its bid form (the bid amount for any options left blank would be set to zero);
- send the bid form to the EAS, so that it can be checked for validity against the auction procedures; and

- provided that all bids in the list are valid according to the auction rules, confirm submission of the list of bids using the confirmation form provided by the bidder interface of the EAS.

A16.144 The submission process would be blocked if any of the bids in the list is invalid. In such a case, none of the bids would be accepted, unless the bidder amends its list and completes the submission process of a valid list of bids.

A16.145 Upon receipt of a valid submission of a list of bids, the EAS interface would provide a confirmation page, listing the bids received by the EAS. Conversely, if the submission process fails, the EAS interface would revert to the bid form. It is the responsibility of the bidder to check (through its bidder interface) that their list of bids has been successfully received by the auction server, and to alert Ofcom if they suspect any problems have occurred.

A16.146 The process of submitting a list of bids is only completed when the bidder confirms the submission. A list sent to the server to check for validity but not confirmed would be discarded by the EAS.

A16.147 Once the EAS has received a confirmation of a valid submission of a list of bids in the round, the bidder would not be able to revise or withdraw this submission, nor submit any further bids.

A16.148 Any bidder who does not submit a list of bids before the end of the round would lose the opportunity to submit bids. In this case, the bid for all its options would be set to zero by default.

Determination of winning assignments

A16.149 The determination of winning frequency assignments would be calculated independently for each category of spectrum.

A16.150 For each category of spectrum, the EAS would sum the bid amounts of the bids that can be accepted in each alternative possible frequency assignment plan. The winning frequency assignment plan would be one that yields the greatest value of bids corresponding to the frequency options assigned to the bidders. If there are multiple frequency assignment plans that yield the greatest value, one of these would be selected as the winning frequency assignment at random.

Determination of additional prices

A16.151 The determination of additional prices is calculated independently for each category of spectrum. The total additional price to be paid by each bidder would be equal to the sum of additional prices they have to pay.

A16.152 Additional prices to be paid by winning bidders for the specific options they are assigned are based on the concept of opportunity cost.

A16.153 For each category of spectrum, the opportunity cost of assigning a subset of bidders their corresponding options is calculated as the difference between:

- the highest value of bids that could be achieved across all alternative frequency assignments if all the bids from the bidders in the subset were set to zero; and
- the sum of bids that are accepted from bidders that are not included in the subset in the winning frequency assignment.

A16.154 The standalone opportunity cost of a bidder is the opportunity cost of the subset that includes only this bidder.

A16.155 For a given frequency range, the additional prices must satisfy the following conditions:

a) the additional price for each bidder cannot be negative;

b) the additional price for each bidder cannot exceed the bid specified by the bidder for the option it is assigned;

c) the sum of additional prices for each subset of bidders (including subsets containing a single bidder, and the subset containing all bidders) must be at least the joint opportunity cost for that subset of bidders;

d) the total sum of additional prices must be the smallest across all possible sets of prices that meet the three conditions above.

A16.156 If there are multiple combinations of prices (one for each winning bidder) that satisfy the conditions above, then the additional prices would be the unique combination of prices that minimises the sum of squares of the differences between each bidder's additional price and its standalone opportunity cost across all sets of prices that satisfy all four the conditions above.

Round extensions

A16.157 A round **extension** grants additional time for a bidder who has not made a submission before the scheduled end of round. Round extensions are specific to each bidder. A given round may only be extended once for a bidder, for a maximum extension time specified in the auction rules.

A16.158 Bidders start the auction with a number of extension rights (in previous awards this number has been three) for the primary bid rounds. If a primary bid round extension is granted to a bidder, its extension rights for the Primary Bids Round would be reduced by one. Ofcom may grant additional extension rights, either to all bidders or to specific bidders, at its absolute discretion.

A16.159 Bidders also have an extension right for each of the supplementary bids round and the assignment stage (if a bidding round is required).

A16.160 A round extension for a bidder would be triggered automatically in the event that:

- the bidder has not made a submission by the scheduled end of the round;
- the bidder is eligible to make a submission in the round; and

- if the round is a primary bid round, the bidder has one or more extension rights left.

A16.161 More than one bidder may trigger a round extension simultaneously, in which case all bidders that have been granted a round extension would have an extension right deducted. However, bidders who do not have any extension rights left would not be granted a round extension, even if the round is extended for other bidders.

A16.162 When a round is extended for a bidder, the EAS would provide the revised deadline for the bidder to make their submission on the bidder's interface. The EAS may display a message on the interface of other bidders to alert them to the fact that the round has been extended for another bidder, along with the revised deadline for that bidder's submission.

A16.163 The revised deadline for bidders who are granted a round extension would be 30 minutes later than the originally scheduled end of the round. However, the extended round may terminate earlier if all bidders for which the round has been extended submit their bid(s) before the revised deadline.

Further deposit payments

A16.164 At any point during the auction, Ofcom may require bidders to increase their financial deposit up to an amount equal to the highest bid submitted by the bidder. In the event an additional deposit payment is required, Ofcom would notify bidders of this requirement, specify a payment deadline for bidders, and provide details of how to make the additional deposit.

A16.165 Failure to make a sufficient additional deposit before the specified deadline may result in:

- the bidder being prevented from submitting any further bids;
- some or all bids submitted by the bidder in earlier rounds being cancelled; and/or
- the bidder being excluded from the auction.

Extraordinary events

A16.166 Ofcom retains discretion to respond to extraordinary events that might otherwise compromise the auction by taking the following actions:

- rescheduling a round that has been scheduled and has not yet started;
- rescheduling the end of a round in progress;
- cancelling a round in progress;
- cancelling one or more completed rounds;
- suspending the auction;
- cancelling the auction;
- cancelling some or all bids submitted by one or more bidders in earlier rounds; and
- excluding one or more bidders from the auction.

A16.167 Bidders who breach the auction procedures may forfeit part or all of their deposit.

Information released at the end of the auction

A16.168 The auction ends with the completion of the assignment stage. At this point, the following information would be released to all bidders:

- the frequencies assigned to each bidder that has been awarded spectrum;
- The coverage obligation, if any, awarded to each bidder; and
- the price to be paid by each bidder that has been awarded spectrum, including a breakdown of the base price and any additional prices.

A16.169 The current expectation is that Ofcom would also release all the bid data from the auction.

Glossary of defined terms

Aggregate demand – the total demand for lots in a lot category and for the coverage obligations in the geographic coverage obligation category in a primary bid round.

Assignment stage – the second stage of the auction that determines the specific frequencies won by bidders in line with the bandwidths won in the principal stage.

Additional price – the price to be paid by a winner bidding for its assigned frequency option as determined by the assignment stage, in addition to the base price.

Activity –the eligibility points associated with the package bid for in a primary bid round.

Activity rules – various rules governing the ability of bidders to make primary round bids and supplementary bids depending on their previous primary round bids.

Base price – the price to be paid by winners of bandwidths (and also possibly coverage obligations) determined by the principal stage.

Bid – a list of lots containing at least one spectrum lot and possibly including one geographic coverage obligation submitted by a bidder in a round in the principal stage in the auction, entailing a commitment to pay an amount if the bid is a winning bid.

Bid amount – the total price of a bid for a package in the principal stage, entailing a commitment to pay up to this amount if the bid is a winning bid. A bid amount shall be no lower than £1,000.

Chain bid – One or more bids increasing bid amounts for constraining packages made in a primary bid round at the same time as making a relaxed primary round bid in order to satisfy relative caps.

Confirmation – the process of irrevocably committing one or more bids to the EAS that have previously been submitted to the EAS and checked for validity.

Consolidated Fund – the Government's general bank account at the Bank of England.

Constrained package – a package where the bid value is constrained in respect of a constraining package to satisfy revealed preference constraints.

Constraining package – a package subject to a bid in an eligibility-reducing round that establishes relative caps on packages with eligibility equal to the bidder's eligibility in that round.

Coverage obligation – an obligation that bidders can include in their bids in the principal stage to include in their licence obligations to meet a geographical coverage obligation if won, but not associated with any spectrum.

EAS – **electronic auction system** – the web-based system used to run the auction where bidders use a standard web browser to make an encrypted connection to the auction system.

Eligibility – a quantity in part determining which packages a bidder can bid for in a primary bidround in line with the **activity rules**. Eligibility in a primary bid round is set equal to the smaller of the bidder's eligibility and its activity in the previous primary bid round.

Eligibility points – a number of points assigned to a lot for the purposes of measuring and controlling bidding activity. The eligibility of a package is the sum of the eligibility points of its constituent lots.

Eligibility-reducing round – A primary bid round in which the bidder's activity is strictly less than its eligibility and so its eligibility in the next round is reduced compared with the current round.

Eligibility reduction cap – relative caps on packages with eligibility greater than the bidder's eligibility (during the primary bid rounds phase) or with eligibility greater than the bidder's eligibility in the final primary bid round (during the supplementary bids round), defined with respect to the bidder's choice in the last eligibility-reducing round in which the bidder's eligibility was still greater than or equal to the eligibility of the package. The bid amount for a package X is limited to the highest bid amount for the package for which the bidder made a primary round bid in that round (the constraining package), plus the difference in the round prices of the package in question and the constraining package in that round.

Extension – a right to be granted additional time to submit a bid. Only one extension right may be used in a round.

Final price cap – relative caps on supplementary bids for any package other than the final primary bid round package, defined with respect to the bidder's choice in the final primary bid round. The bid amount for a package X is limited to the bid amount for the final primary bid round package, plus the difference in the round prices of the package in question and the final primary bid round package in the final primary bid round.

Financial deposit – a monetary deposit required after bidder qualification in order to guarantee any bids made and compliance with auction rules, and which determines the bidder's initial eligibility to bid and which Ofcom might require a bidder to increase in the course of the auction.

Frequency assignment plan – a feasible assignment of specific frequencies for a band that matches the bandwidths that each winner of the principal stage has been allocated.

Frequency option – a position within a band where a winner of the principal stage could be allocated frequencies in at least one frequency assignment plan for that band.

Initial eligibility – a bidder's eligibility at the start of the clock rounds, determined by the initial size of its financial deposit.

Initial deposit – a monetary deposit required as part of the application process prior to qualification of bidders.

Lot category – a grouping of lots in the principal stage that are undifferentiated and functionally equivalent for the purposes of making bidders.

Minimum revenue core – prices determined for winning bids such that every winner and group of winners pays at least joint opportunity cost and, subject to these price floors, the total revenue raised is minimised.

Non-zero package – a package containing at least one lot.

Package – a combination of lots subject to a bid that would not be split or subdivided.

Primary bid rounds – rounds forming the first phase of the principal stage in which Ofcom announces a price per lot for each lot category and for the coverage obligation and bidders make a single package bid with a bid amount determined by the announced prices.

Primary round bid – a bid submitted by a bidder for a package in a primary bid round that complies with the activity rules.

Principal stage – the first CCA stage of the auction that determines the bandwidths won by bidders in each category and the assignment of coverage obligations. The principal stage consists of two phases: the primary bid rounds phase and the supplementary bids round.

Provisional supplementary bids – a list of supplementary bids maintained for bidders' convenience within the EAS that bidders can modify prior to submission and confirmation during the supplementary bids round.

Qualified applicant – a party who has applied, lodged the necessary initial monetary deposit, satisfied various suitability criteria and been announced as qualified to bid in the auction by Ofcom. A qualified applicant that does not subsequently withdraw its application before the withdrawal deadline will be a bidder.

Relative cap – A limit on the bid that a bidder can make for a package determined by one or more relevant revealed preference constraints.

Relaxed primary round bid – a primary round bid for a package with eligibility exceeding the bidder's eligibility in the clock round in which the bid is made.

Revealed preference – the concept that a previous choice between two packages can be used to impose consistency requirements on a bidder, limiting the bids that the bidder can subsequently express for one package it did not choose relative to another package it did choose.

Revealed preference constraints – the formal expressions in the EAS that implement the revealed preference concept.

Reserve price – a price set by Ofcom expressing the minimum value that bidders need express for individual lots to be awarded to them within the winner determination.

Round price – the price for lots, set by Ofcom for each of the lot categories, that is used to calculate round prices in a given round of the primary bid rounds phase. The round price must be positive for spectrum lots and negative or zero for the coverage obligation.

Spectrum cap – a limit on the number of lots which can be acquired in one or more categories of spectrum lots and which may depend on relevant existing spectrum holdings of the bidder.

Spectrum lot – a lot in the principal stage relating to a certain amount of bandwidth within one of the spectrum categories without further specification of its frequency.

Submission – the process of submitting one or more bids to the EAS for checking of their validity, resulting either in an explanation of why one or more bids are invalid, or the option to submit a confirmation of the bid(s).

Supplementary bid – a bid for a package of spectrum lot(s) and possibly including a geographic obligation, made in the supplementary bids round

Supplementary bids round – the second phase of the principal stage in which bidders may submit multiple, mutually exclusive package bids, with bid amounts determined by the bidder subject to rules to ensure consistency of those bids with the preferences expressed by the bidder in the primary bid rounds.

Valid Bid – a bid that complies with all auction activity rules and is acknowledged as such by the EAS and confirmed by Ofcom.

Winner determination – the process of taking all bids made in the course of the auction (and which have not been disqualified), including the reserve prices, and determining a feasible combination of winning bids, picking at most one bid from each bidder, to maximise the total value of winning bids.

Winning bid – a bid made in the course of the auction by a bidder that is consistent with the set of bids that maximise the total value of winning bids. A winning bid is used to inform the setting of the base price for the package in the winning bid.

Zero bid – a bid for a zero package of no lots at a bid amount of zero. If a bidder submits a zero bid in a primary bid round, no further primary bid round bids may be submitted by the bidder during the primary bid rounds phase (though the bidder may make bids in the supplementary bids phase).

A17. Responses to our March 2018 consultation

A17.1 In this annex we provide an overview of the main points made by stakeholders in response to our March 2018 consultation, which we have addressed in this consultation document (in particular, Sections 4 and 7). In addition, we provide more detail on why we are no longer proposing an indoor premises obligation, or an information sharing requirement, which we initially proposed in our March 2018 consultation. We also set out our consideration of a rural roaming requirement in the award, as suggested by a number of stakeholders in response to our initial consultation.

Consultation responses

A17.2 We received 27 responses to our March 2018 consultation. Respondents included the four mobile network operators, a number of groups representing the interests of rural consumers, groups representing the interests of business, national Governments, local authorities and individual citizens.

A17.3 Responses to our initial consultation broadly fell into two categories: the mobile operators (except for H3G) argued that our proposals were too ambitious on the basis that we had underestimated the costs and time required for improving mobile coverage; the majority of other respondents said that we should be more ambitious in our coverage targets and aim to deliver more coverage within a shorter timeframe. A number of common themes emerged from responses:

- **Costs and benefits of the proposed obligations**: Respondents expressed significantly divergent views on the level of coverage that we should be seeking to achieve, and the costs and benefits associated with it. The majority of respondents agreed that we should include coverage obligations in the award and considered both the types of obligations and the proposed levels for them, to be appropriate. A number of respondents, including many of the groups representing the interests of citizens and consumers, suggested that we should aim for obligations which could potentially apply to all operators, and/or for higher targets. Three mobile operators (BT/EE, O2 and Vodafone) argued that the costs of meeting each of the obligations could exceed our initial estimate of £300m (with one operator, Vodafone, claiming that costs would be much higher) and raised concerns about the proportionality of our proposals. One mobile operator (H3G) suggested that we could more effectively deliver the benefits we were seeking to achieve with these obligations by a single, more stretching obligation that included a requirement to offer rural roaming.
- **Alternative suggestions for auction design:** Respondents including BT/EE, O2 and Vodafone suggested that bidding for spectrum should be decoupled from taking on coverage obligations, and that the coverage obligations should provide operators an opportunity to '"bid' for discounts. They also suggested that procuring coverage using

the proceeds of an auction, but not directly as part of the spectrum award process, might deliver better outcomes (for coverage, and the allocation of spectrum in the auction).

- **Coverage requirements in each of the UK nations:** Responses from the Scottish and Welsh Government both welcomed the recognition of a need for national coverage requirements, but suggested more needed to be done to equalise the coverage differential with other UK Nations.
- **The timescale for delivery:** Many responses from groups representing rural consumers and businesses suggested coverage needed to improve more quickly than the 3-year period we initially proposed. However, three MNOs suggested this time window was not deliverable for the level of coverage improvement we were seeking, and that more time was needed. In making this point BT/EE cited its experience of delivering rural mobile coverage for the Emergency Services Network.
- **Information sharing:** Many respondents agreed that sharing information on the location of new sites to be built in rural areas may facilitate sharing of these sites, and some considered a single grid of masts in rural areas shared by many operators was the most appropriate and efficient outcome for rural coverage. Some mobile operators were sceptical as to the impact that our proposals would have on existing levels of sharing or suggested that we should leave this matter to industry.

A17.4 We have addressed most of these comments in Sections 4 and 7. In the rest of this annex, we consider the comments concerning our initial proposals for a 'premises obligation' and information sharing, and stakeholders' suggestions on roaming.

Our initial proposal for a 'premises obligation'

A17.5 In our March 2018 consultation, alongside our proposals for geographic coverage, we also proposed to include an obligation requiring an operator to provide new indoor coverage to 120,000 unserved premises (the "premises obligation") that, according to our initial estimates, are likely not to have good indoor coverage from any operator at the time of the award.

A17.6 As part of the consultation, we also set out our analysis that 60% of the 200,000 premises we expected to be without indoor coverage could be served for slightly less than £300m.

A17.7 In response, BT/EE argued that a solution requiring the build of new macro sites might not be proportionate given the availability of alternative solutions, such as pairing a mobile signal at an outdoor coverage level with Wi-Fi calling. Vodafone also suggested that other technology could be used to deliver the indoor element of premises coverage, so reducing the cost for operators with additional geographic coverage, whilst noting that the cost per premises of such an obligation could be high.

A17.8 In relation to our cost estimate for the premises obligation that we initially proposed, operators also indicated that they expected costs could exceed our estimate of £300m, with Vodafone indicating that the costs could be very substantially in excess of this and costs per premises as high as [✂ REDACTED]. O2 noted that the costs for this obligation would be highly dependent on the specific premises involved and our coverage requirements, and that this presented a challenge for further cost analysis.

A17.9 BT/EE said it was concerned that “a cost benefit analysis is unlikely to be positive for rolling out indoor coverage where customers have outdoor mobile coverage and a good fixed broadband service”.

A17.10 In light of stakeholders’ comments, we have undertaken some further work in order to better understand the potential benefits delivered by the premises obligation that we initially proposed. This additional analysis shows that a large majority of the premises which will not have good indoor coverage from any operator in June 2019, will have good outdoor coverage from at least one operator.

A17.11 Whilst we still consider there to be incremental benefits from higher quality mobile coverage over and above supplementary indoor coverage from services such as WiFi calling – which is not yet available for everyone – we recognise these incremental benefits are more marginal where good outdoor coverage is available. We also think the number of consumers switching to the obligation winner could be much lower than we had previously assumed, because of the existing coverage levels in the area. This might reduce the benefits that a premises obligation of the kind that we initially proposed would deliver.

A17.12 Finally, we also consider that it is difficult for us to specify this obligation in a way that ensures the worst served premises, i.e. the premises with no indoor or no good outdoor coverage from any operator, will benefit. We expect this to be a relatively small pool – around 30,000 premises – some of which will have some poorer quality 2G or 3G coverage available. While we consider the benefits of coverage for those individual homes and businesses without good coverage would be very considerable, we also think that costs could be very high, because of the way these premises are dispersed across the UK landmass.

Our revised approach to improving coverage where people live

A17.13 Taking into account the responses we received to the March 2018 consultation, as well as the additional analysis we have carried out since March, our view is that the cost of delivering the premises obligation that we initially proposed would likely exceed the potential benefits delivered by the obligation.

A17.14 We continue to believe that improving coverage in areas where people live, work and visit is important. This is one of a number of factors that has led us to consider that we should include a ‘premises requirement’ in the geographic obligations, which would require the operator that wins the obligation to deliver outdoor coverage to an additional 140,000 premises that it does not currently deliver coverage to. This would ensure that the increased geographic roll-out is focused on areas where people are more likely to live, work and visit.

A17.15 We recognise that our geographic obligations are unlikely to deliver substantial increases in coverage for many premises in the most remote areas. For those premises which would not receive indoor coverage improvements as a result of these obligations, there would be alternative solutions available, such as WiFi calling and smart repeaters (which can provide indoor coverage where there is good outdoor coverage). The new Broadband Universal Service obligation, which will provide the right to request a broadband service of at least 10 Mbit/s, will also be an important enabler of connectivity to premises.

A17.16 In addition, we are taking steps to make spectrum available to a wide variety of other users on a shared basis, including those wishing to deploy mobile coverage improvement schemes for rural coverage or indoor connectivity. We are consulting on proposals to facilitate third party access to awarded mobile spectrum bands as well as enabling shared access to spectrum in the 1800MHz and 2300MHz bands.[478] Both these bands are available in consumer handsets and could support additional community led coverage schemes.

A17.17 We recognise that some smaller or more remote communities may not receive 4G coverage as part of these obligations. For any such communities, public procurement – along the lines of the Scottish Government's 4G Infill programme – remains an option that is potentially well-suited to targeting remaining priority areas at a local level.

National roaming

A17.18 Some respondents to the March 2018 consultation suggested that we use the award to require an operator to offer national roaming (i.e. where that operator is required to allow other operators' customers to "roam" onto its network where it has better coverage). H3G, in particular, suggested that we consider imposing a single geographic coverage obligation including a roaming requirement. In principle, this provision could remove the need for a second geographic obligation by providing consumers of all operators with access to the new coverage.

A17.19 We have considered the arguments for including a requirement in the auction for the winner of the coverage obligation to offer roaming on its 700 MHz spectrum. We consider that the case for including such a requirement is uncertain for the following reasons, which we expand on below:

- the benefits are uncertain and could potentially be relatively limited (particularly as the requirement could only be applied to the spectrum we are auctioning);
- it would introduce a material risk into the auction of delay and could risk coverage obligations going unsold; and
- there are risks to investment, although these could be mitigated to some extent.

Benefits of a roaming obligation

A17.20 An effective roaming obligation would require:

[478] In referring to the 1800 MHz band we here mean 1781.7-1785 MHz paired with 1876.7-1880 MHz. In referring to the 2300 MHz band we here mean 2390-2400 MHz.

- that an operator would be willing to acquire such an obligation; and
- that other operators would agree to take part in the roaming offer.

A17.21 Our engagement with operators suggests there would be limited appetite to acquire such an obligation. Reasons that have been expressed to us include the possible costs of implementing such a service, and the perceived impact on the business case for building the new coverage required by the obligation.

A17.22 We also note that this auction does not provide a vehicle for ensuring other operators would take up a roaming offer for their customers. It would be for operators to decide whether they wished to take up the offer on behalf of their customers. The operators' responses to the Government's 2014 consultation on partial not spots suggest that the non-obligated operators might not be interested in buying roaming services (with the level of wholesale pricing and quality of service likely to be key factors).

A17.23 In practice, even if we could devise a roaming requirement that an operator might be willing to buy, the benefits to consumers would depend on the type of service offered, and how extensively this was taken up by other operators. We note also that the technical challenges associated with roaming mean that it may not be implemented in a way that fully mirrored the experience provided by a consumer's own network.

A17.24 We also note that, since this requirement would be limited to 700 MHz spectrum, consumers of the roaming operator might not notice meaningful improvements in their coverage as a result of the roaming arrangement if the obligation operator deployed its 700 MHz spectrum only in areas where roaming would be limited (and used other spectrum elsewhere).

Effect on the auction

A17.25 The possibility of roaming would introduce additional uncertainty to the auction. Bidders would have to decide what the coverage lots were worth in relation to the non-coverage lots, knowing that the holder of the non-coverage lot may be able to use roaming to achieve the same level of coverage as the holder of the coverage lot. The differential between the coverage lots and the non-coverage lots would depend to some extent on the wholesale price of roaming and the amount of roaming expected to take place, both of which would be unclear at the time of the auction.

A17.26 For example, suppose a bidder (Bidder A) is not interested in winning the coverage lot, but is deciding what bids to submit on the spectrum lots. Bidder A would like to extend coverage, ideally by roaming onto another bidder's network, or alternatively by using 700 MHz spectrum. Bidder A therefore has a difficult decision of whether to bid a low value on 700 MHz, assuming another operator will win the roaming lot, or to bid a high value for the spectrum given it will also be used to improve their coverage objective. An operator who is interested in buying the coverage lots could decide not to bid for them on the basis that they would be able to increase coverage by roaming onto the network of whoever does win them.

Effect on investment

A17.27 Introducing a roaming requirement into the coverage obligation could affect investment in a number of different ways:

- non-roaming operators might decommission existing masts in some rural areas if roaming was cheaper or more efficient. If left unmitigated this could result in a reduction in coverage in some areas;
- operators might stop building new masts to expand coverage in rural areas if doing so no longer gave them a competitive advantage; and
- operators might be deterred from upgrading masts to new technologies in existing partial not spots in rural areas if other operators could piggy-back off their networks. For example, there is a risk roaming could have an adverse effect on incentives to invest in 5G.

A17.28 We have therefore concluded that it would not be appropriate to seek to include a rural roaming requirement in the 700 MHz and 3.6-3.8 GHz award. However, we recognise that there may be cases where a roaming deal that is entered into voluntarily provides bidders with a cost-effective way to deliver the coverage improvements we are seeking for consumers. We therefore continue to be open to such voluntary arrangements being entered into for the purposes of meeting the coverage obligation, as we explained in Section 4.

Information sharing on the deployment of new infrastructure

A17.29 In our March 2018 consultation, we said that it may be appropriate for operators to make information about the location of new sites in rural areas available to the other operators at least 30 days in advance of a planning notification.

A17.30 Stakeholders' responses suggested a general recognition that sharing information was important, and that greater information sharing, if delivered in an effective and light touch way, would be positive. The Local Government Association (LGA) agreed with this proposal and recommended that, as part of the information sharing process, MNOs share their roll-out plans with local government up to six months before submitting a planning application, highlighting a strong desire for greater coordination.

A17.31 Some operators agreed that sharing information could help maximise the benefits for consumers and noted the considerable sharing that occurs today, and the existing incentives and processes in place to facilitate it. Vodafone considered that greater information sharing, to facilitate site sharing, was to be welcomed in principle, but regretted that "*the result will be that BT/EE's masts (built for ESN) will already be past the point when Ofcom's proposals would bite*". O2 noted that to really deliver on this intent, there could be common site design templates for macro, micro and in-building sites to facilitate sharing, but that industry could be best placed to deliver on this further. BT/EE noted that the three-year deadline for meeting the coverage obligations that we initially proposed was “unsympathetic” to the requirement for greater sharing, and that in any event this requirement was likely to be ineffective.

A17.32 They suggested that a requirement would need to be placed not only on the proposed obligation holder but on those interested in sharing to respond in a timely way. They also said that shared sites tended to be more expensive. In our stakeholder engagement following the March 2018 consultation, all operators have emphasized the high levels of existing sharing in place in the UK and the strong incentives they believe operators have to share information when this is the most appropriate solution.

A17.33 We note that, whilst there are significant levels of infrastructure sharing in the UK, there continues to be some evidence that sharing is not taking place everywhere that it might. For example, there is relatively little sharing between the two established infrastructure sharing joint ventures, MBNL and CTIL.

A17.34 We note also that, while operators do have established mechanisms for sharing information on sites once they have been built, this is less common for sites in the planning stage, and that this may be limiting opportunities for positive cooperation. We do not yet see the comprehensive sharing of new sites being built in remote areas, where the benefits of cost sharing could be considerable for consumers and operators alike.

A17.35 We continue to consider that further information sharing between all operators as they plan their networks could be beneficial, provided it is carried out consistent with competition law. However, we note that an obligation in a spectrum licence would only apply to those operators who hold such a licence: even if we included this requirement in all the licences that we are awarding (rather than just those with coverage obligations), we cannot guarantee all operators would win spectrum in this award.

A17.36 Further, a requirement in a 700 MHz licence could only relate to 700 MHz spectrum and infrastructure on which 700 MHz spectrum is used, and would therefore not necessarily lead to comprehensive information sharing. Therefore, our current view is that this is not the most appropriate mechanism for giving effect to our policy intent.

A17.37 We also consider that there is some merit in the argument made by some operators that, in the first instance, the best approach would be for operators themselves to develop an approach that works within their own processes. We encourage operators to further develop their existing processes for sharing information amongst themselves on the location of proposed new mast sites in rural areas, consistent with competition law.

A17.38 We will keep industry progress towards sharing under review, and consider whether further steps, such as facilitating industry dialogue, clarifying any competition concerns or highlighting best practice, are needed.

A18. Glossary of terms used in this consultation

2003 Act	The Communications Act 2003.
3GPP	The 3rd Generation Partnership Project (3GPP) is a body that develops standards for mobile technology.
4G	Fourth generation mobile phone standards and technology.
5G	Fifth generation mobile phone standards and technology.
5G NR	5G New Radio – a new air interface developed for 5G.
AAS	Active Antenna Systems.
AR	Augmented reality.
ARPU	Average revenue per user.
BEM	Block edge mask.
BS	Base station.
Capex	Capital expenditure.
CCA	Combinatorial clock auction.
CDF	Cumulative distribution function.
CEPT	The European Conference of Postal and Telecommunications Administrations.
CLA	Country Land and Business Association.
CMA	Competition and Markets Authority.
CPI	Consumer Price Index.
CRF	Common Regulatory Framework.
CSR	Call success rate.
CTIL	Cornerstone Telecommunications Infrastructure Limited.
dB	Decibel. A notation for dealing with ratios that vary over several orders of magnitude by using logarithms.
dBi	Decibels relative to an isotropic radiator.
dBm	The power ratio in decibels (dB) of the measured power referenced to

	one milliwatt (mW).
DCMS	Department for Digital, Culture, Media and Sport.
DCR	Digital Communications Review.
DEFRA	Department for Environment, Food and Rural Affairs.
DL-SCH	Downlink shared channel.
DMSL	Digital Mobile Spectrum Limited.
DTT	Digital Terrestrial Television – Broadcasting delivered by digital means. In the UK and Europe, DTT transmissions use the DVB-T and DVB-T2 technical standards.
EBITDA	Earnings before interest, taxes, depreciation and amortization.
ECC	Electronic Communications Committee – One of the three business committees of the European conference of Postal and Telecommunications.
EIA	Equality Impact Assessment.
EIRP	Equivalent Isotropically Radiated Power. This is the product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna (absolute or isotropic gain).
eMBB	Enhanced Mobile Broadband.
ESN	Emergency Services Network.
ETSI	The European Telecommunications Standards Institute.
EU	European Union.
FDD	Frequency Division Duplex – a technology where separate frequency bands are used for send and receive operations.
FL	Fixed links.
FWA	Fixed wireless access.
GDP	Gross domestic product.
GHz	Gigahertz. 1,000,000,000 (or 10^9) oscillations per second.
GPS	Global Positioning System.
GVA	Gross value added.
HHI	Herfindahl Hirschman Index.
IBW	Instantaneous bandwidth.
IoT	Internet of Things.
ITU	International Telecommunications Union - Part of the United Nations with a membership of 193 countries and over 800 private-sector entities

	and academic institutions. The ITU's headquarters are in Geneva, Switzerland.
JBV	Joint bidding vehicle.
KPI	Key performance indicator.
LGA	Local Government Association.
LNA	Low noise amplifier.
LNB	Low noise block.
LSA	Licensed shared access.
LTE-LAA	LTE Licensed Assisted Access.
LTE	Long Term Evolution. Part of the development of 4G mobile systems that started with 2G and 3G networks.
M2M	Machine to machine.
Massive MIMO	A MIMO system with a large number of antennas.
MBNL	Mobile Broadband Network Limited.
Mbps	Megabits per second.
MHz	Megahertz. A unit of frequency of one million cycles per second.
MIMO	Multi-input and multi-output.
MIP	Mobile Infrastructure Project.
mMTC	Massive machine type communications.
mmWave	Millimeter Wave.
MNO	Mobile network operator.
MOCN	Multi operator core network.
MoU	Memorandum of understanding.
ms	Millisecond.
MVNO	Mobile virtual network operator.
NAO	National Audit Office.
NFU	National Farmers Union.
NIC	National Infrastructure Commission.
OECD	The Organisation for Economic Co-operation and Development.
Ofcom	The Office of Communications.
ONS	Office for National Statistics.

OOB	Out of band.
PES	Permanent Earth Station.
PMSE	Programme-making and special events. A class of radio application that support a wide range of activities in entertainment, broadcasting, news gathering and community events.
PPDR	Public protection and disaster relief.
PPP	Purchasing power parity.
QoE	Quality of experience.
QoS	Quality of service.
RAN	Radio access network.
RF	Radio frequency.
ROES	Receive-only earth stations.
RSA	Recognised Spectrum Access.
RSPG	Radio Spectrum Policy Group. A high level advisory group that assists the European Commission in the development of radio spectrum policy.
RSRP	Reference signal received power.
SDL	Supplemental downlink. – where unpaired spectrum is used for downlink transmission only.
SES	Satellite earth stations.
SINR	Signal to interference and noise ratio.
SMRA	Simultaneous multiple-round auction.
STPR	Social time preference rate.
SUT	Single user throughput.
TCO	Total cost of ownership.
TDD	Time Division Duplex – a technology where the uplink is separated from the downlink by the allocation of different time slots in the same frequency band.
TEF	Thermally efficient.
TFAC	Technical frequency assignment criteria.
TRP	Total radiated power.
UHF	Ultra high frequency.
UL/DL	Uplink/Downlink.
URLLC	Ultra reliable low latency communications.

USO	Universal service obligation.
VoLTE	Voice over LTE.
VoWiFi	Voice over WiFi.
VR	Virtual reality.
WACC	Weighted average cost of capital.
WiFi	Commonly used to refer to wireless local area network (WLAN) technology, specifically that conforming to the IEEE 802.11 family of standards.
WRC-15	World Radio Conference 2015.
WTP	Willingness to pay.
WT Act	Wireless Telegraphy Act 2006.