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

Annexes

ANNEXES:

Publication date: 13 March 2020

Contents

Annex

A1. Relevant documents published before and since the December 2018 consultation

A1.1 Our publication of the December 2018 consultation on the award of the 700 MHz and 3.6-3.8 GHz award followed a number of earlier consultations on various matters relating to the spectrum and its availability.

A1.2 The responses generated, and the conclusions we reached through those consultation exercises, helped to inform the proposals set out in the December 2018 document.

A1.3 Those earlier documents are summarised below:

- In **May 2014** we published a consultation on proposals to make spectrum in the 700 MHz band available for mobile broadband from 2022, or possibly two years earlier.[1] It proposed moving existing DTT and PMSE services out of the 700 MHz band and into other bands. It went on to present our initial assessment of the costs and benefits of such a change, and said there would be significant benefits to citizens and consumers.
- In **November 2014** we published a statement setting out a decision to proceed with the proposals to make the 700 MHz spectrum available for mobile.[2] The statement included a further assessment of the costs and benefits of clearing existing users from the band, taking account of stakeholder responses, including early analysis of coexistence issues between DTT and new mobile services.
- In **March 2016** we published a consultation setting out proposals to make the 700 MHz spectrum available for mobile earlier than had been anticipated in the May 2014 document.[3] We said it would be possible to accelerate clearance of the band so that it became available for mobile by no later than Q2 2020. It also set out proposals to include the 700 MHz band 'centre gap' in any future award.
- In **October 2016** we published a statement setting out our decision to proceed with the proposals set out in the March 2016 consultation.[4] We also set out a decision to allow interim DTT multiplexes currently operating in the centre gap to continue until at least 1 May 2020, or until mobile downlink services in this spectrum were deployed. Finally, we set out a decision to serve notice on PMSE users that from 1 May 2020 they would no longer have access to 700 MHz spectrum.
- Also, in **October 2016** we published a consultation setting out our initial thinking on expanding access for mobile services in the 3.6-3.8 GHz band. We noted the band was currently used for fixed links and satellite services - but said the band was a high priority band for future mobile use, due to the large amount of spectrum available and the interest in this band for the rollout of future 5G services

[1] https://www.ofcom.org.uk/consultations-and-statements/category-1/700mhz
[2] https://www.ofcom.org.uk/__data/assets/pdf_file/0024/46923/700-mhz-statement.pdf
[3] https://www.ofcom.org.uk/consultations-and-statements/category-1/maximising-benefits-700mhz-clearance
[4] https://www.ofcom.org.uk/__data/assets/pdf_file/0031/92659/Maximising-the-benefits-of-700-MHz-clearance-Statement.pdf

- In **May 2017** we published a consultation on our more detailed technical analysis of coexistence issues between future mobile services in the 700 MHz band and DTT in the adjacent band.[5] We also discussed potential solutions to mitigate the risk of interference to DTT.
- In **July 2017** we published a statement and further consultation on use of the 3.6-3.8 GHz band for mobile.[6] The statement element confirmed a decision to proceed with making the band available for mobile. The consultation element set out proposals to remove current authorisations for fixed links and to no longer take registered satellite earth stations with a receive component in the 3.6GHz to 3.8GHz band into account for frequency management purposes.
- In **October 2017** we published a statement confirming our approach on the revocation of fixed links licences in the 3.6-3.8 GHz band and on the proposal to no longer take satellite earth stations into account for spectrum management purposes.[7] We said we would begin the statutory process to enact these decisions.
- In **December 2017** we published an update to our analysis of coexistence issues for the 700 MHz band spectrum.[8] The update presented our conclusions on the May 2017 technical assessment, having taken account of stakeholder responses.
- In **February 2018** we published an update on when we expected spectrum in the 3.6-3.8 GHz band to become available, following the decisions we set out in the October 2017 statement.[9] We said that spectrum will be available to enable future mobile services in many areas from June 2020, but not necessarily nationwide, before the end of 2022.
- In **June 2018** we published a consultation on a request by UK Broadband for variations to its licence in the 3.6 GHz band (3925-4009 MHz).[10] Most notably, it requested shifting its holding down by 5 MHz; surrendering its rights to use 4 MHz of spectrum at the top of the resulting block; and changing the applicable technical conditions. We set out our view that we were minded to grant the requested variation.
- In **December 2018** we published a statement setting out our decision to grant the UK Broadband request.[11]

A1.4 Since the publication of the December 2018 consultation on the award of the 700 MHz and 3.6-3.8 GHz spectrum bands, we have published two further consultations on the award:

- In **June 2019** we published a consultation setting out proposals for supporting the defragmentation of the 3.6-3.8 GHz band through the auction process.[12]

---

[5] https://www.ofcom.org.uk/__data/assets/pdf_file/0018/101619/Coexistence-of-new-services-in-the-700-MHz-band-with-digital-terrestrial-television.pdf
[6] https://www.ofcom.org.uk/__data/assets/pdf_file/0017/103355/3-6-3-8ghz-statement.pdf
[7] https://www.ofcom.org.uk/__data/assets/pdf_file/0019/107371/Consumer-access-3.6-3.8-GHz.pdf
[8] https://www.ofcom.org.uk/__data/assets/pdf_file/0025/108655/update-coexistence-700-mhz.pdf
[9] https://www.ofcom.org.uk/__data/assets/pdf_file/0018/110718/3.6GHz-3.8GHz-update-timing-spectrum-availability.pdf
[10] https://www.ofcom.org.uk/__data/assets/pdf_file/0017/115343/Variation-UK-Broadband-Licence-3.6-GHz-spectrum.pdf
[11] https://www.ofcom.org.uk/__data/assets/pdf_file/0014/130253/Statement-UK-Broadbands-spectrum-access-licence-3.6-GHz.pdf
[12] https://www.ofcom.org.uk/__data/assets/pdf_file/0011/152102/consultation-defragmentation-spectrum-holdings.pdf

- In **October 2019** we published a consultation setting out proposals for a revised auction design based on a Simultaneous Multi-Round Ascending (SMRA) format.[13]

A1.5 In addition to the documents listed above, there is a further relevant document which was published alongside the December 2018 consultation. 'Enabling opportunities for innovation' consulted on proposals to make spectrum available in a range of spectrum bands on a shared basis.[14]

A1.6 We said the spectrum we identified could support deployment of local networks in sectors including industrial Internet of Things (IoT), enterprise, logistics, mining and agriculture, as well as help to improve the quality of coverage in poorly served areas. A statement setting out our decisions on those matters was published in **July 2019.**[15]

[13] https://www.ofcom.org.uk/consultations-and-statements/category-2/award-700-mhz-3.6-3.8-ghz-spectrum-revised-proposals
[14] https://www.ofcom.org.uk/__data/assets/pdf_file/0022/130747/Enabling-opportunities-for-innovation.pdf
[15] https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

A2. Additional issues raised in responses to the December 2018 consultation

A2.1 In this annex we address issues raised in responses to the December 2018 consultation that are not fully discussed elsewhere in the statement.

Our consultation proposals

A2.2 In the December 2018 consultation (paragraphs 1.10-1.12 and annex 5) we set out our plans to award the 700 MHz and 3.6-3.8 GHz bands through an auction of UK-wide licences. We said an award of UK-wide licences was appropriate in this case because the bands are particularly suitable for mobile broadband use, for which we expect there to be national demand.

A2.3 We noted that some stakeholders had suggested awarding the spectrum in alternative ways, such as through local or regional licences, to enable different uses of the frequencies. In summary, we considered that alternative uses of mobile spectrum could be supported by using other bands identified for shared access and/or through proposed mechanisms to facilitate access to all mobile spectrum. We said that 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.

A2.4 Alongside the December 2018 consultation, we published our plans to allow some spectrum bands to be shared by different users (the '2018 spectrum sharing consultation').[16]

A2.5 Most of the responses addressed in this annex make similar points to those already discussed in our December 2018 consultation or in our statement following the 2018 Spectrum sharing consultation (the '2019 spectrum sharing statement').[17] Some address further alternative ways in which the 700 MHz and 3.6-3.8 GHz spectrum might be accessed, either to improve mobile coverage or to allow access for alternative uses of the spectrum.

A2.6 Below we set out the stakeholder responses and our assessment of these by issue.

Award of UK-wide licences

A2.7 Eight stakeholders commented on our proposal to award the 700 MHz and 3.6-3.8 GHz bands through an auction of UK-wide licences.

[16] Ofcom's consultation of 18 December 2018 entitled "Award of the 700 MHz and 3.6-3.8 GHz spectrum bands"; see https://www.ofcom.org.uk/consultations-and-statements/category-1/award-700mhz-3.6-3.8ghz-spectrum.
[17] Ofcom's statement of 25 July 2019 entitled "Enabling wireless innovation through local licensing"; see https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation.

A2.8 FMS Solutions Ltd questioned licensing the MNOs in areas they will never cover because it would be uneconomic for them to do so. It suggested mapping the areas that MNOs would not cover, *“based on the cost of base station deployment versus the economic return from the area”* so that third parties with a solution for mobile coverage in that area, including MNOs or self-help schemes, can apply to Ofcom for a local licence.[18]

A2.9 Ruckus Networks said that the assignment of spectrum on a national basis is not the only option and that local area licensing is an alternative. In its view, this could provide more comprehensive in-building and rural coverage by allowing SMEs and building owners to access mobile spectrum where it would not be economical for MNOs to provide this coverage. It noted that this approach is being adopted in the Netherlands.[19]

A2.10 North Yorkshire County Council, Stewart Stevenson MSP, Nominet and the Welsh Government raised concerns that rural areas will be left behind in 5G roll out and the digital divide will widen.[20]

A2.11 Nominet acknowledged the effectiveness of national licences in MNO deployment at scale but noted that the spectrum resource is not used everywhere and it is not meeting the needs of users “in many places”, recommending that Dynamic Spectrum Access (DSA)[21] would be the most efficient means to manage spectrum to benefit all consumers, allowing local use of unoccupied spectrum. Both Nominet and FMS Solutions Ltd noted the support of this approach by the IET 5G Further Faster (5GFF) group.[22] The IET said that its 5GFF partners are willing to assist Ofcom with drafting the technical standards for DSA.[23] Stewart Stevenson MSP also supported the use of DSA.[24]

Ofcom assessment

A2.12 Both the 700 MHz and 3.6-3.8 GHz bands have properties that make them particularly suitable for mobile broadband use. We expect there to be national demand for this.

A2.13 As set out in section 8 of this document, and having regard to the characteristics of the bands and the particular circumstances, we have concluded that the most efficient way to meet this demand is through a UK-wide award of national spectrum licences. This will allow MNOs and/or other bidders to offer UK-wide services.

A2.14 It is not feasible for Ofcom to anticipate which smaller geographic areas the existing operators may or may not choose to serve with 3.6-3.8 GHz spectrum. We consider the option of creating multiple local/regional ‘lots’ would result in an overly complicated auction that is not justified in this case.

[18] FMS Solutions Ltd response to the December 2018 consultation, page 3.
[19] Ruckus Networks response to the December 2018 consultation, questions 2 and 12.
[20] North Yorkshire County Council response to the December 2018 consultation, question 1; Stewart Stevenson MSP response to the December 2018 consultation, page 1; Nominet response to the December 2018 consultation, page 4; Welsh Government response to the December 2018 consultation, page 1.
[21] DSA allows users to access spectrum for periods when it is not being used by others (such as the main licensed user)
[22] Nominet response to the December 2018 consultation, pages 6-8; FMS Solutions Ltd response to the December 2018 consultation, pages 3-4.
[23] IET response to the December 2018 consultation, page 7.
[24] Stewart Stevenson MSP response to the December 2018 consultation, page 2.

A2.15 We acknowledge the concern expressed about rural coverage, and welcome the industry-led commitments announced in October 2019 to improve coverage through a Shared Rural Network.

A2.16 We have set out our decision on enabling shared access to a range of spectrum bands in our 2019 spectrum sharing statement. This includes Local Access licences to enable access to licensed mobile spectrum, some of which could be used for mobile broadband. However, we would not expect access to newly awarded bands to be possible straight away (and possibly not for some considerable time), as the licensees will need time to decide where they intend to use the frequencies themselves.[25]

A2.17 We do not currently intend to make access to mobile bands through Local Access licences available via DSA. We consider that the manual approach we have outlined in the spectrum sharing statement will enable us to respond appropriately to initial requests for access to mobile spectrum and to assess the level and nature of demand. We are, however, considering the use of DSA in the shared access bands (the 1800 MHz and 2300 MHz shared spectrum, 3.8-4.2 GHz band and lower 26 GHz band), as outlined in sections 3 and 6 of our spectrum sharing statement.[26]

Spectrum reservation

A2.18 Six stakeholders called for spectrum to be reserved for innovation or other uses.

A2.19 The IET noted that its 5G Further Faster (5GFF) group had hoped for some spectrum to be reserved for innovation.[27] iWireless Solutions similarly supported the option of setting aside 10-20 MHz of the 3.6-3.8 band for innovation.[28]

A2.20 Farndale Free Range Ltd urged Ofcom to make this spectrum available to rural ‘fixed wireless broadband’ suppliers, whilst still licensing it to mobile network operators in urban areas.[29]

A2.21 [✂ REDACTED][30]

A2.22 The BBC raised concerns that our proposals could make the ‘5G pioneer bands’ unavailable for use in 5G testbed trials after the auction. It called for Ofcom to consider how parts of the bands might be made available for this purpose.[31]

Ofcom assessment

A2.23 Our 2019 spectrum sharing statement set out how we intend to support innovation through allowing shared use of spectrum in the 3.8-4.2 GHz, 1800 MHz and 2300 MHz

[25] Ofcom’s statement of 25 July 2019 entitled “Enabling wireless innovation through local licensing”; see https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation.
[26] Ofcom’s statement of 25 July 2019 entitled “Enabling wireless innovation through local licensing”, sections 3 and 6; see https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation.
[27] IET response to the December 2018 consultation, question 5.
[28] iWireless Solutions response to the December 2018 consultation, page 2.
[29] Farndale Free Range Ltd response to the December 2018 consultation.
[30] [✂ REDACTED]
[31] BBC response to the December 2018 consultation, page 3.

bands, as well as the lower 26 GHz band (one of the pioneer 5G bands in Europe), through our new Shared Access licence. This includes use by rural fixed wireless broadband suppliers. The statement also set out our decision to start granting Local Access licences to enable access to licensed mobile spectrum, which would also apply to the 700 MHz and 3.6-3.8 GHz bands, once these have been awarded and licensees have decided where they intend to use the frequencies. We believe that these measures provide suitable access to spectrum for innovation and we therefore will not be reserving spectrum for innovation in the 700 MHz or 3.6-3.8 GHz bands.

A2.24 There is no specific spectrum set aside for Innovation and Trial licences, which may include those used for 5G testbed trials. Our guidance notes set out that these licences cannot be renewed and there is no guarantee that a further licence can be granted. We understand that at the time of the award there may be a number of Innovation and Trial licences in force in the bands being awarded, and we may issue further non-operational licences in this spectrum - subject to an assessment that these would not cause harmful interference.[32]

Spectrum sharing

A2.25 Fourteen stakeholders responded about issues related to spectrum sharing: Telint Ltd, the University of Strathclyde, the IET, Google, Nominet, iWireless Solutions, Digital Colony Partners, [✂ REDACTED], Farndale Free Range Ltd, the Advisory Committee for Wales, Kent County Council, Ruckus Networks, Federated Wireless, and Stewart Stevenson MSP. The majority of issues raised by these stakeholders are addressed in our spectrum sharing statement.[33] We address below comments not directly addressed in that statement.

A2.26 The IET advocated sharing in all three 5G pioneer bands: 700 MHz, 3.4-3.8 GHz and 26 GHz.[34] Kent County Council supported Ofcom's proposal to enable spectrum sharing by not guaranteeing exclusive use of the spectrum awarded. Stewart Stevenson MSP suggested that sharing should be applied to the 3.6-3.8 GHz band because it may be the only means that large rural communities have of accessing 5G.

A2.27 Federated Wireless suggested that the technology used to implement dynamic spectrum sharing in the 3.5 GHz band in the United States could be deployed to enable sharing in the 700 MHz and 3.6-3.8 GHz bands in the UK. It believed that 'dynamic shared' technology combined with tiers of commercial access should be implemented to introduce 5G. Its view was that there is enough spectrum in the 3.6-3.8 GHz band to license multiple MNOs and still provide spectrum for opportunistic or unlicensed access, which will drive the widespread deployment of 5G technologies and services.[35]

---

[32] Ofcom's document of 9 March 2018 entitled "Innovation and Trial licensing: Guidance notes for applicants"; see https://www.ofcom.org.uk/__data/assets/pdf_file/0014/53105/ofw357nonopguide.pdf.
[33] Ofcom's statement of 25 July 2019 entitled "Enabling wireless innovation through local licensing"; see https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation.
[34] IET response to the December 2018 consultation, page 7.
[35] Federated Wireless response to the December 2018 consultation.

A2.28 Farndale Free Range Ltd asked Ofcom to consider multiple usage options. It suggested that 3.6-3.8 GHz spectrum could be licensed for mobile, for use in city areas, and shared in rural areas with Fixed Wireless Access broadband providers. Ruckus Networks supported sharing in underused MNO spectrum, particularly to provide in-building coverage.[36]

A2.29 Digital Colony Partners, [✂ REDACTED], Google and the University of Strathclyde suggested that shared spectrum could be used for neutral host infrastructure to achieve improved coverage in rural areas. The Scottish Government and Scottish Futures Trust said they are already working with mobile operators to develop a sustainable neutral host model in their Scottish 4G Infill Programme.[37]

A2.30 The IET suggested that shared spectrum in this band would be more useful in wide contiguous blocks.[38]

A2.31 The Advisory Committee for Wales was greatly interested in using sharing to provide coverage in rural areas where there is unused spectrum. It suggested a funding model where a fee would be charged for every 1% of the coverage target that bidders would not accept. That money would then be set aside to fund organisations willing to provide coverage in difficult to serve areas.[39]

Ofcom assessment

A2.32 Our 2019 spectrum sharing statement set out our decision to start awarding Local Access licences to enable access to licensed mobile spectrum, which would apply to the 700 MHz and 3.6-3.8 GHz bands once these have been awarded.[40] We note the comments about allowing spectrum for shared use by neutral host infrastructure and we consider that the shared licences we have made available in bands awarded to MNOs (and other bands) are likely to open up new opportunities for this sort of spectrum use. Our general policy remains that licences issued by Ofcom do not guarantee exclusive use of the spectrum awarded. In the future we may grant additional authorisations to allow the use of all, or part, of the spectrum, including the spectrum that is the subject of this award process.

A2.33 The sharing measures set out in the spectrum sharing statement include access to large contiguous blocks of spectrum in the 3.8-4.2 GHz and lower 26 GHz bands, as requested by the IET, and therefore we do not intend to set aside any wide contiguous spectrum in the 3.6-3.8 GHz band for sharing.

A2.34 In light of the industry-led commitments to improve coverage, we have decided not to include coverage obligations in this auction, meaning that the model proposed by the

[36] Farndale Free Range Ltd response to the December 2018 consultation; Ruckus Networks response to the December 2018 consultation.
[37] Digital Colony Partners non-confidential response to the December 2018 consultation; [✂ REDACTED]; University of Strathclyde response to the December 2018 consultation; Google response to the December 2018 consultation, page 6; Scottish Government/Scottish Futures Trust response to the December 2018 consultation.
[38] IET response to the December 2018 consultation, questions 1, 4.
[39] Kent County Council response to the December 2018 consultation, question 12; Stewart Stevenson MSP response to the December 2018 consultation, pages 1-2; Nominet response to the December 2018 consultation, page 4, 11; Advisory Committee Wales response to the December 2018 consultation.
[40] Ofcom's statement of 25 July 2019 entitled "Enabling wireless innovation through local licensing"; see https://www.ofcom.org.uk/consultations-and-statements/category-1/enabling-opportunities-for-innovation.

Advisory Committee for Wales would not be viable. We understand the utility of using sharing to improve rural coverage and note that we include this as a potential use for bands covered by spectrum sharing in the spectrum sharing statement.

Network roaming

A2.35 In the December 2018 consultation (paragraphs A17.18-A17.28), we provisionally 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 recognised 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.

A2.36 We also said that we did not rule out the possibility of looking to impose roaming conditions, as appropriate, in 700 MHz licences in the future, noting in particular that these are licences of at least 20 years' duration. We proposed to include this point in the Information Memorandum for this award, so that all bidders would be aware that this is a possible option that we might wish to consider in the future. We said that any future proposals to impose roaming obligations would be subject to detailed analysis and consultation at the time, in line with our general approach.[41]

A2.37 Roaming was supported by seventeen stakeholders in their consultation responses (H3G,[42] the Communications Consumer Panel and Advisory Committee for Older and Disabled People,[43] [✂ REDACTED],[44] Kent County Council,[45] Shropshire Council,[46] Professor Stephen Temple, the Country Land and Business Association (CLA) and the Countryside Alliance,[47] FMS Solutions Ltd,[48] the Welsh Government, the Rural Services Network, the University of Strathclyde, Digital Colony Partners, North Yorkshire County Council, the Local Government Association, Shropshire Council, and the Scottish Government and Scottish Futures Trust). Some of these responses suggested alternative models of roaming and highlighted potential risks of going ahead with a roaming obligation.

A2.38 We received a further response on roaming in response to our October 2019 consultation on revised proposals for the 700 MHz and 3.6-3.8 GHz auction. The Communications Consumer Panel and Advisory Committee for Older and Disabled People (ACOD) welcomed the potential for increased mobile coverage promised by the Shared Rural Network (SRN). However, it expressed concern about the consequences for consumers and citizens if MNOs fail to provide the promised level of mobile coverage.

A2.39 The Consumer Panel and ACOD noted that licence obligations in relation to required coverage would take effect from 2026, with interim annual coverage updates until 2025. It

---

[41] December 2018 consultation, paragraphs 10.22-10.23.
[42] H3G non-confidential response to the December 2018 consultation, pages 1, 3, 11-12, 17-26, 28-29, 31. H3G suggested that a rural roaming obligation should be attached to a single coverage lot in the auction.
[43] Communications Consumer Panel response to the December 2018 consultation.
[44] [✂ REDACTED]
[45] Kent County Council response to the December 2018 consultation, question 12.
[46] Shropshire Council response to the December 2018 consultation, page 6.
[47] CLA response to the December 2018 consultation, page 4; Countryside Alliance response to the December 2018 consultation.
[48] FMS Solutions Ltd response to the December 2018 consultation, pages 3-4.

said Ofcom should apply a safeguard for consumers and citizens - potentially by mandating some form of national roaming if annual progress is inadequate.

Ofcom assessment

A2.40 As set out in section 2, the four MNOs and the Government have now agreed to full funding of the Single Rural Network programme with the MNOs' commitments having been given effect through binding licence obligations. Having considered stakeholders' comments and the MNOs' commitments, we remain of the view 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, but we do not rule out the possibility of looking to impose roaming conditions, as appropriate, in 700 MHz licences, in the future.

Health concerns

A2.41 In response to our December 2018 consultation, Dense Air Ltd and [✂ REDACTED] raised concerns about the effect of 5G rollout on health. We received further submissions on the alleged dangers of emissions as a result of 5G deployment from the Let's Talk 5G group and from Jessica Learmount in response to our October 2019 consultation on revised auction proposals. In addition, Dense Air was concerned that licence conditions allowing conventional cell sites (rooftops or towers) with high radiated power levels could create health and safety concerns in public areas.

A2.42 In the UK, Public Health England (PHE) takes the lead on public health matters associated with radio frequency electromagnetic fields, or radio waves, and has a statutory duty to provide advice to Government on any health effects that may be caused by exposure to EMF emissions.

A2.43 PHE's main advice is that EMF emissions should comply with the ICNIRP Guidelines.[49] On 5G, PHE's view is that *"the overall exposure is expected to remain low relative to guidelines and, as such, there should be no consequences for public health".* [50]

A2.44 Ofcom is responsible for managing the use of radio spectrum in the UK. We take PHE's advice into account, as appropriate, in our management of the radio spectrum.

A2.45 We have carried out EMF measurements around mobile phone base stations for many years and published the results of these measurements on our website.[51] In recent months, Ofcom has measured EMF levels in locations near newly deployed 5G-enabled base stations. In all cases, the measured EMF levels have been well within the levels for general public exposure from the ICNIRP Guidelines. The highest level measured in our recent measurements was approximately 1.5% of the levels identified in the ICNIRP Guidelines.

---

[49] The current set of guidelines is available at the following link: https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf]. A summary of PHE advice on radio waves can be found on its website

[50] https://www.gov.uk/government/publications/5g-technologies-radio-waves-and-health/5g-technologies-radio-waves-and-health

[51] https://www.ofcom.org.uk/spectrum/information/mobile-operational-enquiries/mobile-base-station-audits

A2.46 A summary report of these measurements has been published on our website[52] . We have also recently published a consultation setting out proposals to include a condition in spectrum licences (and other spectrum authorisations) that will require spectrum users to ensure they comply with the levels for general public exposure from the ICNIRP Guidelines.[53]

A2.47 We will publish a statement in 2020. If we proceed with the proposals and do so prior to the grant of the licences, we will revise the licences accordingly before grant. If we decide to proceed with the proposals after grant of the licences, then we will vary the licences to include the new conditions.

[52] https://www.ofcom.org.uk/spectrum/information/mobile-operational-enquiries/mobile-base-station-audits/2020?utm_medium=email&utm_campaign=Ofcom%20publishes%20latest%20spectrum%20measurement%20results&utm_content=Ofcom%20publishes%20latest%20spectrum%20measurement%20results+CID_376f7d6ac510c926db5681373dfa3a9c&utm_source=updates&utm_term=latest%20results%20from%20our%20spectrum%20measurement%20programme

[53] https://www.ofcom.org.uk/consultations-and-statements/category-1/limiting-exposure-to-emf?utm_medium=email&utm_campaign=Ofcom%20publishes%20latest%20spectrum%20measurement%20results&utm_content=Ofcom%20publishes%20latest%20spectrum%20measurement%20results+CID_376f7d6ac510c926db5681373dfa3a9c&utm_source=updates&utm_term=proposing%20new%20licence%20conditions

A3. Current state of the UK mobile market

Summary and introduction

A3.1 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, subscriber shares, spectrum shares and pricing trends, mobile data growth and consumer preferences.

A3.2 The UK mobile sector is a relatively mature market which consists of four mobile network operators (MNOs) and a small, but growing, subset of mobile virtual network operators (MVNOs). MNOs use their mobile networks to provide retail services under their brand. They also provide mobile network services (wholesale services) to a number of MVNOs. Some of these MVNOs are controlled by the MNOs and some are independent.

A3.3 Of the MNOs, O2 and BT/EE are the largest providers of both retail and wholesale services and have been for the recent past. H3G is still the smallest MNO but has been growing consistently, in contrast to Vodafone which has been losing market share.

A3.4 Despite its smaller spectrum holdings, O2 became the largest MNO in 2017 in terms of wholesale share.[54] It has consistently been the market leader when it comes to annualised churn rates, maintaining a 2 percentage point advantage on its rivals, and its customers have historically had the lowest monthly data traffic which may be part of the reason why its spectrum constraints have not materially hampered its growth. BT/EE's spectrum position is, and has been, very different to O2, with a significantly greater share of overall spectrum. As discussed in annex 5, BT/EE's network outperforms the other MNOs' in most performance tests and has become the joint largest carrier of data traffic overall, alongside H3G.

A3.5 Vodafone is the third largest MNO in the UK; however, it has recently been experiencing falling wholesale subscriber shares and negative revenue growth, although its revenue growth is still higher than that of other MNOs. Positively, it has seen improvements in its net additions and has gradually reduced its annualised churn rate to the same level as BT/EE and H3G. H3G is the smallest, and generally cheapest, MNO but has data-hungry customers; its customers use almost double the amount of data per month than that of the next highest MNO. H3G's wholesale subscriber share continues to grow, but at a lower rate in more recent years. More recently, it has performed relatively less well in download speeds and data coverage.

A3.6 Market concentration is comparable to other European countries with four MNOs[55] and, having fallen in the aftermath of the Orange and T-Mobile merger, has stabilised. Across

[54] Wholesale shares include both the MNOs' own retail subscribers and hosted MVNOs' subscribers.
[55] Denmark, France, Netherlands, Spain, Sweden.

the market, prices, revenues, and ARPUs[56] have been falling, however all four MNOs appear to be financially viable and prepared to invest in their networks for 5G.[57]

A3.7 Some of our key findings, covered in more detail below, include:

- Mobile subscriptions have plateaued at around 92 million, however mobile data traffic continues to rise, and consumers are placing more importance on their smartphones for getting online.
- Since 2016, O2has been the largest wholesale mobile service provider with a 34% share of the market. It overtook BT/EE who follows closely with 32% of the market. Vodafone's declining market share currently sits at 22%, whilst H3G is growing, but still trails behind with 12%.
- Similarly, O2 is the largest retail provider, with 31% of the market.[58] Enders Analysis reported that independent MVNOs represent 11% of the market, only 1 percentage points behind H3G.
- The UK's market concentration has gradually fallen since the merger of T-Mobile and Orange and is now at a level comparable with other European countries with four MNOs. Similarly, the UK also has a similar level of spectrum concentration to the other four-player countries, having reduced since the last auction.
- UK mobile prices have generally been on a downward trend and compare well with European counterparts; the UK consistently scores amongst the best countries for value.
- Mobile revenues have been falling all through 2019 for most MNOs after a period of stability, however bundled services are now more important than ever, accounting for 75% of total revenues; that is, the providers are making less of their revenue from out-of-bundle charges.
- We consider all of the MNOs to be financially viable. Profitability appears to be stable and capex is rising for three of the four MNOs; Vodafone has seen reductions in its capex over the last few years.
- Mobile data traffic has risen substantially over recent years and increased by 37% from 2017 to 2018.
- Consumer satisfaction with UK mobile services remains high.
- A number of factors 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, web browsing is the most important mobile service for customers, followed by voice calls and then video streaming.

A3.8 This annex is structured as follows:

- Relevant trends in the mobile services sector
- Relevant changes to the structure of the market

[56] ARPU refers to the 'average revenue per user'.
[57] We discuss the arrival of 5G in more detail in annex 7.
[58] O2's subscriber share includes Tesco Mobile and giffgaff.

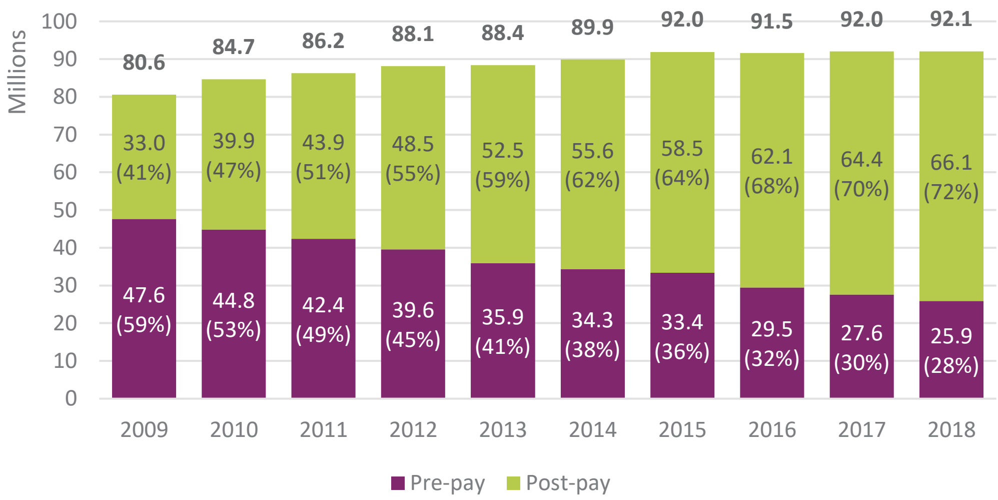
- Provision of wholesale mobile services
- Provision of retail mobile services
- Market concentration and spectrum concentration
- Evolution of UK mobile prices
- International comparison of mobile prices and coverage
- Mobile revenues
- Financial position of MNOs
- Mobile Data Traffic
- Factors considered by mobile consumers when choosing providers

Relevant trends in the mobile services sector

A3.9 The total number of mobile subscriptions in the UK has grown in recent years and has begun to plateau; the number of subscriptions reached 92 million by the end of 2015, before falling slightly in 2016 but returning to 92 million in 2017 and 2018, as shown in Figure A3.1.

A3.10 Furthermore, the number of post-pay subscriptions has overtaken pre-pay subscriptions and continues to grow. Post-pay became more popular than pre-pay in 2011 and accounted for 72% of subscriptions in 2018.

Figure A3.1: Mobile subscriptions by pre-pay and post-pay



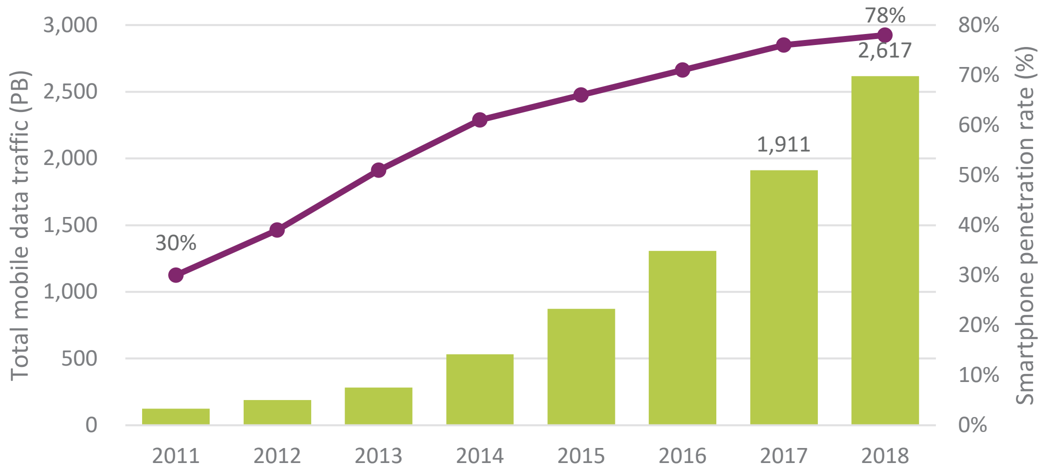
Source: Ofcom/operators

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

A3.11 Simultaneously, there has been a rapid increase in the growth of mobile data traffic and smartphone penetration (Figure A3.2). Smartphone penetration reached 78% in H1 2018[59] whilst total mobile data traffic increased by 32% between 2017 and 2018 to over 2,600 PB.

[59] Source: Ofcom Technology Tracker, Quarter 1 2011 - 2014, Half 1 2015-2018, Base: all adults age 16+, QD4 (QD24B): *Do you personally use a smartphone?*

Figure A3.2: Total mobile data traffic and smartphone penetration rate, 2011-2018

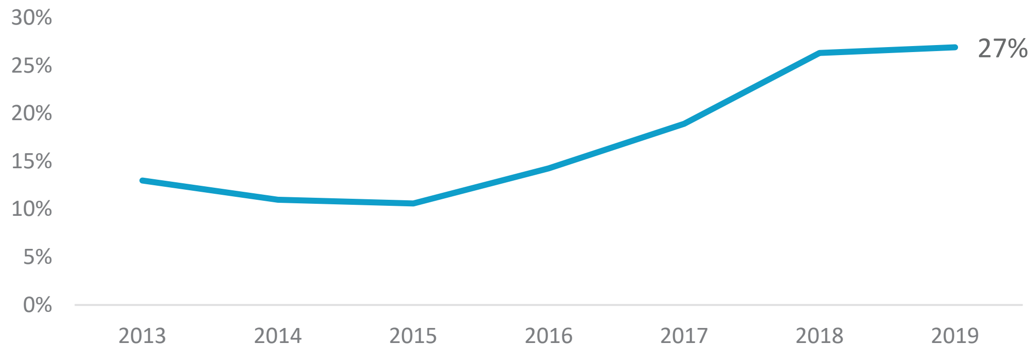


Source: Analysys Mason and Ofcom Technology Tracker

A3.12 The average monthly data use per mobile subscriber increased eight-fold in the five years to June 2017[60] and increased by 25% in the year to 2018.[61] Smartphones have become a key channel to access the internet and use data-intensive services such as streaming videos and music; Ofcom research found that in 2018, 67% of mobile users used their mobile phone for general browsing/surfing the internet and 76% used it for web and data access, up from 28% and 35% respectively in 2011.[62]

A3.13 Consumers are also changing the way they purchase mobile connectivity. Since 2013, SIM-only contracts have become more popular. In 2013, only 13% of pay-monthly mobile packages were SIM-only. This figure had risen to 27% by 2019, as shown in Figure A3.3.

Figure A3.3: SIM-only as a proportion of pay-monthly packages



Source: Ofcom, Technology Tracker 2013 – 2019

---

[60] Ofcom, Communications Market Report 2018.
[61] Ofcom, Communications Market Report 2019.
[62] Ofcom, Communications Market Report 2018.

Relevant changes to the structure of the market

A3.14 In 2010, Deutsche Telekom (T-Mobile) and France Telecom (Orange) merged their UK mobile operations into Everything Everywhere (now EE), thereby reducing the number of MNOs in the UK market from five to four.

A3.15 In 2012, Vodafone acquired Cable and Wireless' (C&W) global operations including those in the UK.[63]

A3.16 In 2015, BT agreed to acquire EE, and the merger was completed in 2016 after receiving clearance from the CMA.[64]

A3.17 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.

A3.18 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.[65]

A3.19 In 2017, H3G acquired UK Broadband[66], which holds a spectrum licence that we varied on 14 December 2018 for the use of certain frequencies in the 3.4-3.8 GHz band (as well as licences for other, higher frequency spectrum bands).

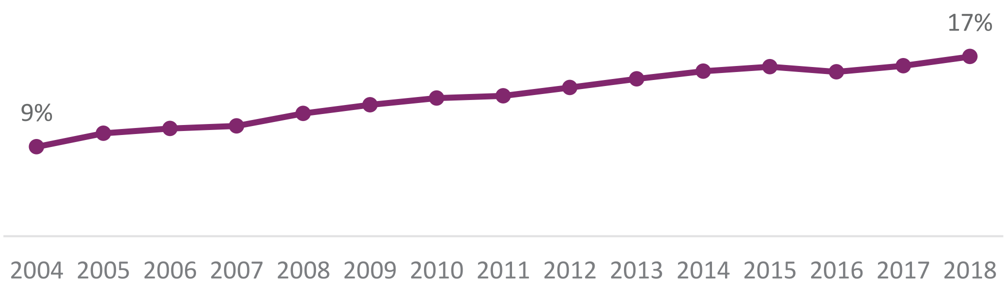
Provision of wholesale mobile services

A3.20 There are four UK MNOs: BT/EE, H3G, O2 and Vodafone. All four MNOs have their own mobile network services and use these to provide retail mobile services under their own brand name.

A3.21 The four MNOs also provide wholesale mobile network services to a number of mobile virtual network operators (MVNOs) who use these services to provide their own retail mobile services. MVNO subscriptions have been increasing steadily since their introduction in 2004 (Figure A3.4), and currently all MNOs host at least one MVNO.

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

Figure A3.4: MVNO subscribers as percentage of total[67]

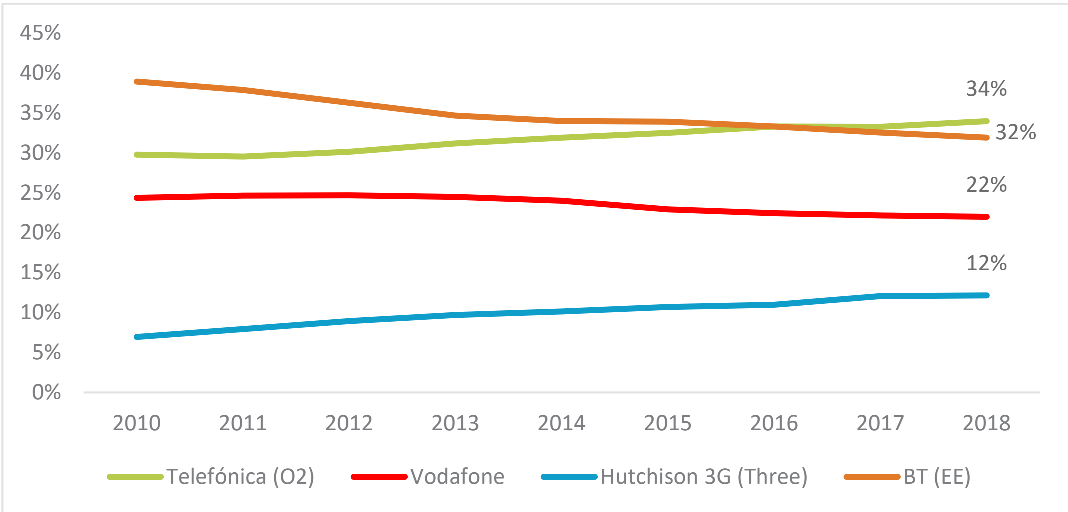


Source: Analysys Mason

A3.22 The wholesale subscriber shares of MNOs include both the MNOs' own retail subscribers and hosted MVNOs' subscribers. H3G and O2 increased their wholesale subscriber shares between 2010 and 2018, whilst the shares of BT/EE and Vodafone decreased (Figure A3.5).

A3.23 As of 2018, O2 had the largest wholesale subscriber share of 34%, followed closely by BT/EE with 32%. Vodafone had the third-largest share with 22%, ahead of H3G with 12% of the wholesale market.

Figure A3.5: Wholesale subscriber shares by network



Source: Analysys Mason

Provision of retail mobile services

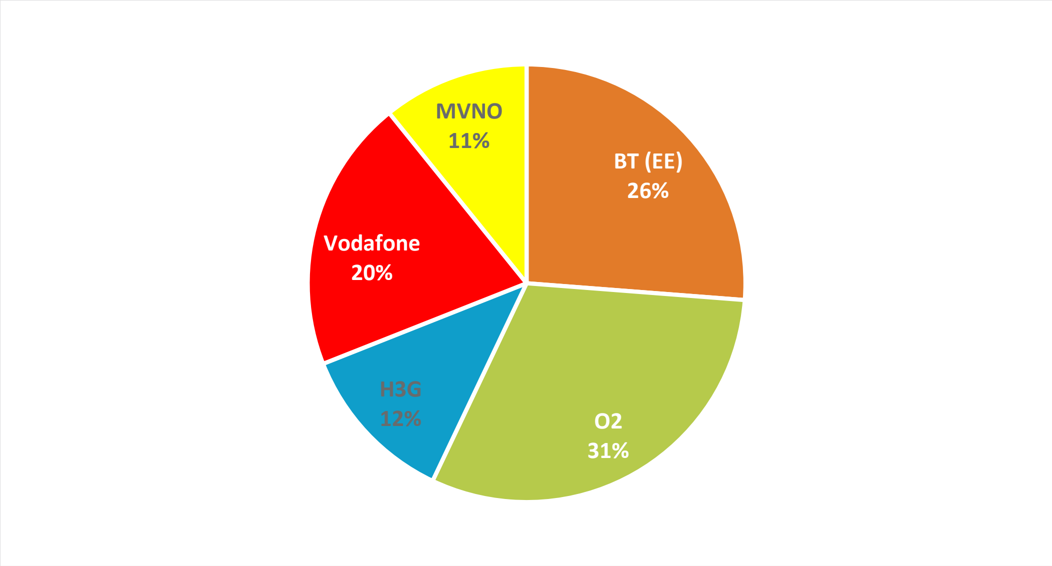
Retail market shares

A3.24 According to Enders Analysis, as of Q2 2019, O2 had the largest retail subscriber share of 31% which includes the share of Tesco Mobile (the joint venture between O2 and Tesco)

[67] This graph includes Tesco Mobile and giffgaff as MVNOs. Later in this annex, we combine Tesco Mobile and giffgaff with O2 as the former is a joint venture between O2 and Tesco, and the latter is owned by O2's parent company, Teléfonica. The difference between the shares of MVNO in the two graphs does not necessarily equate to the actual market share of Tesco Mobile and giffgaff as the graphs are generated from different sources.

and giffgaff. BT/EE had the second largest share, with 26%, followed by Vodafone with 20%.

Figure A3.6: UK mobile retail subscriber shares, Q2 2019[68]



Source: Enders Analysis

A3.25 Ofcom also collects confidential information from providers, which shows a similar picture to the Enders Analysis data [✂ REDACTED].

[68] This graph includes Tesco Mobile and giffgaff as part of O2's subscriber share, and not as part of the MVNOs share. Earlier in this annex, we included Tesco Mobile and giffgaff's subscriber shares in the subscriber share of MVNOs. The difference between the shares of MVNO in the two graphs does not necessarily equate to the actual subscriber share of Tesco Mobile and giffgaff as the graphs are created from different sources.

Figure A3.7: Total mobile subscription share by retail operator[69]

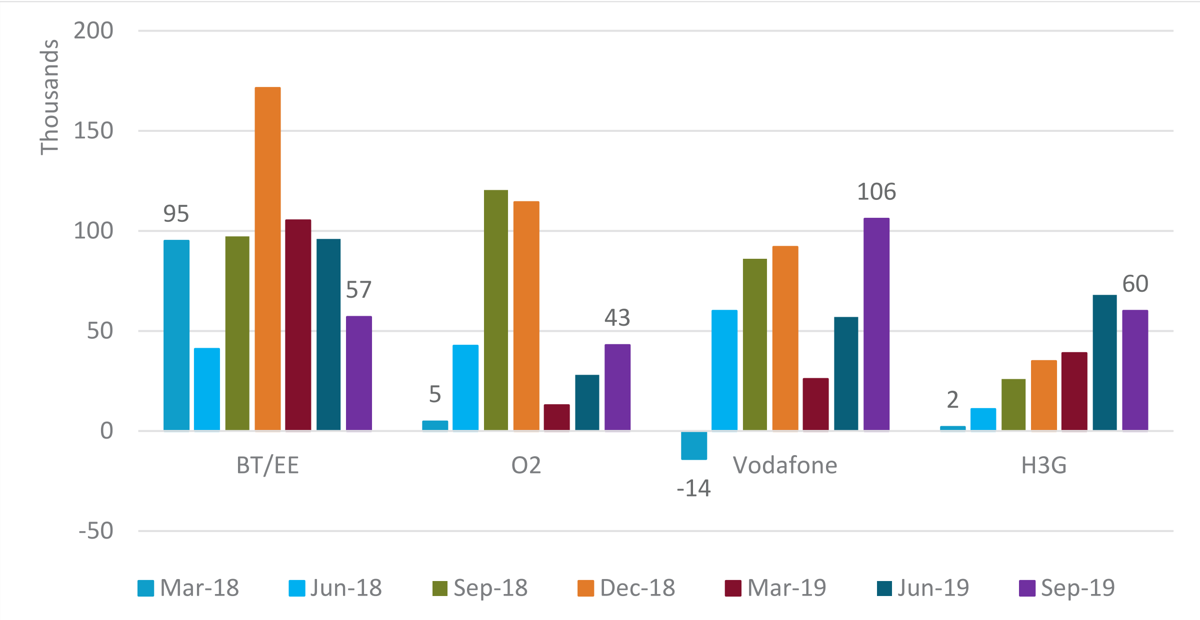
[✂ REDACTED]

Additions and churn

A3.26 Net additions and churn may also give an indication of the position of providers in the retail mobile services sector. In terms of contract net additions, which can be seen in Figure A3.8 below, BT/EE appears to have experienced falling contract net additions in 2019, resulting in the second lowest score by Q3 2019, even after high contract net additions in Q4 2018 and early 2019.

A3.27 H3G has seen steadily increasing contract net additions throughout 2018 followed by an increased 2019 performance. Additionally, Vodafone had the highest contract net additions in Q3 of 2019, despite a quarter of net losses in 2018.

Figure A3.8: Contract net additions



Source: Enders Analysis

A3.28 As of the end of 2019, O2 had the lowest annualised contract churn, with rates of 12.0%.[70] The other three MNOs had almost identical levels of churn; BT/EE and HG3 marked the upper limit at 14.4% (Figure A3.9).

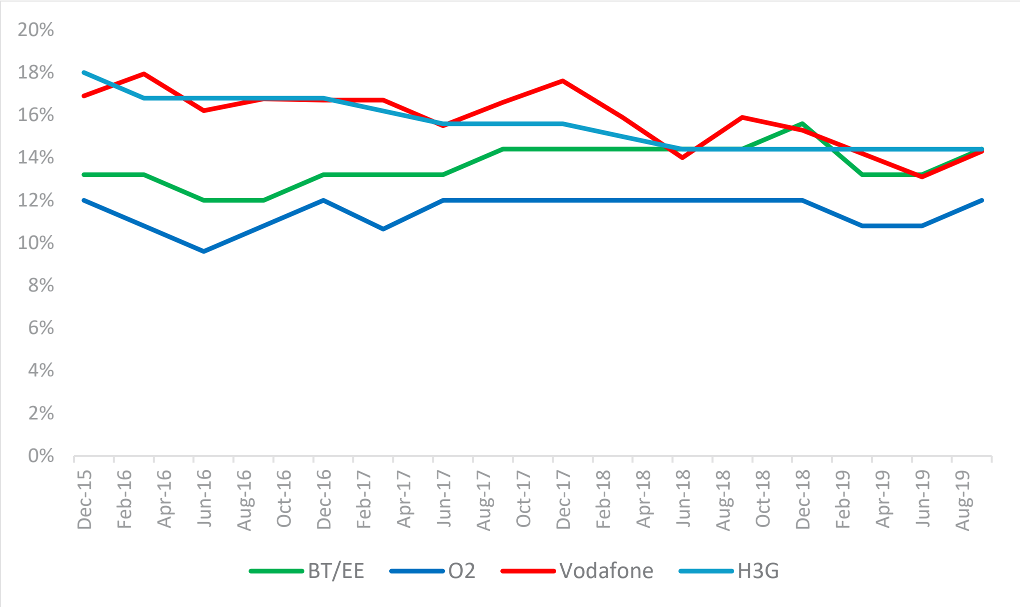
A3.29 Over the past few years, H3G and Vodafone have tended to have the highest churn rates, however it appears that H3G, Vodafone and BT/EE have converged to almost the same

[69] [✂ REDACTED]

[70] Churn rates measure the percentage of subscribers who discontinue their subscription within a given time period; it is an indicator of how well companies retain their customers.

level in more recent times. Despite their historically inferior spectrum position, O2 remains an outlier with its industry-leading low churn rate.

Figure A3.9: Annualised contract churn



Source: Enders Analysis

Market concentration and spectrum concentration

Market concentration

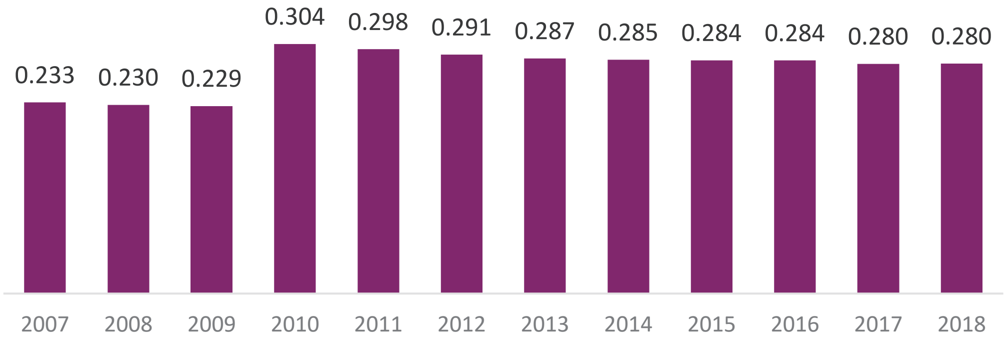
A3.30 Market concentration does not directly show the level of competition within a market. It gives an indication as to whether one or several large players exist in the market but does not take account of many factors which may determine the level of competition.

A3.31 The UK's HHI was 0.280 in 2017 and remained at this level in 2018 (Figure A3.10).[71] The last significant change to the UK's market concentration occurred in 2010, when T-Mobile and Orange merged to become EE; the UK's HHI jumped from 0.229 in 2009 to 0.304 in 2010,

[71] The Herfindahl-Hirschman Index (HHI) is a common measure of market concentration. It is calculated by squaring the subscriber share of each firm and summing the resulting numbers. It can range from close to zero to one (or 10,000 if using integers rather than percentages), where one represents a monopoly.

but this has since gradually fallen to the current level, likely due to the growth of H3G, as shown in Figure A3.5.

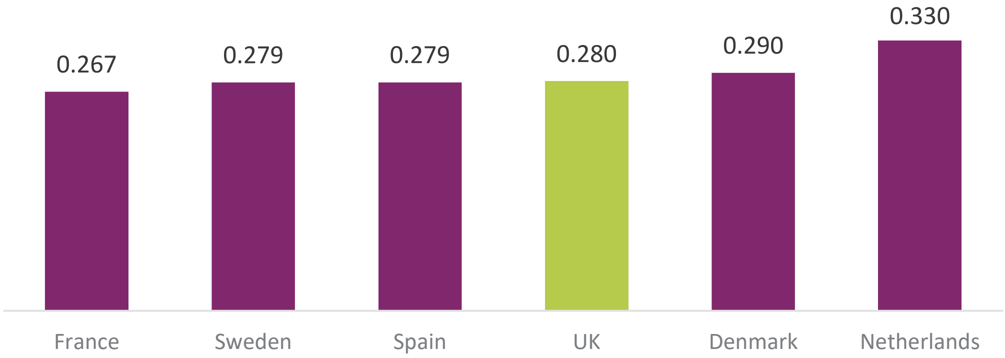
Figure A3.10: UK market concentration[72]



Source: Ofcom analysis of Analysys Mason data

A3.32 Our analysis shows that the UK has a similar market concentration to other European countries with four MNOs (Figure A3.11). Out of the six countries in the sample, the UK has the fourth lowest market concentration, just ahead of Sweden and Spain, which rank second and third, respectively.

Figure A3.11: Market HHI indices for different countries in 2018



Source: Ofcom analysis of Analysys Mason data

Spectrum concentration

A3.33 We have also used the HHI to compare the levels of spectrum concentration between the different countries, i.e. using spectrum shares rather than market shares. We have included spectrum holdings in the 700MHz, 800 MHz, 900 MHz, 1400 MHz, 1800 MHz, 2.1 GHz, 2.3 GHz, 2.6 GHz paired and unpaired, and 3.4-3.8 GHz bands.[73]

A3.34 We find that the UK has the third-highest level of spectrum concentration when considering currently useable spectrum (Figure A3.12). The UK is more similar to countries

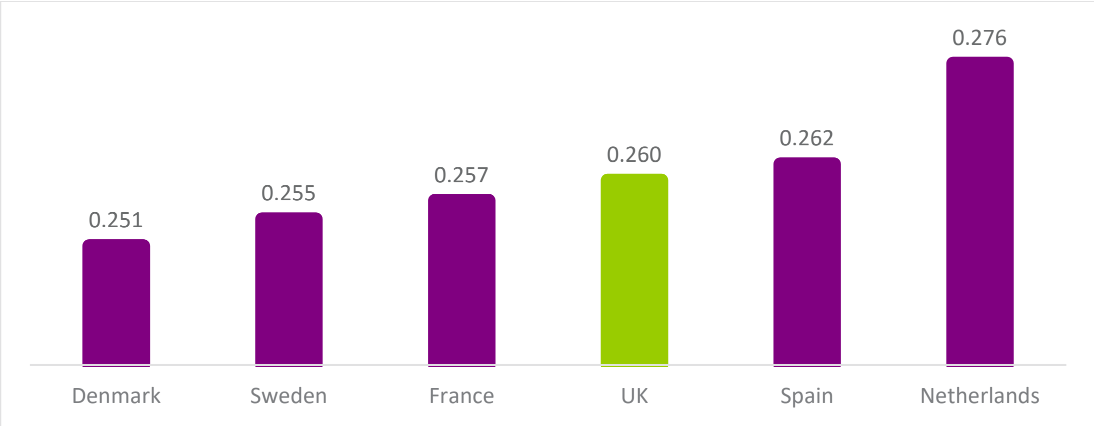
---

[72] We have used wholesale subscriber shares to allow for consistent comparison over time. The use of retail subscriber shares, and therefore the inclusion of MVNOs, would likely cause market concentration to decrease.

[73] Only the UK has operators with 1400 MHz and 2.3 GHz spectrum in this sample, and only the UK and Spain have allocated spectrum in the 3.4-3.8 GHz band.

such as France, Sweden, Denmark and Spain, rather than the Netherlands, which is significantly higher than other countries with four MNOs.

Figure A3.12: Spectrum HHI of different countries

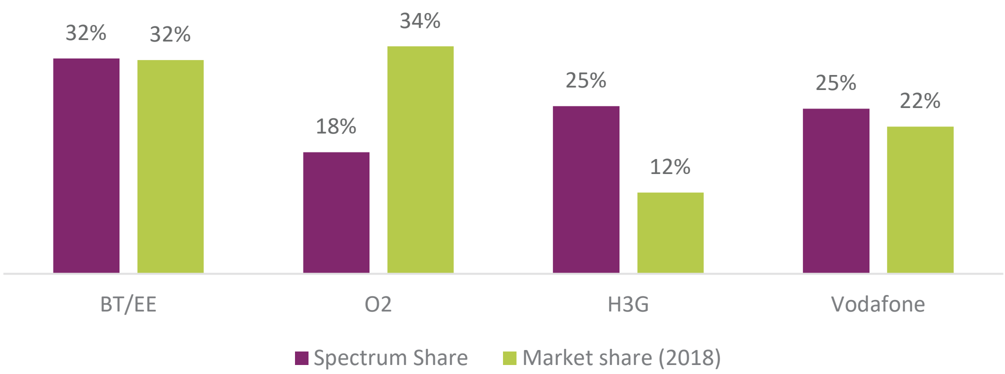


Source: Ofcom analysis of data from Cullen International from October 2019

Spectrum holdings and market shares

A3.35 The UK MNOs each hold different amounts of spectrum. However, there is not a mechanical relationship between spectrum shares and market shares, and we see significant differences for some MNOs.[74] Comparing all allocated spectrum to wholesale market shares, O2 has a substantially higher market share than spectrum share. In contrast, H3G has a substantially higher share of spectrum than market share, with the second largest holding of overall spectrum behind BT/EE, though this is a relatively new position as it includes its holdings of 3.4-3.8 GHz which have only recently become useable.

Figure A3.13: Spectrum holdings and wholesale subscriber shares



Source: Ofcom / Analysys Mason; this includes 3.4-3.8 GHz spectrum (where it has been allocated)

[74] We have used wholesale market shares because this measures total users on each MNO's network and the need for capacity.

Evolution of UK mobile prices

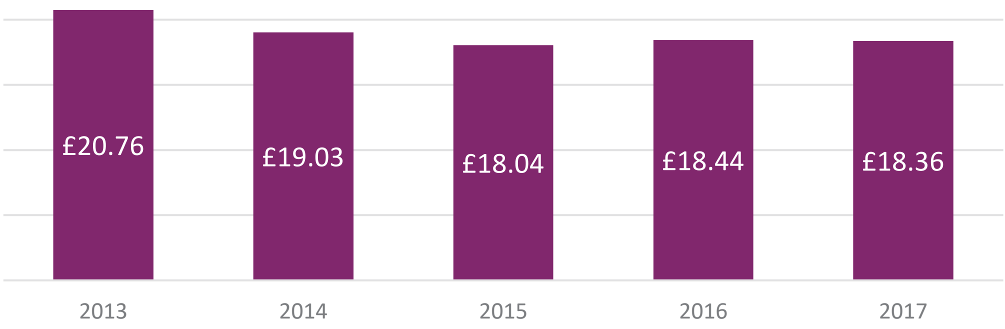
A3.36 We have previously assessed the pricing trends of mobile services in our "Pricing trends for communication services in the UK" and "An econometric analysis of pricing trends in the UK" reports. Both reports concluded that there had been a general downward trend in UK mobile prices and are summarised below.

A3.37 Additionally, Enders Analysis have compared recent SIM-only prices between MNOs to establish which provider offers the cheapest SIM-only tariffs. This is also summarised below.

Pricing trends for communications services in the UK[75]

A3.38 In this report, we used a basket approach to assess the pricing trends in the mobile market. In the period 2013 to 2017, the weighted average cost of the average basket fell by 11.5% – this was in spite of an increase in data usage and voice minutes. This is shown in Figure A3.14 below.

Figure A3.14: Weighted average monthly prices for average mobile use baskets (excluding handsets): 2013 to 2017 (£ per month)[76]



Source: Ofcom, using data provided by Teligen

An Econometric analysis of pricing trends in the UK[77]

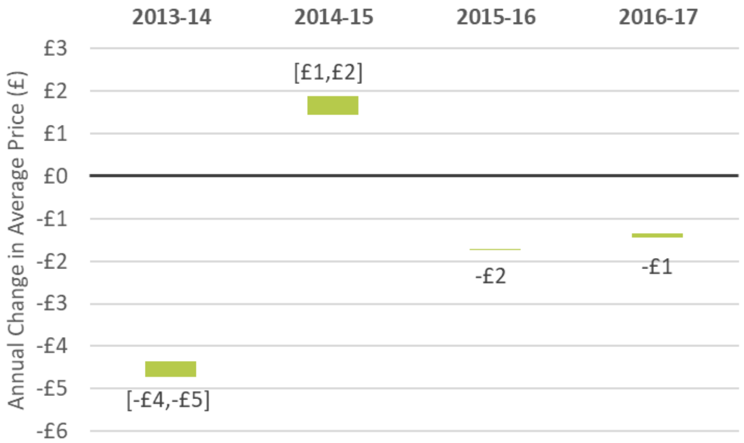
A3.39 In this report, we used an econometric approach to estimate the change in mobile prices in the UK over time, controlling for relevant product features, handset quality, firm-specific characteristics and time critical factors. Further detail of the methodology and modelling can be found in our report.

A3.40 For each period, we estimated a range for the change in prices, represented in Figure A3.15 below by the upper and lower bounds of the green bars. The findings suggest that,

[75] Pricing trends for communications services in the UK (2018). This report is also summarised in more depth in Annex 6 of our December 2018 Consultation.
[76] The chart shows the weighted average price of a basket of mobile services, adjusted for inflation, based on average use by all consumers in each year. For example, in 2013 the average monthly use per mobile phone was 0.3GB of data, 143 voice minutes and 136 SMS, whilst in 2017 the average monthly use was 1.9GB of data, 158 voice minutes and 59 SMS.
[77] An Econometric analysis of pricing trends in the UK (2018).

with the exception of the period 2014 to 2015, average prices of mobile phone tariffs have fallen over time to the extent of about £6 over the period.

Figure A3.15: UK mobile price trends for available post-pay plans including handsets for each year

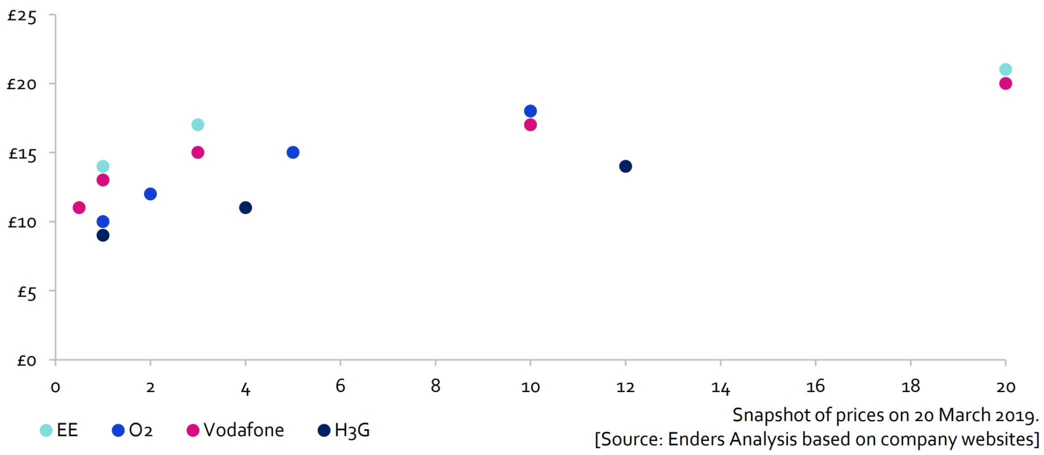


Source: Ofcom, 'An econometric analysis of pricing trends in the UK'

SIM-only pricing

A3.41 Due to the wide variety of handsets and different contract structures, it can be difficult to compare general pricing across providers. However, Enders Analysis compared SIM-only contracts between providers (Figure A3.16) and found that, in general, BT/EE is the most expensive. Vodafone were found to be second most expensive, followed by O2. H3G were consistently found to be the cheapest provider.

Figure A3.16: SIM-only pricing by data allowance (GB)



Source: Enders Analysis

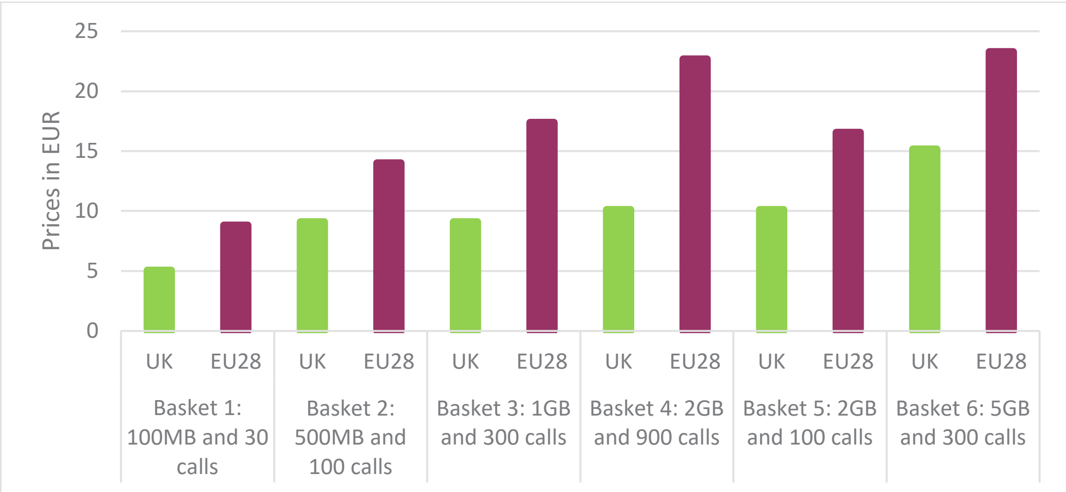
International comparison of mobile prices and 4G coverage

International comparison of mobile prices

A3.42 The "Mobile Broadband Prices in Europe 2018" report, published by the European Commission, compared mobile broadband prices across the EU member states as well as a collection of non-EU countries.[78] The report compared handset-based and data-only price plans.

A3.43 The report found that the UK performed well compared to other EU countries with regards to handset plans, as shown in Figure A3.17 below. UK prices were found to be below the EU28 average for all handset-based baskets analysed by the European Commission. Specific figures for data-based plans by country were not made available by the European Commission, however its report showed that the UK is in the 'least expensive' or 'relatively inexpensive' clusters for all data-based plans analysed.

Figure A3.17: Comparison of the least expensive handset offers – UK vs. EU average



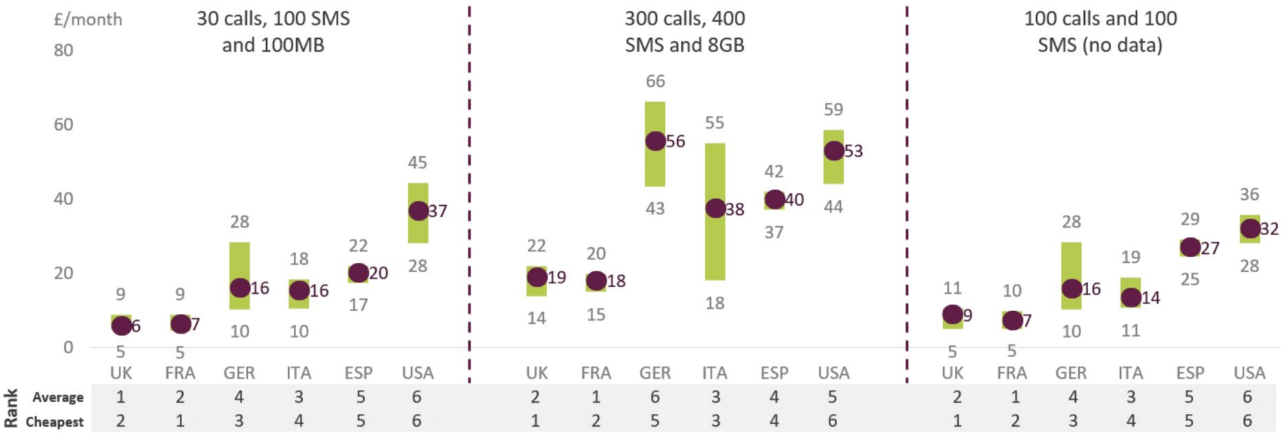
Source: EC Mobile Broadband Prices in Europe 2019

A3.44 Ofcom's 2017 International Communications Market Report compared three mobile basket prices for six countries: the UK, France, Germany, Italy, Spain and the USA.[79] Handset costs were excluded but selective discounts, such as 'friends and family' calls, were included.

A3.45 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 A3.18).

[78] Mobile Broadband Price in Europe 2018.
[79] Ofcom 2017 International Communications Market Report.

Figure A3.18: Comparative mobile phone pricing



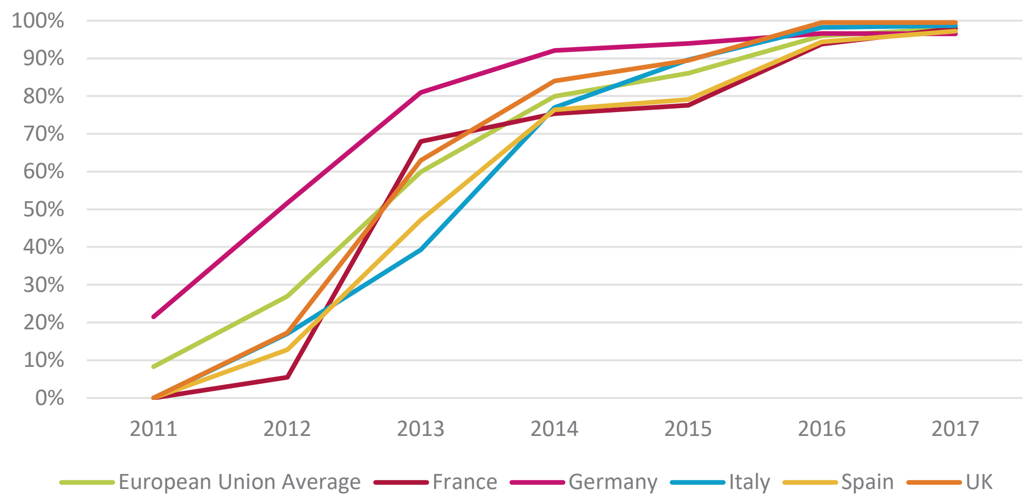
Source: Ofcom, using data provided by Teligen

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.

International comparison of coverage

A3.46 The UK performs well in comparison to other European countries in terms of 4G mobile broadband household coverage. Of the five countries included in the sample, Germany had the greatest 4G coverage in 2011 and led the way until 2016. Since then, all five countries have converged to a very high level of coverage, but as of 2017, the UK led them all in 2017 (Figure A3.19). The UK has been ahead of the EU average since 2013.

Figure A3.19: European 4G mobile broadband coverage (% of households)[80]



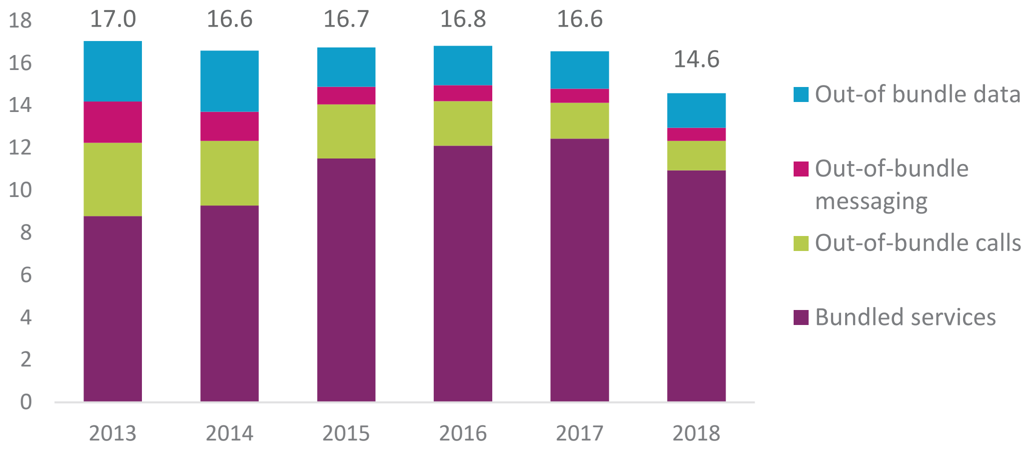
Source: EU Digital Agenda Scoreboard

[80] See EU Digital Agenda Scoreboard.

Mobile revenues

A3.47 Mobile retail revenues experienced a sharp drop in 2018, from a relatively stable level between 2013 and 2017 (Figure A3.20), to £14.6 billion in real terms. The composition of mobile retail revenues has changed over recent years; the proportion of total mobile retail revenues arising from bundled services was 52% in 2013, but now stands at 75% in 2018.[81]

Figure A3.20: Mobile revenue by service (£bn)



Source: Ofcom CMR 2019

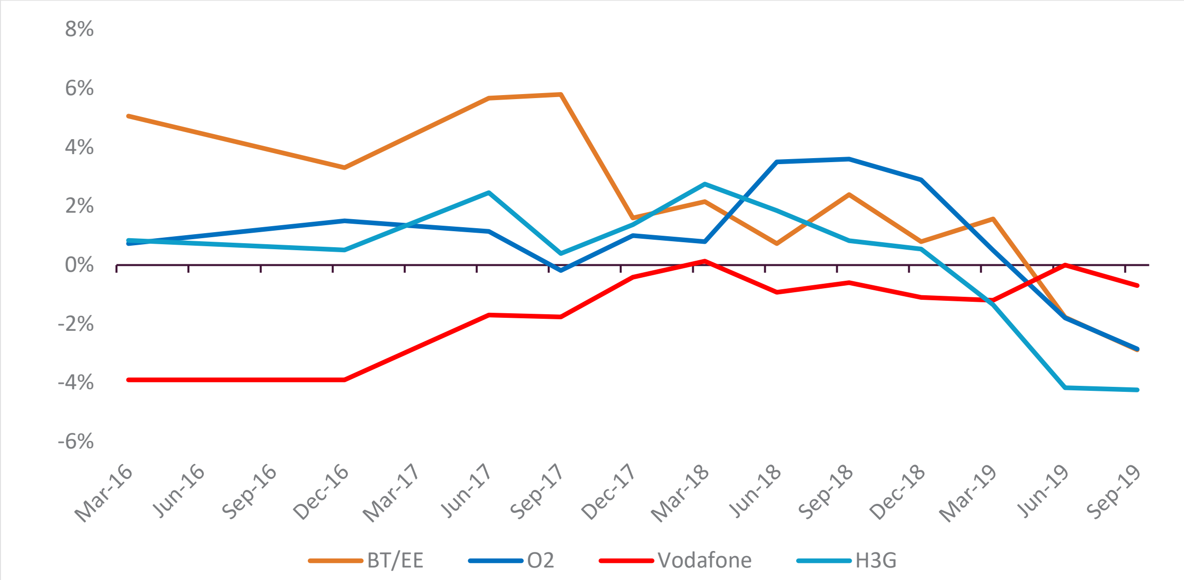
Note: Data have been adjusted for CPI (2018 prices)

A3.48 Enders Analysis looked at mobile service revenue growth by operator (Figure A3.21) and found that Vodafone has experienced negative revenue growth for all but two quarters between Q4 2016 and Q3 2019, and then only barely positive.

A3.49 The other three MNOs have not fared much better recently. All the other MNOs have had negative mobile service revenue growth since Q2 2019, with H3G experiencing the worst growth rate in Q3 2019.

[81] 'Bundled services' refer to those which are included in a pre-determined monthly cost; most commonly for a package of minutes, texts and data.

Figure A3.21: Reported mobile service revenue growth by operator

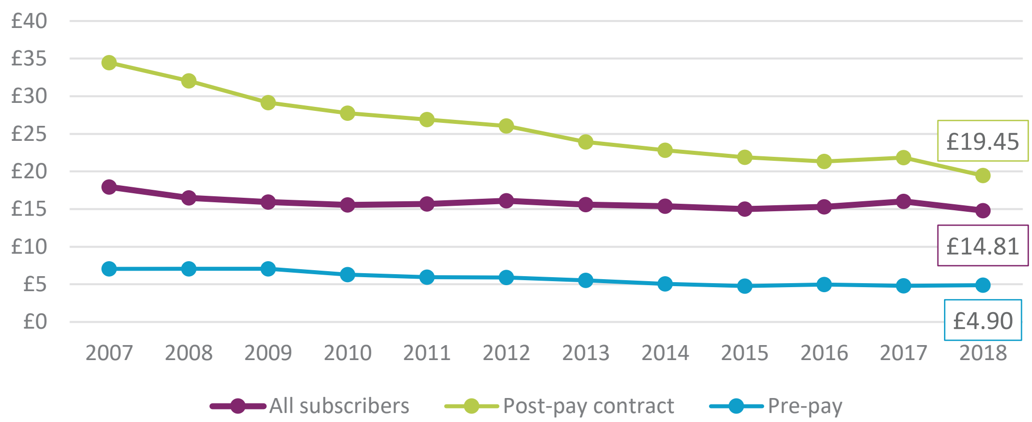


Source: Enders Analysis

Revenue per subscriber

A3.50 Across all providers, average monthly retail revenues per subscriber have fallen slightly over the last decade. The average monthly revenue per post-pay subscriber has fallen more dramatically over the period but this has not translated to a dramatic fall in the figure for all subscribers due to the fact that in the early part of the period, pre-pay contracts were far more common, as seen in Figure A3.22.

Figure A3.22: Average monthly retail revenue per subscriber (£ per month)



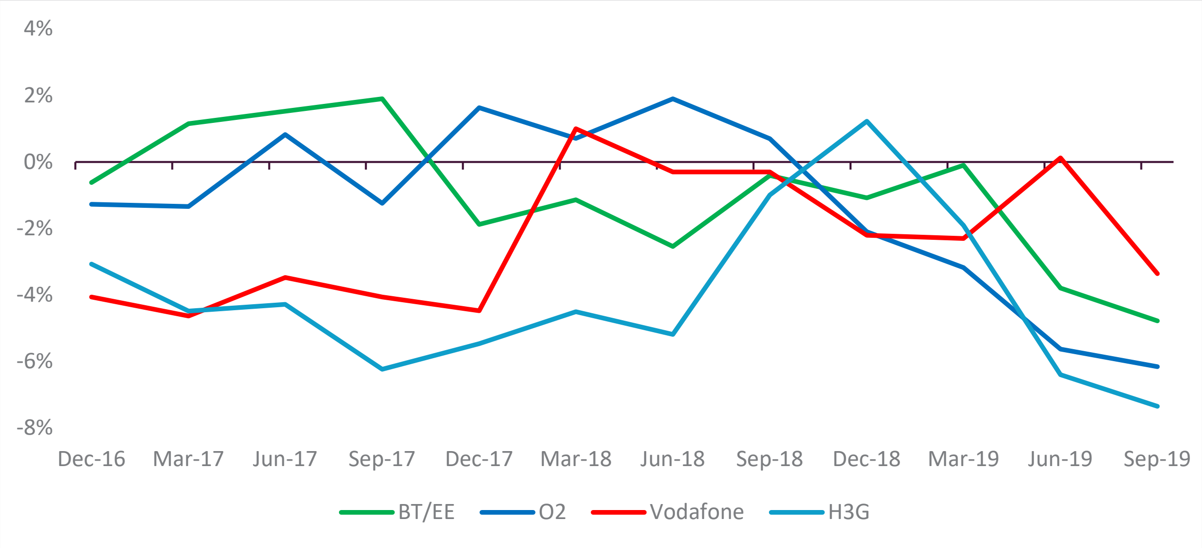
Source: Ofcom

Note: From 2018, bundled revenues are reported according to the new IFRS15 accounting standard, and they do not include any device revenues.

A3.51 According to Enders Analysis (Figure A3.23), since Q2 of 2019 all MNOs have seen negative growth in their contract ARPU. In September 2019, H3G had the lowest ARPU growth even after a brief moment of positive growth in December 2018. Additionally, O2 had the second lowest ARPU growth in September 2019 after mostly positive growth in 2018.

A3.52 BT/EE, O2 and Vodafone all saw negative growth from Q4 of 2018, however Vodafone (just) had positive growth in Q2 in 2019. While BT/EE has seen negative growth in contract ARPU since Q4 2017.

Figure A3.23: Contract ARPU growth



Source: Enders Analysis

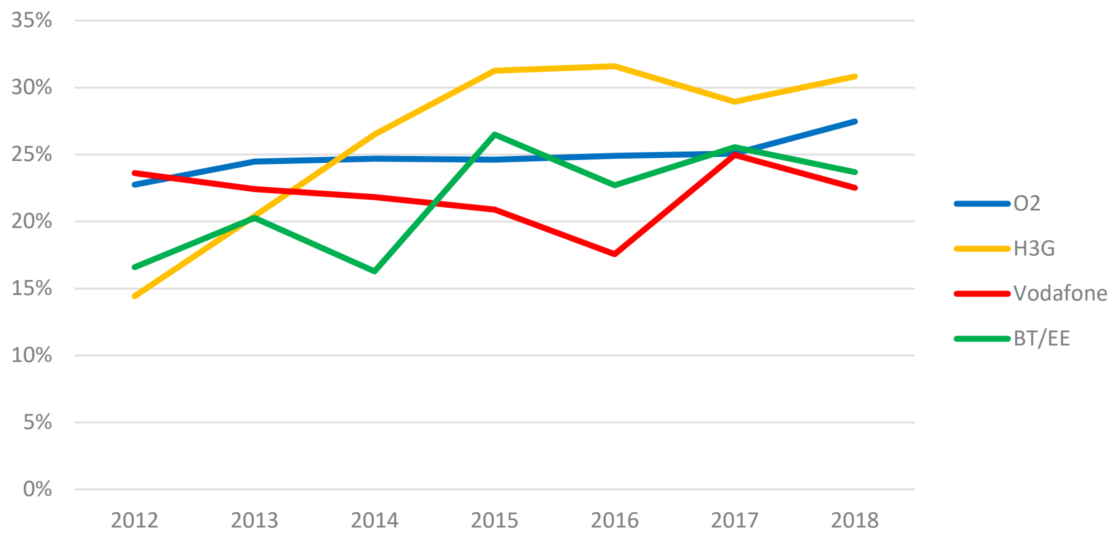
Financial position of the MNOs

A3.53 This section looks at the financial performance of the four MNOs, particularly their profitability and capital expenditure ("capex").[82, 83] As in the December 2018 consultation, we conclude that currently all MNOs appear to be financially viable although we do note a slight deterioration in their recent financial performance.

A3.54 Profitability of the four MNOs, as measured by EBITA margin,[84] has been relatively stable over the last few years, with the exception of H3G which has seen margins broadly increasing since it was established in 2004. It should also be noted that H3G is currently the smallest of the operators with revenues less than half that of the other three MNOs.

[82] All data has been collected from publicly available financial reports. O2 and Vodafone report in Euros, therefore figures have been translated into GBP using historical exchange rates from S&P Capital IQ.
[83] EE results from 2012 to 2015 (December year-end), 2016 onwards from BT Group Financial Results, 2018 results are BT Consumer and EE combined as BT no longer splits out profitability between fixed and mobile. BT mobile revenue share is 38% of the combined revenues.
[84] Earnings before interest, taxation, depreciation and amortisation.

Figure A3.24: EBITDA margin

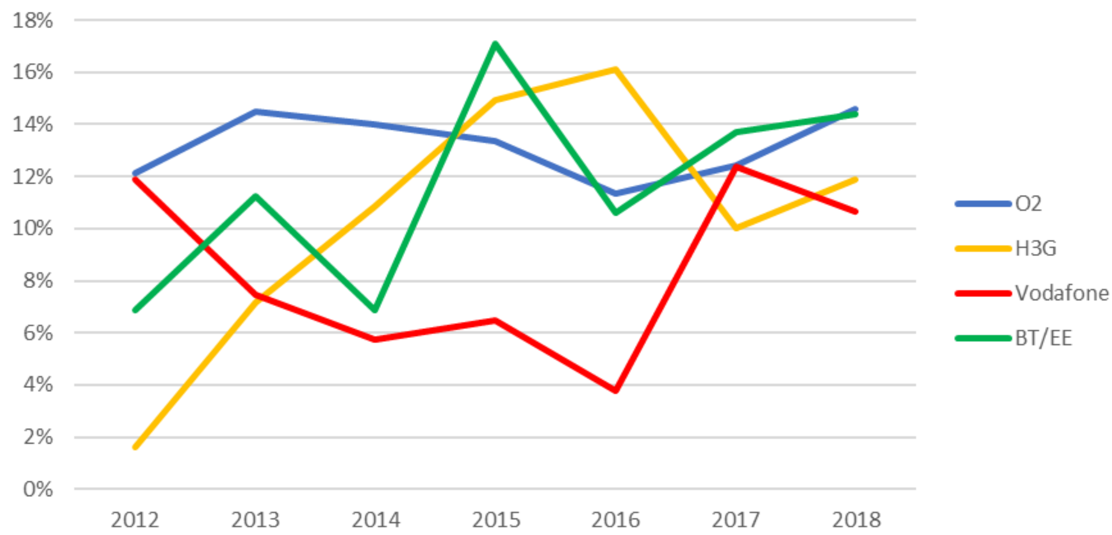


Source: Ofcom, using MNO financial reports and S&P Capital IQ

A3.55 Another key metric for assessment of financial performance is EBITDA less capex which is a measure of the current operational earnings of 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. We exclude spectrum purchases as these are considered one-off expenses and therefore would distort trends in financial health when compared across time.

A3.56 EBITDA less capex margins vary across MNOs and vary significantly through time. However, all MNOs have positive margins with either no clear, or broadly increasing, trend over the period since 2012.

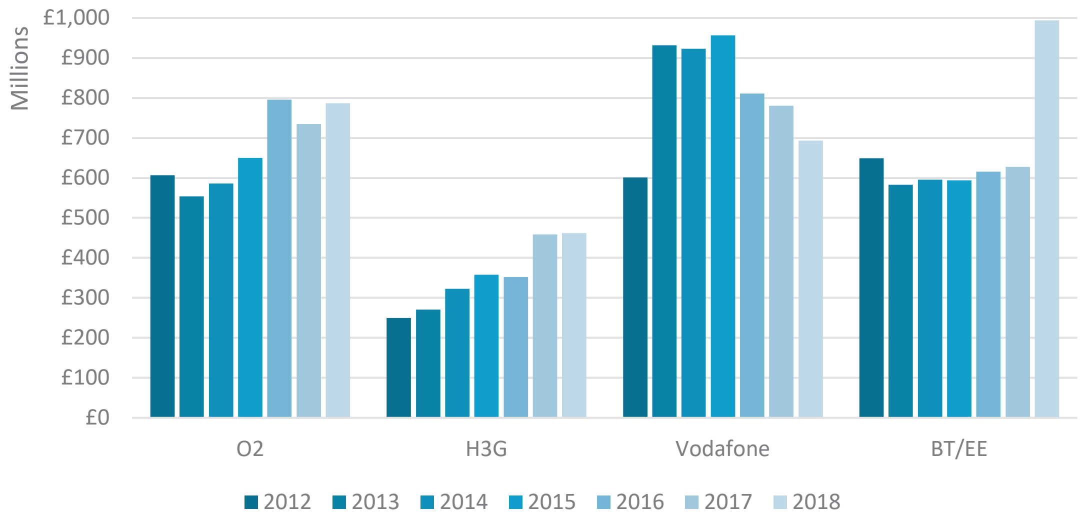
Figure A3.25: EBITDA less capex (excluding spectrum) margin



Source: Ofcom, using MNO financial reports and S&P Capital IQ

A3.57 Levels of capex over the last few years have varied by MNO. O2, H3G and BT/EE have all seen increases in absolute levels of capex, whereas Vodafone's capex has decreased. In absolute terms, H3G has had lower levels of capex than its rivals, however this may be explained by the relative size of H3G. Therefore, we have also looked at capex as a ratio of revenue.

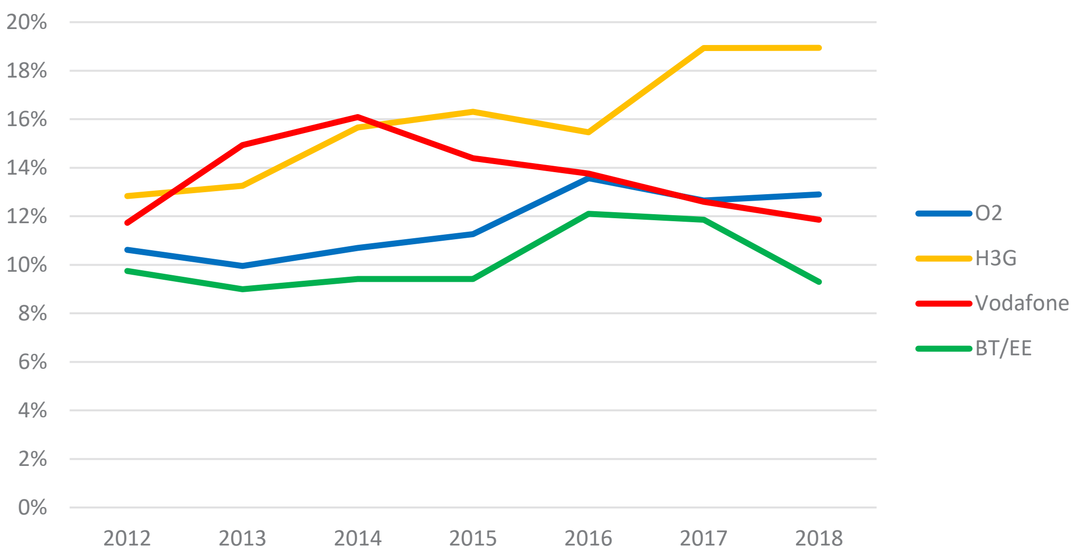
Figure A3.26: Capex (excluding spectrum), 2012 - 2018[85]



Source: Ofcom, using MNO financial reports

A3.58 When considering the ratio between capex and revenue, H3G exhibits the highest ratio. In the last few years, it has invested a larger proportion of its revenue into capital than the other MNOs.

Figure A3.27: Capex to revenue ratio



[85] The 2018 figure for BT/EE is not directly comparable to the other figures in the series; this is due to the change in reporting stated in footnote 83.

Source: Ofcom, using MNO financial reports

A3.59 The evidence shown above does not include the MNOs' more recent financial results for part of their latest financial year, which have indicated a slight worsening financial performance (with the exception of O2). We deal with each MNO individually below:

a) O2's most recent financial results[86] show an improvement in revenues (5% increase to £4,692m), EBITDA margin (3 percentage point increase to 30%), and EBITDA less capex margin (3 percentage point increase to 18%). O2 attributes the improvement to demand for premium handsets coupled with ongoing efficient cost management. Despite the overall increase in capex (7% increase), EBITDA less capex margins improved due to a reduction in costs and increase in revenue;[87]

b) H3G's most recent financial results[88] show a reduction in revenues (2% fall to £1,167m), EBITDA margin (c.2 percentage point fall to 29%) and EBITDA less capex margin (c.5 percentage point fall to 15%). H3G attributes the deterioration in financial performance to higher costs incurred (related to network and IT transformation projects) and lower net customer service margin (due to market competition and regulatory impact), which is partly offset by higher other margin through various initiatives;[89]

c) Vodafone's recent financial results[90] show a minimal increase in revenues (0.2% increase to £2,794m), a reduction in EBITDA margin (1 percentage point fall to 21%), and EBITDA less capex margin (1 percentage point fall to 10%). Vodafone attributes the deterioration in performance (EBITDA margin and EBITDA less capex margin) to increased costs, mainly as a result of increased licence fees;[91] and

d) BT/EE's recent financial results[92] show a slight reduction in revenue (0.6% fall to £5,194m), EBITDA margin (1 percentage point decrease to 23%) and EBITDA less capex margin (3 percentage point fall to 14%). BT/EE has attributed this decrease in profitability to increased spectrum licence fees and content costs. The EBITDA less capex margin has also worsened due to increased spend on the core broadband and 5G networks (capex increased by 22%).[93]

A3.60 Another factor to consider when assessing the MNOs financial health is the impact of further cash required to fund replacement of Huawei equipment given the ban of Huawei equipment in core parts of the network. BT/EE has already stated that the ban will cost

[86] For the 9 months ending September 2019.
[87] Ofcom analysis of Telefonica's 2019 results for 9 months ended September 2019. Note: Telefonica's results have been converted from Euros to GBP using historical rates sourced from S&P Capital IQ.
[88] For the 6 months ending June 2019.
[89] Ofcom analysis of CK Hutchison Holdings Limited's 2019 interim results.
[90] For the 6 months ending September 2019.
[91] Ofcom analysis of Vodafone's 2019 results for 6 months ended September 2019. Note: Vodafone's results have been converted from Euros to GBP using historical rates sourced from S&P Capital IQ.
[92] For the 6 months ending September 2019.
[93] Ofcom analysis of BT's 2020 half year financial results. It should be noted that BT no longer splits out mobile results from fixed and therefore these numbers include both fixed and mobile.

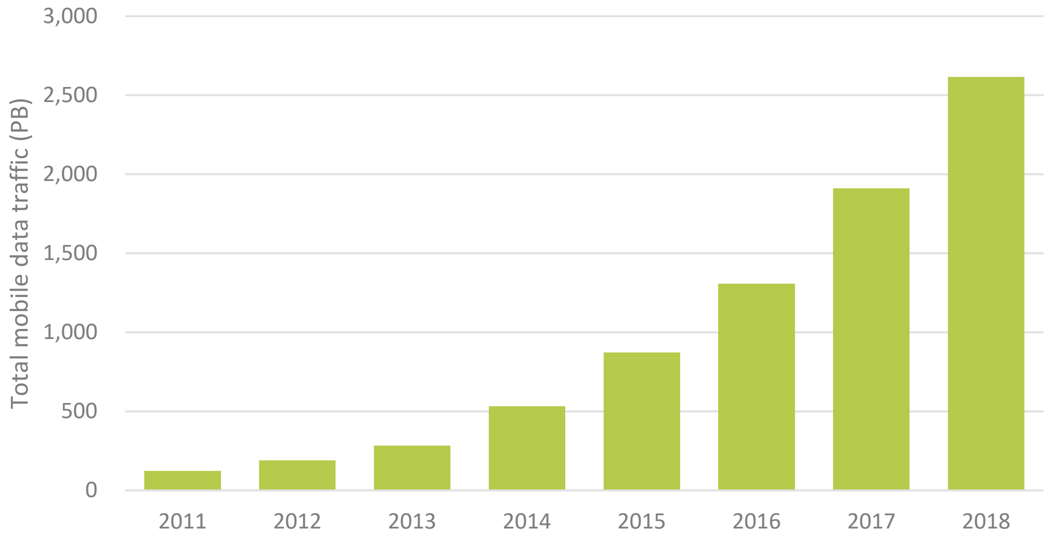
£500m over the next five years.[94] Vodafone Plc also announced it will cost €200m across its European core network over five years.[95] We await disclosure from the other UK MNOs as part of their next results announcement. These funds would have otherwise been used for other purposes, for example further investment in 5G networks.

A3.61 Overall despite a slight worsening in recent financial performance (with the exception of O2), the MNO's remain profitable (that is, EBITDA and EBITDA less capex are both positive) and continue to invest in their networks.

Mobile data traffic

A3.62 Mobile data traffic has risen substantially over recent years and looks set to continue; traffic grew from just over 100 PB in 2011, to more than 2,600 PB in 2018. Between 2017 and 2018, there was a 37% increase in data traffic.

Figure A3.28: Total mobile data traffic, 2011-2018



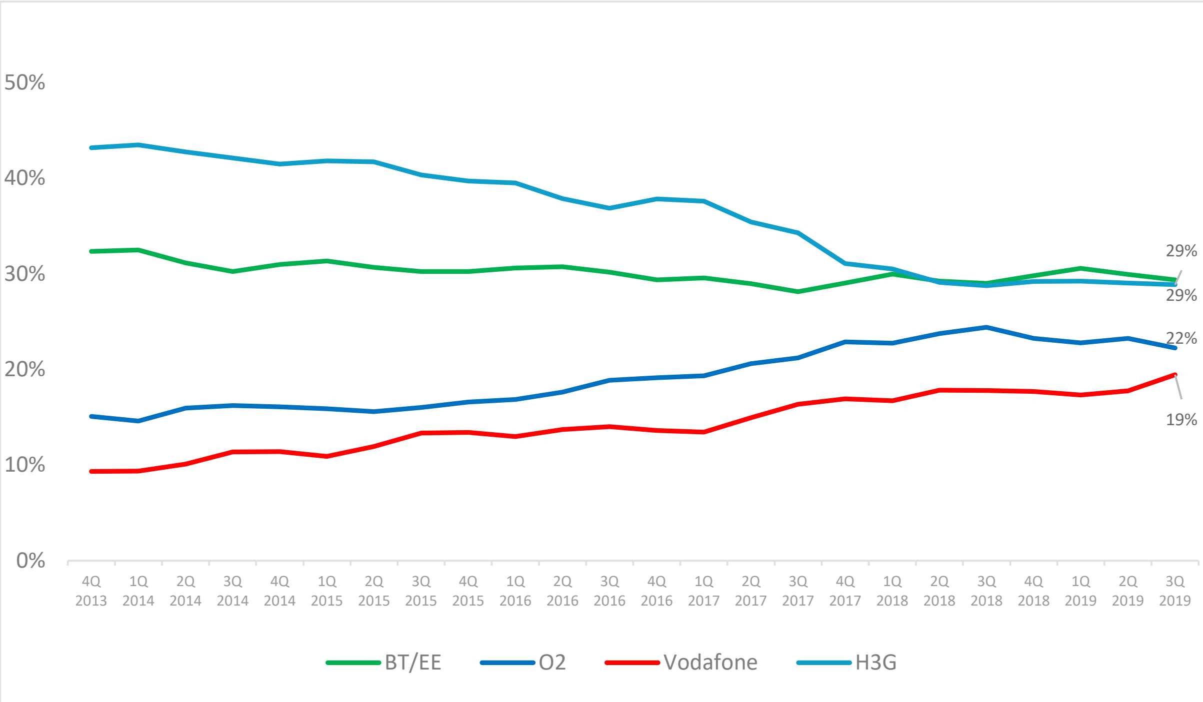
Source: Analysys Mason

A3.63 The share of data carried by each operator varies considerably. As shown in Figure A3.29 below, BT/EE and H3G are the largest carriers of mobile data traffic with 29% of data traffic being carried on each of their networks.

A3.64 Prior to Q1 2018, H3G carried the largest proportion of mobile data traffic on its network despite having the lowest wholesale share of subscribers over this period, as shown in Figure A3.5, however its share of data traffic has been falling and is now comparable with that of BT/EE.

[94] BT Plc Financial Results Q3 2019/20.
[95] Vodafone Plc Financial Results Q3 2019/20.

Figure A3.29: Share of data traffic by operator

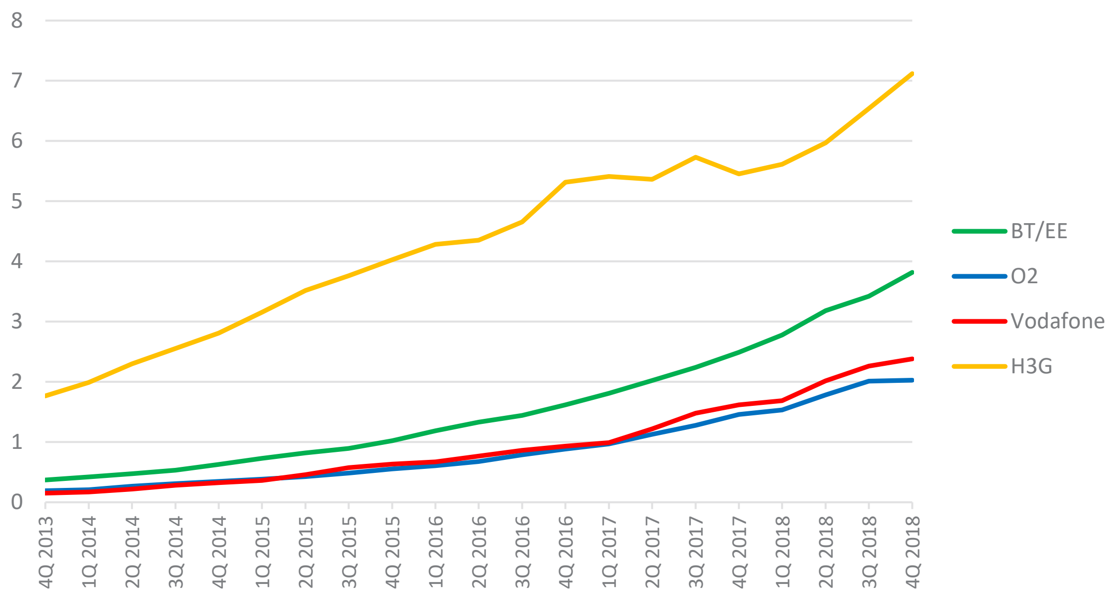


Source: Enders Analysis

A3.65 H3G has consistently seen much higher data traffic per subscriber (Figure A3.30) which explains why it, historically, carried the greatest proportion of data traffic on its network. The most recent data shows that subscribers using H3G's network use an average of 7.1 GB per month.

A3.66 The other three MNOs have also seen increases in data traffic per subscriber, however BT/EE's growth has been more substantial than that of O2 and Vodafone.

Figure A3.30: Monthly data traffic per subscriber, by operator (GB)



Source: Enders Analysis / Analysys Mason

A3.67 We discuss the future growth of mobile data traffic in annex 7.

Factors considered by mobile consumers when choosing a provider

Introduction

A3.68 This section considers specific consumer drivers for choosing a mobile network. We assess the reasons consumers report for choosing a mobile network, what they specifically value from a mobile service, and hence which factors may drive retail competition. Reasons for choosing a network vary across consumer surveys but key drivers largely fall within a few areas:

- Price – the monthly, and sometimes upfront, cost of the service;
- Network quality – this includes aspects such as reliability, coverage, download and upload speeds, latency, webpage browsing times, call quality and call success rates;
- Bundle – what services are included, for example data, call and text allowances;
- Device – the range of devices offered as part of the desired price plan; and
- Customer Service – this includes the ease of contact, the courtesy and politeness of advisors and the willingness to help resolve issues.

A3.69 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. [96]

[96] Ofcom, Award of the 2.3 and 3.4 GHz spectrum bands.

A3.70 Since then, in summary, little has changed. Price and network quality remain the key drivers of consumer decisions about which service provider to choose.

A3.71 Exploring network quality in more depth, reliability and coverage are viewed as the most important factors. Data speeds are considered significantly less important, and this has been the case for the past four years. This is discussed in more detail in the sub-section below.

A3.72 The demand for data (volume) generally continues to increase, and this is largely driven by 4G penetration. That said, most consumers still consider web browsing and voice calls to be the most important mobile services.

A3.73 On the whole, UK consumers continue to express reasonably high levels of satisfaction with their mobile service (93%), and their signal strength/reception (87%).[97] This is true across the board for all four MNOs. The rural/urban divide remains, and customer satisfaction rates are significantly lower for rural consumers.

A3.74 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 usage). Price, whether relating to their previous contract or to 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 stated coverage and reliability**;** 43% listed how much data they would get with their plan.[98]

[97] Ofcom, Comparing Service Quality 2018.
[98] Ofcom, Ofcom Consumer Engagement Quantitative Research 2018.

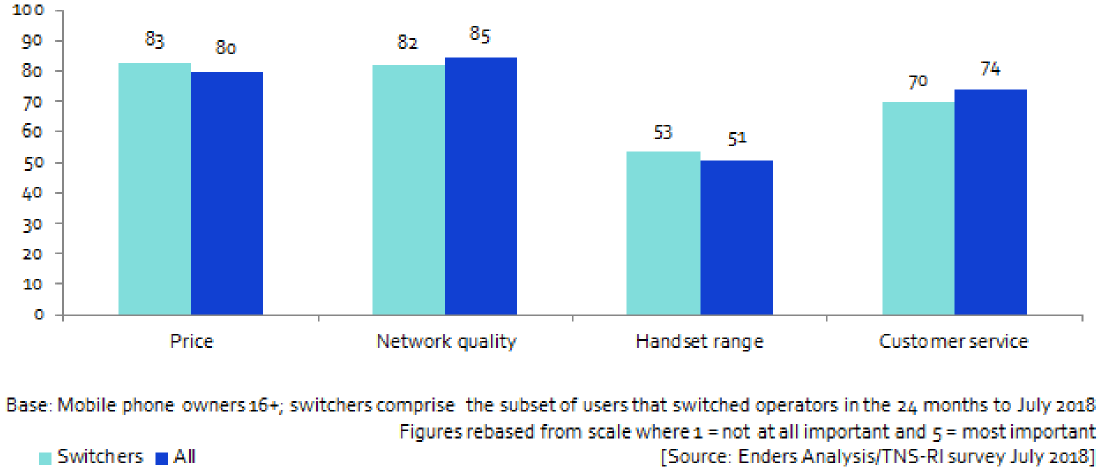
Table A3.1: Ofcom Consumer Engagement Quantitative Research 2018 - What did you consider when taking out your current mobile phone deal?

	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%**

Source: Ofcom consumer Engagement Qualitative Research 2018

A3.75 As shown in Figure A3.31, Enders Analysis also reports that price and network quality are most important for customers, followed by customer service and then handset range. This varies slightly for consumers who have recently changed operators ("switchers"). Switchers place slightly more importance on price and handset range than the general population, and slightly less importance on network quality and customer service. These results are based on a survey of 1,000 people carried out in July 2018.

Figure A3.31: Importance when choosing a mobile network provider



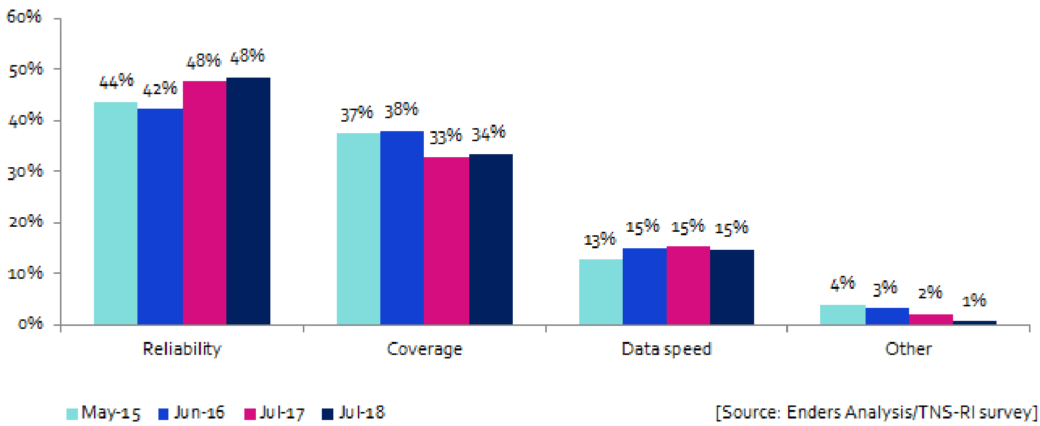
Base: Mobile phone owners 16+; switchers comprise the subset of users that switched operators in the 24 months to July 2018
Figures rebased from scale where 1 = not at all important and 5 = most important
[Source: Enders Analysis/TNS-RI survey July 2018]

Network quality

A3.76 Network quality is a broad concept, covering aspects such as coverage, reliability, 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 considered important for consumers to qualify a network as 'reliable'.

A3.77 Figure A3.32 shows Enders Analysis research undertaken in July 2018 on the most important factor for the quality of a mobile network. Reliability is considered the most important factor, followed by coverage.[99] Data speeds are considered significantly less important and this has not changed in the last four years.

Figure A3.32: Most important factor for the quality of a mobile network



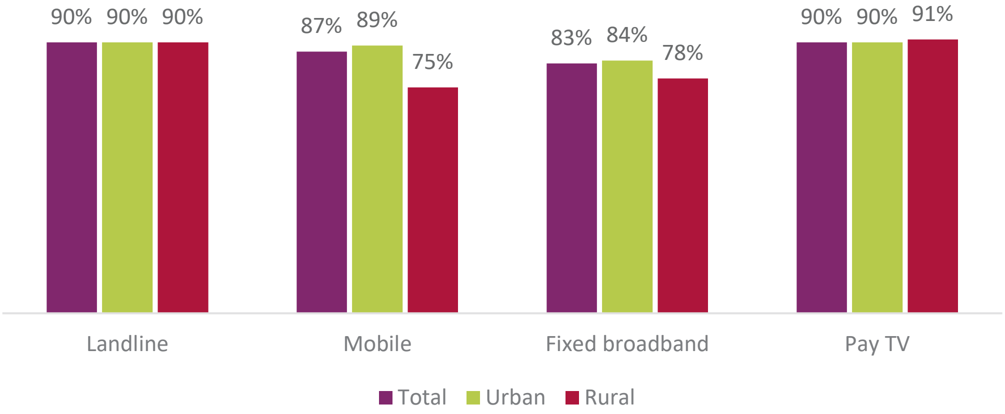
[Source: Enders Analysis/TNS-RI survey]

[99] However, coverage and reliability are closely linked and may be used interchangeably to describe difficulty gaining access to the network. Conversely, people may report good reliability if they have good mobile coverage.

A3.78 Global Wireless Solutions also reported that, when asked to consider the five most important factors for choosing a network, respondents were twice as likely to identify reliability over network speed.[100]

A3.79 Rurality also has an impact on customers' perception of reliability. According to the 2019 Ofcom Customer Satisfaction Tracker, satisfaction for reliability among mobile customers was 89% in urban areas, while for rural areas it was significantly lower at 75%.[101]

Figure A3.33: Ofcom consumer satisfaction tracker 2019-Percentage satisfied with reliability of service from communication provider

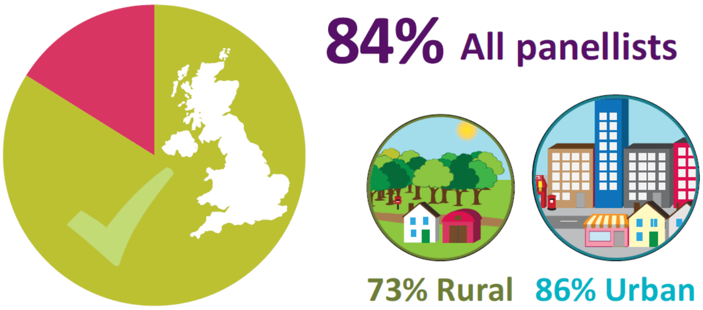


Source: Ofcom Consumer satisfaction tracker 2019

A3.80 A similar pattern is reported by the Ofcom Consumer Mobile Experience Report 2018[102] which (although limited to the experience on Android) found that 84% of Android smartphone users were 'very' or 'fairly' satisfied with their overall mobile network performance, but this varied between rural and urban areas with figures of 73% and 86%, respectively.

[100] Global Wireless Solutions, 'Poor signal drives half a million millennials to throw their phones in anger'.
[101] Ofcom, Customer Satisfaction Tracker 2019.
[102] Ofcom, Consumer mobile experience.

Figure A3.34: Ofcom consumer mobile experience-2019, Overall satisfaction with mobile network performance



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: Ofcom consumer mobile experience 2019[103]

Satisfaction with indoor coverage

A3.81 The consumer experience of network coverage and reliability differs when comparing indoor and outdoor services. The Connected Nations Report 2018 found that voice call coverage from all four operators is available to 93% of UK premises (up from 90% in 2017), and 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.[104]

A3.82 However, a survey by uSwitch published in 2017 suggests that, despite improvements in coverage, consumers are still struggling with network reliability indoors. This survey reports 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 26% of customers in urban areas.

A3.83 The 2017 uSwitch survey also found that the consumer experience of indoor reliability also differs between network provider. It found that O2 customers reported significantly higher rates of satisfaction with their indoor coverage. O2 customers were most likely to rate their indoor mobile signal as 'excellent' (71%), while H3G and BT/EE customers were the least likely (68%).[105]

A3.84 That said, it is uncertain whether the quality of indoor coverage was in itself a significant consumer driver. Where there was 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 Wi-Fi to send messages or make calls.

---

[103] Ofcom: Consumer Mobile Experience 2019
[104] Ofcom, Connected Nations 2018.
[105] uSwitch, 'Three in ten mobile users suffer patchy or no call reception at home'.

Customer satisfaction

A3.85 Which? conducts an annual satisfaction survey of mobile networks, asking over 6,100 people about a number of aspects of their mobile phone service including customer service, ease of contact and value for money.[106] 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 January and February 2019 are as follows:

Table A3.2: Which? 2019 satisfaction scores

	BT/EE	O2	H3G	Vodafone
Customer score	56%	62%	69%	51%

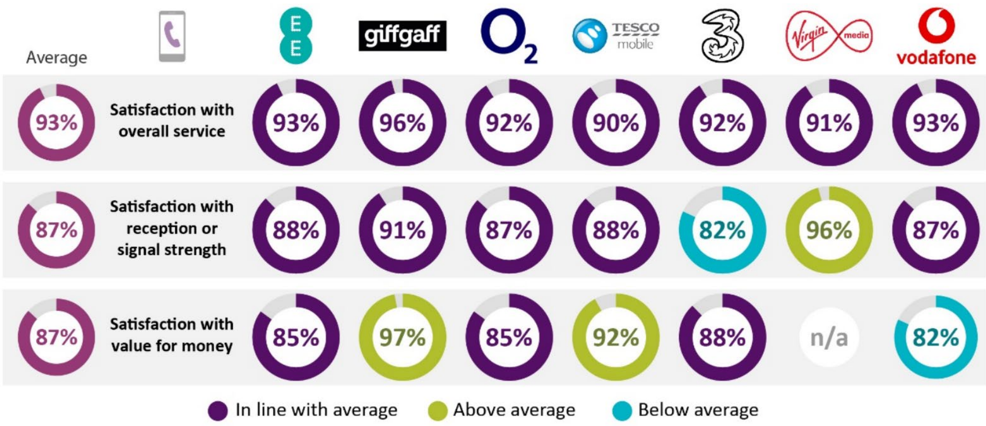
A3.86 The overall Customer score is comprised of four factors: customer service, ease of contacting, value for money and incentives. H3G had the highest customer score of the four MNOs, offering very good value for money as well as decent customer service and ease of contacting. O2 had the second highest score due to offering decent customer service and ease of contacting but obtained a much lower rank for value for money than H3G. 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 51%, with low scores in all categories.

A3.87 Ofcom research suggests that consumer satisfaction with their mobile service is high, but heavily driven by their experience of coverage and reliability. As shown below in Figure A3.35, Ofcom's 'Comparing service quality 2018' highlighted that 93% of customers reported that they were satisfied with their overall mobile service. Ranking first, 96% of giffgaff customers reported that they were satisfied with their mobile service.[107] The MNOs followed closely behind with between 92-93% of customers reporting that they were satisfied.

A3.88 87% of customers were satisfied with their mobile reception/signal strength. Satisfaction with coverage varies between network operator. Of all the mobile providers, MVNO customers were the most content with their reception/signal strength, with Virgin media (96%) and giffgaff (91%) recording the highest levels of satisfaction on this measure. Of the MNOs, BT/EE, O2 and Vodafone customers reported similar satisfaction levels with reception or signal strength to the industry average, however H3G had the lowest level of satisfaction of 82%.

[106] Which?, 'Best and worst UK mobile networks'.
[107] Ofcom, Comparing Service Quality 2018.

Figure A3.35: Customer satisfaction with mobile provider



Source: Comparing Service Quality 2018 [108]

A3.89 Of those consumers who were dissatisfied with their service, the most common reasons were network reliability issues – 63% were dissatisfied with reception or coverage. The second highest source of dissatisfaction concerned the price, or value for money, of their mobile service (16%).

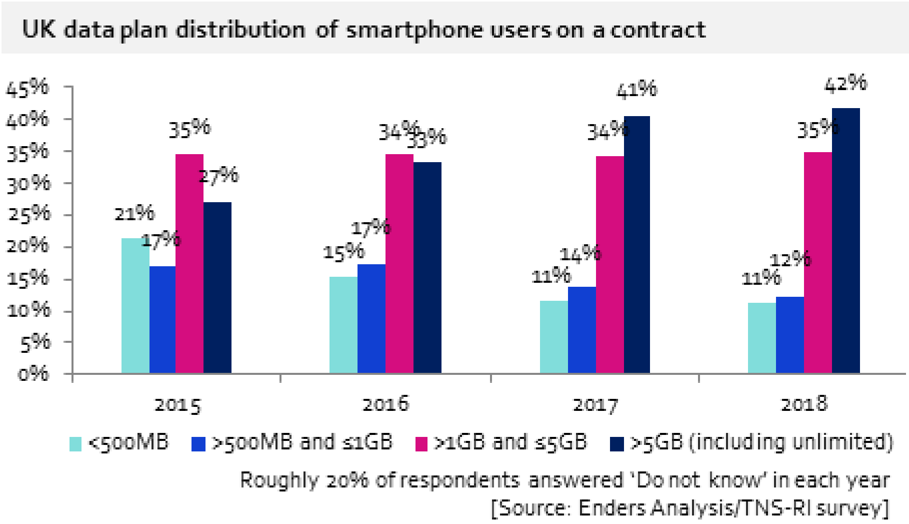
Importance of data

A3.90 Although data speed is not seen as the most important factor for the quality of a mobile network (Figure A3.32), mobile data traffic increased by 32% between 2017 and 2018 and the data allowance of a bundle is considered the second most important aspect, after price, when selecting a new mobile service plan.

A3.91 Figure A3.36 shows the distribution of data plans in the UK up until 2018. Enders Analysis reports that the proportion of consumers opting for larger data plans has increased over recent years. The growth of data plans exceeding 5GB stalled in 2018, however data plans including at least 1GB of data account for 77% of all plans.

[108] Ofcom: Comparing service quality report

Figure A3.36: Enders Analysis assessment of UK data plan distribution smartphone users on a contract



A3.92 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.

Which mobile services do consumers consider most important?

A3.93 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.

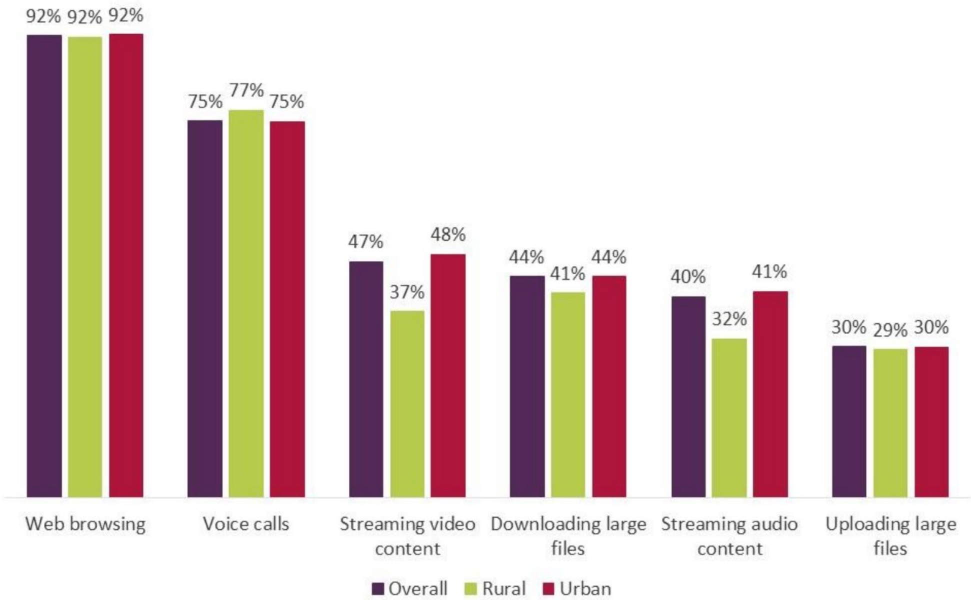
A3.94 There is some evidence that the penetration of smartphones may be slowly changing the way consumers use their phones. According to Deloitte's "Mobile Consumer Survey 2018" report, short-form video is the second most popular form of content on a smartphone; a fifth of respondents watch short videos daily, whilst almost half do so weekly. [109] That said, Deloitte's report is clear that watching long-form videos (e.g. TV programmes, live TV) on smartphones is still relatively infrequent due to the constraint of the screen size.

A3.95 Ofcom's Consumer Mobile Experience report shows that web browsing was recorded as 'extremely' or 'very' important in more cases than voice calls. [110] Figure A3.37 shows the overall importance of mobile services split by rurality. With the exception of streaming video content, there were no substantial differences in importance rankings across other activities, indicating that smartphone users in rural areas prioritise the same mobile activities as those in urban areas. Figure A3.38 shows the overall importance of mobile

[109] Deloitte, Mobile consumer survey 2018.
[110] Ofcom, Consumer mobile experience 2018.

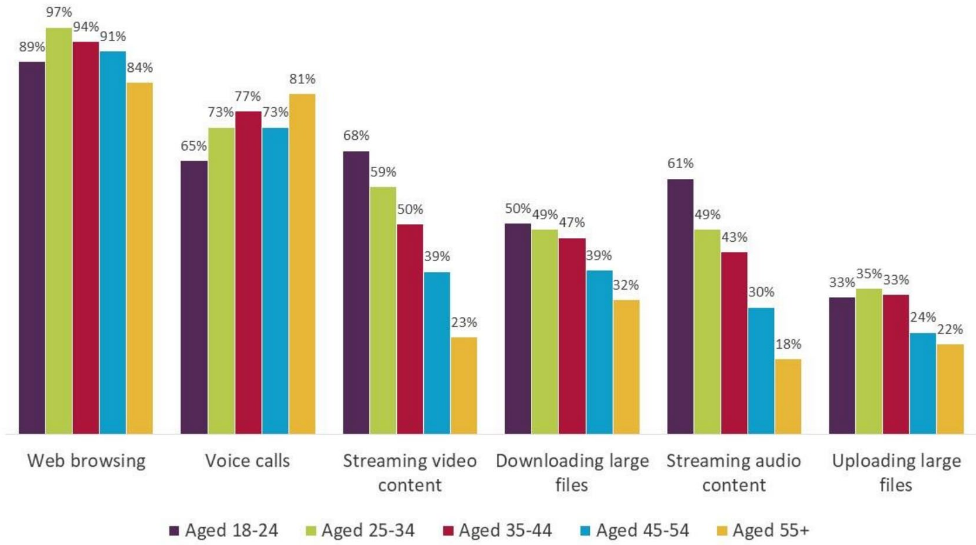
services split by age. There were significant differences by age, particularly in the importance attributed to streaming video and audio which were deemed more important by the younger demographic.

Figure A3.37: Overall importance of mobile services, by rurality



Source: Ofcom Consumer mobile experience[111]

Figure A3.38: Overall importance of mobile services, by age



Source: Ofcom Consumer mobile experience

A3.96 Global Wireless Solutions, however, reported in 2018 that consumers rated making calls and sending text messages as more important than browsing the internet or watching videos.[112]

[111] Ofcom: Consumer Mobile Experience Document

[112] Global Wireless Solutions, 'Poor signal drives half a million millennials to throw their phones in anger'.

Additional data on mobile consumers' preferences provided by BT/EE

A3.97 In its response to the December 2018 consultation, BT/EE argued that the increasing availability of tools available to check coverage meant that it was becoming easier for consumers to choose the operator which provided the best indoor and deep indoor coverage [✂ REDACTED].

A3.98 [✂ REDACTED].

Figure A3.39 – [✂ REDACTED][113]

Figure A3.40 – [✂ REDACTED]

Figure A3.41 – [✂ REDACTED]

[113] The raw data for this chart was provided to Ofcom by BT/EE. This chart was constructed by Ofcom based on the data provided.

A4. Mobile spectrum bands

Summary and introduction

A4.1 This annex outlines which mobile spectrum bands we have identified as 'relevant' spectrum in the context of our competition assessment for the 700 MHz and 3.6-3.8 GHz spectrum award.

A4.2 The pool of 'relevant' spectrum includes the frequencies that will be useable for mobile at the time of this award or soon after. In reaching our conclusions we build on the assessment set out in the December 2018 consultation, taking account of the relevant stakeholder responses to the December 2018, June 2019 and October 2019 consultations and additional evidence that has become available since the consultation was published.

A4.3 We consider the following spectrum bands to be useable:

1) Currently useable bands: 800 MHz, 900 MHz, 1400 MHz, 1800 MHz, 2.1 GHz, 2.3 GHz, 2.6 GHz and 3.4-3.6 GHz; and
2) Bands that will be useable by mid-2020 or shortly after: 700 MHz paired, 700 MHz downlink-only and 3.6-3.8 GHz.[114]

A4.4 We do **not** consider the following spectrum bands to be useable in the context of this auction:

1) mmWave spectrum, 1900 MHz spectrum, and the unawarded parts of the 1400 MHz band; and
2) the 15 MHz of the unpaired 2.6 GHz spectrum that has low power restrictions. This is in line with the 2.3 and 3.4 GHz award where we considered that the low power restrictions on portions of the unpaired 2.6 GHz spectrum represented a material constraint on use of the band.

A4.5 The rest of this annex presents our assessment of each of the spectrum bands we have considered.

Criteria for the assessment of usability of a spectrum band

A4.6 We define three conditions to consider a mobile band as 'useable' in the context of the 700 MHz and 3.6-3.8 GHz award.[115]

Figure A4. 1 Usability criteria for spectrum bands

Criteria	Rationale
Allocation	The band has been allocated for providing mobile services. There should also be sufficient time to allow for

[114] 3.6-3.8 GHz will be useable in some parts of the UK before mid-2020, subject to coordination requirements to account for existing users.
[115] We note that these usability criteria were developed for previous awards with sub 6 GHz spectrum in mind, and apply particularly to spectrum bands in this frequency range.

	a network to be rolled out after the spectrum has been awarded.
No major constraints on use	The band can be used to provide mobile services. Constraints that would preclude this may include, for example, on-going clearance programmes carried out in the band. In any case, constraints must not be so significant that they limit the ability of licensees to use the band to deliver capacity where they need it.
Ecosystem	There is a sufficiently developed range of equipment available to make the spectrum useful 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 increasing capacity whilst being supported in only a few user devices. Traffic from devices that can use the new spectrum band can be offloaded to those frequencies, freeing up other bands for devices that cannot use the new band.

Current and future useable mobile bands

A4.7 In the December 2018 consultation, we considered 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 band** was currently useable. Since then, we have not seen or received any evidence to contradict this view. As such, we consider this spectrum to be useable and we include it in the relevant pool in the context of this auction.

A4.8 We do not include all 50 MHz of the **unpaired 2.6 GHz band** in our pool of useable spectrum. This is because there is a power restriction to a maximum of 25 dBm on the top 5 MHz (held by BT/EE) and the lowest 5 MHz of any individual company's holding in the unpaired 2.6 GHz band. This power limit has been put in place to manage the risk of interference for users of both paired and unpaired spectrum in the band. As a result, this spectrum does not meet our second criteria for usability: there are material constraints on the use of the band.

A4.9 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.

A4.10 Since the award of the **2.3 GHz band**, O2 has rolled out a significant number of cell sites in the band[116], and more devices have come into the market that support the band, including the latest iPhone and Samsung Galaxy S20.[117]

A4.11 The supplementary downlink spectrum in the **1400 MHz band** can be now used in combination with more spectrum bands, making it more flexible. [118] Currently, there are around 80 devices supporting the band including the latest iPhone, Samsung Galaxy and Google Pixel.[119]

The 700 MHz band

A4.12 In our 2018 December consultation, we said that both the 700 MHz paired and 700 MHz downlink-only spectrum were relevant bands of spectrum. The clearance of the band was progressing as planned and looked set to be useable by mid-2020. We said that there was a wide ecosystem of devices supporting the 700 MHz paired spectrum band,[120] and we expected that equipment for the 700 MHz SDL band could be quickly made available once the band had been awarded and demand from the MNOs grew.

Available equipment

A4.13 At present, there are more than 500 mobile devices supporting 700 MHz FDD for 4G (E-UTRA LTE band 28).[121] We are not aware of any devices that currently support 5G NR in the 700 MHz FDD (band n28), however, evidence suggests devices will be available from 2020.[122]

A4.14 Arqiva noted in its response to our December 2018 consultation that, at the time, there were "no handsets in circulation which support 3GPP band 67" (700 MHz downlink-only).[123]

A4.15 In its response to the October 2019 consultation, H3G stated that [✂ REDACTED] whilst [✂ REDACTED][124]

---

[116] O2 deploys 2.3 GHz in 1,000 sites in 2018 https://news.o2.co.uk/press-release/o2-to-connect-1000-locations-to-latest-4g-spectrum-in-rapid-rollout/ Accessed 17/12/2019.
[117] https://www.apple.com/iphone/LTE/ and https://www.samsung.com/uk/smartphones/galaxy-s20/ Accessed 27/01/2020.
[118] SDL combinations with LTE Band 32 in Release 15 include 800 MHz FDD, 900 MHz FDD, 1800 MHz FDD, 2100 MHz and 2600 MHz FDD.
[119] GSMA Arena Devices supporting LTE Band 32 https://www.gsmarena.com/search.php3?s4Gs=32 Accessed 15/11/2019.
[120] GSMA Arena. Devices supporting LTE Band 12 https://www.gsmarena.com/results.php3?s4Gs=12 Accessed 17/02/2020.
[121] 3GPP uses bands to show which frequencies are supported by handsets. In this example, E-UTRA LTE band 28 refers to E-UTRA LTE technology using 700 MHz FDD spectrum. Conversion tables can be found online. For example, https://www.gsmarena.com/search.php3?s4Gs=28 Accessed 15/11/2019.
[122] Although 5G NR band n28 (700 MHz FDD) is considered as one of the primary bands for 5G, this band is not widely supported in the first release of 5G devices in 2019, but will be supported in the second generation chipsets from 2020 onwards and in devices from 2021, according to the evidence we have from [✂ REDACTED].
[123] Arqiva non-confidential response, page 6.
[124] [✂ REDACTED]

A4.16 We are not aware of any devices currently supporting 700 MHz downlink-only spectrum and the evidence we currently hold suggests that this band could only be supported in mainstream devices from late 2020 at the earliest.[125]

A4.17 Since the publication of our December 2018 consultation, Italy and Sweden have carried out auctions of the 700 MHz downlink-only spectrum; both resulting in unsold 700 MHz downlink-only lots. It is possible that this may result in lack of demand for handset manufacturers to support this band in devices.[126]

A4.18 However, we do not believe this to be a constraint because, once spectrum is allocated, it should be possible to add support for the 700 MHz downlink-only spectrum in new handsets fairly quickly after chipsets begin to support the band because many of the necessary components (e.g. low frequency antennas) will already be in devices in order to support 700 MHz paired spectrum.

A4.19 Our final decision is to include 700 MHz in the pool of relevant spectrum. Although we expect that MNOs will only demand support for the SDL band from handset manufacturers after the spectrum is awarded, we continue to believe that it will be possible to include support for new 5G handsets fairly quickly. We expect the 700 MHz paired spectrum to become useable by Q2 2020[127] and based on the evidence we currently hold the 700 MHz SDL band will likely be available from late 2020 at the earliest.

The 3.4-3.6 GHz band

A4.20 In our December 2018 consultation we considered this band to be useable from 2019. We said that, whilst it was likely that devices supporting the 3.4 GHz band for LTE would be limited, early devices (2019) supporting 5G NR would include support for the band.

A4.21 Since then, all four MNOs have launched 5G networks in several cities across the UK using this spectrum. We have also spoken to several device and chipset manufacturers who confirmed that equipment for this band exists.[128] The band has been allocated and faces no major constraints on use, therefore we have decided to include 3.4-3.6 GHz as a relevant mobile band.

Available equipment

A4.22 5G NR support in the 3.4-3.6 GHz band (either for 5G NR n77 or n78 bands) is already available in several chipsets.[129] Moreover, evidence from industry suggests that 3.4-3.8 GHz band is key for the initial deployments of 5G networks. For example, Vodafone stated in its response to our December 2018 consultation that "*the 3.4 - 3.6GHz band is vital – and largely unmatched – in setting the competitive landscape for mobile services.*"[130] BT/EE also

---

[125] [✂ REDACTED]

[126] Results of Italy 700 MHz spectrum auction https://5gobservatory.eu/italian-5g-spectrum-auction-2/ and Sweden https://www.pts.se/en/news/press-releases/2018/700-mhz-auction-is-closed--auction-proceeds-were-28-billion-sek/

[127] https://www.ofcom.org.uk/__data/assets/pdf_file/0021/143328/april-2019-update-700-mhz-clearance.pdf

[128] [✂ REDACTED] and https://www.phonearena.com/search/?term=5g+phones Accessed 27/02/2020.

[129] from [✂ REDACTED]

[130] Vodafone non-confidential response, page 16.

stated in its response to our December 2018 consultation that the "*3.4-3.8 GHz band is widely recognised to be the band most widely supported for 5G in the first years following launch.*"[131] Similarly, in its response to the October 2019 consultation, [✂ REDACTED][132]

A4.23 All things considered, we believe that the ecosystem supporting these bands exists and will continue to grow quickly in the next few years.

The 3.6-3.8 GHz band

A4.24 In our December 2018 consultation, we set out the significant developments regarding the 3.6-3.8 GHz band that occurred after our July 2017 statement. Firstly, we had taken decisions on our approach to existing users of the band, ensuring that Permanent Earth Station (PES) licensees vacate the band by mid-2020 and fixed links licensees by the end of 2022.[133] Further, through our engagement with fixed link (FS) stakeholders we reached agreements with fixed link (FS) licensees to ensure that most fixed links users vacate the band by March 2020.

A4.25 Secondly, we had more certainty on the development of equipment for the band, notably that upcoming 5G NR capable devices would support the whole 3.4-3.8 GHz range and concluded that these should be available no later than 2019.

A4.26 We believed that some fixed links would remain until the end of 2022. We carried out an interference analysis and concluded that while some deployment restrictions would remain as a consequence of coordination requirements in a few areas of the country between mid-2020 and end of 2022, these would not be material enough to prevent an MNO from deploying the spectrum nationally. These restrictions would disappear if the new licensees reached an agreement with the remaining users to clear the band before the end of 2022.

A4.27 We therefore considered in our December 2018 consultation that the 3.6-3.8 GHz band would be useable, subject to coordination with existing users, from mid-2020 or earlier in some parts of the country.

A4.28 We have not received any responses from stakeholders suggesting that the 3.6-3.8 GHz spectrum band should not be included in the pool of relevant spectrum. Therefore, we have decided to include 3.6-3.8 GHz in the pool of relevant spectrum.

A4.29 We now summarise developments since the December 2018 consultation supporting our decision.

[131] BT/EE non-confidential response, page 49.
[132] [✂ REDACTED]
[133] Ofcom consumer access to the 3.6 – 3.8 GHz spectrum.
https://www.ofcom.org.uk/__data/assets/pdf_file/0019/107371/Consumer-access-3.6-3.8-GHz.pdf and Ofcom update on spectrum availability https://www.ofcom.org.uk/__data/assets/pdf_file/0018/110718/3.6GHz-3.8GHz-update-timing-spectrum-availability.pdf

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

A4.30 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 European Radio Spectrum Policy Group (RSPG). We decided to make the band available for mobile services in October 2017[134] 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.

A4.31 In February 2018 we published an update on the timing of availability of the 3.6-3.8 GHz band.[135] This 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.

A4.32 Since our December 2018 consultation, we have continued to engage with all the fixed link users in the band and several have agreed to vacate the band before mid-2020. At the time of publication of this statement only one user, [✂ REDACTED] has not agreed to move early and therefore several fixed links in northern Scotland as well as a link between Portsmouth and the Isle of Wight are likely to remain in place until the end of 2022.

Interference analysis in the 3.6-3.8 GHz band

A4.33 In the December 2018 consultation we presented an interference analysis focusing on a fixed link from Portsmouth to the Isle of Wight.[136] This is the only link potentially constraining deployments in densely populated areas between mid-2020 and end of 2022. The link operates a 30 MHz carrier with a centre frequency of 3740 MHz.

A4.34 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 (within this 50 km radius) 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 power or careful antenna pointing), most of the sectors that failed could be deployed with minimal impact on network performance.

[134] Ofcom consumer access to the 3.6 – 3.8 GHz spectrum. https://www.ofcom.org.uk/__data/assets/pdf_file/0019/107371/Consumer-access-3.6-3.8-GHz.pdf
[135] Ofcom update on spectrum availability https://www.ofcom.org.uk/__data/assets/pdf_file/0018/110718/3.6GHz-3.8GHz-update-timing-spectrum-availability.pdf
[136] 2018 consultation annex 15 https://www.ofcom.org.uk/__data/assets/pdf_file/0021/130737/Annexes-5-18-supporting-information.pdf

We conclude, therefore, that this should not prevent MNOs from deploying this spectrum nationally. The population potentially affected by this link is estimated to be c. 500,000.

A4.35 In its response to the October 2019 consultation, O2 requested [✂ REDACTED] [137]

A4.36 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 those incumbent users vacate the band (see section 8 for further details).

A4.37 It is 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.

Available equipment

A4.38 The list of spectrum bands in 3GPP Release 15[138] identifies bands n77 (3.3-4.2 GHz)[139] and n78 (3.3-3.8 GHz) as 5G NR bands. The majority of devices that have been offered by MNOs for their 5G launches contain band n78, meaning they are compatible with both the 3.4-3.6 GHz and 3.6-3.8 GHz spectrum bands. We now expect that the number of devices supporting both of these bands will most likely grow at the same pace. At the time of this publication, there are around 24 devices supporting the 3.4-3.6 GHz and 3.6-3.8 GHz spectrum bands.[140]

We have excluded some mobile bands from the pool of relevant spectrum for this award

A4.39 In our December 2018 consultation, we mentioned that there were a number of other frequencies that might become useful for mobile access in the future. We published an update to our mobile data strategy in June 2016.[141] 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 the mmWave bands.[142] We now explain in more detail our reasoning for excluding these spectrum bands.

[137] [✂ REDACTED]
[138] Ericsson paper on spectrum bands https://www.ericsson.com/assets/local/policy-makers-and-regulators/180119-3gpp-spectrum-bands.pdf
[139] 3.3 – 3.4 GHz is likely to be used indoors in Asian markets only.
[140] GSMA Arena, services supporting 5G https://www.gsmarena.com/search.php3?chk5G=selected Accessed 15/11/2019
[141] 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.
[142] 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*".

We exclude the 3.8-4.2 GHz, 1800 MHz and 2390-2400 MHz sharing bands

A4.40 As set out in our July 2019 statement[143], we decided to support innovative services by enabling localised access to spectrum bands supporting mobile technology. We have decided to make three bands supported by mobile technology available 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).[144]

A4.41 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 services can use bespoke equipment as opposed to mass market consumer devices (such as mobile handsets) where use of internationally harmonised bands would be required. Both the 1800 MHz and 2.3 GHz bands are already supported by mobile networks and handsets. This means that this spectrum can be used immediately, for example by mobile coverage improvement scheme providers in rural areas and for in-building coverage, or to provide private localised mobile networks.

A4.42 Our decision to license these bands on a localised basis means that they cannot 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 or offer private mobile and fixed networks. We therefore do not consider them relevant for the purposes of the competition assessment for this auction.

We exclude the mmWave bands

General overview of mmWave bands

A4.43 In the context of this document we define mmWave spectrum to be spectrum above 24 GHz, especially if it has been identified for 5G mobile use (for example, spectrum that has been identified for IMT in the ITU Radio Regulations).[145] mmWave has the potential to provide high capacity given the large amounts of spectrum available.

A4.44 5G technology can make use of spectrum above 6 GHz which is an improvement over previous generations of mobile technology which could not. One of the key outcomes of the World Radiocommunications Conference (WRC) of 2019 was the identification of the 24.25-27.5 GHz, 37-43.5 GHz and 66-71 GHz bands for the deployment of 5G networks, including the necessary measures to protect existing users, such as Earth exploration satellite services, meteorological radars and other passive systems.[146]

---

[143] Enabling wireless innovation through local licensing", Ofcom, 25 July 2019. https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

[144] Enabling wireless innovation through local licensing", Ofcom, 25 July 2019. https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

[145] ITU towards "IMT for 2020 and beyond" https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx Accessed 17/02/2020.

[146] WRC-19 identifies additional frequency bands for 5G https://news.itu.int/wrc-19-agrees-to-identify-new-frequency-bands-for-5g/ Accessed 17/12/2019.

A4.45 We have identified 26 GHz[147] as one of the key 5G bands[148] along with the 700 MHz and 3.4-3.8 GHz bands. It has also been identified at the European level as the 5G 'pioneer band'. We have added the bottom part of the 26 GHz band (24.25-26.5 GHz) to our spectrum sharing framework for indoor only applications.[149]

A4.46 We have also made changes to the authorisation regime in the 57-71 GHz band,[150] and implemented common technical conditions across the 57-71 GHz band for fixed and mobile use on a licence exempt basis.

A4.47 We note there is ongoing interest in using some of the mmWave bands to provide mobile services, given the outcome of WRC19 and the decisions from countries and administrations to make available some mmWave spectrum.[151]

A4.48 We also note there is a growing range of devices (including handsets and CPEs) supporting some of the mmWave bands. Qualcomm told us that [✂REDACTED][152]. However, at present, there only a few commercially available devices supporting the mmWave bands.[153] At present, in the UK, mmWave bands are being used by mobile operators but not for mobile services.[154]

We are not including mmWave in the relevant pool of spectrum because it is uncertain whether it will be used in the same way as sub-6 GHz spectrum to deliver mobile services

mmWave has different characteristics to sub-6 GHz spectrum

A4.49 While mmWave spectrum bands offer high bandwidth, they are subject to much higher signal losses than sub-6 GHz spectrum when blocked by obstacles such as walls, buildings, trees and terrain. As such, mmWave 5G cell sites deployed to service mobile handsets in built up areas will likely have a shorter range than traditional mobile macro sites. For example, it is likely that 26 GHz cells will typically have a radius ranging from 50 meters to a few hundred meters.[155]

---

[147] 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 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.
[148] Ofcom 5G update https://www.ofcom.org.uk/__data/assets/pdf_file/0021/97023/5G-update-08022017.pdf
[149] Ofcom Shared access licences https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/shared-access Accessed 27/02/2020.
[150] https://www.ofcom.org.uk/__data/assets/pdf_file/0017/115631/statement-fixed-wireless-spectrum-strategy.pdf
[151] Countries like Italy, Russia and Australia have started processes to allocate or auction mmWave bands for mobile use; mmWave deployments in Russia https://telecoms.com/499131/russia-jumps-on-the-mmwave-train/ Accessed 05/12/2019 and mmWave spectrum developments in Australia https://www.communications.gov.au/publications/coexistence-terrestrial-and-satellite-services-26-ghz Accessed 02/03/2020.
[152] [✂ REDACTED]
[153] According to GSA, December 2019: Spectrum above 6 GHz: Global Licensing & Usage Overview.
[154] As long as they are compliant with the technical in block and out of block limits conditions specified in the licences https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/mobile-wireless-broadband/above-5ghz
[155] "5G spectrum access at 26 GHz and update on bands above 30 GHz", Ofcom, 28 July 2017, https://www.ofcom.org.uk/__data/assets/pdf_file/0014/104702/5G-spectrum-access-at-26-GHz.pdf

A4.50 mmWave spectrum therefore has very different coverage and capacity qualities to sub-6 GHz spectrum. We therefore do not consider it can currently be considered substitutable for sub-6 GHz spectrum.

There remains uncertainty around how mmWave spectrum will be used to deliver mobile services

A4.51 There are only a few international mmWave mobile deployments[156] and a small but growing ecosystem of devices supporting some of the mmWave bands.[157] Whilst there is consensus that some of the mmWave bands will be used for mobile, there is no firm evidence about when and how this spectrum will be used for mobile in the UK. This is due, primarily, to the different propagation characteristics of the mmWave band when compared to sub-6 GHz frequencies.[158]

A4.52 In response to the December 2018 consultation, Vodafone agreed with our view that mmWave spectrum was not a substitute for lower frequencies.[159] BT/EE said that a 37% overall cap would not recognise the different properties of the various spectrum bands or their ability to provide coverage or deliver capacity on a per MHz basis and that if a cap were applied including mmWave spectrum the 37% cap would be increasingly inappropriate.[160] We address BT/EE concerns in section 4. We note that none of the other operators commented on our proposal not to include mmWave spectrum in the relevant spectrum for this auction.

A4.53 In accordance with the approach set out in annex 8 of the December 2018 consultation, we have decided not to include mmWave spectrum in the pool of relevant spectrum for this award. This is because we consider it is so different in nature to sub-6 GHz spectrum that it cannot reasonably be considered a substitute for sub-6 GHz spectrum. Further, although as set out above we expect mmWave spectrum to be used to offer 5G services in the future, there is currently considerable uncertainty around how and when it will be used for mobile. We also note that at present, no mmWave bands meet our criteria for usability, though they may do within the timeframe relevant for this competition assessment.

A4.54 On the basis of the evidence above, we have therefore decided not to include mmWave spectrum in the pool of relevant spectrum as part of the competition assessment for this award.[161]

---

[156] In particular, we note Verizon has deployed its 5G network using 28 GHz and 39 GHz mmWave spectrum, and its coverage maps show that there is 5G coverage using mmWave spectrum in parts of around 30 US cities. Verizon's 5G coverage maps. https://www.verizonwireless.com/5g/coverage-map/?AID=11365093&SID=66960X1514734Xb808a1edb06769243d8ae3832b114297&vendorid=CJM&PUBID=7596969&cjevent=10d33484388111ea817600900a18050d Accessed 16/01/2020; we also note developments in South Korea. https://www.fiercewireless.com/tech/samsung-sk-telecom-rev-5g-mmwave-at-racetrack Accessed 27/02/2020

[157] As we explain in A4.51.

[158] 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.

[159] Vodafone non-confidential response, page 13.

[160] BT/EE non-confidential response to the December 2018 consultation, paragraph 3.147.

[161] We also note that, if in the future mmWave bands were to provide a significant source of capacity, the potential for different patterns of network deployment could have implications for how mmWave bands might be combined with a pool of spectrum of lower frequency bands for the purpose of competition assessment.

We exclude other spectrum bands – the lower part of 2.3 GHz, upper 1400 MHz band and the 1900 MHz band

A4.55 In the December 2018 consultation we said that we had no concrete plans to award these bands and, therefore, we did not consider them useable spectrum in the context of the competition assessment for this auction. We received no objections to exclude these bands from the pool of relevant spectrum.

The lower 2.3 GHz band

A4.56 The Public Sector Spectrum Release (PSSR) programme is investigating how 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 and, in any case, will not be available for some years.

The upper 1400 MHz band

A4.57 Ofcom intends to make the 1492-1517 MHz band available for future mobile services. This will comply with European Commission Decision 2018/661 of 26 April 2018 which harmonises the 1492-1517 MHz band for downlink-only mobile services on an EU-wide basis. We started the process to make the band available for mobile by announcing in our July 2018 statement the closure of the band for new fixed links and technical variations from 5 January 2019. We are currently taking the necessary clearance action in line with the EU harmonisation measures to make the band available for future downlink-only mobile services.

A4.58 We are not aware of any devices supporting this band yet although we would expect equipment to become available once the band has been awarded for mobile use. We have no firm plans to award this band and we do not consider this would happen within the timelines relevant to this auction.

The 1900 MHz band

A4.59 With regards to the **1900 MHz band**,[162] our position as outlined in the July 2017 statement is unchanged, i.e. we do not consider the unpaired 1900 MHz spectrum to be relevant to our analysis of competition in mobile services. Although this band is licensed to three of the four MNOs for mobile use, it is currently unused for mobile access and is unlikely to be

[162] BT/EE has a licence covering 1899.9 – 1909.9 MHz (TDD); H3G has a licence covering 1914.9 – 1920.0 MHz (TDD) and O2 has a licence covering 1909.9 – 1914.9 MHz (TDD) https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/mobile-wireless-broadband/below-5ghz Accessed 27/02/2020.

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.

A4.60 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[163] 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.[164]

A4.61 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.

A4.62 In line with our framework, we do not consider that the 1900 MHz is useable for the purposes of our competition analysis for this award as there are major constraints on the use of the band. Therefore, our view that this spectrum is not relevant for our analysis remains unchanged.

[163] EE application for a licence variation in support of enhanced mobile communications for the emergency services 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

[164] 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.

A5. Current performance of UK mobile networks

A5.1 This annex provides an overview of the current performance of the UK mobile networks and assesses how the MNOs are using their spectrum to deliver services to consumers. In conjunction with the analysis presented in other annexes, it has informed our assessment of whether competition is working well for UK consumers and whether UK MNOs are delivering a good service.

A5.2 This annex considers data received directly from the MNOs as well as the results of independent third-party surveys and analysis.

Current UK spectrum deployment

A5.3 The MNOs each hold varying amounts of spectrum across different frequency bands and use this spectrum to deliver 2G, 3G, 4G and 5G 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.

A5.4 We think it is too early to assess the full impact that the 2.3 and 3.4 GHz award has had on MNOs' deployment strategies and network capacity. However, we have noted below the steps that they have already taken in relation to this spectrum.

A5.5 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 uses its 800 MHz and 2.6 GHz spectrum to deliver a 4G service, as well as some 1800 MHz spectrum which is being 'refarmed' (i.e. repurposed) from 2G to 4G. BT/EE holds some 3.4 GHz spectrum which it used to launch a 5G service in the UK in May 2019.

A5.6 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 refarming some of its 1800 MHz 2G spectrum and 2100 MHz 3G spectrum to 4G. It has also started deploying its 2.3 GHz spectrum to increase the capacity of its 4G network. O2 holds some 3.4 GHz spectrum which it used to launch a 5G service in October 2019.

A5.7 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. H3G plans to use the spectrum it holds in the 3.4-3.8 GHz band to launch its mobile 5G service in early 2020.

A5.8 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 uses its 800 MHz and 2.6 GHz spectrum to deliver a 4G service and has also 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. Vodafone holds some 3.4 GHz spectrum which it used to launch a 5G service in the UK in July 2019.

A5.9 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.

Comparison of UK mobile networks

A5.10 In annex 3, 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 the MNOs perform across three key aspects of network quality: reliability, speed and coverage.

Reliability

A5.11 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.

A5.12 We have considered the following sources of evidence in our assessment of network reliability, which is in line with the approach that we set out in the December 2018 consultation:

i) the reports published by Rootmetrics and Umlaut, which conduct various UK-wide tests to assess a number of factors related to network reliability;

ii) Ofcom's Mobile Matters report, which outlines the results of a number of tests conducted to assess network performance; and

iii) test results published by Global Wireless Solutions, which performs reliability testing across a number of UK towns and cities.

A5.13 The latest **Rootmetrics**[165] research was published in August 2019. This rates MNOs' performance across six categories: overall performance, reliability, speed, data, call and text performance in the first half of 2019, looking at performance across the whole of the UK, including cities, villages, roads and indoor locations. These latest scores are presented in Table A5.1 below, alongside the scores for the first half of 2018[166] which were presented in the December 2018 consultation. The results remain largely consistent across both periods.

[165] https://assets.ctfassets.net/ob7bbcsqy5m2/3lhKn6jK9irHm3pdT5bQwK/df95780ff59a08f6470967f05573ffa0/UK_Review_of_the_Mobile_Landscape_1H_2019.pdf

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

Table A5.1: Rootmetrics' assessment of mobile performance

Category	BT/EE		O2		H3G		Vodafone	
	1H 2018	1H 2019	1H 2018	1H 2019	1H 2018	1H 2019	1H 2018	1H 2019
Overall	96.0	96.1	86.6	90.5	93.0	92.1	93.0	95.2
Reliability	97.6	97.5	91.6	94.7	96.5	95.7	96.5	96.8
Speed	91.8	93.1	73.1	78.5	82.9	81.9	82.9	91.9
Data	96.0	96.8	86.4	89.9	92.1	91.4	92.1	96.1
Call	95.6	94.9	85.6	90.3	93.8	92.5	93.8	93.5
Text	99.1	99.2	96.6	97.7	96.8	96.8	96.8	99.2

Source: Rootmetrics, August 2018 and August 2019

A5.14 According to the latest Rootmetrics scores, BT/EE has outperformed or matched the other MNOs in each of the six test categories. It has now come first or joint first in every category for the fourth consecutive test period. Vodafone came second in all categories, which is an improvement compared to the 2018 report. H3G is generally in third place, followed by O2 which is fourth in most categories.

A5.15 Rootmetrics defines network reliability as a holistic look at reliability performance across mobile internet, call, and text testing. BT/EE continues to hold the highest Rootmetrics score in this area.

A5.16 **Umlaut** (formerly P3) conducts independent annual network tests, assessing performance in large cities, smaller towns and on roads and railways. Umlaut's latest 2019 report[167] was published in January 2020 and is based on walktests and drivetests conducted in November 2019, as well as crowdsourced data collected from June to November 2019.

A5.17 The latest report shows BT/EE as its overall winner, graded as 'very good' and outperforming the other MNOs in Umlaut's voice and data tests, as well as via its crowdsourced data. Vodafone came second in its report, graded as 'good', with O2 in third place, graded as 'satisfactory' and H3G in fourth, graded as 'sufficient'. This represents an improvement in performance from O2, which came last in Umlaut's report from the previous year.[168] Umlaut comments that the UK market is separated into 'two stronger and two less powerful providers'.

A5.18 In the 2017 Umlaut report[169] cited in the December 2018 consultation, BT/EE was also the overall winner and was graded 'very good'. This report was based on tests conducted in

[167] https://umlaut.com/uploads/documents/2019-Network-Test-UK.pdf
[168] https://www.p3-group.com/en/wp-content/uploads/2018/12/Report_P3-connect-Mobile-Benchmark-UK-2018.pdf
[169] http://www.p3-networkanalytics.com/wp-content/uploads/2017/10/171024_P3-connect-Mobile-Benchmark-UK-2017-FV.pdf

September 2017. The only notable difference between the two reports is that H3G received a grading of ‘good’ in the 2017 report, whereas its grading has fallen two grades to ‘sufficient’ in the 2019 report.

A5.19 In terms of voice services, Umlaut analyses call success ratios, call setup times and speech quality. According to Umlaut’s 2019 report, BT/EE delivered the best overall voice performance, with Vodafone also performing strongly; in fact outperforming BT/EE in city walk tests and on railways. O2 comes in third place and H3G in last place. Umlaut comments that H3G is falling behind the other MNOs.

A5.20 In terms of data services, Umlaut conducts tests relating to data rates and the availability and stability of networks. According to the 2019 report, BT/EE delivers the best overall data performance, with Vodafone in second place, O2 in third and H3G last.

A5.21 Umlaut’s report also assesses crowdsourced data which was collated over a six-month period from April to November 2019. With regards to its category of operational excellence which assesses data service availability, Umlaut reports that BT/EE and O2 showed no service degradations during this time period, Vodafone had one day with degradations, and H3G three days with degradations. Umlaut comments that the low numbers of service outages over a long observation period of six months demonstrates a high level of reliability of UK mobile networks. To note that the report also assesses voice and data coverage and data speeds; BT/EE comes first in each of these areas.

A5.22 Ofcom’s **Mobile Matters** report[170], published in October 2019, outlines key findings from crowdsourced data collected from around 150,000 Android devices across the UK between 1 January and 31 March 2019. In terms of reliability, the report states that tests showed no significant differences in 4G data service availability by mobile network, but 3G connections on the H3G network were more likely to succeed than those on other mobile networks.

A5.23 In December 2018, **Global Wireless Solutions**[171] released the results of over 2.6 million tests it conducted in 2018 to evaluate MNOs’ mobile network performance across 38 cities and towns in the UK. The results show that O2 was the most reliable network in the highest number of the towns and cities tested, followed by H3G, with Vodafone and BT/EE sharing third place. The results of the latest testing were comparable to Global Wireless Solutions’ previous year’s report which was based on testing carried out between November 2017 and February 2018 across 32 towns and cities, where O2 came top in 17 of the towns and cities tested.

Speed

A5.24 Several independent tests measure the speed of the UK’s mobile networks. These include the aforementioned Rootmetrics report, Ofcom’s Mobile Matters report, OpenSignal speed tests and video speed analysis and Tutela speed assessments.

[170] https://www.ofcom.org.uk/__data/assets/pdf_file/0038/169769/mobile-matters-report.pdf
[171] https://news.gwsolutions.com/2018/12/21/2018-year-in-review-gws-releases-mobile-network-connectivity-results-for-businesses-and-consumers-in-the-uk/

A5.25 All 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.

A5.26 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.

A5.27 Ofcom's **Mobile Matters** report[172] found that in data collected between January and March 2019, 4G connections were fastest on the BT/EE network and slowest on the H3G network. 3G connections were also fastest on the BT/EE network but slowest on the O2 network.

A5.28 **OpenSignal**'s latest UK Mobile Network Experience Report[173] was published in October 2019 and is based on speed tests carried out between June and August 2019. These latest scores are presented in Tables A5.2 and A5.3 below, alongside the scores from a previous Mobile Networks Update report from October 2018 which were presented in the December 2018 consultation.[174] The results remain consistent across both reports, with BT/EE generally outperforming the other MNOs in both speed and latency.

A5.29 BT/EE registered an overall average speed of 31.5 Mbps, ahead of Vodafone on 22.0 Mbps, H3G on 18.2 Mbps, and O2 on 15.1 Mbps. BT/EE was also the fastest network when assessing 4G download speeds. H3G recorded the fastest 3G download speeds. OpenSignal noted that BT/EE's 3G speeds have dropped significantly, stating that this is due to it refarming its 3G spectrum.

Table A5.2: OpenSignal download speeds

Category	BT/EE		O2		H3G		Vodafone	
	Oct 18	Oct 19	Oct 18	Oct 19	Oct 18	Oct 19	Oct 18	Oct 19
Download Speed – Overall (Mbps)	25.9	31.5	12.8	15.1	15.6	18.2	18.4	22.0
Download Speed - 4G (Mbps)	28.9	33.7	14.6	16.9	18.8	21.6	21.9	25.1
Download Speed - 3G (Mbps)	7.2	5.5	4.6	5.3	7.8	8.2	4.6	5.0

Source: OpenSignal, October 2018 and October 2019

A5.30 The OpenSignal report also looked latency in milliseconds, which is presented in Table A5.3 below, alongside the scores from a previous report from October 2018. BT/EE showed the

[172] https://www.ofcom.org.uk/__data/assets/pdf_file/0038/169769/mobile-matters-report.pdf
[173] https://www.opensignal.com/reports/2019/october/uk/mobile-network-experience
[174] https://www.opensignal.com/reports/2018/10/uk/mobile-networks-update

lowest latency for its 4G network, and Vodafone for its 3G network. All MNOs have displayed improvements in latency compared to the previous year.

Table A5.3: OpenSignal latency

Category	BT/EE		O2		H3G		Vodafone	
	Oct 18	Oct 19	Oct 18	Oct 19	Oct 18	Oct 19	Oct 18	Oct 19
Latency - 4G (ms)	39.8	37.3	42.4	37.4	48.2	46.3	40.8	39.4
Latency 3G (ms)	61.0	57.4	73.8	71.9	64.1	63.0	62.5	57.1

Source: OpenSignal, October 2018 and October 2019

A5.31 **OpenSignal** also published a State of Mobile Video Experience report[175] in November 2019, which analyses how consumers experience video over mobile networks in 100 countries around the world, awarding each country a video experience score. These scores reflect performance in picture quality, video loading time and stall rate. The report states that high speeds do not necessarily equate to a good video experience at a country level. For example, South Korea has the highest overall download speed but only achieved 21st place in the overall video experience analysis, whereas the Czech Republic is the 2nd placed country for video experience but is not in the top ten countries for overall download speed.[176] OpenSignal states that this is due in part to the operators' management of video traffic on mobile devices so as not to impact the experience of non-video usage.

A5.32 OpenSignal's aforementioned UK Mobile Network Experience Report from October 2019 provides further detail on the video experience offered by each MNO. The video experience scores are replicated in Table A5.4 below, alongside overall video experience scores from its previous mobile video experience analysis published in October 2018.[177]

A5.33 According to the latest report, BT/EE and Vodafone have similar scores and were both categorised as 'Very Good', which OpenSignal describes as generally exhibiting fast loading times and only occasional stalling. H3G and O2 were scored as 'Good', meaning that users are likely to be experiencing longer load times before playback begins and some stalling, especially at higher resolutions. Each MNO has seen its score improve considerably over the past year.

[175] OpenSignal The State of Mobile Video report, https://www.opensignal.com/reports/2019/11/state-of-mobile-video-2019. Measurements took place from August – October 2019.
[176] OpenSignal The State of Mobile Network Experience report, https://www.opensignal.com/sites/opensignal-com/files/data/reports/global/data-2019-05/the_state_of_mobile_experience_may_2019_0.pdf. Measurements took place from January – March 2019.
[177] https://opensignal.com/blog/2018/10/23/europe-shone-in-our-mobile-video-experience-analysis-but-the-winner-wasnt-who-youd-expect/

Table A5.4: OpenSignal video experience

Category	BT/EE		O2		H3G		Vodafone	
	Oct 18	Oct 19	Oct 18	Oct 19	Oct 18	Oct 19	Oct 18	Oct 19
Video Experience – Overall (0-100 points)	62.2	68.4	58.5	64.6	56.3	62.5	62.2	67.7

Source: OpenSignal, October 2018 and October 2019

A5.34 The latest **Tutela** speed test results were published in its Mobile Experience Report in November 2019.[178] The report shows BT/EE as having the fastest network, with an average download speed of 23.0 Mbps. Vodafone registered an average download speed of 13 Mbps, O2 of 10.9 Mbps and H3G of 10.5 Mbps. These findings were based on 47.5 million speed tests conducted between August and October 2019. These latest scores are presented in Table A5.5 below, alongside the scores from its August 2018 report which were presented in the December 2018 consultation.[179]

A5.35 The overall rankings of the MNOs have remained the same, however Vodafone and O2 have seen their average download speeds decrease compared to August 2018. It is worth noting that Tutela's Mobile Experience Report from July 2019 shows download speeds more in line with the August 2018 figures, with each MNO demonstrating increased download speeds.

Table A5.5: Tutela download speeds

Category	BT/EE		O2		H3G		Vodafone	
	Aug 18	Nov 19	Aug 18	Nov 19	Aug 18	Nov 19	Aug 18	Nov 19
Download Speed – 3G and 4G (Mbps)	21.4	23.0	12.9	10.9	8.8	10.5	16.7	13.0

Source: Tutela, August 2018 and November 2019

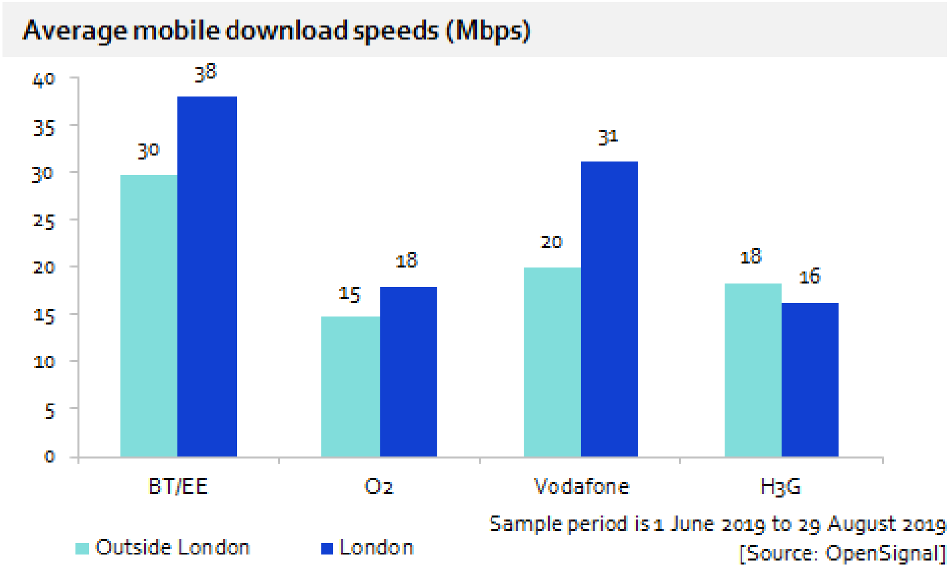
A5.36 In August 2018, Tutela reported that O2 had started deploying its 2.3 GHz spectrum.[180] The average download speed recorded by Tutela on 2.3 GHz spectrum was 26.9 Mbps, which was 80% faster than O2's average 4G download speed of 14.7 Mbps. However, Tutela noted that O2's overall standing compared to the other operators still remained the same due to the limited deployment of the 2.3 GHz spectrum at that time.

[178] https://insights.tutela.com/report/united-kingdom-mobile-experience-report-november-2019/view/
[179] https://insights.tutela.com/report/united-kingdom-mobile-experience-report-august-2018/?_sft_country=united-kingdom. The December 2018 consultation presented separate speeds for 3G and 4G; a combined speed has now been presented here in order to be directly comparable with the latest November 2019 report.
[180] https://www.tutela.com/blog/the-impact-so-far-of-o2s-uk-spectrum-investment

Comparing speeds in London with those in the rest of the UK

A5.37 Figure A5.1 below shows an Enders Analysis chart which presents some OpenSignal data on average download speeds in London compared to the rest of the UK. Both BT/EE and Vodafone show substantially higher speeds in London than elsewhere. Only H3G shows lower speeds in London.

Figure A5.1: Enders Analysis average download speeds – London and outside London



5G speeds

A5.38 There have been some recent reports comparing the performance of 5G networks, for example from Rootmetrics, Ookla and Global Wireless Solutions.[181] These show much faster 5G download speeds compared to non-5G speeds, but these speeds vary across cities and within cities.

A5.39 We believe it is still too early to draw conclusions about 5G network quality, as these tests are based on the results of initial 5G deployments in a limited number of locations.

Coverage

A5.40 In this section we look at the voice and data coverage performance of the MNOs, including the coverage they provide using different types of technology.

A5.41 We apply different signal strength thresholds for different technologies to reflect a minimum level of satisfactory quality of service (QoS).[182]

[181] Rootmetrics: http://www.rootmetrics.com/en-GB/content/5g-first-look-london-the-promise-potential-and-performance, Ookla: https://www.speedtest.net/insights/blog/5g-united-kingdom-2019, Global Wireless Solutions: https://news.gwsolutions.com/2019/11/14/global-wireless-solutions-releases-first-look-at-5g-performance-in-london/
[182] The signal strength thresholds that we have applied are: 2G (-81dBm), 3G (-100dBm) and 4G (-105dBm). Note that 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 and reduce signal strength by 10 dB, although we acknowledge that some buildings will block signals more than others in reality.

A5.42 We consider three types of coverage: 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 10 dB.

Voice coverage

A5.43 Table A5.6 presents the voice coverage of the MNOs in November 2019 across landmass, outdoor premises and indoor premises, based on data provided to Ofcom by the MNOs.

Table A5.6: Voice coverage

	Landmass	Outdoor Premises	Indoor Premises
BT/EE	86.0%	99.6%	96.3%
O2	91.4%	99.9%	99.2%
H3G	85.4%	99.5%	95.6%
Vodafone	91.3%	99.8%	98.8%

Source: Ofcom analysis of MNO data from November 2019

A5.44 O2 and Vodafone outperform BT/EE and H3G by approximately 5% in landmass coverage and 3% in indoor premises coverage. All MNOs have an outdoor premises voice coverage of more than 99%.

Data coverage

A5.45 Table A5.7 presents the data coverage of the MNOs in November 2019 across landmass, outdoor premises and indoor premises, based on data provided to Ofcom by the MNOs.

A5.46 We have focused on good quality 4G data coverage, which we define as delivering an expected minimum QoS of a single-user download speed of 2 Mbps with a better than 90% probability. This corresponds to a signal strength threshold of -105dBm. We started measuring data coverage in this way in 2017 in light of evolving consumer demand and technology improvements.

Table A5.7: Good data coverage (4G) with a minimum download speed of 2 Mbps

	Landmass	Outdoor Premises	Indoor Premises
BT/EE	83.9%	99.3%	92.1%
O2	76.4%	99.1%	95.1%
H3G	79.3%	98.5%	89.1%
Vodafone	80.6%	99.1%	94.1%

Source: Ofcom analysis of MNO data from November 2019

A5.47 BT/EE outperforms the other MNOs by a significant margin in landmass coverage for good quality data services. All MNOs have similar outdoor premises coverage of approximately 99%, and O2 and Vodafone are ahead in indoor premises coverage.

Coverage by frequency layer

A5.48 The MNOs demonstrate different deployment approaches in providing coverage across landmass, outdoor premises and indoor premises. The following paragraphs and accompanying table provide more detail regarding their coverage by frequency layer.

A5.49 BT/EE relies on [✂ REDACTED] to provide 3G coverage. It relies on [✂ REDACTED]. We observe that [✂ REDACTED].

A5.50 O2 relies on [✂ REDACTED] to provide 3G coverage, [✂ REDACTED]. It relies mostly on [✂ REDACTED]. Even though O2's [✂ REDACTED].

A5.51 H3G is the only MNO that does not have a 2G network and it relies on [✂ REDACTED] to provide 3G coverage. It uses [✂ REDACTED] to provide 4G coverage, [✂ REDACTED], but it has also deployed [✂ REDACTED] in a few areas. In contrast to [✂ REDACTED].

A5.52 Vodafone shows a profile of layers which is [✂ REDACTED]. It also relies heavily on [✂ REDACTED]. Notably, its [✂ REDACTED].

A5.53 Table A5.8 presents MNOs' coverage across frequency bands for landmass, outdoor premises and indoor premises.

Table A5.8: Coverage by frequency band[183]

MNO	Frequency band	Landmass	Outdoor Premises	Indoor Premises
BT/EE	GSM1800	[✂]	[✂]	[✂]
	UMTS2100	[✂]	[✂]	[✂]
	LTE800	[✂]	[✂]	[✂]
	LTE1800	[✂]	[✂]	[✂]
	LTE2600	[✂]	[✂]	[✂]
O2	GSM900	[✂]	[✂]	[✂]
	UMTS900	[✂]	[✂]	[✂]
	UMTS2100	[✂]	[✂]	[✂]
	LTE800	[✂]	[✂]	[✂]
	LTE2100	[✂]	[✂]	[✂]
	LTE2300	[✂]	[✂]	[✂]
H3G	UMTS2100	[✂]	[✂]	[✂]
	LTE800	[✂]	[✂]	[✂]
	LTE1400	[✂]	[✂]	[✂]
	LTE1800	[✂]	[✂]	[✂]
Vodafone	GSM900	[✂]	[✂]	[✂]
	UMTS900	[✂]	[✂]	[✂]
	UMTS2100	[✂]	[✂]	[✂]
	LTE800	[✂]	[✂]	[✂]
	LTE1800	[✂]	[✂]	[✂]
	LTE2100	[✂]	[✂]	[✂]
	LTE2600	[✂]	[✂]	[✂]

Source: Ofcom analysis of MNO data from November 2019

[183] Different technologies have different speed thresholds which are reflected in the coverage figures

A6. Potential competition concerns relating to asymmetries in low frequency spectrum - supporting information

Summary

A6.1 This annex sets out the supporting evidence considered in the assessment of potential competition concerns relating to low frequency spectrum. It covers technical information and the relevant stakeholder responses to the December 2018, June 2019 and October 2019 consultations. The document covers the following:

- the use of low frequency spectrum for providing indoor mobile coverage (in particular, deep indoor locations) and alternatives to this: Wi-Fi and Voice over Wi-Fi, LTE-LAA, indoor small cells, repeaters and femtocells;
- the potential role of low frequency spectrum in providing 5G services, including Internet of Things (IoT) and Ultra Reliable Low Latency Communications (URLLC);
- what we consider to be low frequency spectrum and which mobile bands we include within this definition; and
- the technical description of the models we have used to assess whether supplementary downlink spectrum (SDL) in the 1400 MHz band should be included in our pool of relevant spectrum and the ability of different spectrum bands to provide indoor mobile coverage.

Approaches for providing deep indoor mobile coverage

Providing deep indoor coverage with low frequency spectrum

We said that low frequency spectrum was important for providing deep indoor coverage, but that there were other ways to provide this type of coverage and that this was only one aspect of mobile network competition

A6.2 In our December 2018 consultation (paragraphs 5.273 and 5.287 to 5.295), we explained that low frequency spectrum was useful for providing indoor coverage due to its more favourable propagation characteristics (where other frequency bands might not be that efficient), especially for applications that required large volumes of data.

A6.3 We considered that using data-intensive services deep indoors was very much a subset of consumers' concerns and therefore we did not consider that the ability of operators to compete for customers was likely to be materially affected by a relative disadvantage in this aspect of coverage. We said that BT/EE and H3G would remain strong competitors in the market even without additional low frequency spectrum, and they should be able to win 700 MHz in this award if they needed it to compete. We also considered other alternative ways to provide this type of coverage, such as Wi-Fi, that operators could make use of to provide deep indoor coverage where needed. We therefore did not propose a sub cap on low frequency spectrum in this award.[184]

Some respondents disagreed with our assessment about providing data intensive services in deep indoor locations with little low frequency spectrum

A6.4 Both BT/EE and H3G argued that our assessment underestimated the negative effects on the ability to provide data intensive services in deep indoor locations if either of them did not acquire low frequency spectrum in the auction. To prevent this situation, H3G suggested a cap limiting each bidder to 2x10 MHz of 700 MHz FDD spectrum;[185] BT/EE suggested a 75 MHz ‘safeguard cap’ (limiting Vodafone and O2 to 20 MHz each).[186]

A6.5 BT/EE argued that the statistics collected from cell sites where both 1800 MHz and 800 MHz were deployed at the same time showed that, even when 1800 MHz was prioritised over 800 MHz, [✂REDACTED]. It said that [✂REDACTED].[187]

A6.6 H3G said that its estimates suggested that its spectrum holdings would not [✂ REDACTED]. In this context, providing a good quality of service indoors (which H3G claimed could only be achieved with larger shares of low frequency spectrum) was a competitive differentiator.[188]

A6.7 Further, H3G said that [✂ REDACTED][189] and that operators with more low frequency spectrum (Vodafone and O2) had a capacity advantage in “*harder to serve areas*”, showing a 4-6% difference in “*good*” indoor 4G coverage.[190] H3G provided [✂REDACTED].[191] It said that, as a result of this, it would take longer to meet consumer traffic demand: to support an average user data throughput of 2 Mbps [✂ REDACTED]. H3G stated that around [✂ REDACTED][192] of the traffic on its network was due to video streaming.

A6.8 Similarly, BT/EE disagreed with our definition of the data throughput required for basic services (200 kbps), as the most visited websites and video streaming already consumed at least 2 Mbps for a good customer experience.[193]

A6.9 H3G said that acquiring 700 MHz spectrum would allow it to load balance between 800/1400 MHz and 700 MHz, relieve congestion, and provide a better customer experience in hard to reach areas. Although only a few areas could benefit from load balancing on the 800 MHz and 1400 MHz layers, the 700 MHz could be used in a much larger proportion of

[184] December 2018 consultation, paragraph 5.273, paragraph 5.287 to paragraph 5.295 and annex 10.
[185] H3G non-confidential response to the October 2019 consultation, paragraph 6.8 and 14.1-14.12. In its previous response to the December 2018 consultation, H3G had proposed a cap of 80 MHz (37%) of sub-1 GHz spectrum holdings, which would have limited Vodafone and O2 to 2x10 MHz of 700 MHz FDD and 5 MHz of 700 MHz SDL spectrum. See H3G non-confidential response to the December 2018 consultation, page 33.
[186] BT/EE non-confidential response to the December 2018 consultation, paragraphs 6 and 3.113-3.147 and non-confidential response to the October 2019 consultation, paragraphs 4 and 3.13.
[187] [✂ REDACTED]
[188] H3G non-confidential response to the December 2018 consultation, p.37.
[189] H3G confidential response to the December 2018 consultation, paragraph 4.1.
[190] H3G non-confidential response to the December 2018 consultation, paragraph 4.1.
[191] H3G confidential response to the December 2018 consultation, Figures 5 and 6.
[192] H3G confidential response to the December 2018 consultation, paragraph 4.1.
[193] BT/EE non-confidential response to the December 2018 consultation, paragraph 3.31, reiterated in [✂ REDACTED]

locations because 700 MHz had similar propagation and building penetration losses to 800 MHz whereas 1400 MHz did not.[194]

A6.10 H3G pointed out that our modelling results indicated that a mobile network based on 2x20 MHz of 1800 MHz spectrum would require approximately 2,000 additional mobile sites to provide an indoor service which is still inferior to one based on 2x10 MHz of 700 MHz spectrum but superior to one with 2x5 MHz of 700 MHz and that such results supported H3G's views that [✂ REDACTED].[195] H3G estimated that [✂ REDACTED].[196]

Having less low frequency spectrum may limit provision of data intensive services in deep indoor locations, but it is possible to use other frequency bands to provide coverage for basic connectivity and some data intensive applications for the majority of indoor locations

A6.11 In line with our position in the December 2018 consultation, we recognise that having less low frequency spectrum could limit the provision of some data intensive applications,[197] especially in deep indoor locations. However, there are ways of providing these types of services without acquiring additional low frequency spectrum. Our coverage model (A6.84) shows that a mobile network using 1800 MHz spectrum can deliver a basic service to a significant proportion of indoor and deep indoor locations and a data-intensive service to a reasonable proportion of deep indoor locations.

A6.12 Our model (A6.93) analyses the potential coverage from single frequency layers (for example, 2 x 10 MHz of FDD spectrum in the 1800 MHz band) and does not take into account carrier aggregation or dual connectivity with other frequency layers or mobile technologies, which is frequently used by operators and can improve coverage and speeds. Hence, a mobile network operator (using for example 2 x 20 of 1800 MHz) would have options other than deploying 2,000 additional mobile sites to improve indoor coverage, including, for example, use of Wi-Fi, repeaters or carrier aggregation with other bands.

A6.13 We also note that demand for data intensive services can be met by using other frequency bands. Generally, cellular mobile networks are composed of layers of different frequencies, and nationwide coverage is achieved by using several frequencies, with different cell densities.[198] The data provided by operators in November 2019,[199] showed that both BT/EE and H3G achieve significant coverage with their spectrum above 1 GHz. BT/EE achieves a service of at least 2 Mbps at [✂ REDACTED] of indoor premises and [✂ REDACTED] landmass with its 1800 MHz layer, whilst H3G achieves [✂ REDACTED] indoor premises coverage and [✂ REDACTED] landmass coverage with its 2100 MHz layer. We discuss this data in more detail in annex 5.

[194] H3G non-confidential response to the December 2018, paragraph 4.1.
[195] H3G non-confidential response to the December 2018 consultation, paragraph 4.3.1.
[196] H3G confidential response to the December 2018 consultation, paragraph 4.3.1.
[197] We refer as basic mobile data services like web browsing or email access, and other more data intensive services like full HD video streaming.
[198] According to the classification described in "*5G NR: The next generation wireless access technology*" Erik Dahlman, Stefan Parkvall and Johan Sköld.
[199] The coverage figures are extracted from the data included in the formal request of information to operators from November 2019.

A6.14 We note that H3G has deployed 1400 MHz SDL on several sites. H3G has announced plans to roll out using the band nationwide.[200] According to the Mobile Europe news release,[201] "*6,000 sites carrying 80% of Three's traffic will be upgraded with new antennas and 1400MHz L-Band spectrum. Three says customers with compatible handsets will see speed improvements of up to 150%, or 50% for those without.*" Under the current licence conditions, the coverage footprint of 1400 MHz could match that of 800 MHz, making it very suitable to provide coverage to deep indoor locations, although we recognise that this might trigger additional site deployment costs.[202]

A6.15 Having considered the relevant responses, we still believe that, although low frequency spectrum is better for providing data intensive services in deep indoor locations, other frequency bands can be used to provide good levels of coverage of basic and data intensive services to a large proportion of indoor locations.

Some respondents argued that, without additional low frequency spectrum, a network with an already congested uplink would not cope with future traffic demands

A6.16 In its response to the December 2018 consultation, BT/EE stated that the model we used in our assessment had several limitations as a theoretical network.[203] BT/EE said that, as the model analysed each frequency layer independently, it might overestimate the real indoor coverage provided uniquely by an 1800 MHz frequency layer. BT/EE argued that, as the model compared the performance of 2 x 20 MHz of 1800 MHz against 2 x 10 MHz of 700 MHz, "*Ofcom was acknowledging that the propagation characteristics of 1800 MHz were worse than those of 700 MHz and that 700 MHz is scarce and more valuable than 1800 MHz*." [204]

A6.17 In its response to the October 2019 consultation, H3G stated that [✂REDACTED].[205]

A6.18 H3G also stated that [✂ REDACTED]. H3G also included estimates of the percentage of locations and users that could only be served in the uplink with the 800 MHz layer [✂ REDACTED] and that meant that around [✂ REDACTED]. [206]

A6.19 H3G included a description of the demand model used to estimate traffic both in uplink and downlink for the next years. Based on this, H3G emphasised that, although the number of sites that will become downlink-congested will slightly increase over the next few years, the same model estimated [✂ REDACTED] would need to be upgraded by 2030. H3G argued that, [✂ REDACTED].[207]

---

[200] "Three UK reports H1 19 results", H3G, 1 August 2019, http://www.threemediacentre.co.uk/news/2019/three-uk-reports-h119-results.aspx Accessed 8 August 2019.
[201] Three to enhance 4G with 1400MHz spectrum https://www.mobileeurope.co.uk/press-wire/three-to-enhance-4g-with-1400mhz-spectrum Accessed 03/12/2019.
[202] Due to the need for more powerful, expensive, power amplifiers.
[203] December 2018 consultation, annex 10.
[204] BT/EE non-confidential response to our 2018 December consultation, paragraph 3.42, reiterated in [✂ REDACTED].
[205] [✂ REDACTED]
[206] [✂ REDACTED]
[207] [✂ REDACTED]

Uplink congestion can limit or degrade the provision of some services, but it is unclear from the evidence provided to what extent consumers are being affected by this

A6.20 BT/EE presented evidence from its network to support its argument that [✂REDACTED]. BT/EE said that [✂REDACTED] of its 800 MHz sectors are using [✂REDACTED] of the available sector uplink capacity which BT/EE said indicated that these sites were [✂ REDACTED]. BT/EE compared these figures with its 1800 MHz layer and said that [✂ REDACTED]. BT/EE said that [✂ REDACTED]. [208]

A6.21 We acknowledge from the evidence provided by BT/EE that users in areas which are both busy and hard to reach might suffer congestion at busy times, reducing the quality of service offered to the customers located in these areas. However, it is unclear from the BT/EE response how many users are in these areas and therefore unclear what the overall impact on consumers is.

A6.22 We observe from the coverage information submitted by operators in November 2019 that BT/EE achieves [✂ REDACTED] indoor premises coverage with its 1800 MHz layer and that it achieves a [✂ REDACTED] level of indoor premises coverage with its 800 MHz layer, [✂ REDACTED]. We also observe that BT/EE achieves [✂ REDACTED] outdoor premises coverage with its 1800 MHz layer and that it achieves a [✂ REDACTED] level of outdoor premises coverage with its 800 MHz layer, [✂ REDACTED]. This suggests that the number of users who can only be covered by 800 MHz might represent a [✂ REDACTED] of BT/EE's customers. We discuss this data in more detail in annex 5.

A6.23 If expanding capacity in the areas where 800 MHz is congested is important, we consider that BT/EE could have options to expand its capacity using techniques such as selectively densifying its 800 MHz layer or using small cells.

A6.24 In its response to the October 2019 consultation, H3G stated that, without additional low frequency spectrum, [✂ REDACTED] and that it [✂ REDACTED]. H3G said that [✂ REDACTED] [209] H3G argued that, to be able to address this capacity demand and effectively compete with the other operators, an additional investment of [✂ REDACTED] would be required if it did not acquire any 700 MHz spectrum.

A6.25 We consider that H3G’s model contains several pessimistic assumptions that overestimate demand and underestimate H3G’s ability to provide capacity to meet that demand. We address this in the following paragraphs.

A6.26 To estimate the capacity required to address traffic until 2030, H3G uses a speed baseline derived from the USO broadband obligation speeds. [210] The USO speeds were defined for fixed broadband services and H3G does not explain why these speeds would be appropriate for a mobile service. The 1 Mbps speed baseline in the USO was defined for fixed services from which consumers typically expect higher data rates than mobile

---

[208] [✂ REDACTED]

[209] H3G Confidential response to the October 2019 consultation, Page 3.

[210] For the USO, Government has defined decent broadband as a service that can provide a download speed of 10 Mbps, and an upload speed of 1 Mbps upload. There are other technical features that ensure a quality service. https://www.ofcom.org.uk/phones-telecoms-and-internet/advice-for-consumers/broadband-uso-need-to-know

services. H3G states in its response that [✂ REDACTED].[211] If we apply a downlink baseline speed of 2 Mbps (consistent with our definition of good quality 4G data coverage), and apply a 1:10 UL/DL ratio,[212] the baseline uplink speed would drop to ~200 kbps. This is one fifth of the uplink baseline speed derived from the USO, and we would expect that this would significantly reduce the number of sites that require any upgrades to address or prevent congestion.

A6.27 H3G estimates congestion on a per-site basis using a metric called [✂ REDACTED]. If the [✂ REDACTED] exceeds a certain threshold, then the site is considered to be congested. We acknowledge that H3G's model accounts for some capacity improvements such as [✂ REDACTED], but we consider these predictions remain pessimistic as these do not include other ways to increase capacity including selective densification or the use of small cells. Additionally, H3G does mention offload onto frequency layers, but does not mention offload into license-exempt technologies such as Wi-Fi. We note that Cisco has estimated that mobile traffic offloaded onto Wi-Fi is predicted to increase towards 50% of total mobile data traffic.[213]

A6.28 In summary, we consider that H3G's uplink congestion modelling is based on several pessimistic assumptions that overestimate the costs that H3G would face if it did not acquire 700 MHz spectrum.

Ways to improve indoor coverage other than using low frequency spectrum

We said operators could meet part of the deep indoor coverage demands with alternative technologies

A6.29 In our December 2018 consultation, we said that Wi-Fi, femtocells, repeaters and small cells were the most effective alternative ways to improve indoor coverage, with Wi-Fi playing a more significant role than the other solutions.[214] We also considered other approaches which could improve network performance indoors, including macrocell densification and the use of advanced antenna technologies. These are summarised in Figure A6.1.

[211] [✂ REDACTED]

[212] Consistent with current DL and UL traffic ratios described in ITU "IMT Vision –Framework and overall objectives of the future development of IMT for 2020 and beyond" https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

[213] Cisco VNI Complete Forecast Highlights https://www.cisco.com/c/dam/m/en_us/solutions/service-provider/vni-forecast-highlights/pdf/Global_2020_Forecast_Highlights.pdf Accessed 27/02/2020.

[214] December 2018 consultation, paragraph A8.9.

Figure A6.1 Alternative ways to improve indoor coverage

Solution	Why this solution is relevant
Wi-Fi continued to be fundamental for the services people use on their mobile phones, with consumers using apps over Wi-Fi rather than mobile networks 75% of the time, an increase of 6% since 2016.	We said this might be due to a 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. We also noted that MNOs had started offering Voice over Wi-Fi (VoWi-Fi)[215] and that this technology was gaining momentum. We also considered LTE-LAA (Licence Assisted Access) in our December 2018 consultation, stating that the take up of this technology was still at the early stages although some mobile devices, such as Google Pixel 3 and the iPhone XR and XS, supported LTE-LAA.
Indoor small cell solutions could provide coverage to areas where there was weak or no coverage or enhance capacity in 'hot-spot' areas.	These are low-powered base stations located inside a building and are usually deployed as an addition to a macrocell layer, re-using the same frequency or using a different one. We noted some operators had deployed or trialled small cells, although these deployments were limited to a few areas.[216]
Cellular repeaters can be operated in the UK under the terms of the MNOs' licences or under a licence exemption (provided the repeater meets certain technical conditions).	These devices overcome the loss in signal strength associated with thick walls and metallised glass by retransmitting the signal from outside a building to inside the building. We said they could offer an effective solution in cases where there was mobile phone coverage outside a building but where the coverage inside was poor.
Femtocells could be used as an indoor solution for users with poor mobile coverage in areas where a fixed broadband connection was available.	Some MNOs offer services using these devices which may provide improved in-building coverage and data rates. 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).
Densifying the macrocell network by building new sites	Macro cell densification may allow better coverage indoors as the average received signal

[215] Voice over Wi-Fi is a technology that allows users to make mobile phone calls over Wi Fi without needing to use a separate data calling app like Skype or Whatsapp .

Solution	Why this solution is relevant
	strength is increased.[217] However, it may also be necessary to further manage the inter-cell interference, as the distance between cells is reduced. We acknowledged that densification might not be possible in all circumstances and that planning permission or site permission limitations could slow down the rate at which operators built new base stations.
Use of advanced antenna techniques such as Massive MIMO and beamforming.	Massive MIMO systems, such as those being deployed by the MNOs in the 2.6 and 3.4-3.6 GHz TDD bands today, enable dynamic beamforming. This technology can enhance the throughput offered at the cell edge, including some indoor locations. However, due to the larger size, weight and wind load required for mMIMO antennas, we acknowledged that it was currently not feasible to exploit mMIMO to extend coverage in sub-2 GHz cellular networks.

A6.30 We acknowledged that indoor small cells, repeaters and femtocells might not be cost-effective to provide additional coverage in all indoor locations or might offer only marginal gains.

Some respondents did not agree these technologies were effective substitutes for low frequency spectrum

A6.31 H3G said that Wi-Fi offload was not an effective solution for all deep indoor traffic on its cellular network, that Wi-Fi might have limitations in areas without access to good quality fixed broadband and that quality of service could not be guaranteed.[218]

A6.32 H3G referred to the 2018 Mobile insights report from HarrisX[219] which stated that “mobile subscribers (worldwide and in the US) who have to off-load traffic to Wi-Fi report poorer customer satisfaction with their mobile service”.[220] H3G also included some results from a report from Opensignal[221] that stated that consumers increasingly override their

[216] “Arqiva and O2 to improve mobile connectivity in London Boroughs”, O2, Accessed 24 06 2019.https://news.o2.co.uk/press-release/arqiva-and-o2-to-improve-mobile-connectivity-in-london-boroughs/ “In-Building Coverage”, Vodafone, Accessed 24 June 2019. https://www.vodafone.co.uk/business/business-mobile-plans/mobile-plan-features/in-building-coverage
[217] As the average site-user distance is reduced.
[218] H3G non-confidential response to our December 2018 consultation, paragraph 4.3.3.
[219] HarrisX Mobile insights report, 2018.
[220] H3G non-confidential response to the December 2018 Consultation, paragraph 4.3.3.
[221] Opensignal “The state of Wi-Fi vs Mobile network experience as 5G arrives” https://www.opensignal.com/sites/opensignal-com/files/data/reports/global/data-2018-11/state_of_wifi_vs_mobile_opensignal_201811.pdf

smartphone's automatic Wi-Fi choice, and instead select mobile data for a faster download speed. If a user switches off Wi-Fi and then they find the mobile experience to be poor, it will reduce satisfaction levels. It also argued that operators needed to deliver good in-building mobile network coverage to be successful.[222]

A6.33 Additionally, H3G stated that small cells might be a viable solution to increase network capacity in urban hot-spots but that they were not widely used in rural locations. It said that deploying small cells was not a cost-effective solution when deployed in great numbers and that it had estimated that using small cells as an additional measure to provide equivalent capacity to deploying 10 MHz of 700 MHz spectrum would be [✂ REDACTED] times more expensive". [223]

A6.34 H3G said that repeaters were not an effective solution to increasing the level of service indoors, as they depended on the quality of existing outdoor coverage and only worked to extend coverage from a donor macro cell but would not be effective to improve the level of service (for example, increased capacity or higher speeds). [224]

A6.35 H3G also said that femtocells might be an alternative to provide indoor coverage, but it would be difficult to define use cases in less densely populated areas as femtocells could be expensive to deploy and consumers might not want to bear that cost, especially if they could get good indoor coverage without a femtocell.[225]

A6.36 H3G said that technologies including beamforming and massive MIMO would be available mostly in high frequency 5G and would therefore not be effective for providing wide area or indoor coverage. [226]

A6.37 H3G noted that increasing the number of sectors per site would only be effective in providing additional capacity in urban areas where demand was evenly spread but not in less densely populated areas (such as rural areas). Increasing the sectors per site would require site strengthening or rebuild, and new equipment that would result in higher site opex and was, therefore, potentially not a commercially practical option. [227] BT/EE said that it had deployed several complementary networks including outdoor small cells, indoor femtocells and Wi-Fi and, while these could be used to provide indoor coverage in some cases, they were not yet a cost-effective solution when compared to the deployment of a cellular macrocell network to reach the same levels of coverage. [228]

Wi-Fi can help to provide indoor coverage in many circumstances, although it is unlikely to be a complete substitute for low frequency spectrum

A6.38 As we explain in section 4, and having considered responses to the December 2018 and October 2019 consultations, we believe that operators can make use of alternative

[222] H3G non-confidential response to our December 2018 consultation, paragraph 4.3.3.
[223] H3G confidential response to the December 2018 Consultation, paragraph 4.3.2.
[224] H3G non-confidential response to the December 2018 Consultation, paragraph 4.3.2.
[225] H3G non-confidential response to the December 2018 Consultation, paragraph 4.3.2.
[226] H3G non-confidential response to the December 2018 consultation, paragraph 4.3.2.
[227] H3G non-confidential response to the December 2018 consultation, paragraph 4.3.2.
[228] BT/EE non-confidential response to the December 2018 Consultation, paragraph 3.52, reiterated in [✂ REDACTED]

methods for providing deep indoor coverage. In particular, Wi-Fi is widely used to provide both voice and data services to mobile users and evidence suggests that it will continue to play an important role in delivering mobile broadband to consumers in the future. Cisco forecasts that, by 2022, 51% of global total IP traffic will be Wi-Fi (whilst 29% will be wired and 20% will be cellular).[229] We note that MNOs are increasingly offering VoWi-Fi; customers can therefore make voice calls in areas where there is not enough mobile coverage but there is Wi-Fi available, such as deep indoors.[230]

A6.39 We believe Wi-Fi might not substitute for a good level of mobile coverage in all indoor scenarios, for example it is unlikely to be a feasible substitute in those situations where access to neither a broadband line nor fixed wireless access is available. However, Wi-Fi hotspots in public spaces are becoming increasingly available. Cisco forecasts that the number of global public Wi-Fi hotspots (including home-spots) will grow four-fold from 2017 to 2022 (from 124 million in 2017 to 549 million by 2022).[231] However, we note that Wi-Fi service take-up depends on factors such as fees, access restrictions and service quality offered in such public places.

A6.40 Ease of Wi-Fi connectivity is likely to continue to improve, for example, Access Traffic Steering, Switching and Splitting (ATSSS) technology, which allows for seamless handover between mobile and Wi-Fi networks, is currently in the specification stage by both the Broadband Forum[232] and 3GPP, and is scheduled to be finalised as part of 3GPP Release 16 in March 2020.[233] We are aware that at least one UK MNO, BT/EE, is driving this standardisation work.[234]

A6.41 The Opensignal report[235] that H3G mentioned in its response to the December 2018 consultation gives a breakdown of countries where Wi-Fi can offer smartphone users a faster experience. In the case of the United Kingdom, and contrary to what H3G suggested, Wi-Fi speeds are around 10 Mbps higher than overall mobile broadband speeds and the UK has some of the fastest Wi-Fi speeds out of the 33 countries sampled. H3G also referenced a HarrisX report[236] that finds that users in the US that have off-loaded into Wi-Fi have a lower satisfaction rate as compared to those users that do not off-load into Wi-Fi.

---

[229] Cisco Wi-Fi: the world's wireless workforce https://blogs.cisco.com/sp/5g-gets-top-billing-but-dont-forget-wi-fi Accessed 05/11/2019.

[230] 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.

[231] Cisco Wi-Fi: the world's wireless workforce https://blogs.cisco.com/sp/5g-gets-top-billing-but-dont-forget-wi-fi Accessed 05/11/2019.

[232] "5G Convergence", Manuel Paul, Broadband Forum, July 2018, Accessed 08/06/2018, https://www.itu.int/en/ITU-T/Workshops-and-Seminars/201807/Documents/4_Manuel_Paul.pdf

[233] "Study on access traffic steering, switch and splitting support in the 5G System (5GS) architecture", 3GPP, TR 23.793 V16.0.0, 19 December 2018, accessed 8 August 2019. https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3254

[234] 01:55:00 of the webcast, "Technology business briefing", BT/EE, 25 June 2019, accessed 9 August 2019, https://www.btplc.com/Sharesandperformance/Financialreportingandnews/Quarterlyresults/index.htm

[235] Opensignal "The state of Wi-Fi vs Mobile network experience as 5G arrives" https://www.opensignal.com/sites/opensignal-com/files/data/reports/global/data-2018-11/state_of_wifi_vs_mobile_opensignal_201811.pdf

[236] HarrisX Mobile insights report, 2018.

However, we note that this difference is small (from 75% carrier satisfaction rate among non-offloaders and 72% among Wi-Fi offloaders) and does not offer a break-down of the type of Wi-Fi networks the users are off-loading into which can have a significant impact in the quality of service that users experience.

A6.42 We observe that H3G and BT/EE are launching a Fixed Wireless Access service, as they recently announced the launch of a 5G Smart Hub.[237] These services use a hub (often referred to as “consumer premises equipment”) which is backhauled using the mobile network to provide indoor Wi-Fi access. We note that whilst fixed wireless access provides an alternative to a fixed line, consumers can use it to access data and voice services indoors using Wi-Fi and voice over Wi-Fi.

A6.43 We acknowledge H3G’s view that small cells could be unsuitable for widespread geographic coverage because the costs would be high. However, we believe that they could still provide targeted coverage for hard to reach locations in rural or urban premises. We also acknowledge that small cells might be difficult to install in some circumstances: for example, installation may require access rights from the building owner and there may be issues with multiple operators accessing the same site if there are space or power restrictions. However, we consider that this could be overcome if several operators shared the same equipment, avoiding the need for additional installation visits and equipment.

A6.44 We disagree with H3G that mobile phone repeaters cannot improve the indoor signal. We acknowledge that repeaters cannot improve the indoor signal to a better level than the outdoor signal. Nonetheless, in most circumstances, making the indoor signal almost as good as the outdoor signal would present a material improvement in coverage, because the outdoor signal would not be attenuated by building walls or metallised windows.

A6.45 We understand that massive MIMO can be used with either LTE or 5G NR technologies, but that the active antenna systems enabling massive MIMO can get impractically large at lower frequencies.[238] As we said previously, this means that massive MIMO technologies may not significantly increase the indoor coverage of mobile networks below 2 GHz. For mobile networks using spectrum above 2 GHz and below 6 GHz, our understanding is that the dynamic beamforming provided by massive MIMO is likely to allow base stations using those frequencies to match the indoor coverage of base stations using 1800 MHz but is unlikely to allow them to match the indoor coverage of base stations using low frequency spectrum at 1500 MHz or below.

A6.46 We understand increasing the number of sectors per site can be used to increase the capacity in some locations where there are high traffic demands (such as stadiums or shopping malls). We acknowledge that increasing the number of sectors will only marginally improve data speeds in low density areas such as rural locations, but these areas are also those least likely to be capacity constrained.

[237] Launch of 5G smart hub, BT/EE Accessed 18/09/2019 https://shop.ee.co.uk/dongles/pay-monthly-mobile-broadband/htc-5g-hub/details and H3G https://5g.co.uk/news/5g-mobile-smart-hub-three/4766/ accessed 18/12/2019

[238] https://carrier.huawei.com/~/media/CNBGV2/download/products/antenna/New-5G-New-Antenna-5G-Antenna-White-Paper-v2.pdf

A6.47 Our views about the ability of Wi-Fi, cellular repeaters, small and femtocells and other technologies to provide indoor coverage of a similar quality to macrocells using low frequency spectrum have not changed since the December 2018 consultation. These alternative technologies can be used to provide coverage in hard to reach areas in many circumstances, however, we acknowledge that they may not be a complete substitute for macrocells using low frequency spectrum in all situations.[239]

The role of low frequencies for providing 5G services

Low frequency spectrum and eMBB

What we said in the December 2018 consultation

A6.48 In our December 2018 consultation we stated that what constituted '5G spectrum' would change over time depending on which bands were supported in the 3GPP standards for 5G use and were available in handsets. 5G has been designed to be delivered in spectrum bands at low, mid and high frequencies, which each have different characteristics and can be used to deliver different aspects of mobile services to consumers.

A6.49 We said that low frequency spectrum was likely to support wide area coverage, because of the advantageous propagation characteristics of the band, and it would likely be used for enhanced mobile broadband and some IoT applications. [240] We noted, however, that there was significant uncertainty about whether these applications would appear in the first deployments of 5G, and whether they would uniquely require low frequency spectrum. Moreover, we noted that there was unlikely to be a significant difference in the consumer experience between 4G and 5G in some hard to reach areas which only had coverage using low frequency spectrum because 5G technologies for enhancing mobile broadband mostly exploit mid-frequency spectrum.

BT/EE and H3G argued [✂ REDACTED] without additional low frequency spectrum

A6.50 In its response to our December 2018 consultation,[241] H3G stated that [✂REDACTED]. H3G said that 700 MHz was important for IoT and that [✂REDACTED], whereas other operators with larger shares of low frequency spectrum would extend their 5G nationwide network to around [✂REDACTED] Of landmass.[242]

A6.51 BT/EE noted competition in the context of new 5G services would be harmed if insufficient 700 MHz spectrum was available to all MNOs to provide a competitive offering for 5G mobile services.[243]

[239] The experience provided by these alternative technologies may not be exactly the same e.g. use of Wi-Fi requires the customer to connect to a Wi-Fi network.
[240] December 2018 Consultation, paragraph 5.204 to 5.207
[241] H3G confidential response to the December 2018 Consultation, paragraph 4.4 [✂ REDACTED]
[242] H3G confidential response to the December 2018 consultation 4.4, reiterated in its [✂ REDACTED]
[243] BT/ non-confidential response to the December 2018 Consultation, paragraph 3.65 -3.66, reiterated in [✂ REDACTED]]

A6.52 BT/EE also said that sub-1 GHz spectrum was important to deliver mobile services for users moving at high speeds between coverage of different base stations (e.g. on a train). It said that base stations using frequencies above 1 GHz would require a denser deployment for contiguous coverage along road and rail routes than base stations using sub-1 GHz frequencies and that this would be economically unfeasible. [244]

Initially, the 5G and 4G broadband experience in low frequency bands will be very similar and it is likely that 4G will continue to play an important role in 5G networks for some time

A6.53 As we discuss in annex 7, we expect that 5G services will start with enhanced mobile broadband (eMBB) and will over time come to include ultra-reliable low latency services (URLLC) and massive Machine Type Communications (mMTC).

A6.54 Mobile operators support mobile broadband (MBB) services using 3G and 4G technologies. Whilst operators have started offering enhanced mobile broadband services[245], it is still unclear how these services will evolve over time, but it is likely that 4G technology will remain an important way to support them for several years.[246]

A6.55 In low frequency bands, 5G NR capacity and peak speeds are unlikely to be significantly better than LTE.[247] The main technology contributing to greater capacity in future mobile networks is massive MIMO which is unlikely to be feasible in low frequency bands as the antennas would be too bulky and heavy. Consumers may therefore not notice any difference in experience between eMBB served over LTE, 5G NR or a combination of the two in low frequency bands.

A6.56 4G LTE is likely to be around for some time; the GSMA observed that there are 750 operators running LTE worldwide, with 333 operators investing in LTE in 141 countries.[248] 4G LTE standards are being further developed alongside 5G New Radio (NR). We give more details in annex 7.

A6.57 Dynamic spectrum sharing (DSS) can be used to deploy both LTE and 5G NR carriers in the same spectrum band once devices that support 5G NR in that band are available. We understand that this may require a capacity trade-off in areas where the LTE network is already heavily used, as DSS incurs a capacity loss of 7 to 10%[249] due to additional signalling. As we explain in section 4, we believe it is unclear whether users will have a noticeably different experience when using a 4G or 5G carrier in low frequency bands.

Low frequency spectrum, mMTC, IoT and URLLC

What we said in the December 2018 consultation

A6.58 In our December 2018 consultation, we concluded that low frequency spectrum did not offer a distinct competitive advantage in providing 5G services, although we acknowledged

[244] BT/EE non-confidential response to the December 2018 consultation, paragraph 3.56, reiterated in [✂ REDACTED]]
[245] We explain further about UK operators' roll-out plans in annex 7.
[246]We explain further in annex 7.
[247] 5G NR uses a "lean carrier" approach to reduce control signalling which may give a modest improvement relative to LTE.
[248] As published in their Evolution from LTE to 5G: Global Market Status, May 2019.
[249] Evidence from meeting [✂ REDACTED]

that 700 MHz spectrum might be a useful band for providing 5G coverage in hard to reach areas.

H3G and BT/EE claimed access to additional low frequency was key for them to deliver mMTC, IoT and URLLC services

A6.59 BT/EE said that sub-1 GHz spectrum would be critical to deliver some 5G mobile services, and also for meeting the differentiated requirements of 5G applications (such as IoT) as they emerged. [250] Access to sufficient low frequency spectrum was key to offer NB-IoT and massive machine type communications (mMTC) as the propagation characteristics of sub-1 GHz bands were particularly suitable to ensuring a good battery life and a wider coverage footprint. [251] In the absence of 700 MHz, [✂REDACTED] [252]

A6.60 BT/EE stated that sub-1 GHz was important for URLLC. This was because URLLC would likely use Joint Transmission Coordinated Multi-Point (JT-CoMP). JT-CoMP transmits the same message from adjacent base stations to improve the likelihood that an urgent transmission is received by the target device and this requires overlapping coverage. BT/EE claimed that achieving such overlapping coverage using frequencies above 1 GHz was not economically possible. [253]

Some uncertainties remain around how operators will deliver mMTC, IoT and URLLC services, but we do not consider that 700 MHz spectrum will be necessary to deliver them

A6.61 We recognise that there is still uncertainty about the need for 700 MHz for 5G services and that, in the medium term, 5G services including IoT/mMTC or URLLC might require some dedicated spectrum resources. The evidence we have suggests these can be delivered by any frequency band provided that the specific requirements (such as latency, reliability or battery life) of the 5G use case are met. In any case, according to the information we have gathered as part of our assessment, we do not believe there are 5G use cases in the pipeline that could only be delivered by either low frequency spectrum or, more specifically, 700 MHz.

A6.62 We accept that it might not be possible to re-farm 800 MHz for these services if 4G is still widely used and/or low frequency bands such as 800 MHz and 900 MHz are not made available in devices and network equipment for 5G. However, we note that Dynamic Spectrum Sharing (DSS) could be used in environments where the LTE layers are not heavily congested, with a capacity loss of around 7% to 10%. This mechanism can be used in any frequency band specified by 3GPP for both LTE and 5G NR, which is the case for most sub-6 GHz mobile bands.

---

[250] BT/EE non-confidential response to the December 2018 consultation, paragraph 3.53, reiterated in [✂ REDACTED]
[251] BT/EE non-confidential response to the December 2018 consultation, paragraph 3.57, reiterated in [✂ REDACTED]
[252] BT/EE confidential response to the December 2018 consultation, paragraph 3.58, paragraph 3.59, reiterated in [✂ REDACTED]
[253] BT/EE non-confidential response to the December 2018 consultation, 3.62, reiterated in [✂ REDACTED]]

A6.63 We consider that devices will soon support 5G in other frequency bands.[254] For example, using its 1800 MHz layer, BT/EE achieves[255] [✂ REDACTED] indoor premises coverage and [✂ REDACTED] landmass coverage, and H3G achieves [✂ REDACTED] landmass coverage with its 2100 MHz layer. This is a substantially higher than the [✂ REDACTED] That H3G argues would be only be capable of offering in absence of additional low frequency spectrum.

A6.64 Many devices already support 700 MHz FDD LTE and we consider that LTE will continue to be an important part of 5G networks for some time. We expect other low frequency bands that have already been standardised under 3GPP to be made available for 5G handsets and CPEs in the next few years. This is confirmed by information that we have received from equipment manufacturers[256] that indicates that 5G NR FDD sub-1 GHz bands will be supported in devices from late 2020 or early 2021.

A6.65 It is uncertain to what extent 5G NR will be necessary to support mMTC or URLLC, especially in the short term, as the majority of cases today can be supported with existing technology, especially for narrow-band applications. For example, NB-IoT (Narrow band Internet of Things) is a Low Power Wide Area (LPWA) technology included in the LTE standards since Release 8.[257] NB-IoT has been designed for networks of high density, low cost, long battery life devices. NB-IoT can be deployed in band, within an LTE carrier with minimal capacity reduction (from 7% to 10%), but it can also be deployed in the LTE guard bands, with no capacity reduction though at a reduced power level. This means that operators can support NB-IoT services using their existing spectrum holdings without the need to sacrifice significant capacity on their existing LTE networks.

A6.66 NB-IoT is supported in devices in spectrum bands from sub-1 GHz to 2.6 GHz.[258] This means that an NB-IoT network could be deployed in bands other than sub-1 GHz. Arguably, sub-1 GHz networks could benefit from the better propagation characteristics of the frequency band, reaching significantly more (indoor) locations than the existing LTE network. However, the link budget of NB-IoT has a 20 dB improvement over LTE Advanced[259]; and this link budget improvement applies to all bands where the technology is deployed. Thus, mature macrocell deployments could achieve very high levels of indoor and deep indoor coverage for NB-IoT. We recognise that JT-CoMP may be important for

---

[254] As we explain in annex 7.

[255] Data from November 2019 coverage data submission from MNOs.

[256] Although 800 MHz FDD NR might be delayed as operators heavily use this band to serve 4G traffic; However this delay is not due to a technology-related constraint rather than a low market demand. [✂ REDACTED].

[257] 3GPP Narrow band IoT https://www.3gpp.org/news-events/1785-nb_iot_complete

[258] According to evidence we have from Qualcomm, Huawei and Ericsson.

[259] Ericsson Technology review, NB-IoT applications. https://www.ericsson.com/en/ericsson-technology-review/archive/2016/nb-iot-a-sustainable-technology-for-connecting-billions-of-devices Accessed 03/12/2019. NB-IoT has a link budget of 164dB, whereas the current GPRS link budget is 144dB (3GPP TR 45.820) and LTE is 142.7 dB (3GPP TR 36.888). According to Ericsson. *"the 20dB improvement corresponds to a sevenfold increase in coverage area for an open environment, or roughly the loss that occurs when a signal penetrates the outer wall of a building."* The noise figure assumptions in 3GPP TS 36.888 used in the link budget calculations are more conservative than in the corresponding link budget for GSM in 3GPP TR 45.820. Using the noise figure assumptions from 3GPP TR 45.820, the LTE link budget becomes 142.7dB.

the delivery of URLLC services. However, we do not consider that 5G NR is necessary for JT-CoMP because this technology is also available in LTE Advanced Pro.

We consider that low frequency spectrum includes the 1400 MHz band and other mobile bands at frequencies below this

In our December 2018 consultation, we proposed to include 1400 MHz supplementary downlink spectrum in the group of mobile spectrum bands defined as low frequency spectrum

A6.67 In the December 2018 consultation, we said that we considered spectrum in the 700 MHz, 800 MHz, 900 MHz, and 1400 MHz bands to be low frequency spectrum.

A6.68 We considered the coverage similarities of the 1400 MHz downlink only band and sub-1 GHz bands in our modelling work (detailed further towards the end of this annex). This analysis measured the ability of several spectrum bands (from 700 MHz to 2.6 GHz) to provide indoor coverage in different scenarios. Our analysis showed that:

- Given the current licence conditions, which allow a higher permitted power level than 800 MHz or 900 MHz,[260] a base station using the 1400 MHz downlink-only band can achieve similar coverage to sub-1 GHz spectrum. We therefore consider this band to be in the pool of low frequency spectrum.

- Higher frequency bands such as 1800 MHz, 2100 MHz and 2.6 GHz have different propagation characteristics and each base station has a lower coverage reach when compared to base stations using the 1400 MHz and sub-1 GHz bands, and therefore we do not consider these to be low frequency spectrum bands.

A6.69 We also considered that supplementary downlink spectrum bands such as 1400 MHz could not be used standalone and needed to be used in conjunction with paired Frequency Division Duplex (FDD) carriers. At the time of publication of the 2018 December consultation, SDL carriers in the 1400 MHz band could be paired with FDD carriers in the 800 MHz band under the 3GPP standards.

Some respondents disagreed with our definition of low frequency spectrum

A6.70 Vodafone argued that using the ability of a network to provide deep indoor coverage as a criterion for the definition of low frequency spectrum was arbitrary and lacked justification, as did our 1400 MHz boundary.

A6.71 We disagree with Vodafone. Spectrum bands are widely classified in terms of coverage and capacity capabilities, including coverage in hard to reach areas such as deep indoors. Usually, bands able to provide wide coverage have limitations in terms of capacity and

[260] The current licence conditions permit a maximum EIRP 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; 65 dBm in both 1800 MHz and 2100 MHz bands; and 61 dBm in the 2600 MHz band https://www.ofcom.org.uk/__data/assets/pdf_file/0017/115343/Variation-UK-Broadband-Licence-3.6-GHz-spectrum.pdf

vice-versa; some bands offer a trade-off and offer both moderate coverage and capacity. We note that, in its response to the October 2019 consultation, Vodafone stated that an appropriate breakpoint for coverage spectrum would encompass the 1800 MHz and probably 2100 MHz bands, given that these are demonstrably used as coverage layers already.[261]

We still consider that the 1400 MHz supplementary downlink band to be low frequency spectrum

A6.72 We still consider 1400 MHz and lower frequency bands to be in the pool of relevant low frequency spectrum because they can be used in a similar way in mobile networks.[262] We include the 1400 MHz downlink-only band in the pool of low frequency spectrum as, under the current licence conditions, similar coverage to sub-1 GHz spectrum can be achieved. We explain this point and the model that we used to reach this conclusion further towards the end of this annex.

Downlink coverage modelling and comparison for mobile bands up to 2600 MHz

Description of the model and initial assumptions

A6.73 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.[263] 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 2.6 GHz bands). We considered that this higher power might enable 1400 MHz spectrum 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 licences.

A6.74 As noted in our December 2018 consultation, we have assessed 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 on many factors including the radiated power levels (EIRP), the height, location and orientation of the antenna, the technology used (e.g. 3G or 4G) and, to a lesser extent, the spectrum bandwidth.

[261] Vodafone non-confidential response to the October 2019 consultation, page 5. We explain our views about this point in section 4.
[262] Vodafone non-confidential response to the December 2018 consultation, page 41
[263] https://www.ofcom.org.uk/__data/assets/pdf_file/0022/74461/1.4ghz-consultation.pdf

A6.75 Our analysis is aimed at understanding the coverage that an outdoor macrocell 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).

A6.76 We have modelled a 5 MHz downlink carrier to a user terminal situated within a building, applying the building entry losses described in Figure A6.3 below. We then calculate the coverage area within which a user terminal in an indoor environment would receive a signal with an RSRP[264] greater than or equal to -105 dBm.[265] We have assumed a base station with a height of 20m above ground (a value typical of macrocell deployments). Each base station is modelled as an omnidirectional antenna transmitting at the maximum permitted power EIRP[266] as stated in the current licences.[267] To estimate the link propagation losses, we have used the modified version of the Extended-Hata model[268] in three different propagation environments (urban, suburban and open).

A6.77 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.

A6.78 We have derived building entry losses using Recommendation ITU-R P.2109.[269] 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. 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. We note that, we have recently used different values in other studies. [270] This is because we have gained more knowledge about the building stock since the date of the December consultation. We use a split of 70%/30% of traditional and thermally efficient buildings. Although we note that including a higher proportion of TEF buildings in our analysis will decrease the indoor coverage levels overall and might have an impact on the coverage levels that low

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

[265] As we stated in our consultation on “Improving mobile coverage: proposals for coverage obligations in the award of the 700 MHz spectrum band”[265], we consider a 4G signal strength of -105 dBm to be required to achieve outdoor geographic mobile coverage.

[266] Effective Isotropic Radiated Power.

[267] For 700 MHz the maximum permitted EIRP is the proposed level in the draft licence (see annex 22).

[268] ECO Extended Hata model description http://ecocfl.cept.org/display/SH/A17.3+EXTENDED+HATA+MODEL

[269] https://www.itu.int/rec/R-REC-P.2109/en

[270] Ofcom, Enabling wireless innovation through local licensing, 25 July 2019, https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

frequency spectrum could provide, we understand that the conclusions derived using these new assumptions would be in line with our current ones, for the purposes of comparing different single frequency layers.

A6.79 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 close to windows or external sides of buildings, or further into buildings with 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 A6.2 Cumulative Distribution Function (CDF) of building entry loss and 800 MHz and 2.6 GHz

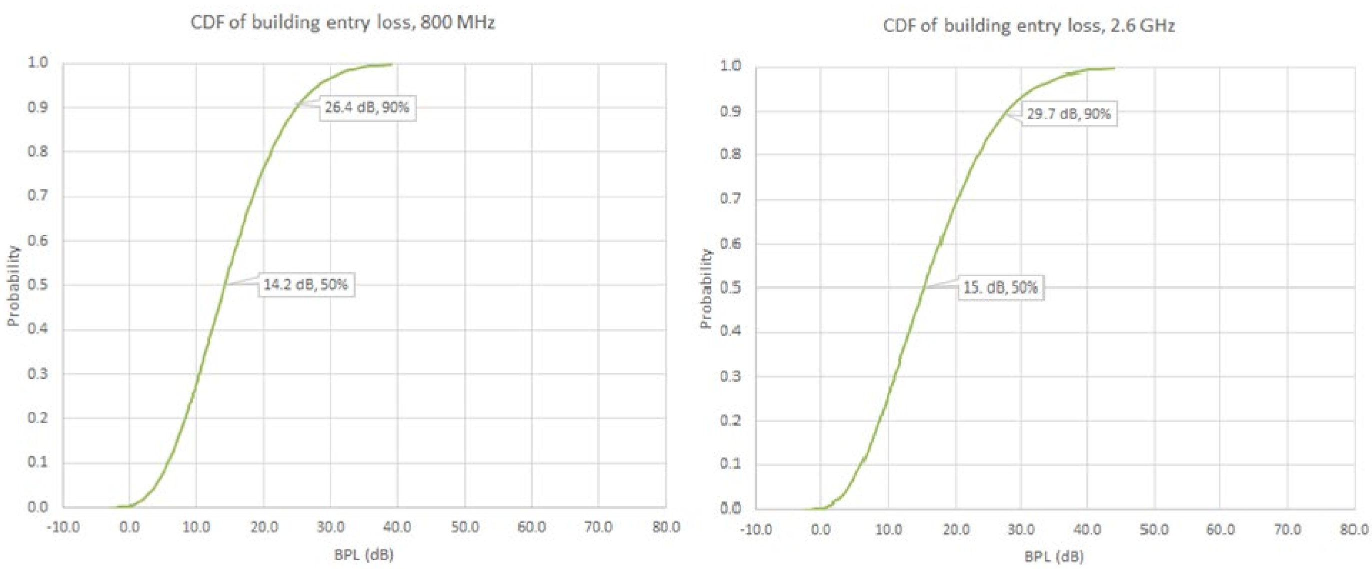


Figure A6.2 Building entry losses from ITU-R P.2109

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

Frequency (MHz)	Building Entry Loss (dB)	
	Shallow 50th percentile CDF	Deep 90th percentile CDF
1400	14.6	28.0
1800	14.9	28.6
2100	15.0	29.1
2600	15.3	29.7

Results: estimated coverage

A6.80 Figure A6.4 and Figure A6.5 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.

A6.81 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. This means that the 800 MHz results will have a value of 1 for the three propagation environments.

A6.82 Results with a value higher than 1 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.

Figure A6.3 Relative potential coverage estimated for shallow indoor locations, normalised to 800 MHz coverage

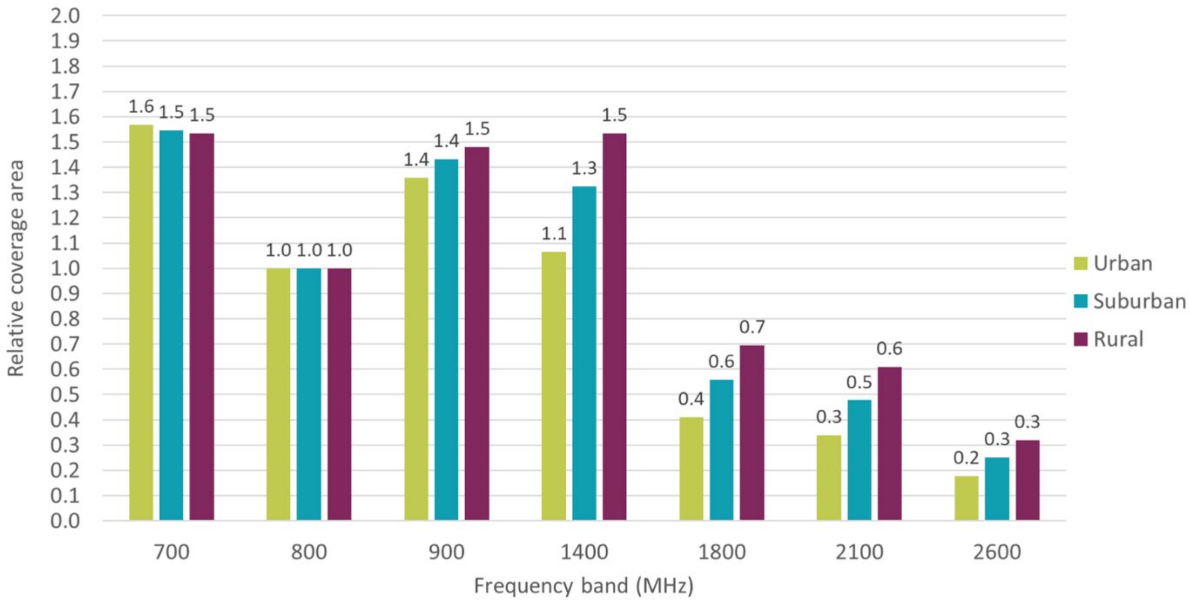
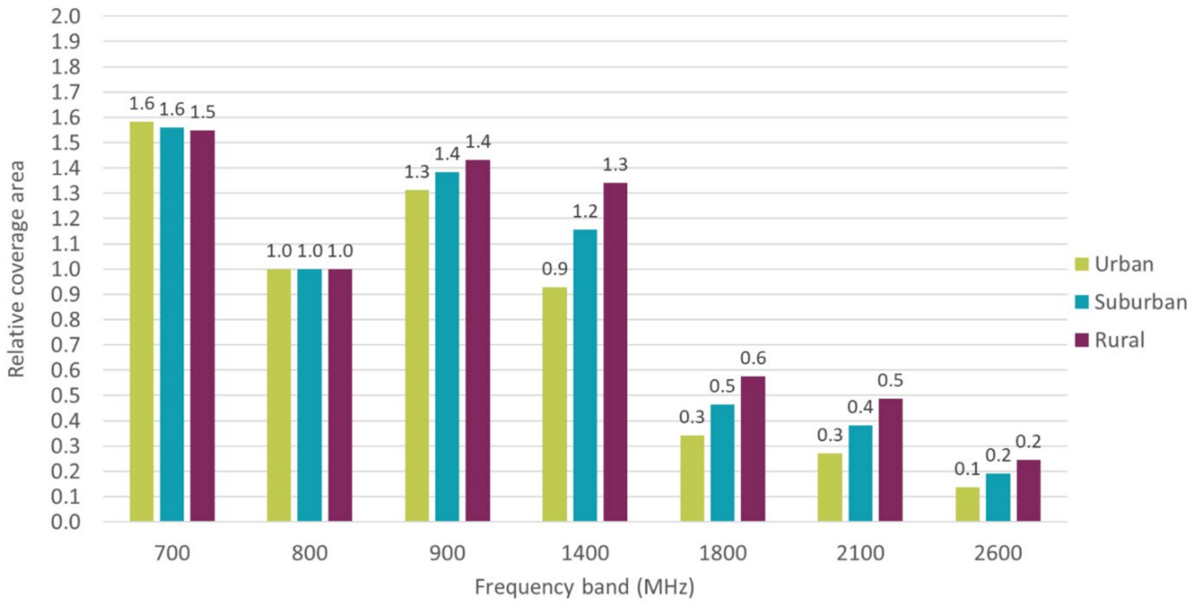


Figure A6.4 Relative potential coverage estimated for deep indoor locations, normalised to 800 MHz coverage



A6.83 These results show that the 1400 MHz potential coverage is estimated to be greater than the 800 MHz potential coverage in all cases, with the exception of the coverage in 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.

Indoor coverage: model description and detailed analysis of results

A6.84 This section contains a high-level description of the indoor coverage model used, a detailed explanation of the key outcomes and a technical description and parameters used.

A6.85 This modelling and its results were also presented in annex 10 of our December 2018 consultation. We also include them here as we refer to the model results in our discussion of competition concerns in low frequency spectrum.

High level description of the model and interpretation of the results

A6.86 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 video streaming.

A6.87 The model is similar to the one we used in our 2012 Statement[271] on the assessment of future mobile competition and award of 800 MHz and 2.6 GHz. We acknowledge that any attempt to derive the performance of a mobile network using a theoretical modelling approach is inevitably going to be affected by a number of sources of uncertainty. For example, our model uses some parameters which can have a high variability (e.g. building penetration loss). To improve the outputs of our model we have validated it against coverage data from operators.

A6.88 Whilst the results presented in this annex reflect the best knowledge we have as a regulator from our own research, expertise and information received from stakeholders, it is unrealistic to believe that our model can be anything more than illustrative of the real performance of actual LTE networks. In developing our model we have exercised our best judgement and accounted for views of stakeholders in selecting appropriate methodology, parameters and assumptions. We recognise that others may disagree with our approach and there may well be alternatives.

A6.89 We believe that the model is useful in comparing the relative variation in performance between macrocell 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. Thus, the results we present here should not be taken as a definitive prediction of macrocell network performance.

A6.90 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

[271] Ofcom assessment of future mobile competition and award of 800 MHz and 2.6 GHz
http://www.ofcom.org.uk/__data/assets/pdf_file/0031/46489/statement.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.

A6.91 We use downlink Single User Throughput (SUT) 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. This model generates a distribution of SUT values across the cumulative population of certain areas of the UK with different population density.

A6.92 We present the results from our modelling in two formats:

- Bar graphs: where each bar represents the percentage of cumulative population within an area that would receive a minimum downlink SUT of either 2 Mbps (representative a basic mobile data service) or 10 Mbps (representative of a data-intensive service).
- 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.

Detailed results

A6.93 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.

A6.94 Figure A6.6, Figure A6.7 and Figure A6.8 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 A6.5 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)

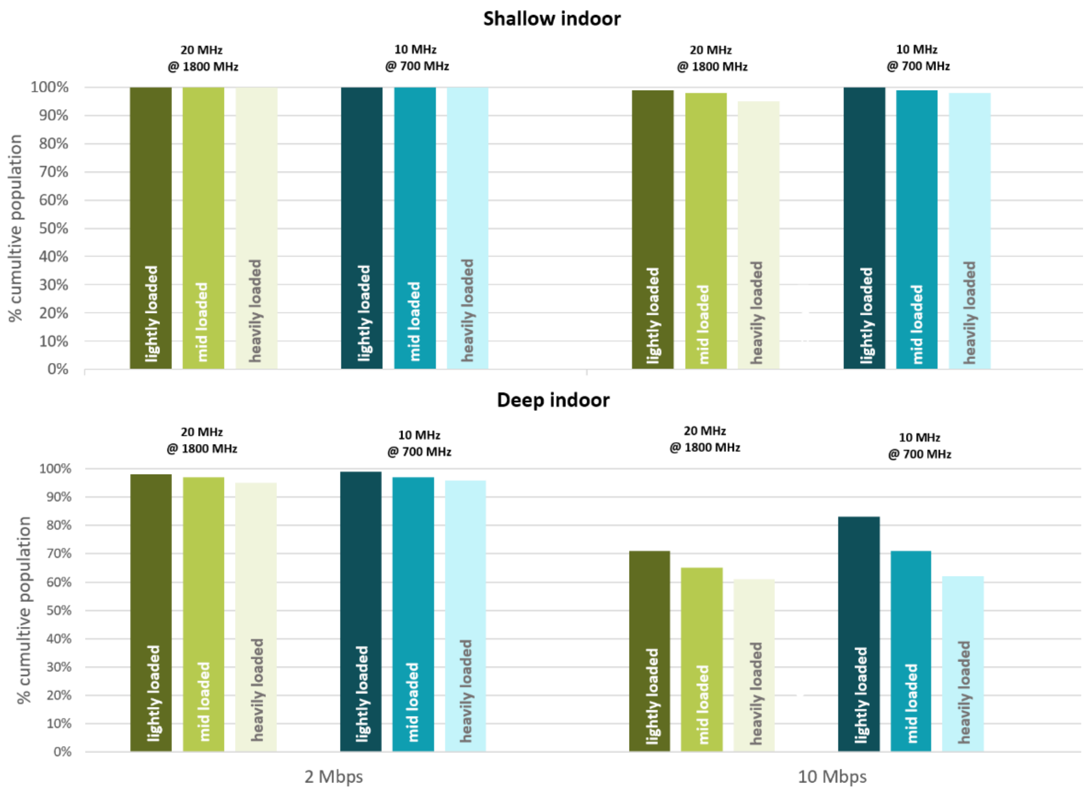


Figure A6.6 Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in the mid densely populated area (2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)

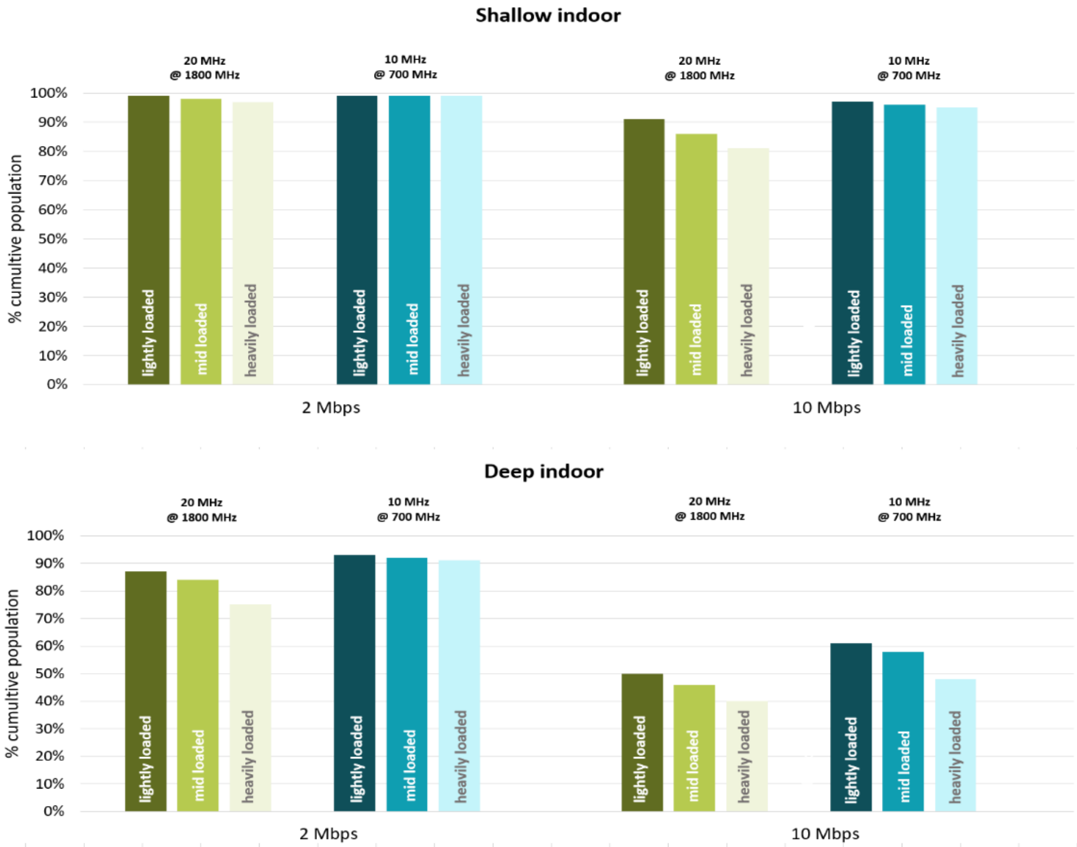
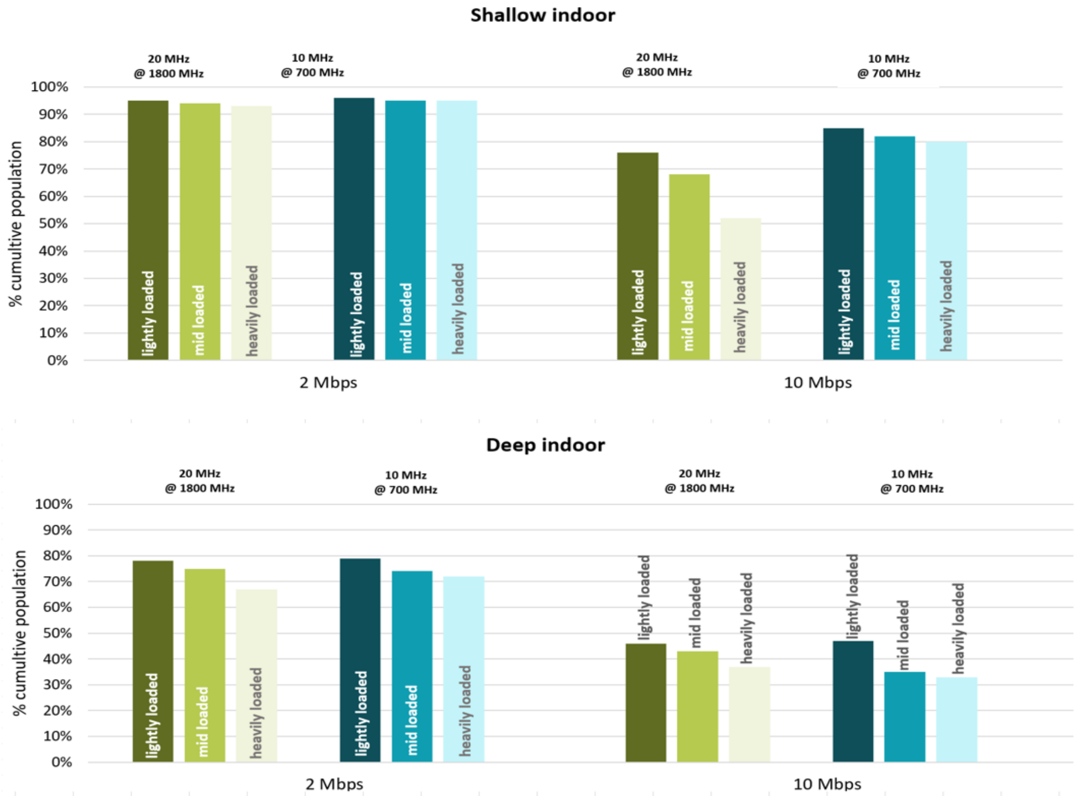


Figure A6.7 Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in the least densely populated area (2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A6.95 As shown in Figure A6.10, Figure A6.11 and 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.

A6.96 Figure A6.8 and Figure A6.9 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.

A6.97 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 A6.8 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)

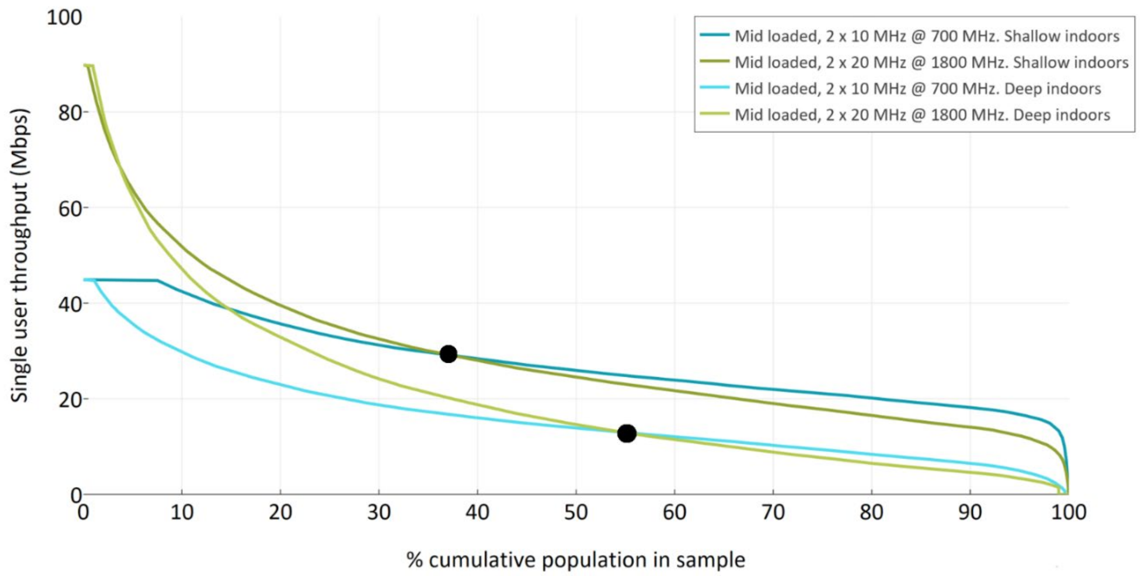
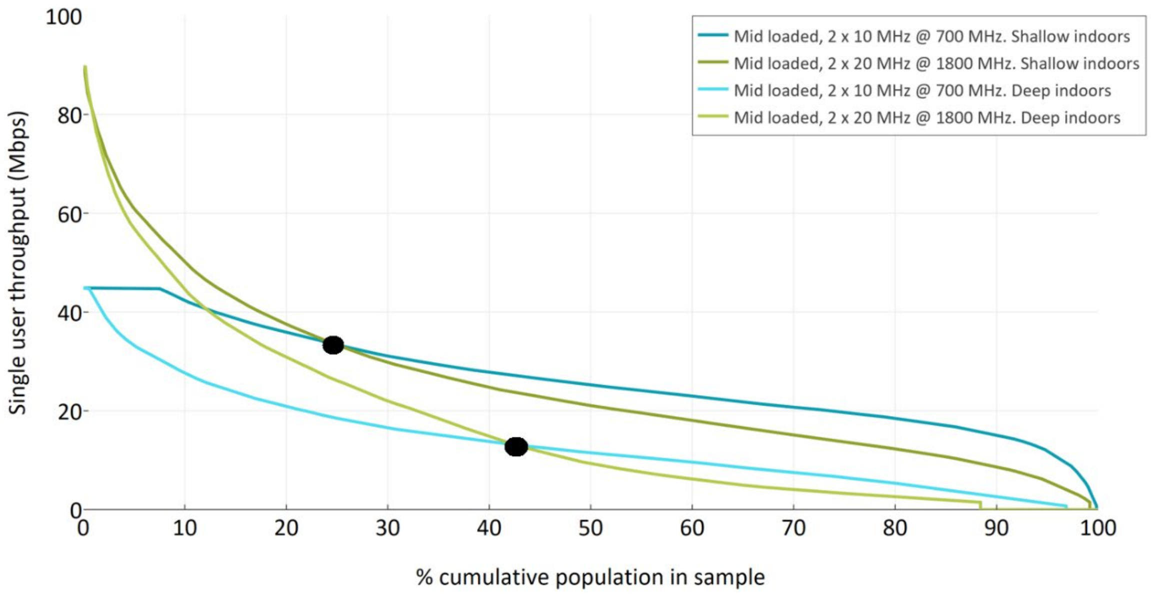


Figure A6.9 SUT distribution curves, shallow and deep indoor locations in the mid densely populated area (2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A6.98 The SUT distributions in Figure A6.9 and Figure A6.10 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.

A6.99 In deep indoor environments, all network configurations considered perform less well than they do in shallow indoor environments, due to the higher building penetration, even though the relative difference between performance of the three networks continues to be evident (Figure A6.9 and Figure A6.10).

A6.100 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 A6.22). Further, 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.

A6.101 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 characterised by SUT ≥ 2 Mbps).

A6.102 Figure A6.10, Figure A6.11 and Figure A6.12 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 A6.10 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)

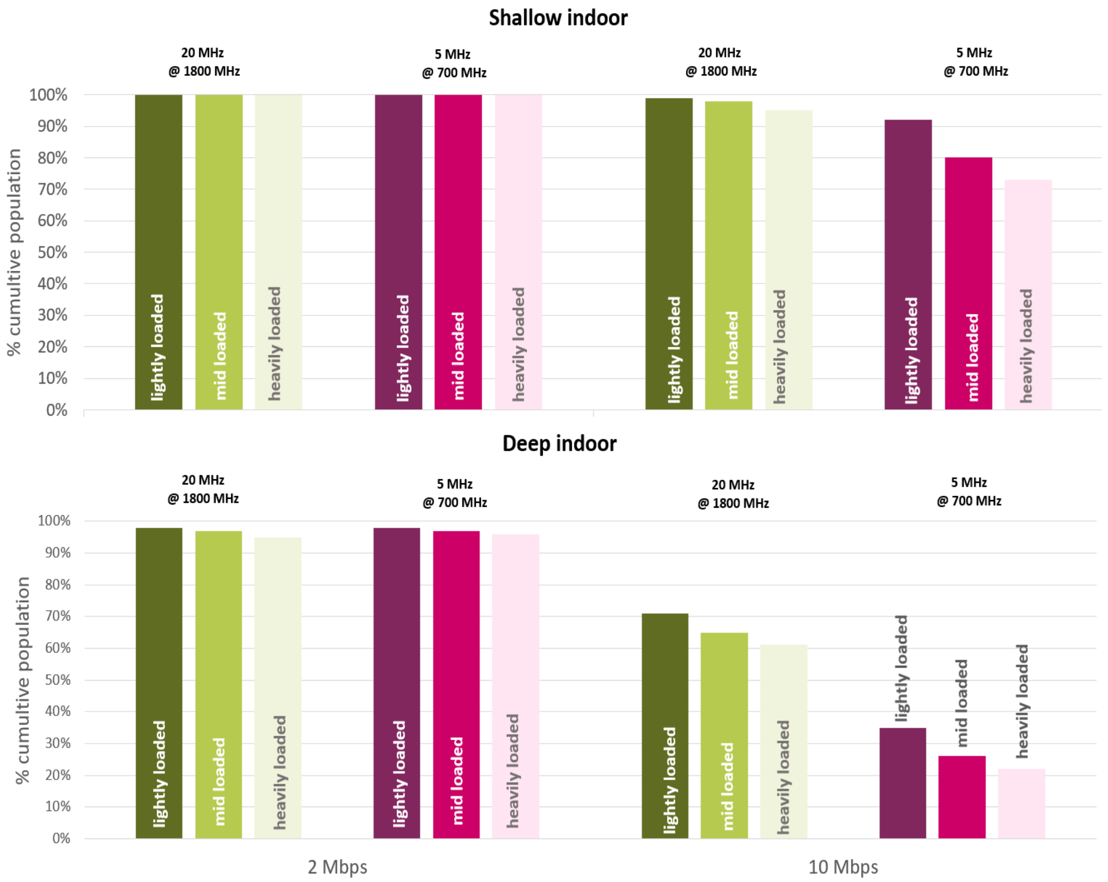


Figure A6.11 Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in mid densely populated areas (2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)

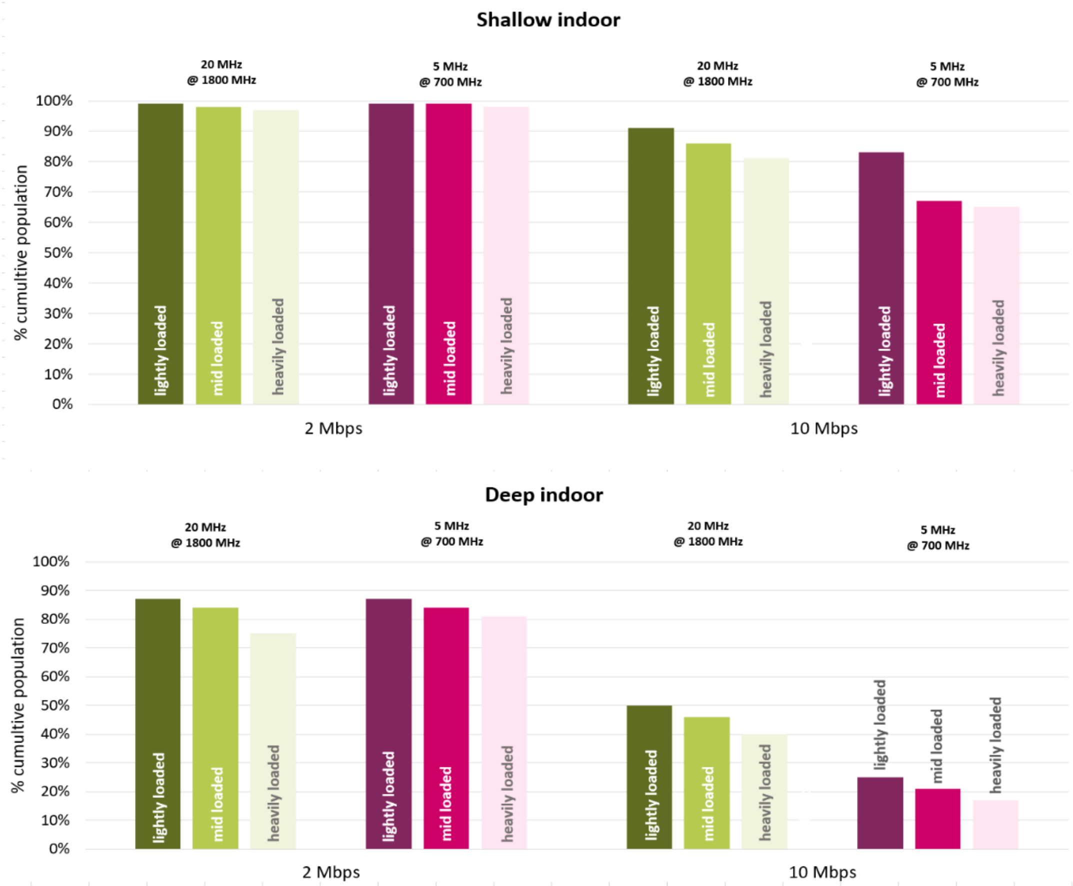
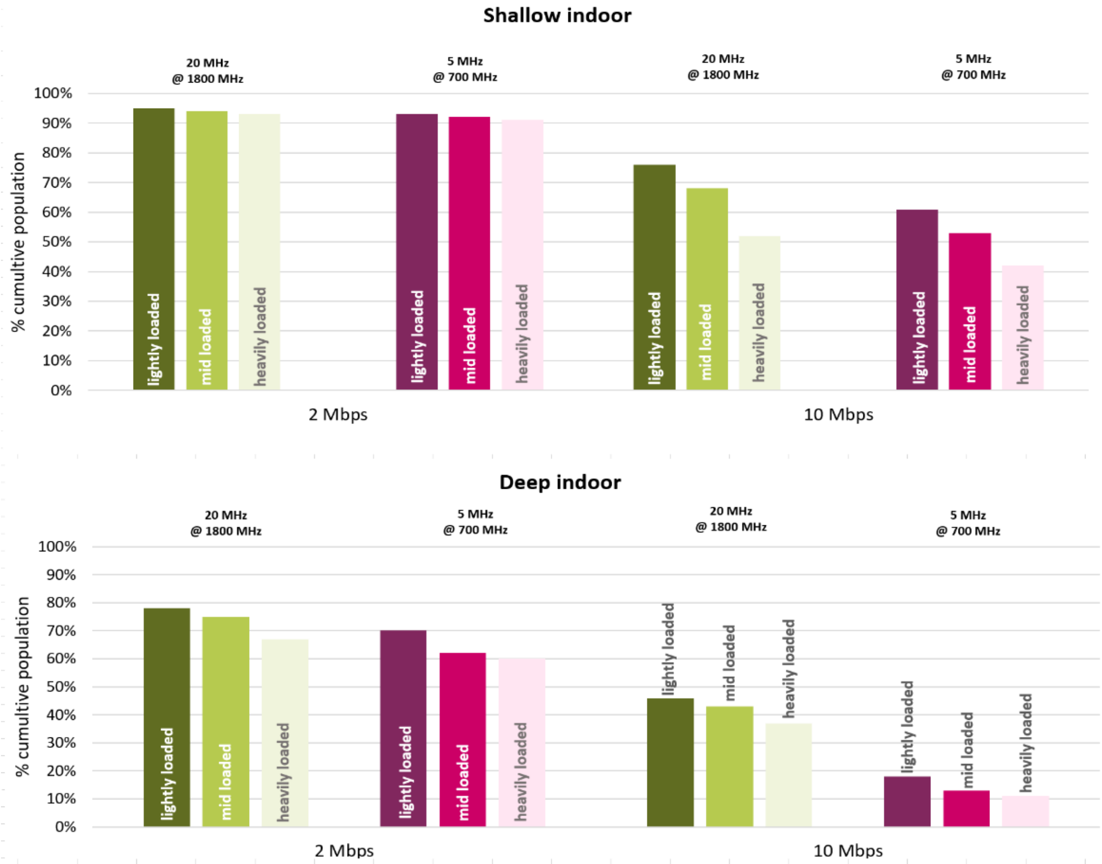


Figure A6.12 Percentage of population at 2 Mbps and 10 Mbps, shallow and deep indoor locations in least densely populated areas (2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A6.103 Figure A6.11, Figure A6.12 and Figure A6.13 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.

A6.104 Figure A6.14 and Figure A6.14 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 A6.13 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)

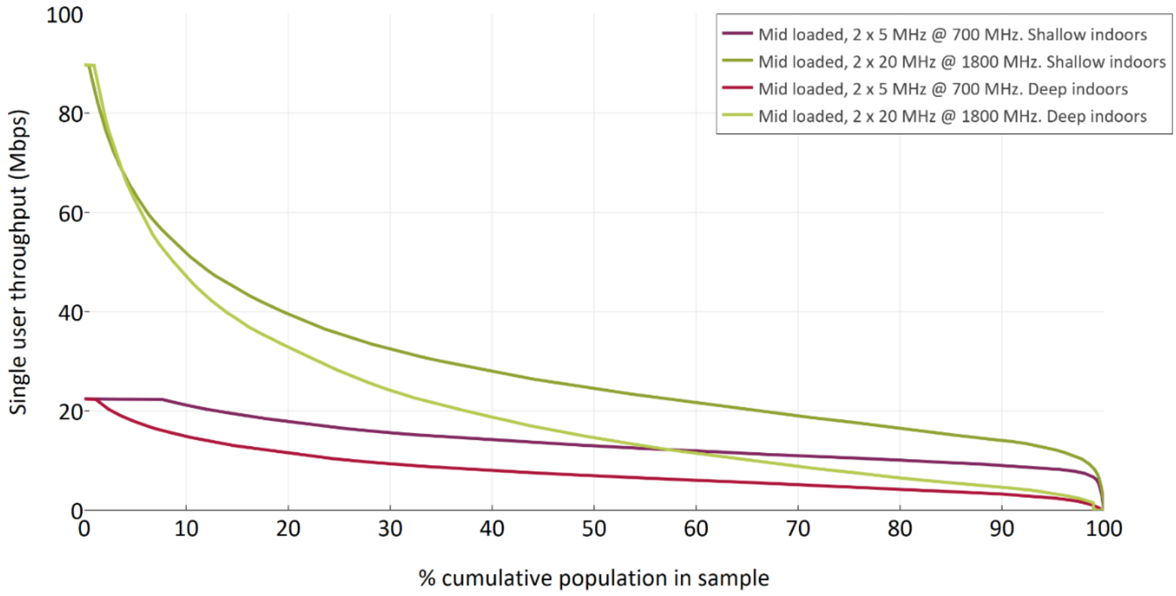
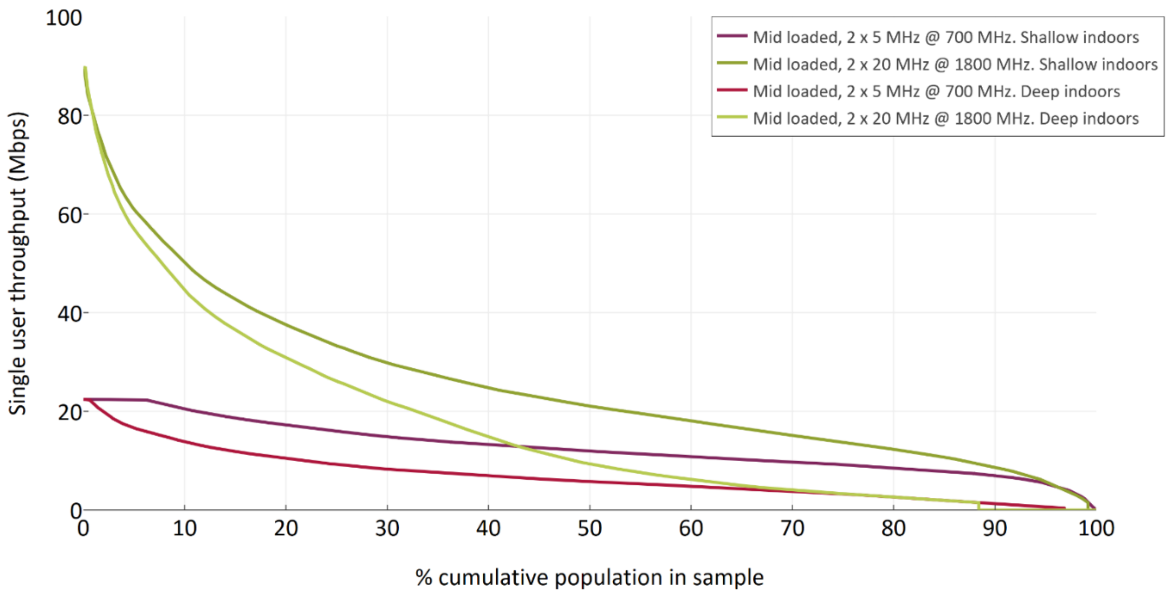


Figure A6.14 SUT distribution curves, shallow and deep indoor locations in mid densely populated areas (2 x 5 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A6.105 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.

A6.106 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 characterised by a SUT≥ 10 Mbps. Hence an operator with only 2 x 5 MHz of low frequency spectrum may want to acquire more.

A6.107 Figure A6.16 and Figure A6.16 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.

A6.108 The figures below 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 A6.15 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)

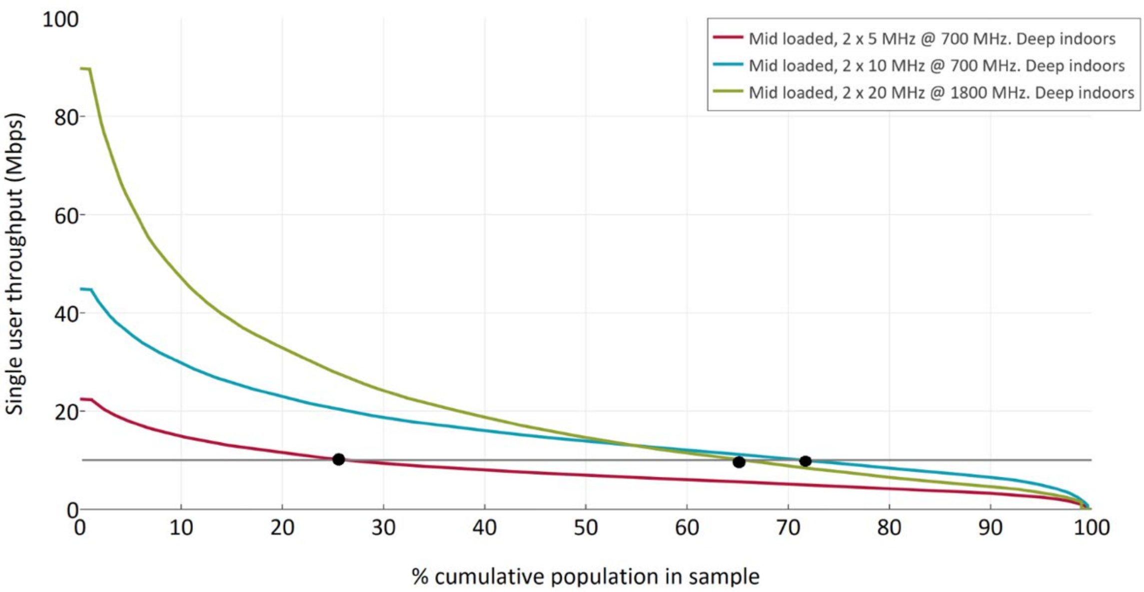
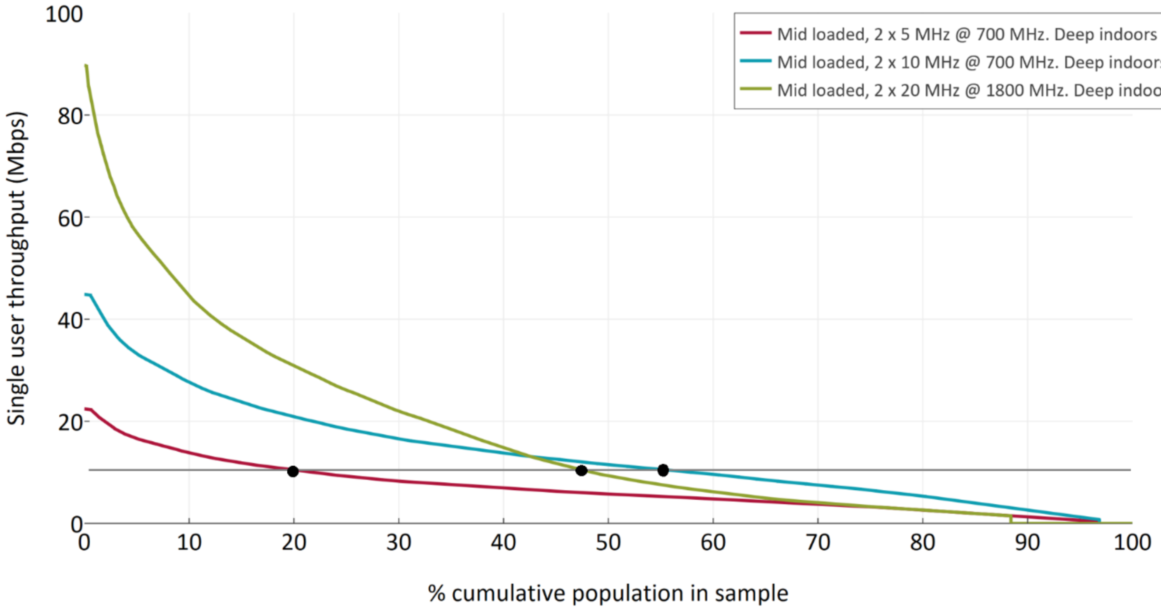


Figure A6.16 SUT distribution curves, deep indoor locations in mid densely populated areas (2 x 5 MHz of 700 MHz, 2 x 10 MHz of 700 MHz and 2 x 20 MHz of 1800 MHz)



A6.109 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. The figures above 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.

Model methodology

A6.110 In this sub-section we present an overview of our modelling of the performance of macrocell LTE networks operating in the 700 MHz and the 1800 MHz frequency bands. 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.[272]

A6.111 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.

A6.112 To assess downlink performance, the model calculates the SINR (DL-SCH[273]) distribution for a hypothetical test terminal located at a reference indoor location at various population 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. We consider the networks used in our

[272] Ofcom 4G coverage methodology https://www.ofcom.org.uk/__data/assets/pdf_file/0020/108209/4g-coverage-methodology.pdf

[273] DL-SCH (Downlink Shared Channel) is the only downlink transport channel available to carry user data between the mobile device and the eNodeB.

modelling to be representative of reasonably mature roll-outs in these two bands. **Error! Reference source not found.** shows the model process flow.

What we consider population points and areas of analysis

A6.113 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.

A6.114 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.

A6.115 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). 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 the 2012 Competition Assessment as they have been updated to reflect the latest Census data (our previous 2012 analysis areas were based on census data from 2001).

Figure A6.17 Analysis areas used in this assessment

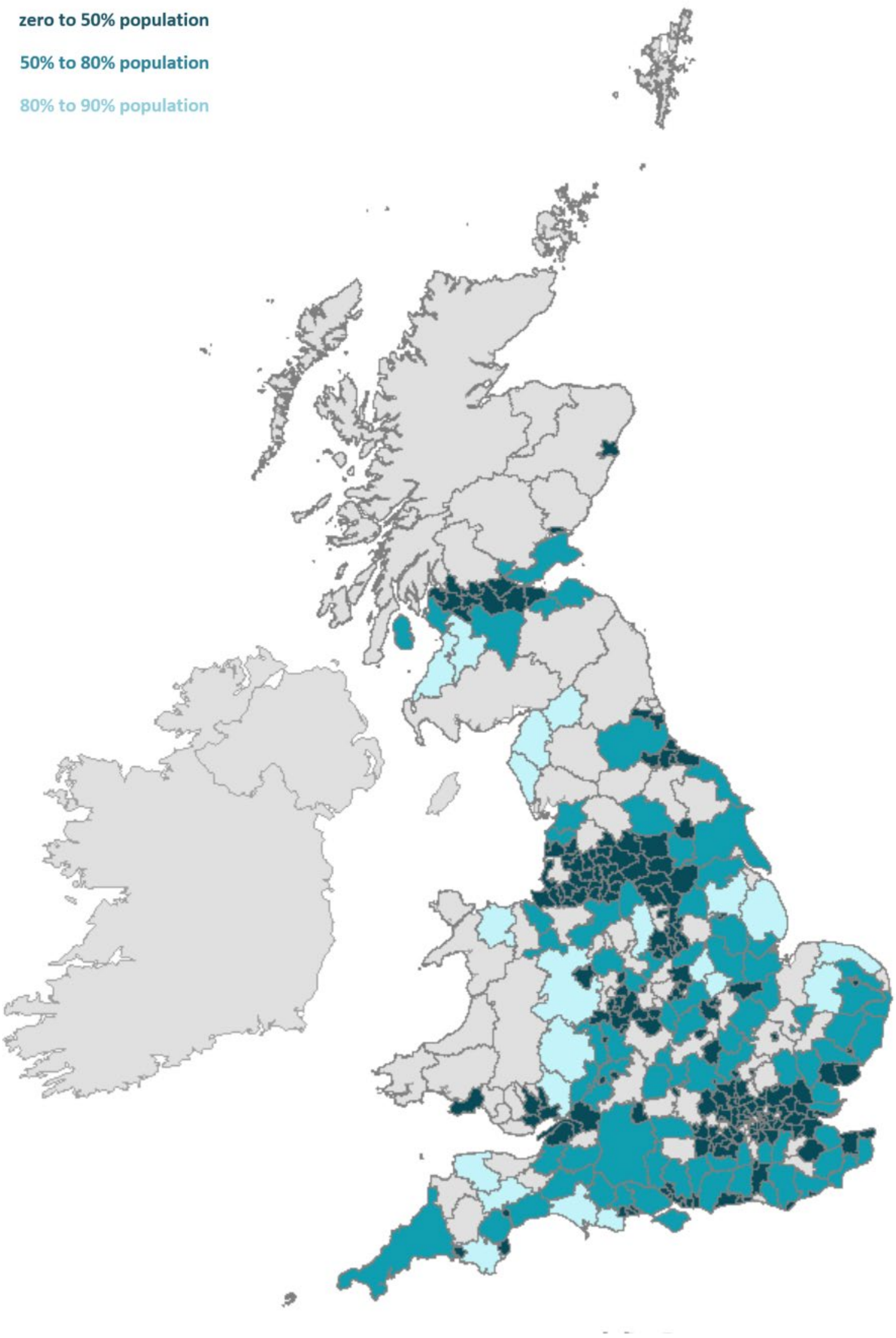
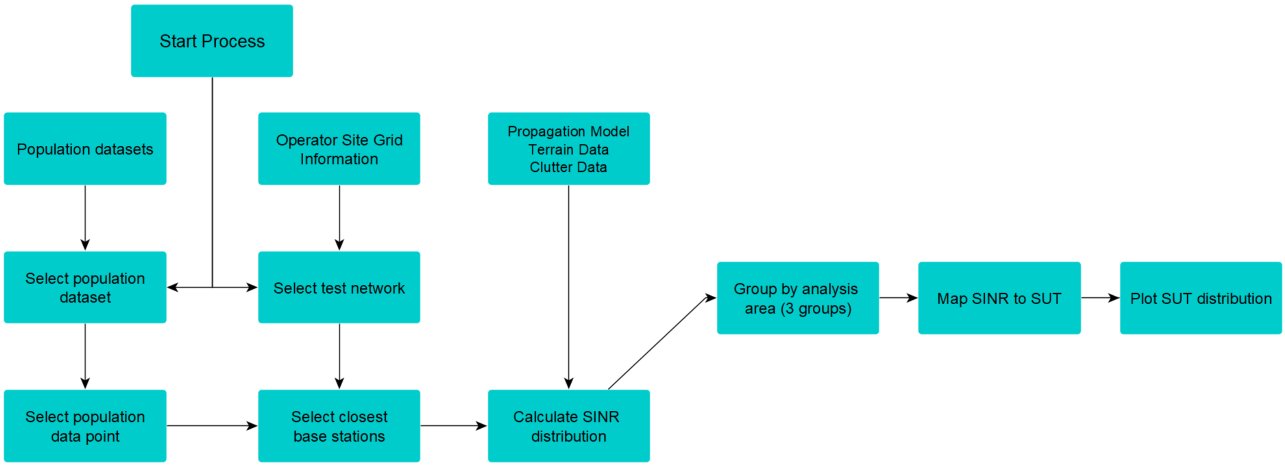


Figure A6.18 Population and population per household for each analysis area

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

Figure A6.19 Model process flowchart



A6.116 The macrocell site grids 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):

a) The nearest 20 base stations to the population data point are identified;

b) 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);

c) The base station sector providing the highest received signal strength at each iteration of the subsequent calculation is designated as the serving sector;

d) 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. The serving sector is assumed to be transmitting at its maximum power.

e) A downlink SINR distribution (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;

f) 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.

Propagation model

A6.117 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.

A6.118 We have implemented a modified version of Recommendation ITU-R P.1812[274] 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

A6.119 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 A1. 1

$$Throughput, Thr, \frac{bps}{Hz} = \mathrm{BW} * \begin{Bmatrix} 0 \; for \; SINR < SINR_{min} \\ \alpha * S(SINR) \; for \; SINR_{min} < SINR < SINR_{max} \\ Thr_{max} \; for \; SINR > SINR_{max} \end{Bmatrix}$$

Where: *S(SINR)* is the Shannon bound: *S(SINR)* = $\log_2(1+SINR)$ (bps/Hz) and:

a) 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)

A6.120 The parameters α, $SINR_{min}$ and Thr_{max} can be chosen to represent different modem implementations and link conditions. The parameters proposed in Figure 6.19 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

Figure A6.20 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)

[274] See ITU-R 1812.2 recommendation https://www.itu.int/rec/R-REC-P.1812/en

A6.121 For the purposes of this analysis, we have chosen to use the values of SINRmin, Thrumax (and hence SINRmax) 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 **Error! Reference source not found.** and **Error! Reference source not found.**).

Building entry loss assumptions

A6.122 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.

A6.123 We have used the building entry loss from Recommendation ITU-R P.2109. 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.

A6.124 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.

A6.125 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.
- **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.

A6.126 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 recognised method for the estimation of building entry loss.

A6.127 It should be noted that, though broadly comparable, our current definition of what constitutes shallow and deep areas within a building are not identical to the definition we used in 2012. The figure below presents the comparison between 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 A6.21 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 MHz	10.5	25.2	14.2	26.5
1800 MHz	13.7	28.9	14.9	28.6

The macrocell networks modelled

A6.128 We have modelled two macrocell 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. The parameters we have used are taken from the MNOs' responses to formal information requests that we issued in June 2018. These parameters 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.

A6.129 The figure below shows the number of sites in each of the analysis areas.[275] This figure 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 A6.22 Sites per analysis area

Analysis area	1800 MHz site grid	700 MHz site grid	Difference (no. sites) between 1800 MHz and 800 MHz sites
Most densely populated	~ 8,700	~ 8,000	~ 700
Mid densely populated	~ 3,900	~ 3,300	~ 600

[275] 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.

Analysis area	1800 MHz site grid	700 MHz site grid	Difference (no. sites) between 1800 MHz and 800 MHz sites
Least densely populated	~ 850	~ 750	~ 100

Effects of nearby sites

A6.130 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)

A6.131 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.

Supporting tables

A6.132 The two figures below 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 A6.23 Percentage of cumulative population with a minimum 2 Mbps, all analysis areas, networks and network loadings

	Network analysed	Lightly loaded		Mid loaded		Heavily loaded	
		Shallow indoor	Deep indoor	Shallow indoor	Deep indoor	Shallow indoor	Deep indoor
Most densely 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 densely 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 densely 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 A6.24 Percentage of cumulative population with a minimum 10 Mbps, all analysis areas, networks and network loadings

	Network analysed	Lightly loaded		Mid loaded		Heavily loaded	
		Shallow indoor	Deep indoor	Shallow indoor	Deep indoor	Shallow indoor	Deep indoor
Most densely 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 densely 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 densely 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%

A7. Supporting information for the competition assessment regarding the 3.6-3.8 GHz band

Summary and introduction

A7.1 In this auction, 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 band is especially important as many mobile operators are using it to deploy the first 5G networks.

A7.2 In this annex we present a technical overview of 5G now and how it would evolve in the future, based on current evidence, and the possible implications for our competition assessment, which we set out in section 4. The issues that we have considered as part of this competition assessment include the concern of Vodafone, O2 and BT/EE that their spectrum holdings might not be enough to compete adequately with H3G in providing the 5G services that are important for competition.

A7.3 We also summarise what we said in the December 2018 consultation, the relevant responses to the December 2018, June 2019 and October 2019 consultations and our updated view in light of these responses and evidence we have gathered. This annex is structured as follows:

- **Part 1: Evolution of 5G services**
  5G services will gradually develop over the next years. These services each have different requirements in terms of, for example, latency or throughput. Operators can make use of different spectrum bands to fulfil these requirements and effectively provide the various 5G services. We include an overview of wireless technologies that could also be used to provide a “5G” service, with an emphasis on Wi-Fi and 4G. We provide an overview of these services and a rough timeline of when equipment and services will be available in the next few years. We also discuss the likely timelines for when different spectrum will be useable for 5G.
- **Part 2: Spectrum required to deliver a 5G service**
  We analyse the spectrum requirements to deliver 5G, how operators could potentially use their spectrum portfolios to deliver 5G services and the importance of using large blocks of contiguous spectrum. We also provide evidence to support the assessment of the competition concerns specific to the spectrum band we are awarding, including the possible performance and cost penalties associated with deployments using fragmented spectrum.

A7.4 Since the publication of the December 2018 consultation we have gained a better understanding of 5G, as the first deployments have been rolled-out, but we recognise there is still uncertainty around how mobile networks will evolve (for example, to support still unknown future 5G services). As such, our assessment unavoidably requires a significant degree of regulatory judgement.

A7.5 In our assessment we include analysis of some categories of 5G services (such as massive machine type communications) and how they could be delivered in different spectrum bands and with different bandwidths. We believe these can be representative of wider 5G services, although we recognise there is uncertainty around future services.

Part 1: Evolution of 5G services

Brief summary of 5G services and their importance now and in the future

A7.6 In this section we discuss how mobile services might develop over the next few years and the importance of 5G and existing mobile technologies for providing those services. We consider it likely that some 5G services will be an evolution of existing services provided by operators and some will be new services, although the latter will appear gradually over the next years depending on demand:

- In the short term, lasting until around 2021, we expect MNOs to expand their mobile, and possibly, Fixed Wireless Access (FWA) capacity to meet the growing data traffic demand. We consider that operators' initial 5G rollouts support our assessment (See paragraph A7.40). Other existing technologies, such as 4G or Wi-Fi, will be important in delivering some of these services, including other non-broadband services (such as Internet of Things for wearables). During this time, the 3.4-3.8 GHz band will continue to be the main spectrum useable for 5G services.
- In the longer term, from around 2021 onwards, and alongside the gradual consumer uptake and demand for broadband services, massive machine-type communications (mMTC) and ultra-reliable low latency communications (URLLC) services may also become more important. In this context we recognise that the importance of these new services to competition in the longer term is inherently more uncertain because they currently represent a significantly smaller proportion of mobile operator revenues than mobile broadband. From around 2021, non-5G technologies will remain important, but 5G technology may better suit some future services. In this long-term period, most mobile bands will useable for 5G.

A7.7 Mobile traffic has increased by 38% with respect to last year (compared to 36% growth the previous year).[276] Cisco forecasts[277] that the total mobile traffic by 2022 will include 71% of 4G traffic, with 12% 5G traffic, and nearly 59% of total mobile traffic (both 4G and 5G mobile traffic) being off-loaded on to Wi-Fi. Analysys Mason anticipates an increase in data traffic demand, predicting that each handset will generate on average 8.7 GB of mobile data traffic per month in 2023, rising to 10.3 GB in 2024.[278] To meet this demand, it is likely that mobile networks will need to expand their capacity and 5G deployments in 3.4-3.8 GHz.

[276] Ofcom Connected Nations 2019 https://www.ofcom.org.uk/__data/assets/pdf_file/0023/186413/Connected-Nations-2019-UK-final.pdf
[277] Cisco Annual Internet Report https://www.cisco.com/c/en/us/solutions/executive-perspectives/annual-internet-report/index.html Accessed 19/02/2020.
[278] Analysis Mason, Wireless Network Data Traffic: Worldwide Trends and Forecasts 2017-2023, April 2019.

A7.8 We expect this data increase to be driven by a number of interrelated factors:

- Increased time spent being connected via mobile data as well as Wi-Fi; [279, 280] adults now spend more time online, compared to 2017;[281]
- Growth in the number of devices as well as growth in the number of subscribers: in 2025, 90 percent of subscriptions are projected to be for mobile broadband. It is estimated that there will be 8.9 billion worldwide mobile subscriptions by the end of 2025;[282]
- Growth of video traffic over mobile networks, particularly as High Definition and Ultra High Definition content is available on the move. Ericsson forecasts that video traffic in mobile networks will grow by around 30 percent annually through 2025 to account for three-quarters of mobile data traffic, from slightly more than 60 percent in 2019. [283]
- Adoption of bigger form factors will also impact the need for higher volumes of data; [284]
- Growth of social network traffic: this is expected to rise 20 percent annually over the next 6 years;[285]
- Growth in the adoption of immersive formats with higher data and video resolution requirements; [286] and
- Growth in the number of IoT connected devices, leading to more data traffic across the network.[287]

A7.9 Demand for Fixed Wireless Access (FWA) services may also 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. We note that:

[279] 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

[280] 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

[281] In particular, 2.9 vs. 2.5 hours. Adults: Media use and attitudes report 2019, published 30 May 2019. https://www.ofcom.org.uk/__data/assets/pdf_file/0021/149124/adults-media-use-and-attitudes-report.pdf

[282] Ericsson Mobility Report November 2019 https://www.ericsson.com/en/mobility-report/reports/november-2019

[283] Ericsson Mobility Report November 2019 https://www.ericsson.com/en/mobility-report/reports/november-2019

[284] Among other metrics, the form factor of a device gives a measure of its screen size. The larger the form factor, the higher volume of data required to deliver a video stream with similar quality.

[285] Ericsson Mobility Report November 2019 https://www.ericsson.com/en/mobility-report/reports/november-2019

[286] Sometimes referred as Virtual Reality video or 3D Video; usually requiting high data rates to support

[287] McKinsey forecasts the worldwide number of IoT-connected devices is projected to increase to 43 billion by 2023 an almost threefold increase from 2018. McKinsey "Growing opportunities in the Internet of Things".https://www.mckinsey.com/industries/private-equity-and-principal-investors/our-insights/growing-opportunities-in-the-internet-of-things Accessed 29/02/2020 GSMA forecasts that by 2025, there will be more than 25 billion IoT connections (cellular and non-cellular) https://www.gsma.com/newsroom/press-release/new-gsma-study-operators-must-look-beyond-connectivity-to-increase-share/ Accessed 19/02/2020.

a) Operators include FWA alongside mobile and broadband services in their retail products and 4G FWA services are available almost UK-wide. Roll-out plans suggest that the growth in FWA capacity (4G and 5G) to serve subscribers will be gradual over the next few years. [288]

b) The Broadband Universal Service Obligation (USO) includes fixed wireless access systems to provide a superfast broadband connection of 10Mbps download and 1Mbps upload speeds. We note, for example, that BT/EE stated that its FWA technology comfortably exceeds all the technical requirements of the USO and can potentially serve around half a million of new customers that currently do not have access to decent broadband. [289]

In both the short and long term, 4G is likely to continue to play an important role in mobile networks alongside 5G

A7.10 Both 4G and 5G are likely to be important for providing mobile broadband services for the next few years. 5G NR [290] [291] has been designed to make more efficient use of spectrum than earlier generations (like LTE) and can be deployed in wider bandwidths than with LTE, although in some cases there will be little difference in the experience for the mobile user. Different industry stakeholders have said that 4G and 5G technologies will continue to coexist for a long period of time, but it is uncertain until when these two technologies will coexist and will depend on operators' individual business plans. [292]

A7.11 We expect that 4G and 5G will coexist for a significant period of time for a number of reasons, as outlined in Figure A7.1 Evidence for the period when LTE and 5G will likely coexist

	Evidence
The number of LTE subscribers is still growing	In the third quarter of 2019 there were nearly 4.7 billion LTE subscriptions worldwide, with over 986 million added in the last year. [293] In Europe, LTE traffic accounts for more than 40% of overall data traffic. [294]

[288] FT/EE FWA https://ee.co.uk/business/large/innovative-business-transformation/rapid-site/ and https://shop.ee.co.uk/broadband/4g-home-broadband Accessed 29/01/2020 ; H3G 4G 5G Home broadband http://www.three.co.uk/store/broadband/home-broadband Accessed 29/01/2020 ; Vodafone Gigacube home broadband https://www.vodafone.co.uk/gigacube/ Accessed 29/01/2020 and "O2 UK joins 5G race, reveals launch date" https://www.sdxcentral.com/articles/news/o2-uk-joins-5g-race-reveals-launch-date/2019/07/ Accessed 29/01/2020.

[289] BT's Response to Ofcom's request for expressions of interest in serving as Universal Service Provider for broadband https://www.ofcom.org.uk/__data/assets/pdf_file/0013/120361/BT.pdf

[290] As defined in 3GPP https://www.3gpp.org/news-events/1929-nsa_nr_5g Accessed 19/02/2020.

[291] 5G NR or New Radio is the air interface designation for 5G.

[292] 5G deployment considerations, Ericsson. https://www.ericsson.com/media-cdn/4a5daa/siteassets/networks/documents/5g-deployment-considerations.pdf and Huawei releases LTE&NR coordination solution, significantly improves 5G network era network efficiency and user experience https://www.huawei.com/en/press-events/news/2019/10/Huawei-Releases-LTE-NR-Coordination-Solution Accessed 27/02/2020.

[293] 5G Forecast and LTE Subscriptions: Ovum Data Q3 2019, Global Suppliers Association. September 2019.

[294] Snapshot of LTE and 5G in Europe, Global Suppliers Association. June 2019. Accessed 27/11/2019.

	Evidence
5G consumer mobile take-up is expected to occur gradually	There are a few tens of commercially available 5G handsets, with around 40 vendors launching products with different form factors in the foreseeable future, including tablets and CPEs.[295]
Operators are still investing in LTE networks	Mobile networks rely heavily on LTE to offer mobile services and are actively investing in new or additional LTE infrastructure for their networks. In Europe, LTE has been launched in more than 50 countries, with more than 200 operators currently investing in LTE.[296]
Some LTE bands will likely be used for LTE for some time.	Operators will continue using some bands to carry LTE traffic, either only for LTE or sharing resources between LTE and 5G. For example, according to [✂ REDACTED][297] and [✂ REDACTED][298], operators may decide to use the 800 MHz band for 4G for the next few years. In its response to the October 2019 consultation, H3G said that [✂ REDACTED].[299]
Use of a 4G/5G hybrid network architecture	The first 5G networks operate in Non-Standalone mode, which uses a 4G connection to route traffic and manage mobility. Operators will most likely transition into standalone 5G mobile networks according to different timetables and we expect this to happen gradually over the next few years.[300]
Example of other legacy technologies	Legacy technologies (such as 2G and 3G) have continued to be used for a significant period after the newer generations were mainstream. 3G traffic still accounts for a (small) percentage of total data traffic whilst 2G continues to be used for (machine to machine) M2M communications. In 2019, 4G carried 90% of UK data traffic and 21% of voice traffic, with 3G and 2G carrying 73% and 6% of voice traffic respectively.[301]
4G technology is evolving in parallel to 5G.	3GPP continues to develop the specifications for 4G[302] and it supports many of the same technology advances (e.g. active antenna systems) and services as 5G (e.g. eMBB services and Narrowband IoT), meaning that in some cases 5G is unlikely to be significantly more capable than LTE-Advanced-Pro.[303] However, there are other 5G technical features (such as access to mmWave spectrum or the ability to achieve latencies of less than 1 ms) that could enable new services.

[295] 5G device ecosystem, Global Suppliers Association. November 2019.
[296] Snapshot of LTE and 5G in Europe, Global Suppliers Association. June 2019. Accessed 27/11/2019.
[297] [✂ REDACTED]
[298] [✂ REDACTED] reiterated in [✂ REDACTED]
[299] [✂ REDACTED]
[300] See paragraph A7.41.
[301] Ofcom 2019 Connected Nations report https://www.ofcom.org.uk/__data/assets/pdf_file/0023/186413/Connected-Nations-2019-UK-final.pdf
[302] There are improvements in the LTE standards in 3GPP Release 14, 15 and 16.
[303] LTE Advanced Pro describes a collection of some of the most recent 4G technology standards. See 3GPP Standard Release 13 and 14 https://www.3gpp.org/specifications/releases Accessed 05/12/2019.

A7.12 In the short term, the expected improvements in 4G technology are likely to bring the performance of a 4G network close to the expected performance of 5G for eMBB and IoT applications. In the long term, 5G is expected to enable new services, for example, ABI research[304] marks three different periods of time for services and their likely coverage. The first period of time spans until 2022 and includes eMBB and FWA services in hot spots as dense urban areas or public spaces. The second time frame includes services such as AR/VR, early industry IoT and private 5G networks over wider areas happening between 2022 and 2030. From 2030 onwards, full indoor-to-outdoor coverage is expected for all of the former cases and the most innovative 5G ones such as autonomous vehicles, AI systems and CaU (connectivity as a utility).This means that even if existing mobile bands cannot be immediately re-farmed for 5G, operators will still be able to take advantage of other technical advances and provide mobile services using LTE for several years.

4G and other solutions could play a significant role to deliver some 5G services, though there is uncertainty about their role to provide future, unknown, services

A7.13 The Internet of Things is a wide term referring to networks of consumer wireless devices and other physical objects that are connected to the Internet, also including massive Machine Type Communications (mMTC) and some Ultra Reliable Low Latency Communications (URLLC).

A7.14 mMTC refers to networks supporting extremely large numbers of wireless devices (usually transmitting low volumes of data). These can include remote sensors, actuators or monitoring equipment, as well as other types of devices, such as smart home hubs or wearable technology. Ultra-reliable low-latency communications (URLLC) services are relevant for scenarios where both a very low response time and guaranteed delivery are required. Examples could include vehicle-to-vehicle communications (with on-board safety control communications), control of industrial processes and remote surgery.

A7.15 4G and other wireless technologies are widely used to provide some of these services and it is likely they will continue to be used to address much of the growing demand for IoT devices over the next few year, because:

- The majority of IoT connections are provided using licence exempt technologies and this is likely to continue for the next few years.[305] Wi-Fi is widely used for applications that need higher volumes of data such as video surveillance, smart buildings, drone connectivity and some industrial automation processes. To cope with increased capacity and throughput demands, the latest generation of Wi-Fi devices (implementing the Wi-Fi 6 standards) can achieve peak speeds around 10 Gbps and support 200 to 400 terminals per access point. Chipset manufacturers like Qualcomm, Broadcom and Intel include Wi-Fi 6 in their product portfolio.[306] Smartphone

[304] ABI Research Evolving 4G networks into 5G https://www.abiresearch.com/market-research/product/1027217-evolving-4g-networks-to-5g Accessed 02/03/2020/
[305] Page 8, "Ericsson Mobility Report", June 2019, Accessed 27/11/2019. https://www.ericsson.com/en/mobility-report/reports/june-2019
[306] Wi-Fi 6 certification guidelines https://www.cbronline.com/news/wi-fi-6-certified Accessed 05/12/2019.

manufactures like Apple and Huawei also include Wi-Fi 6 support in some of their devices.[307, 308]

- Wearable devices, implants, or smart monitors carrying small volumes of data traffic use technologies including Bluetooth, ZigBee or LoRaWAN, which use licence exempt spectrum bands.[309] We note that BT/EE is trialling LoRaWAN for the network and application servers for its water metering network in CityVerve, Manchester [310, 311] and it has launched a smart cycling trial.[312]
- 4G technologies like Narrowband IoT (NB-IoT) and LTE Category M (LTE-M) provide a mobile connection for devices with low requirements in terms of bandwidth or volume of data traffic, using very narrow frequency carriers.[313] These two technologies are the most widely used for IoT in licensed bands; GSMA indicates that there are around 150 operators with NB-IoT or LTE-M deployments in 64 countries, and 62 operators investing in 34 countries.[314]

A7.16 However, it is uncertain whether 4G, Wi-Fi and other technologies will maintain their importance to deliver these services and new services in the future. 5G has been designed to support mMTC and URLLC. At the same time, some key technologies required to achieve extremely low latencies are not yet widely available – such as edge computing or network slicing.

A7.17 At present, 5G URLLC and mMTC are still in the trial and development stage. We note that the UK mobile industry is actively trialling some services as part of the DCMS-funded 5G Testbeds and trials programme[315], including industrial use and tourism. For example, in 2018, Kings College London, in collaboration with BT, Verizon, Unmanned Life and Ericsson, demonstrated a number of services centred around disaster response scenarios, utilising mission critical communications.[316]

5G could improve mobile and FWA capacity and speeds in the short term and may enable new services in the longer term, though the importance of these new services to competition is uncertain

A7.18 As we set out in section 4, we consider the **short term** to be the period where operators rely almost or completely on 3.4-3.8 GHz spectrum to deliver 5G, and the longer term

---

[307] Huawei Wi-Fi 6 technical specs https://e.huawei.com/en/products/enterprise-networking/wlan/Wi-Fi-6/ Accessed 05/12/2019.
[308] Apple 11 Pro technical specs https://www.apple.com/uk/iphone-11-pro/specs/ Accessed 05/12/2019.
[309] Bluetooth and Zigbee are wireless technology standards defined by the IEEE to transfer data between close devices and to create area networks with low-powered devices; LoRa is a long-range wireless energy-efficient communication protocol.
[310]BT Internet of things: Technology and applications www.stjohnpatrick.com/23/SmartIoTConnect2.pdf
[311] BT City Verve smart city report https://www.iot.bt.com/assets/documents/bt-city-verve-smart-city-report.pdf , November 2019 Accessed 05/12/2019.
[312] BT launches Smart Cycle trial https://newsroom.bt.com/bt-launches-smart-cycling-trial/, September 2019 Accessed 05/12/2019.
[313] NB-IoT and LTE-M NB-IoT are technologies that improve coverage, enabling the deep in building coverage required for applications such as smart meters. They can support more than 50,000 devices per cell-site.
[314] NB-IoT and LTE-M Networks Worldwide. Global mobile suppliers association, May 2019. Accessed
[315] 5G Testbeds and Trials Programme https://www.gov.uk/government/collections/5g-testbeds-and-trials-programme Accessed 19/02/2020.
[316] BT, Verizon, Ericcson and Unmanned Life partnership at King's College London. https://www.btplc.com/Innovation/Innovationnews/Operatorscollaborate/index.htm Accessed 05/12/2019.

when operators will be able to use their other spectrum bands for 5G. We consider that, in the short term, demand will be for mobile broadband and FWA and that mobile networks will use 4G and 5G to serve this demand. Addressing this growing demand will likely require operators to increase the capacity of their networks. For example, they can use more efficient radio technologies like massive MIMO, densify their networks or offload traffic onto Wi-Fi, depending on demand in an area.

A7.19 In the **longer term**, mobile networks may increasingly support URLLC and mMTC services, however, it is very uncertain when these will become important for consumers and competition, and to what extent.

5G has been designed to use a large range of frequency bands, and it is likely to be available in most mobile bands in the future

We said that 5G has been designed to use a large range of spectrum bands and combinations of bands

A7.20 In our December 2018 consultation we said that what constitutes '5G spectrum' would change over time depending on which bands were supported in the device ecosystem. Over time we expected many, if not all, of the existing UK mobile bands could be used for 5G and could be deployed for 5G use.[317] We identified three spectrum groups:

- **Low-frequency spectrum (1400 MHz and below):** suitable to support improved coverage and broadband user experience (eMBB). mMTC may, at least for many services, rely primarily on low frequency spectrum, though access to mid and high frequencies may allow the development of a wider set of services; URLLC could be deployed in low frequencies to provide reliable communications in outdoor locations;
- **Mid-frequency spectrum (above 1400 MHz and up to 6 GHz):** suitable to meet the increasing capacity demand for mobile broadband (eMBB). Additionally, it could support low latency for high data rate URLLC services. Included in this group is the 3.4-3.8 GHz band, which is identified as one of the primary 5G bands and is the first to be supported in equipment and devices[318]; and
- **High-frequency spectrum (above 6 GHz)**: suitable to support new 5G applications that require high capacity and very low latency indoors and outdoors for either eMBB or URLLC. Ofcom has recently added the lower 26 GHz band to the pool of bands of the spectrum sharing framework, under which users can apply for indoor local licences.[319]

A7.21 We said that over time we expected that many, if not all, of the existing UK mobile bands could be used for 5G, including the 800 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2300 MHz and 2600 MHz bands and that the speed at which existing bands could be used for 5G would depend to a large extent on requests from MNOs to chipset makers and device manufacturers to include frequency band support in new devices.

[317] December 2018 Consultation, paragraph A7.37.
[318] [✂ REDACTED]
[319] Chapter 5, Ofcom Enabling wireless innovation through local Licensing, https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

Some stakeholders disagreed with our assessment of when spectrum bands other than 3.4-3.8 GHz could be used for 5G

A7.22 In response to the 2018 December consultation, Vodafone raised concerns about our assessment of the use of the 2.3 GHz and 2.6 GHz bands as an effective substitute for spectrum in the 3.4-3.8 GHz band. Vodafone said that "*using 2.3 GHz and 2.6 GHz as a supply-side substitute for 3.4-3.6 GHz spectrum only works if a comparable ecosystem exists in the form of both network and user equipment*" and that "*holding such 4G spectrum at a time when they are seeking to match competitors with superior 5G-ready spectrum stocks might be irrelevant*".[320]

A7.23 According to Vodafone, the 2.3 GHz and 2.6 GHz bands could not substitute for 3.4-3.8 GHz, certainly in the short term but possibly in the long term too, due to the lack of device ecosystem and appropriate base station equipment. Vodafone argued that vendors will most likely not provide 5G equipment, and terminals in particular, for bands which would only be used in the UK. It said that other countries can provide "*adequate contiguous 3.4-3.8 GHz spectrum" there is "no other market demand*" for terminals and equipment in other bands.[321] Vodafone reiterated this point in its response to the October 2019 consultation, and also said that [✂ REDACTED].[322]

A7.24 Vodafone suggested the inclusion of a "transitional period" during which only 3.4-3.8 GHz spectrum bands will be available for 5G during which it said that [✂ REDACTED]. Vodafone highlighted that a single operator (H3G) would hold 36% (140 MHz of the 390 MHz) of the spectrum useable for 5G in the 3.4-3.8 GHz band during this period. Vodafone said in its response to the October 2019 Consultation *"the usage of frequencies in the 2.x GHz band is not an effective substitute in the short-medium term, because there is no eco-system to support 5G services. The analysis which Ofcom sets out in Figure 5.6 of the consultation is flawed, because it presents no analysis of when there will be an ecosystem to facilitate refarming of existing bands to 5G, in comparison to when the "wide range of 5G services" will be required.*[323]

A7.25 Vodafone argued that, even after the "transitional period", there would be significant technical complexities to overcome for future 5G NR deployments in these two bands, mainly due to bigger size, weight and form factor of massive MIMO antenna panels for 2.3 or 2.6 GHz spectrum.[324] Vodafone's estimates of massive MIMO antenna characteristics from different suppliers indicate an increase of [✂ REDACTED] weight and [✂ REDACTED] Width for 64T64R panel antennas for 2.3 GHz and 2.6 GHz, respectively when compared with equivalent 3.4-3.8 GHz massive MIMO antennas.

A7.26 O2 raised in its response to the October 2019 consultation that [✂ REDACTED].[325]

[320] Vodafone non-confidential response to the December 2018 consultation, page 14
[321] Vodafone non-confidential response to the December 2018 consultation, page 14.

[323] Vodafone non-confidential response to the October 2019 consultation, page 9.
[324] Vodafone non-confidential response to the December 2018 consultation, page 14.
[325] [✂ REDACTED]

We still consider that existing mobile bands will be useable for 5G soon with no significant constraints

A7.27 In the December 2018 consultation we said we expected all, or the majority, of mobile bands would be useable for 5G, but we recognised there was uncertainty around the precise timelines. Since the publication we have gathered further clarification on timelines and, if any, possible constraints on the use of these bands. We believe that operators will be able to use their existing spectrum mobile bands to offer 5G services from late 2021 or early 2022. This is based on the evidence we have from two industry surveys carried out in May and December 2019 respectively. These surveys included RF manufacturers and vendors which play a key role in the development of mobile equipment (including handsets, devices and base station equipment).[326]

A7.28 We have considered Vodafone's response that we should give more detail on the timelines for when 5G could be useable in each band. This will be primarily driven by the bands supported by the device ecosystem and, to a lesser extent, the availability of base station equipment and massive MIMO antennas. We have spoken to device and equipment vendors about timeline for band support in handsets and base station equipment.[327]

A7.29 Turning to **handset and device availability**, we understand that many devices support LTE use in most mobile bands and that 3.4-3.8 GHz can be used for 5G.[328] We believe that this will remain the case until late 2021 or early 2022, when devices are likely to have implemented support for 5G in existing mobile bands.[329]

A7.30 This means that 5G NR is likely to be supported in the 700 MHz, 800 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2300 MHz and 2600 MHz bands in handsets and devices from late 2021 or early 2022. The 2.6 GHz TDD band may be available sooner, between 2020 and 2021. Lastly, the 1400 MHz SDL and 700 MHz SDL bands may develop to a slower pace due to a lack of market demand.[330]

A7.31 In relation to **base station equipment**, most 5G deployments will use conventional antenna systems,[331] however, we have also considered when massive MIMO antennas will become available in existing mobile bands because these antennas could be important for increasing capacity in the busy areas that could be important for competition. Although not necessary for a 5G service, massive MIMO will likely be an important part of 5G networks and base station equipment may only be available in TDD bands at first.[332]

[326] In particular [✂ REDACTED]
[327] [✂ REDACTED]
[328] And some of the mmWave bands but supported in fewer devices.
[329] [✂ REDACTED]
[330] We give further details in annex 4.
[331] Page 18, paragraph 2.5.1, "5G Implementation Guidelines", GSMA, July 2019, Accessed 27/11/2019. https://www.gsma.com/futurenetworks/wp-content/uploads/2019/03/5G-Implementation-Guideline-v2.0-July-2019.pdf
[332] [✂ REDACTED]

A7.32 We note that there have been several trials of massive MIMO equipment in 2.3 GHz and 2.6 GHz TDD spectrum to provide 5G. This is relevant given the O2 and Vodafone spectrum holdings in these bands. In particular:

- Vodafone has trialled dual-band massive MIMO in Spain with equipment supporting 5G in the 3.7 GHz band and 4G in the 2.6 GHz TDD band. [333] Vodafone observes that this reduces the size and weight by half when compared with deploying two separate antennas while maintaining 90% of the capacity, and that only a software update is required to upgrade from 4G to 5G.
- [✂ REDACTED]
- Sprint has launched its 5G network using 2.5 GHz TDD in the US and uses massive MIMO antennas in this frequency band.[334]
- O2 has trialled 2.3 GHz massive MIMO in the UK[335] and there is ongoing work to harmonise the technical conditions for massive MIMO in this band across Europe.[336] The proximity of the 2.3 GHz band to the 2.6 GHz band means the technical challenges are likely to be similar, although the 2.3 GHz band has been awarded by only a few European countries, so it might not be an early priority for vendors.

A7.33 We therefore do not consider that base station equipment availability is likely to be a significant constraint on the usability of bands other than 3.4-3.8 GHz for 5G. This is because most 5G deployments will use conventional antenna systems and bands other than 3.4-3.8 GHz will likely be useable for massive MIMO antenna systems soon.

We consider there is a low risk that networks will become congested before operators can re-farm spectrum bands other than 3.4-3.8 GHz for 5G

A7.34 We have considered the "transitional period" that Vodafone's identifies where bands other than 3.4-3.8 GHz could not be used for 5G. We consider that if there were to be such a period, it is most likely to occur from now until 2021 to 2022. We consider, however, that soon after this the majority, if not all, devices will support existing mobile bands for 5G. We consider it is unlikely that operators will experience significant congestion on their 5G networks before they can refarm bands other than 3.4-3.8 GHz for 5G.

A7.35 We disagree with O2 when it says that [✂ REDACTED]. We have no evidence that capacity constraints will be a significant block to MNOs re-farming 4G bands to 5G.

---

[333] Vodafone's press release of 24 February 2019, available at https://www.saladeprensa.vodafone.es/c/notas-prensa/np_5g_mwc/ (in Spanish).

[334] Sprint lights up true mobile 5G in Dallas Forthttps://newsroom.sprint.com/sprint-lights-up-true-mobile-5g-in-dallas-fort-worth.htm *"Sprint is using 64T64R (64 transmitters 64 receivers) 5G MassiveMIMO radios from Ericsson. These radios support split-mode, enabling Sprint to simultaneously deliver LTE Advanced and 5G NR service. Sprint's 5G MassiveMIMO radios run on its 2.5 GHz mid-band spectrum, and they are deployed on Sprint's existing 4G cell sites, providing a nearly identical footprint for both 2.5 GHz LTE and 5G NR coverage."* Accessed 05/12/2019.

[335] O2 launches pilot to boost London network ahead of 5G https://news.o2.co.uk/press-release/o2-launches-pilot-to-boost-london-network-ahead-of-5g/ Accessed 05/12/2019.

[336] ECC PT1 recently developed the attached work items on 2.3 – 2.4 GHz to produce a Report and update ECC Decision 14(02). The Report is due to be completed in July 2021 and the revised Decision by July 2022.

A7.36 We understand that Dynamic Spectrum Sharing (DSS) could facilitate refarming of 4G bands to 5G. DSS enables the dynamic allocation of spectrum resources for 4G and 5G based on demand for each service using the same frequency carrier to carry both 4G and 5G traffic. DSS might reduce capacity by 7 to 10 %[337] when compared with a 4G-only carrier because both 4G and 5G signalling is transmitted in the same spectrum, but the benefits of dynamic sharing between 4G and 5G may improve the overall spectrum efficiency of the network when compared with assigning static 4G and 5G carriers. DSS is already being used by some operators (such as AT&T and Swisscom)[338] and may only require a software upgrade for some sites.

Part 2: Spectrum required to offer a 5G service

80-100 MHz contiguous spectrum can be beneficial to deliver 5G services but operators have used smaller bandwidths to provide 5G

A7.37 In our December 2018 consultation we said that there was no clear requirement in the published 5G standards or recommendations (from 3GPP or IMT-2020[339]) specifying a minimum spectrum bandwidth necessary to deliver a 5G service.[340] The ITU-R report M.2410 references a bandwidth of 100 MHz for spectrum below 6 GHz, but this is for the purposes of evaluation of IMT-2020 radio interface technologies only. At the same time, it is clearly stated that this is the maximum aggregated system bandwidth, and that this can be supported by either single or multiple radio frequency (RF) carriers.

A7.38 We said we understood that the 3.4-3.8 GHz band was important in this context, as it is one of the primary bands for 5G, and the first one being used for early 5G deployments, especially in European countries.[341]

A7.39 We said we understood that there were benefits from using a single, wide, contiguous carrier, however, there was no evidence to suggest that 5G could not be delivered with smaller or non-contiguous carriers in other frequency bands. Some stakeholders disagreed with our views on contiguous spectrum but provided no evidence of specific services that required 80-100 MHz of spectrum. We summarise here the latest developments, relevant responses to the December 2018 consultation and our updated views. We analyse two periods of time: a short and a longer term, based on the evidence we have gathered about equipment availability.

---

[337] [✂ REDACTED]
[338] https://www.fiercewireless.com/5g/nokia-to-introduce-dss-product-2020; and https://www.ericsson.com/en/news/2019/11/5g-spectrum-sharing-call-ericsson-swisscom-qualcomm Accessed 15/01/2020.
[339] 3GPP is the 3rd Generation Partnership Project. It develops specifications for new technologies of cellular networks https://www.3gpp.org/ ; IMT 2020 are the requirements issued by the Radiocommunication Sector of the International Telecommunication Union for 5G networks, devices and services. https://www.itu.int Accessed 05/12/2019.
[340] December 2018 Consultation, A7.55.
[341] In January 2019, the European Commission decided to harmonise spectrum for the future 5G in the 3.6 GHz band https://ec.europa.eu/digital-single-market/en/news/commission-decides-harmonise-radio-spectrum-future-5g

Since the December 2018 consultation, several UK mobile operators have started rolling out 5G using less than 80 MHz spectrum

A7.40 In the December 2018 consultation we said that operators had announced their initial 5G plans based on their current 3.4-3.6 GHz holdings and that we expected they would likely deliver new 5G services using a portfolio of different spectrum bands in the longer term.[342] Since then:

- In May 2019 BT/EE became the first UK operator to launch 5G[343] in several spots in London, Cardiff, Edinburgh, Belfast, Birmingham and Manchester and it said that 26 cities would receive coverage by 2020.[344]
- BT/EE has a 3-phase strategy that starts with an NSA (Non-Standalone)[345] architecture with 5G built on top of its existing 4G infrastructure. This will continue until 2022, when Phase 2 begins and BT/EE will use a standalone 5G mobile network, including core components. The 5G core allows for lower latency and network slicing and the third phase, from 2023, will introduce URLLC.
- BT/EE is also launching a Fixed Wireless Access (FWA) service, as we explain in A7.9a) and A7.9b).
- Vodafone introduced 5G in 31 locations in the UK [346] including Glasgow, London, Manchester, Liverpool, Birmingham, Cardiff and Bristol in July 2019[347] and has said it will be extending 5G coverage to other parts in the country in the following years. Vodafone also claims to have been the first to demonstrate haptic technology through 5G.[348] Its 5G offer will include gaming on-the-go, HD streaming and VR as the 5G network will support fast, low latency connections.
- O2 has announced that its 5G service is available in Belfast, Cardiff, Edinburgh, London, Slough and Leeds.[349] O2 is trialling innovative business cases in its 5G innovation spaces of its FTE 100 testbed.[350]
- Whilst being delayed according to their initial plans,[351] H3G has launched 5G mobile in several UK cities and a limited 5G network for home broadband services (FWA) in the London area.[352]

---

[342] December 2018 Consultation, paragraph A7.36 -paragraph A7.37.
[343] BT/EE launch of 5G https://newsroom.ee.co.uk/ee-launching-uks-first-5g-service-in-six-cities-bringing-a-new-era-in-faster-more-reliable-connectivity/ Accessed 05/12/2019.
[344] BT/EE UK 5G coverage https://ee.co.uk/why-ee/5g-on-ee/5g-uk-coverage Accessed 27/11/2019.
[345] A 5G Non-Standalone architecture makes use of 5G Radio Access Technology (RAT) and a 4G core; whilst a Standalone architecture uses 5G technology for both RAT and core.
[346] Vodafone 5G plans https://www.vodafone.co.uk/network/5g#moreplaces Accessed 27/11/2019.
[347] Vodafone 5G plans https://www.vodafone.co.uk/network/5g Accessed 27/11/2019.
[348] Vodafone 5G information https://mediacentre.vodafone.co.uk/news/5g-unlimited-data-more-places-than-any-other-network/ Accessed 27/11/2019.
[349] O2 5G plans https://www.o2.co.uk/5G Accessed 27/11/2019.
[350] O2 5G plans https://news.o2.co.uk/press-release/o2-5g-to-arrive-in-2019-as-company-builds-a-5g-economy-in-partnership-with-british-business/ Accessed 27/11/2019.
[351] Three UK delayed roll-out of 5G mobile https://www.ispreview.co.uk/index.php/2019/11/three-uk-coughs-to-slightly-delayed-rollout-of-5g-mobile.html Accessed 31/01/2020.
[352] Three 5G network http://www.three.co.uk/5g Accessed31/01/2020 and ISP Preview Three UK to Go Live with Ultrafast 5G Mobile at 65 Locations https://www.ispreview.co.uk/index.php/2020/02/three-uk-to-go-live-with-ultrafast-5g-mobile-at-65-locations.html Accessed 19/02/2020.

A7.41 During 2019, UK operators announced that they launched 5G using their 3.4-3.6 GHz spectrum holdings and continue to deploy it in more areas. This means that BT/EE, Vodafone and O2 all launched their 5G service using less than 80 MHz of contiguous spectrum.

Bidding behaviour in the previous award was consistent with a view that 80-100 MHz is desirable but not essential

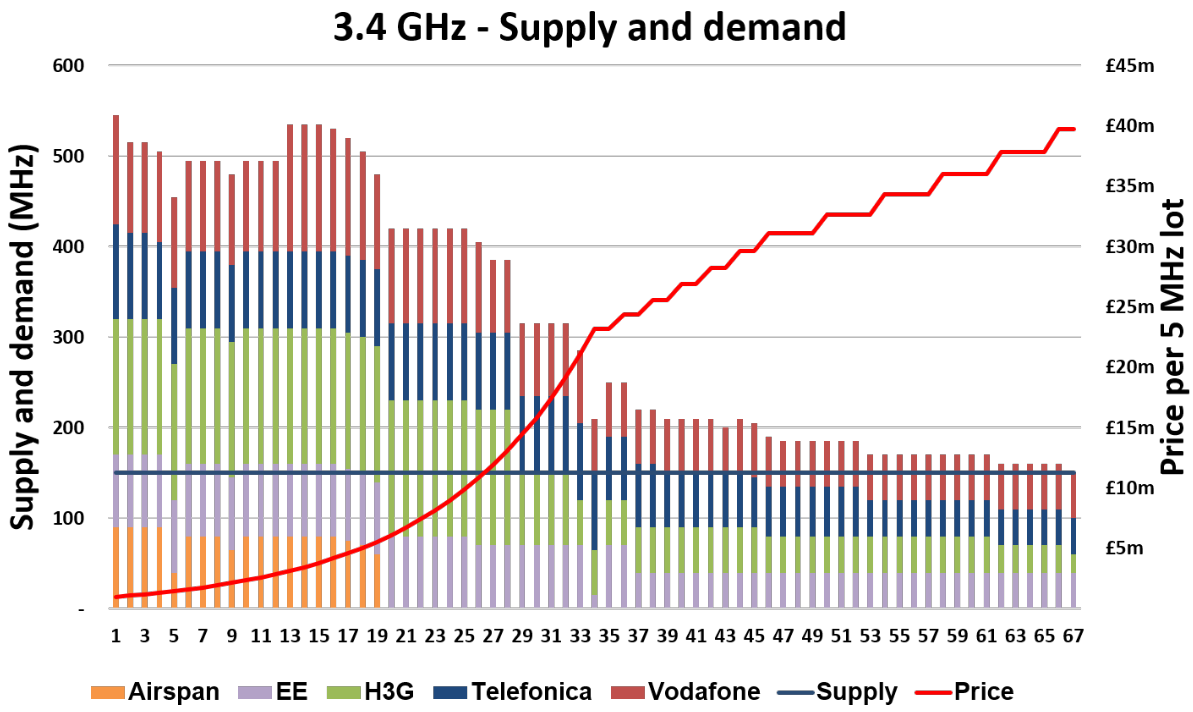
A7.42 Bidding in the 2.3 and 3.4 GHz auction may be a useful indicator of the level of demand for the spectrum we are auctioning in the forthcoming award. In the 2.3 and 3.4-3.6 GHz auction, there was substantial demand for spectrum in the 3.4-3.6 GHz band. At the reserve price of £1m per 5 MHz lot in the first round of the auction there was demand for 545 MHz which was in excess of the 150 MHz available. As the price increased, excess demand persisted, and it took 67 rounds of bidding until the market cleared. Figure A7.**26** provides a summary of the bidding.

A7.43 As shown in the figure below, 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 the early rounds of the auction. The largest bids for each bidder were 80 MHz by BT/EE (noting that it was limited by the overall spectrum cap to a maximum bid of 85 MHz); 90 MHz by Airspan; 105 MHz by O2; 140 MHz by Vodafone; and 150 MHz by H3G.

A7.44 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 O2), and 50 MHz (Vodafone). The last bid for a block of at least 80 MHz was by O2 in round 34 at a round price of about £21.1m per 5 MHz (and for 60 MHz, the last bid was by O2 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.

A7.45 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.

Figure A7.25 Bids for 3.4-3.6 GHz spectrum in the 2.3 and 3.4 GHz auction



A7.46 This, in addition to the fact that operators are already deploying and offering 5G, suggests that, in the short term, operators have enough spectrum to offer 5G services that are relevant for competition (mobile broadband and fixed wireless access).

Some operators disagreed with our views but provided no evidence of specific 5G services that require 80 to 100 MHz contiguous or non-contiguous spectrum

A7.47 BT/EE explained that 3.4-3.8 GHz spectrum was of particular importance given that it is TDD spectrum; TDD allows for asymmetric allocation for downlink and uplink resources and improved massive MIMO performance due to channel reciprocity delivering greater spectral efficiency. According to BT/EE, it was important for operators to acquire contiguous spectrum to deploy the widest supported 5G NR channel bandwidths to deliver ultra-high speeds and ultra-high bandwidth services that it considered important to competition.[353]

A7.48 Vodafone agreed with our assessment in the December 2018 consultation that there was no evidence pointing to services requiring, today, 80-100 MHz contiguous spectrum, but it said that "*when these applications will emerge – competitor nations will have made that volume of spectrum available in contiguous blocks, and the UK will suffer if such services are restricted to one or two of its operators*". Vodafone mentioned the European Commission Implementing Decision regarding the relevant technical conditions applicable to the 3.4-3.8 GHz band which describes 80 to 100 MHz of contiguous bandwidth to be

[353] BT/EE non-confidential response to the December 2018 consultation paragraph 3.136 and 3.137 reiterated in [✂ REDACTED]

preferable for 5G, which GSMA, Ericsson and Huawei agree with. BT/EE also referred to this document and said that "*80-100 MHz facilitate the efficient deployment of 5G wireless broadband services, for example with Active Antenna Systems (AAS) with high throughput, high reliability and low latency*". [354]

A7.49 Vodafone explained that what consumers would value in the future would not only be access to coverage, but to a good quality of coverage. The ability to offer high data speeds to a large volume of users will be key to be a credible competitor. In this context, having access to large contiguous bandwidth, would lead to [✂ REDACTED]. [355]

A7.50 In its response to the December 2018 consultation, O2 quoted CEPT ECC Report 287, which states that "it is important for licensees to have access to large contiguous channels, supporting a variety of applications with high data rates and/or low latency and improved user experience". The same report states that "administrations should allow for the availability of large contiguous blocks of spectrum and should consider prompt action if problems arise resulting from fragmented usage of the 3400 – 3800 MHz bands to enable timely 5G rollout." O2 stated that, considering what is included in this report, Ofcom should take prompt action to defragment the band and allow access to large contiguous spectrum blocks. [356]

A7.51 O2 stated that that 5G NR had been designed to support wideband operation; large contiguous spectrum led to a better user experience (in terms of high data rates), with less terminal complexity and power consumption. It observed that LTE becomes less spectrally efficient when aggregating multiple carriers and that carrier aggregation of 5G NR carriers would not match the performance of a single 5G NR carrier using the same amount of spectrum.

A7.52 O2 also described the impact that smaller or fragmented spectrum holdings would have on performance: [357]

- With smaller bandwidths, consumers will not be able to experience high peak throughputs. O2 estimated that only 940 Mbps maximum speed would be achievable in a 50 MHz carrier when compared to 1.875 Gbps for a contiguous 100 MHz block. [358]
- Two carriers may result in a capacity loss of 15% in a cell site when compared with a single carrier of the same total bandwidth. In this scenario, operators may offer a degraded customer experience if there is traffic congestion in a site.

A7.53 O2 noted that "*the key element for successful deployment of massive MIMO and active antennas is the availability of large contiguous bandwidths, as this will enable absolute gains from massive MIMO to support new usages related to eMBB*". [359]

---

[354] Vodafone non-confidential response to the December 2018 consultation, page 17 reiterated in [✂ REDACTED]
[355] [✂ REDACTED] and [✂ REDACTED].
[356] O2 non-confidential response to the December 2018 consultation, from paragraph 128 to paragraph 133.
[357] O2 non-confidential response to the December 2018 consultation, paragraph 156 and O2 confidential response to the June 2019 consultation, paragraph 14 reiterated in [✂ REDACTED].
[358] O2 confidential response to the June 2019 consultation, paragraph 13.
[359] O2 non-confidential response to the December 2018 consultation, paragraph 133.

A7.54 To support their argument for a 140 MHz frequency cap in the 3.6-3.8 GHz band of 120 MHz, O2 included some evidence from other European spectrum auction awards of 3.4-3.8 GHz held to date and it observed that many operators had secured no more than 140 MHz nor less than 80 MHz contiguous spectrum.

A7.55 In its response to the October 2019 consultation, O2 stated that [✂ REDACTED][360] and that [✂ REDACTED].[361]

Our model suggests that operators could support a wide range of 5G services, including those currently envisaged by 3GPP, using their existing spectrum holdings

A7.56 To inform our assessment about whether 5G services could be offered by a mobile network using different bandwidths we have modelled the Single User Throughput (SUT) that a theoretical cell site could offer across its coverage area. We use SUT as a proxy for the quality of service a mobile user would experience if all the available spectrum resources in the cell were assigned to offer a particular 5G service to that user (for example, to support high definition video streaming). This analysis is a simplification of a real deployment scenario where many users would be sharing the capacity of a cell. We assume different bandwidth configurations that reflect the operators' current holdings in the 3.4-3.8 GHz band, i.e. what an operator would be able to achieve if it acquired no additional spectrum in the auction. We also include two additional scenarios where we explore the impact of fragmented spectrum in delivering SUT.

A7.57 To understand which typical 5G services could be delivered by this set of different bandwidth and MIMO configurations, we have used the requirements set by 3GPP in terms of minimum data rates that would be required to support some possible future 5G services (for example, cloud computing for a connected vehicle).[362] 3GPP identifies the high-level potential requirements for services covering different scenarios, including public safety communications, smart grid systems, drone connectivity, vehicular communications or high-definition live-video streaming.[363] We understand these services can be representative of a wide range of future 5G services, but we recognise that they cannot be representative of all, yet unknown, future services.

A7.58 We include both downlink and uplink in our analysis, as some 5G services require certain volume of traffic available in the uplink as well as downlink (for example, IoT industrial control where sensors or actuators constantly send information back to the base station).

---

[360] [✂ REDACTED]
[361] [✂ REDACTED]
[362] 3GPP TR 22.891 Study on new services and markets technology enablers.
[363] Whilst our assessment focuses only in data rates, 3GPP requirements to support these services are specified across a range of metrics including latency, packet loss, transmission frequency, data-rates and device density. However, our assessment focus solely in providing a basic overview about the data rates that could be offered using existing spectrum holdings with several antenna configurations without consideration of any other technical parameters that would impact these other requirements.

A7.59 The analysis we have carried out is based on an LTE-Advanced[364] link-level performance for 4G communications. Hence, we have adjusted the assumptions for 5G. We have assumed that:

- a typical 5G mobile device might support four downlink spatial streams and two uplink spatial streams under SU-MIMO[365] conditions;[366]
- for a given SINR,[367] the uplink spectral efficiency is the same as the downlink. This is because 5G NR uses OFDM[368] in both the uplink and downlink whereas LTE uses OFDM in the downlink only and SC-FDMA in the uplink.[369]
- 5G NR supports a maximum modulation order of 32 QAM in the uplink; and
- a 1.5 – 2 dB SINR uplink improvement from 2x2 MIMO diversity coherent range enhancement.[370]

A7.60 We conclude from the results that all the proposed cases envisaged by 3GPP could be delivered by the bandwidth and MIMO configurations included in our analysis (see Figure A7.27 and Figure A7.28). These results suggest that whilst greater bandwidths can deliver higher data rates, exploiting MIMO can also deliver similar data rates, in smaller bandwidth carriers. However, we recognise that some services requiring higher datarates (such as live video streaming) will be better provided by larger bandwidth carriers.

A7.61 More specifically, we derive from the results that:

- the best performance is achieved when using a contiguous 100 MHz bandwidth carrier and 4-layer MIMO configuration.
- There is a small throughput reduction when aggregating two 50 MHz carriers, compared to a contiguous 100 MHz carrier. However, we acknowledge that this throughput reduction could be greater if only one of the component carriers can make use of SU-MIMO.
- In general, carriers of 40 MHz with a 2-layer SU-MIMO[371] can provide enough throughput to support some of the most data intensive 5G services described in the 3GPP technical report to a large proportion of locations within the cell, both in downlink and uplink.
- Either increasing the number of SU-MIMO layers or increasing the carrier bandwidth will proportionately increase the SUT. For example, a 100 MHz carrier with 2 SU-MIMO layers support between 18 Mbps to 1 Gbps depending on location within the cell and this SUT doubles to between 36 Mbps and 2 Gbps when 4 SU-MIMO layers are used.
- A single 40 MHz carrier could provide sufficient datarates to support a mobile broadband live video application, although only in locations close to the base station

[364] As defined in Release 12 of the 3GPP standard.
[365] Single User MIMO.
[366] 3GPP MIMO support and User Equipment (UE) categories https://www.3gpp.org/keywords-acronyms/1612-ue-category Accessed 19/02/2020.
[367] Signal to Noise and Interference Ratio.
[368] Orthogonal frequency-division multiplexing.
[369] In real networks the downlink SINR tends to be greater than the uplink SINR which means that the downlink throughput will tend to be much higher than the uplink throughput for a given scenario.
[370] That comes from the requirement for 5G transmissions to make use of at least two antennas in the uplink.
[371] Consistent with widely used MIMO current number of layers configuration.

(or where there is a higher SINR ratio). This could mean that the area within the cell where an operator could effectively provide this service would be small. An operator might seek to overcome this by aggregating additional carriers to make up the total bandwidth necessary to deliver the service. We explain further on this point in part 2 of this document. Whilst there may be other ways to overcome this (such as densification of cell sites), we recognise they might be costlier or not feasible to use.

Figure A7.26 Downlink Single User Throughput (SUT) across different signal strengths in a cell compared with the minimum data rate requirements for some 5G services

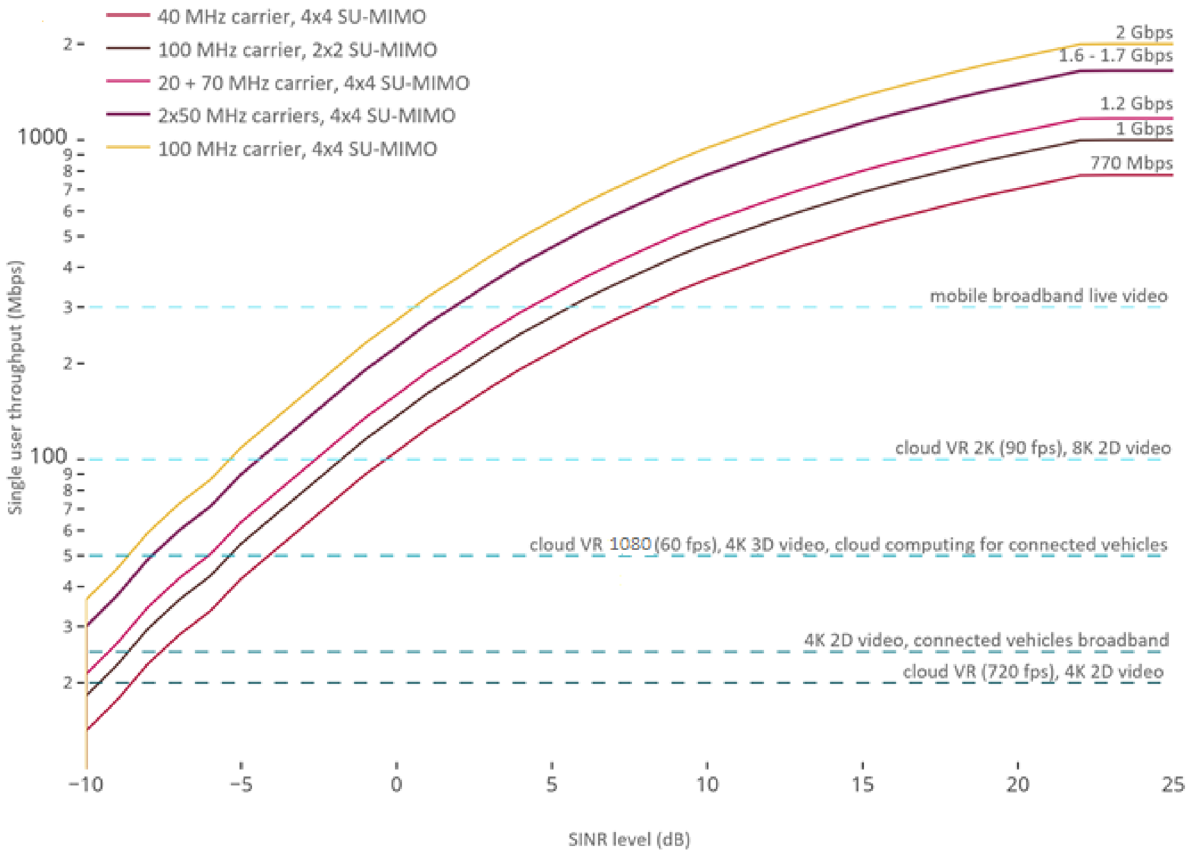
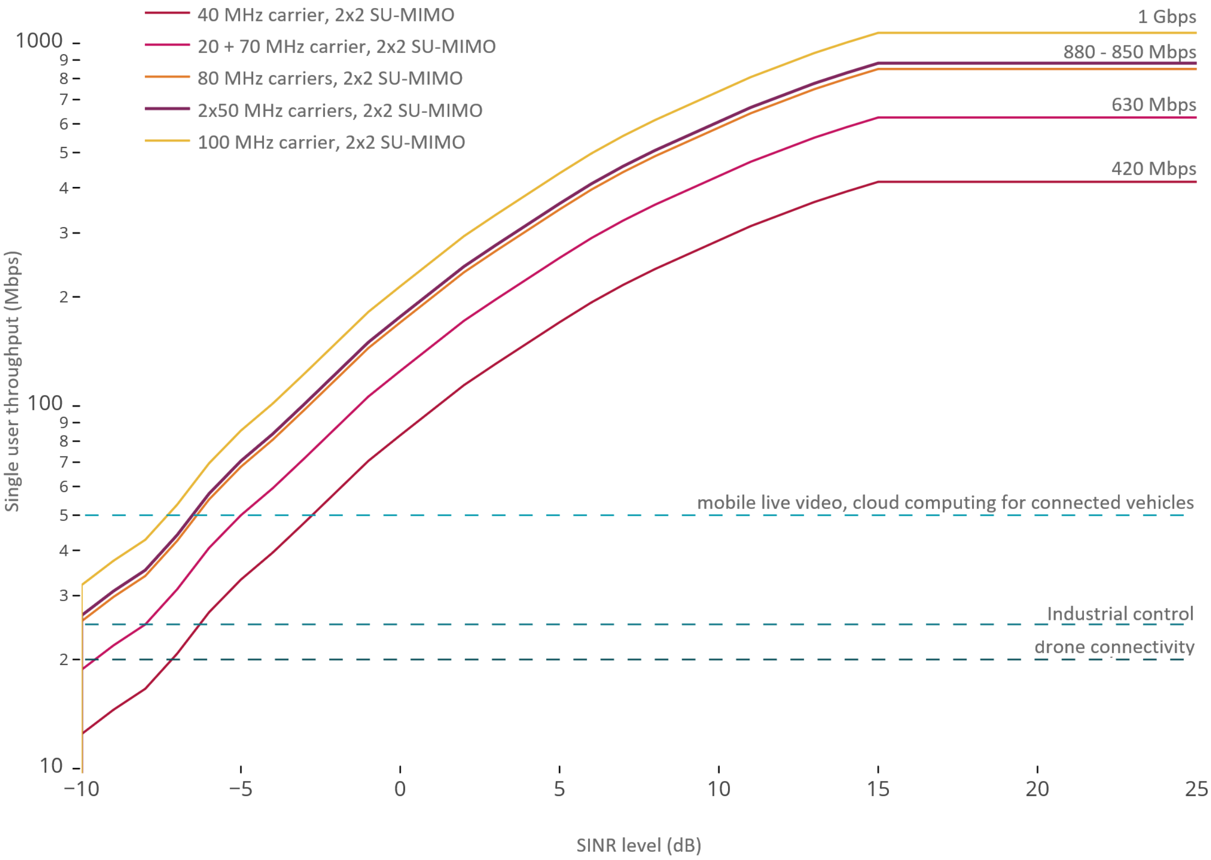


Figure A7.27 Uplink Single User Throughput (SUT) across different signal strengths in a cell compared with the minimum data rate requirements for some 5G services



A7.62 We note that ECC CEPT Report 287 says that "it is important for licensees to have access to large contiguous channels, supporting a variety of applications with high data rates and/or low latency and improved user experience" and that "as expressed by industry, large bandwidths of 80-100 MHz contiguous spectrum are important to deliver high throughput 5G services in the 3400-3800 MHz frequency band." We acknowledge that 80 to 100 MHz of contiguous spectrum may make it easier to support some 5G services, however, it is not a requirement to have access to 80 to 100 MHz contiguous bandwidth to deliver a wide range of 5G services.

A7.63 We note that the IMT-2020 vision as set out by the ITU says that 5G technologies must be able to support 100 MHz spectrum, but does not say that this spectrum needs to be contiguous, nor does it say that this amount of spectrum is necessary for a 5G service. [372]

A7.64 We agree with O2's throughput estimates (*only 940 Mbps maximum speed would be achievable in a 50 MHz carrier when compared to 1,875 Mbps for a contiguous 100 MHz block*). But, as this model shows, even a 40 MHz carrier would deliver sufficient throughput to support a wide range of 5G services as envisaged by 3GPP, in both downlink and uplink.

[372] ITU IMT 2020 and beyond https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx

A7.65 We agree with Vodafone when it argues that greater bandwidth can enable [✂ REDACTED].[373] However, we do not consider this bandwidth necessarily needs to be contiguous; as our model shows, there is only a modest loss in the data rates when multiple carriers are used rather than a single frequency carrier. We consider it likely that operators will be able to aggregate their existing spectrum[374] to have larger bandwidths available to sustain a certain quality of service across the cell and we discuss this next.

If future services require 80-100 MHz spectrum, it is likely that operators will be able to aggregate this bandwidth using their existing holdings

We said that operators may be able to aggregate 80-100 MHz of fragmented spectrum using carrier aggregation or dual connectivity to provide a mobile service

A7.66 In the December 2018 consultation,[375] we said that we believed that all MNOs had a long-term route to offer a wide range of 5G services even if they failed to acquire any spectrum in this auction, acknowledging that the MNOs had told us that it was desirable to have 80-100 MHz of contiguous spectrum to offer 5G services. We said that[376] 5G NR had been designed with carrier aggregation in mind so that operators could 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 expected inter-band aggregation (aggregation between different frequency bands, for instance 3.4-3.8 GHz with 1800 MHz or 2.6 GHz bands) to be supported in devices at a relatively early stage.

A7.67 We said that operators could use dual connectivity 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 a 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. However, we also acknowledged that 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.

A7.68 Further, we stated that 5G NR could be deployed on separate non-contiguous carriers within the 3.4-3.8 GHz band to increase the overall capacity of a cellular site even without intra-band carrier aggregation. From our discussions with mobile operators we understood that the capacity penalty might be in the range of 2–15% when using two non-contiguous bands compared with a single contiguous band of the same total amount of spectrum. This includes losses to additional guard bands and additional signalling overheads.[377] We also

[373] [✂ REDACTED] and [✂ REDACTED].
[374] By either using inter-band or intra-band carrier aggregation or dual connectivity.
[375] Ofcom December 2018 consultation, paragraph 5.222.
[376] Ofcom December 2018 consultation, paragraph A7.47.
[377] 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 additional signalling when using non-contiguous intra-band

acknowledged that it might be more difficult to use active antenna systems on fragmented spectrum, particularly when those spectrum fragments were far from one another in frequency, and we address this issue towards the end of this annex.

Stakeholders broadly agreed with our assessment that spectrum could be aggregated but said there was uncertainty around when aggregation of specific frequency bands would be available and that we had underestimated the performance and cost penalties

A7.69 In its response to the December 2018 consultation, O2 said that, although already included in the current standards, it was uncertain whether particular carrier aggregation band combinations would be implemented in devices and that past evidence suggested that it might be only available in high end devices, especially at first.[378] O2 also stated that [✂REDACTED] and that [✂REDACTED].[379]

A7.70 In its response to the December 2018 consultation, Vodafone said that aggregation of uplink carriers was not usually supported in user terminals, as there were many complex technical issues to overcome. As a result, the user experience delivered for interactive services over fragmented spectrum will be inferior because the uplink peak speeds would be lower than could be delivered over larger blocks of contiguous spectrum. [380]

It remains uncertain whether operators would need 80 to 100 MHz of spectrum to provide future services, but it is likely that operators will be able to aggregate that amount of spectrum from across their existing spectrum holdings

A7.71 We consider that it remains uncertain that future, as yet unknown, 5G services will require 80-100 MHz of spectrum. However, we continue to consider that even if 80-100 MHz of spectrum is required for some of these services then this spectrum does need to be contiguous.

A7.72 5G NR has been designed to use multi-band connectivity over many different frequencies and spectrum bands to deliver services[381] For example, the first 5G rollouts by operators use a non-standalone mode[382] which requires at least one 4G carrier to be used in conjunction with a 5G carrier.

A7.73 5G NR has been designed to make optimal use of wide bandwidths, however, 5G NR has a flexible design which can make use of channel bandwidths as small as 10 MHz in

---

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.

[378] O2 non-confidential response to the December 2018 consultation, paragraph 157.

[379] [✂ REDACTED].

[380] Vodafone non-confidential response to the December 2018 consultation, page 13 and [✂ REDACTED].

[382] 3GPP 5G NR and LTE carrier aggregation and dual connectivity combinations https://www.3gpp.org/DynaReport/38-series.htm Accessed 19/02/2020.

[382] Ericsson Non-standalone and Standalone: two standards-based paths to 5G https://www.ericsson.com/en/blog/2019/7/standalone-and-non-standalone-5g-nr-two-5g-tracks Accessed 19/02/2020.

3.4-3.8 GHz.[383] We note that contiguous intra-band carrier aggregation in 3.4-3.8 GHz has already been included in the 3GPP standards[384] and that non-contiguous intra-band carrier aggregation in 3.4-3.8 GHz is likely to be supported in Release 16. [385]

A7.74 We acknowledge that there remains some uncertainty about if or when these aggregation features will be supported by devices, however, mobile operators have the ability to influence the design choices that chipset manufacturers and device manufactures make. 5G NR carrier aggregation is more spectrally efficient than LTE because it has been designed as a multi-connectivity technology with lower control overheads and narrower guard bands (around 2% compared to 10% for an LTE carrier).

A7.75 We acknowledge that there is some capacity loss tied to using smaller bandwidth carriers when compared with using a single contiguous channel of the same bandwidth. However, we believe consumers may not notice this capacity loss in the first years of 5G rollout when demand will be low, and that operators have many options to expand capacity in the longer term including selective densification in the areas where additional capacity is needed or off-loading into licence-exempt bands using technologies including Wi-Fi.

A7.76 We agree some complex carrier aggregation combinations using several bands at the same time may only be available in high-end devices at first, however, the number of supported carrier aggregation combinations is growing. The GSMA reported that there are more than 250 mobile networks worldwide using some type of carrier aggregation and that more than 20% of mobile processors and platforms support four or more component carrier combinations.[386]

A7.77 We understand that carrier aggregation is more commonly used in the downlink than the uplink because uplink aggregation comes with additional complexity including greater battery drain associated with each component carrier and the need to avoid intermodulation product generation. However, currently most mobile traffic occurs in the downlink, and forecasts point that this trend will continue in the future.[387]

A7.78 We note that Nokia says that 5G is the first radio system designed to support any spectrum between 400 MHz and 90 GHz and that this wide range of spectrum options is needed to provide the combination of high capacity, high data rates, ubiquitous coverage and ultra-high reliability. [388] Nokia states that the aggregation of the different spectrum bands from sub-1 GHz to mmWave will give the optimal combination of coverage, capacity and user data rates.[389]

[383] And 5 MHz in other frequency band, such as 800 MHz or 1800 MHz.
[384] Release 15.2 of 3GPP 38.104.
[385] 3GPP TS 38.101-1 V16.1.0 (2019-09).
[386] GSMA Gigabit LTE: Global status May 2019 Accessed 05/12/2019.
[387] Traffic asymmetry forecast show The DL dominates with around 80-90% of data traffic while UL contributes around 20-10%. From ITU IMT traffic estimates for the years 2020 to 2030 https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2370-2015-PDF-E.pdf
[388] 5G New Radio Network, Nokia https://onestore.nokia.com/asset/205407 Accessed 02/03/2020.
[389] 5G new radio networks. https://onestore.nokia.com/asset/205407 Accessed 02/03/2020.

A7.79 BT/EE said in its June 2019 BT/EE technology business briefing[390] that 5G is being added as a supplement to 4G capacity in areas where BT/EE is deploying 5G. BT/EE is combining it with at least three 4G carriers and, in some cases, even four or five 4G carriers. BT/EE is targeting speeds of 150 Mbps when using its 5G and 4G networks together, compared with 30 Mbps when using its 4G network alone.[391] We also note some commercially available devices including Samsung S10 support dual connectivity between LTE and 5G NR bands.[392]

A7.80 Contrary to Vodafone's views, we consider that the absence of switching of demand between bands in the international auctions does not mean these bands are not substitutes.

A7.81 In summary, whilst we have no evidence of any 5G services requiring at least 80 to 100 MHz (contiguous or otherwise) to deliver 5G, all MNOs will likely have access to at least 80 MHz of spectrum that can eventually be used for 5G over the next few years, or use their existing 4G spectrum to deliver some of these services. As we explain earlier in this document, we expect devices to support 5G NR in most mobile bands soon.

Deployment costs and performance penalties in the 3.4-3.8 GHz band

We acknowledged practical deployment concerns could arise from deploying more than one carrier in the 3.4-3.8 GHz band, but said that these did not present a material risk to competition

A7.82 In the December 2018 consultation, we said that we understood that there could be some practical deployment concerns when there was a large frequency separation between non-contiguous spectrum blocks.[393] At the time of publication, vendors and operators were suggesting that 5G base station equipment including active antenna systems might have an instantaneous bandwidth of approximately 100 MHz.[394] Instantaneous bandwidth (IBW) is important for deploying on fragmented spectrum because it represents the maximum separation between the lowest and highest frequencies that can be supported by a single radio unit. They reported that this might increase to 200 MHz (or slightly more)[395] within the following years but it was unclear when, or if, active antenna systems would support

[390] BT/EE June 2019 business briefing, https://www.btplc.com/Sharesandperformance/Financialreportingandnews/Quarterlyresults/2018-2019/Consumerbusinessbriefing/Downloads/Slides/ConsumerBusinessBriefingpresentationMay2018.pdf Accessed 17/09/2019.
[391] BT/EE Technology business briefing https://www.btplc.com/Sharesandperformance/Financialreportingandnews/Quarterlyresults/2019-2020/Technologybusinessbriefing/Downloads/Slides/Technology-BusinessBriefing-25June-final.pdf Accessed 05/12/2019
[392] See annex 4 for more information about the 3.4 – 3.8 GHz band.
[393] December 2018 consultation, paragraph A7.48
[394] Responses from two operators to further technical questions, [✂ REDACTED], and an e-mail from a vendor, [✂ REDACTED].
[395] Responses from [✂ REDACTED] operators, [✂ REDACTED]; three equipment vendors [✂ REDACTED]; and two component manufacturers, [✂ REDACTED].

the whole 3.4-3.8 GHz band with a single antenna.[396] We said that there might also be demand for active antennas which span more than 300 MHz[397] and this would encourage manufacturers to produce such equipment and/or improve their products to offer solutions that avoid deploying multiple active antenna units.

A7.83 Although we said we did not see any insurmountable technical challenges in achieving active antenna systems spanning 300 MHz, we acknowledged that there might be technical challenges with producing active antennas that could 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. Our view then was that active antennas spanning the full 400 MHz were unlikely to be available in the near future.

A7.84 We also said that it would be difficult for MNOs to share active antennas because they might have different deployment strategies and that there were also some technical barriers. 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 manner. We stated we expected these limitations to be inherent to the early stage of the new technology and that they would reduce in the future as the technology developed and matured. As a result, we said that MNOs would need to deploy additional equipment to use fragmented spectrum and that could come with performance and cost penalties.

A7.85 The next section summarises the responses to our December 2018 consultation and our updated view, including what mitigations could be used to reduce the deployment costs when using fragmented spectrum.

---

[396] 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]; [✂ REDACTED].
Another operator reported that one of their equipment suppliers considered that 400 MHz might be supported in [[✂ REDACTED];[✂ 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] ✂ REDACTED] and [✂ REDACTED] saying that it could be possible by [✂ REDACTED], [✂ 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] [✂ 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] [✂ REDACTED] or [✂ REDACTED] [✂ REDACTED].

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

Some stakeholders agreed with our assessment, but others said that the costs associated with deploying equipment using fragmented spectrum could be significant

A7.86 BT/EE agreed with our judgement about the costs associated with operating spectrum blocks far apart in frequency in the 3.4-3.8 GHz band but argued that the auction process should encourage and facilitate defragmentation of the 3.4-3.8 GHz band.[398]

A7.87 In its response to the December 2018 consultation, O2 said that fragmented spectrum would trigger higher deployment costs that would limit the total potential deployment of 5G. O2 said that it would need to deploy additional equipment to deploy two carriers in fragmented spectrum, which might not be feasible in some sites due to lack of space or planning permission. Even for the sites where deployment was possible, capex would be higher than usual as specialist base station equipment would be required.[399]

A7.88 O2 agreed with our timeline on the availability of the instantaneous bandwidth of AAS technology.[400] According to O2, vendors' roadmaps do not include AAS equipment with an IBW of more than 200 MHz and it considered that equipment with an IBW of 300 MHz would not be available until 2022 at the earliest. O2 acknowledged that other MNOs with fragmented holdings in 3.4-3.8 GHz in other countries could generate greater demand for this type of equipment, however, it also observed that countries in Europe are actively seeking defragmentation of the 3.4-3.8 GHz band. It also acknowledged that other countries such as Australia and the US could push demand for equipment with a large IBW; however, it cautioned that this equipment might not be suitable for use in Europe.[401] O2 said that it might be able to acquire bespoke equipment but that this would likely come with a cost premium of [✂ REDACTED].[402]

A7.89 O2 submitted additional information about the incremental costs associated with deploying equipment using fragmented spectrum in the 3.4-3.8 GHz band as part of its response to the June 2019 consultation.[403] O2 provided a cost model, which it had used to estimate that deploying 5G using fragmented spectrum might cost it an additional [✂ REDACTED][404] when compared with a deployment using the same amount of contiguous spectrum.

A7.90 The O2 cost model estimates the additional expenditure required to overcome the a [✂ REDACTED] capacity loss that it estimates it would incur as a result of deploying when using fragmented spectrum compared with deploying using the same amount of

[398] BT/EE non-confidential response to the December 2018 consultation, paragraph 4.1 to paragraph 4.4 reiterated in [✂ REDACTED]
[399] O2 non-confidential response to the December 2018 consultation, paragraph 156b.
[400] O2 non-confidential response to the December 2018 consultation, paragraph 157.
[401] O2 non-confidential response to the June 2019 consultation, paragraph 8.
[402] O2 confidential response to the July 2019 Defragmentation of spectrum holdings in the 3.4-3.8 GHz band, paragraph 23.
[403] Consultation: Defragmentation of spectrum holdings in the 3.4-3.8 GHz band https://www.ofcom.org.uk/consultations-and-statements/category-3/defragmentation-spectrum-holdings
[404][✂ REDACTED]

contiguous spectrum. [✂ REDACTED].[405] The additional costs are calculated considering a deployment using fragmented spectrum across [✂ REDACTED] sites with active antenna equipment and [✂ REDACTED] sites with passive antenna equipment.[406]. O2's model shows that the costs associated with replacing this lost capacity are [✂ REDACTED] in discounted terms over [✂ REDACTED] when the spectrum fragments span more than [✂ REDACTED] and [✂ REDACTED] in discounted terms over [✂ REDACTED] when the spectrum fragments span less than [✂ REDACTED].

A7.91 The costs for when the spectrum fragments span more than [✂ REDACTED] are higher because O2 said that, in the short term, this might require two sets of radio equipment to be deployed on a site in order to make use of both spectrum fragments. In the longer term, O2 said that both spectrum fragments might be used with one piece of radio equipment but that this piece of equipment would likely be more expensive if the spectrum fragments span more than [✂ REDACTED] than if they were closer together in frequency or contiguous. The model's unit cost assumption for an active antenna with IBW of [✂ REDACTED] is [✂ REDACTED] higher than for one with IBW of [✂ REDACTED], and the corresponding difference in cost between passive antennas with IBWs of [✂ REDACTED] and [✂ REDACTED] is [✂REDACTED].

A7.92 In its response to the December 2018 consultation, Vodafone explained[407] that the available instantaneous bandwidth of antenna equipment in the 3.4-3.8 GHz band may not have a wide enough span to aggregate spectrum at both the top and bottom of the band. Vodafone said [✂ REDACTED].[408]

A7.93 We consider that O2's assessment of the scale of the costs associated with fragmented spectrum are likely to present a pessimistic view for the reasons set out below. We therefore do not infer from this analysis that the costs of fragmentation would be so significant that they would necessarily have an impact on competition.

A7.94 O2 assumes that fragmented spectrum will result in a [✂REDACTED] capacity loss when compared with the same amount of contiguous spectrum and [✂REDACTED].

A7.95 O2 assumes [✂REDACTED] capacity loss when compared using the same amount of contiguous spectrum which is [✂REDACTED] of the 2-15% we considered in our December 2018 consultation and [✂REDACTED] of the 7-15% which O2 itself considers reasonable. Taking [✂REDACTED] therefore represents a [✂REDACTED] approach to replacing the capacity which might be lost as a result of having fragmented spectrum.

A7.96 We consider that the model underlying O2's cost estimates does not consider the ability of O2 to relieve any congestion by taking their full spectrum portfolio into account, for example, by refarming 2G and 3G bands to 4G or 5G or selective densification. It was also unclear to what extent O2 considered whether some sites in some areas might have

[405] [✂ REDACTED]
[406] [✂ REDACTED]
[407] Vodafone non-confidential response to the December 2018 consultation, page 15].
[408] Vodafone confidential response to the December 2018 consultation, page 14 and [✂ REDACTED]

sufficient capacity even in the longer term and whether new site build was necessary to meet consumer demand in these areas. O2 acknowledged that [✂ REDACTED].[409]

A7.97 A further source of potential pessimism is that O2 assumes that equipment with an IBW of greater than [✂ REDACTED]. The costs of future equipment remain uncertain, and wider bandwidth equipment might remain more expensive, but we consider it reasonable to expect that the costs of wider bandwidth equipment might reduce over time, especially the costs of active antenna systems which are a relatively new technology.

A7.98 We also note that O2 and Vodafone have announced a network sharing agreement[410] to speed up their 5G deployments and lower costs. Under this agreement, each party will install its own equipment on 25% of sites in busy urban areas, however, they will share some equipment at the rest of their sites. We note that the cost estimates that O2 has submitted as part of its response to the July 2019 consultation do not factor in this sharing agreement, and as such we consider that these estimates present a more pessimistic view of the costs derived to deploy new 5G sites or upgrading the existing ones.[411]

A7.99 The estimated additional costs could also be considered to be relatively modest [✂ REDACTED].

A7.100 Notwithstanding our view on O2's assessment of the scale of the costs, we also note that [✂REDACTED] of the costs estimated by O2's model is driven by the cost of antenna systems with an IBW of greater than [✂ REDACTED]. Overall, therefore, while O2's model supports the view that an MNO could enjoy material efficiencies if any new spectrum block it acquires in the auction process were contiguous with its existing holdings in the 3.4-3.8 GHz band, it would also enjoy some of those benefits by limiting the total span of frequencies of its final holdings in the band to 200 MHz. We have described this as spectrum with "proximity" elsewhere in this statement.

We now understand that it may be possible to manufacture active antenna systems with an IBW of 400 MHz but they might be more expensive

A7.101 According to the evidence we now have, base station equipment supporting up to 400 MHz of instantaneous bandwidth is currently in test in trial phases.[412] In particular, [✂ REDACTED].[413] [414] Additionally, [✂REDACTED].[415] [✂ REDACTED].[416] But there are no

---

[409] O2 confidential response to the October 2019 consultation, page 28.
[410] Vodafone and o2 finalise 5G UK network agreement https://newscentre.vodafone.co.uk/press-release/vodafone-and-o2-finalise-5g-uk-network-agreement/ and Vodafone extends ultrafast 5G to more UK cities and towns https://www.ispreview.co.uk/index.php/2020/01/vodafone-extend-ultrafast-5g-mobile-to-more-uk-cities-and-towns.html Accessed 29/01/2020
[411] O2 and Vodafone 5G network sharing agreement plans, Accessed 27/11/2019. https://www.rcrwireless.com/20190724/5g/uk-carriers-vodafone-o2-ink-network-sharing-deal-5g
[412] According to evidence from [✂ REDACTED]
[413] [✂ REDACTED]
[414] [✂ REDACTED] and with
[415] [✂ REDACTED]
[416] Emails exchanged between [✂ REDACTED]

clear plans from manufacturers to supply a commercial product until, at least, 2022. [✂REDACTED].[417]

A7.102 In the light of the evidence above, we believe that active antenna systems with an IBW of 300 MHz might be available in the future, but that this design is not included in many equipment manufacturers' roadmaps.[418] We now understand that it may be possible to manufacture active antenna systems with an IBW of 400 MHz[419], but we understand this type of equipment may be challenging to deploy or use and costlier, especially if it is designed for a small pool of operators.

A7.103 Another way to deploy active antenna equipment covering 400 MHz could be to "split mode" antennas where the antenna elements in a single antenna panel are assigned to two different logical RF chains (for example, a 64T64R antenna system split into two 32T32R logical chains). "Split-mode" allows for a single antenna system to use the entire 3.4-3.8 GHz band with two logical RF chains, each with an IBW covering separate 200 MHz spectrum blocks. This technique, however, comes with a coverage performance penalty of [✂REDACTED] and a capacity loss of [✂REDACTED], however, this capacity loss could be lower outside of dense, high-rise areas.[420] According to [✂REDACTED]. We understand that split-mode antenna equipment is already available for operators and that some operators are already considering the use of split-mode equipment in some of their sites in the first 5G roll-outs.[421]

In summary, we consider that operators have ways to deploy and use non-contiguous spectrum in the 3.4 – 3.8 GHz band but it could be more expensive to do so

A7.104 Based on the evidence we have, we understand that, in the absence of any mitigation techniques, non-contiguity might result in higher deployment costs and reduced user experience of 5G services, at least for a time. However, based on the evidence we have, we do not believe this will prevent an operator from offering a wide range of 5G services, as there are ways to deploy and use non-contiguous spectrum carriers in the 3.4-3.8 GHz band, as we describe earlier in this section.

A7.105 At the same time, we think that capacity demands will gradually increase over time, when other technical features may become available to cope with increased demand demand.

A7.106 In the short term, we expect (i) operators to deploy 5G gradually, beginning in areas where data demand is greater rather than nationwide; (ii) some of the services that are considered 5G services for competition (i.e. mobile broadband and Fixed Wireless Access) could be also delivered by technologies like 4G; and (iii) operators can use different

[417] Meeting with [✂ REDACTED]
[418] A ban on the use of Huawei equipment might delay the deployment of such technology [✂ REDACTED] but we do not think the impact would be significant enough to change our assessment.
[419] In conversations with one RF component manufacturer [✂ REDACTED] and two equipment vendors [✂ REDACTED] and [✂ REDACTED].
[420] paragraph 2.5.1, "5G Implementation Guidelines", GSMA, July 2019, Accessed 27/11/2019. https://www.gsma.com/futurenetworks/wp-content/uploads/2019/03/5G-Implementation-Guideline-v2.0-July-2019.pdf
[421] From at least one vendor, [✂ REDACTED].

techniques to reduce the costs of operating non-contiguous spectrum, such as "split-mode" antennas.

A7.107 In the long term, from around 2022, although tied to an increased level of uncertainty around what 5G services will be important to competition, we expect that (i) operators will likely have access to 80-100 MHz of spectrum useable for 5G and may be able to aggregate this spectrum, should it become necessary; and (ii) antenna equipment spanning the entire 3.4-3.8 GHz band will likely become available.

A8. Coexistence issues for the 3.6-3.8 GHz band

Introduction

A8.1 In this annex we present our technical coexistence analysis relating to the 3.6-3.8 GHz band. Much of this analysis was also presented in our December 2018 consultation, which assessed the interference risk from mobile networks operating in the 3.6-3.8 GHz band to fixed links in the same band, as well as to fixed links and satellite earth stations in the 3.8-4.2 GHz band.

A8.2 In line with the December 2018 consultation, we present the following studies:

a) In-band coexistence studies: We conducted an analysis to identify the areas where base stations are likely to cause co-channel interference to the Isle of Wight to Portsmouth fixed link which operates in-band centred in 3740 MHz during the interim period.

b) Adjacent band coexistence studies: We conducted a technical coexistence analysis to identify the adjacent band interference risk from mobile networks operating directly below 3.8 GHz to satellite earth stations and fixed links operating in the 3.8-4.2 GHz band.

Coexistence with other services in the 3.6-3.8 GHz band during the interim period

A8.3 As set out in Section 9 of the December 2018 consultation[422], we have served notices of variation or revocation of existing satellite and fixed links authorisations in the 3.6-3.8 GHz band. However, there will be a period of time between the award of the spectrum and these variations and revocations coming into effect within which we will need to maintain protection for these users. We have decided to adopt the same process as 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 this interim period.

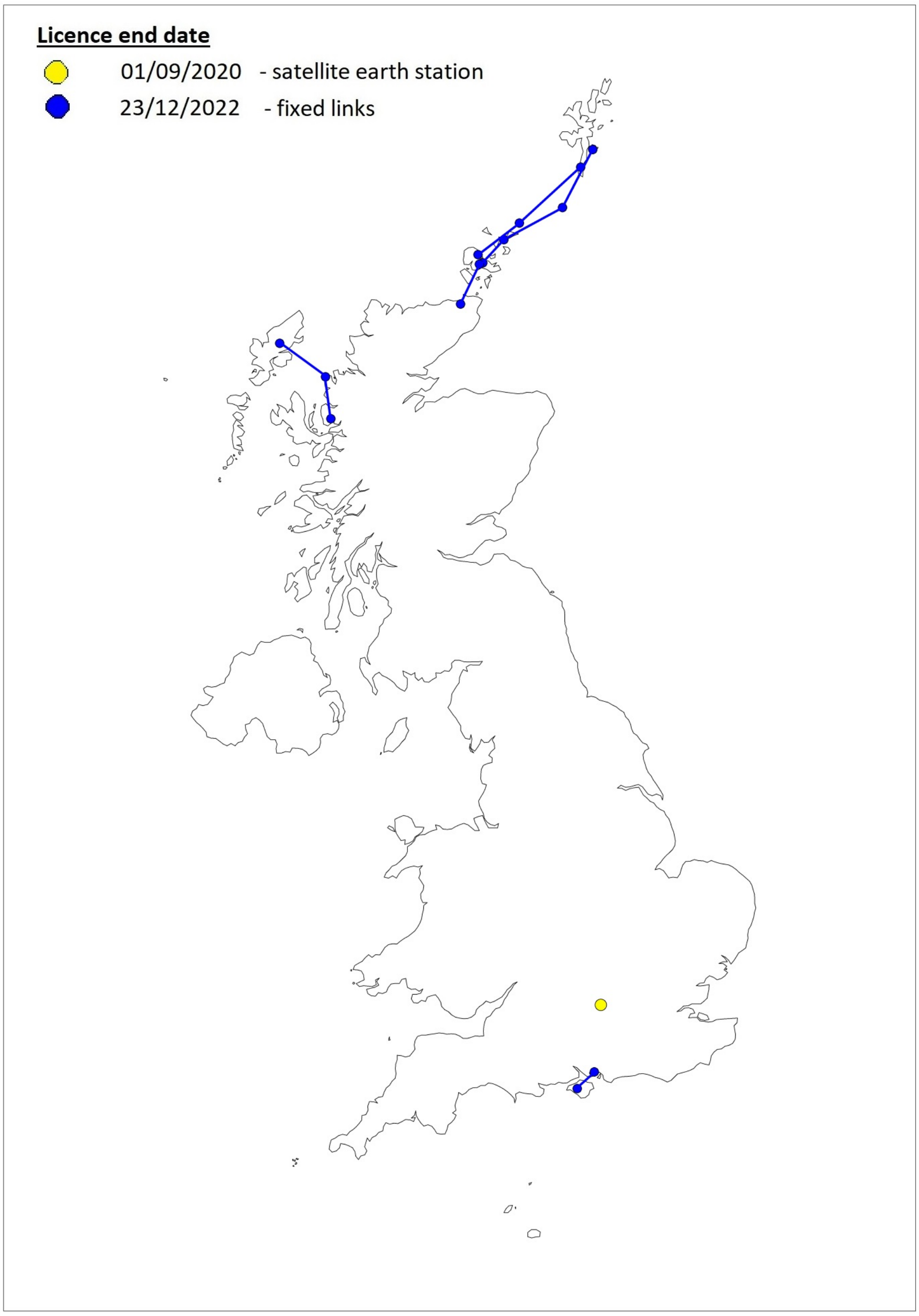
A8.4 While interim protections for satellite earth stations are currently only expected to last for a few months after the spectrum award, the interim protections for fixed links may remain for a longer period[423]. We have therefore looked in more detail at the potential constraints that these interim protections may place on early base station deployments.

[422] December 2018 consultation document: https://www.ofcom.org.uk/__data/assets/pdf_file/0019/130726/Award-of-the-700-MHz-and-3.6-3.8-GHz-spectrum-bands.pdf

[423] We have engaged with the stakeholders in the band and we believe these fixed links are likely to remain until their licence expires in December 2022. We include details of the protection requirements in the award Information Memorandum.

A8.5 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.

Figure A8.1: Locations of the remaining earth stations and fixed links during the interim period



A8.6 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 used to estimate the scale of the likely impact of the protection of this link on the deployment of mobile base stations in the interim period.

A8.7 We concluded 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 corridor 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 be deployed with minimal impact on network performance. The number of people who would normally use their phone in the area potentially affected by this link is estimated to be c.500,000.

Analysis overview

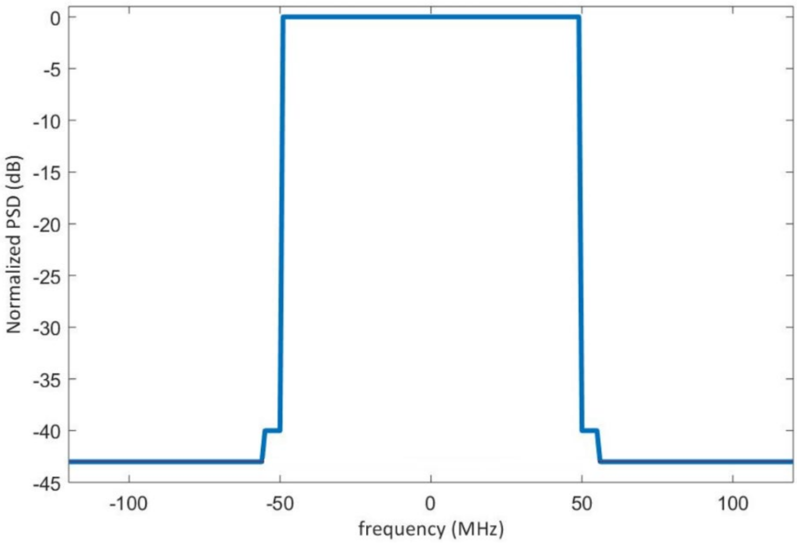
A8.8 For the purposes of the analysis, we assumed that an operator will roll out a 3.6-3.8 GHz network using its existing mid-frequency cell site grid. We have derived our input assumptions based on a national macrocell deployment.[424] Table A8.1 summarises the antenna and base station parameters we have assumed in our analysis and Figure A8.2 illustrates the emissions mask used.

Table A8.1: Parameters used for the coexistence in the 3.6-3.8 GHz band analysis

Parameter	Value
Location and height above ground of base station	These are both based on information we have about an MNO’s 2.1 GHz 3G base station grid
Down tilt and azimuth values for each base station sector	
Carrier frequency	3740 MHz
Carrier bandwidth	100 MHz
In-block EIRP	44 dBW[425]
EIRP emissions mask	The same as the one used for the UKB 3.6 GHz coordination see Figure A8.2

[424] Data extracted from Q4 and Q5 from Ofcom’s information request, June 2018.
[425] 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.

Figure A8.2: Emissions mask used in our analysis



A8.9 We conducted an 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:

- within 50 km of the fixed link receiver (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).

A8.29 We focused our 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.

A8.30 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.

A8.31 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 hypothetical national macrocell deployment within the two areas.

A8.32 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 have decided to use for actual coordination in the interim period until the band is fully cleared.

A8.33 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. EIRP, 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 A8.1 and the parameters of the fixed link were derived from the ETSI SEC 5 type[426]. The power received at the fixed link from the base station sector was calculated using the ITU-R P.452.10[427] propagation model with clutter from Infoterra© 50m resolution maps. We assumed 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 assumed it would be likely to create harmful interference to the fixed link. The failure margin is the difference between the received signal level and the interference threshold.

A8.34 The base station sectors that, under the test assumptions, exceeded the interference criteria for the fixed link were flagged along with the interference exceedance levels.

A8.35 We 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 considered that measures such as using a lower transmit power can, in many cases, be effective without being overly constraining.[428] Higher failure margins (e.g. 10 dB or greater) presented situations where it is likely to be difficult to mitigate, and therefore, it might not be practical to deploy those sectors without significantly affecting their performance or coverage.

A8.36 It should be noted that we only considered single entry interference, rather than the aggregate effect of all base station sectors, which is also the basis for the existing coordination process for UK Broadband.

Results

A8.37 Table A8.2 shows the number of sectors that failed to meet the interference criteria and the failure margin for both areas in our analysis.

Table A8.2: Summary of results for areas A and B

Location[a]	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

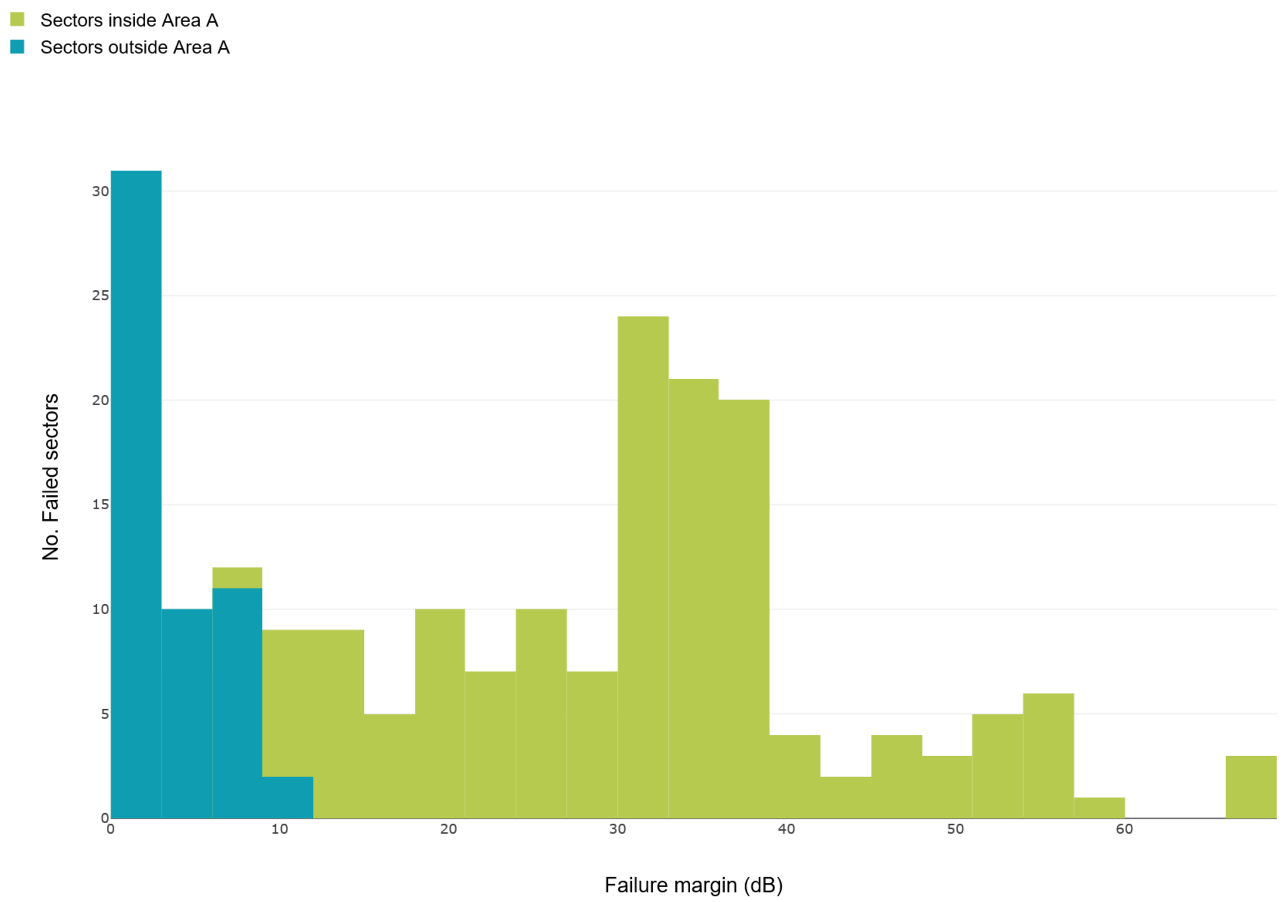
[a] Area A is within 50 km of the fixed link receiver

Area B is within 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.

[426] See https://www.etsi.org/deliver/etsi_en/302200_302299/30221702/03.00.08_20/en_30221702v030008a.pdf
[427] See https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.452-10-200102-S!!PDF-E.pdf
[428] Given that we believe that the 74 dBm 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.

A8.38 Figure A8.3 shows the distribution of the failure margin of the sectors that failed to meet the interference criteria.

Figure A8.3: Histogram of the failure margins for sectors in areas A and B



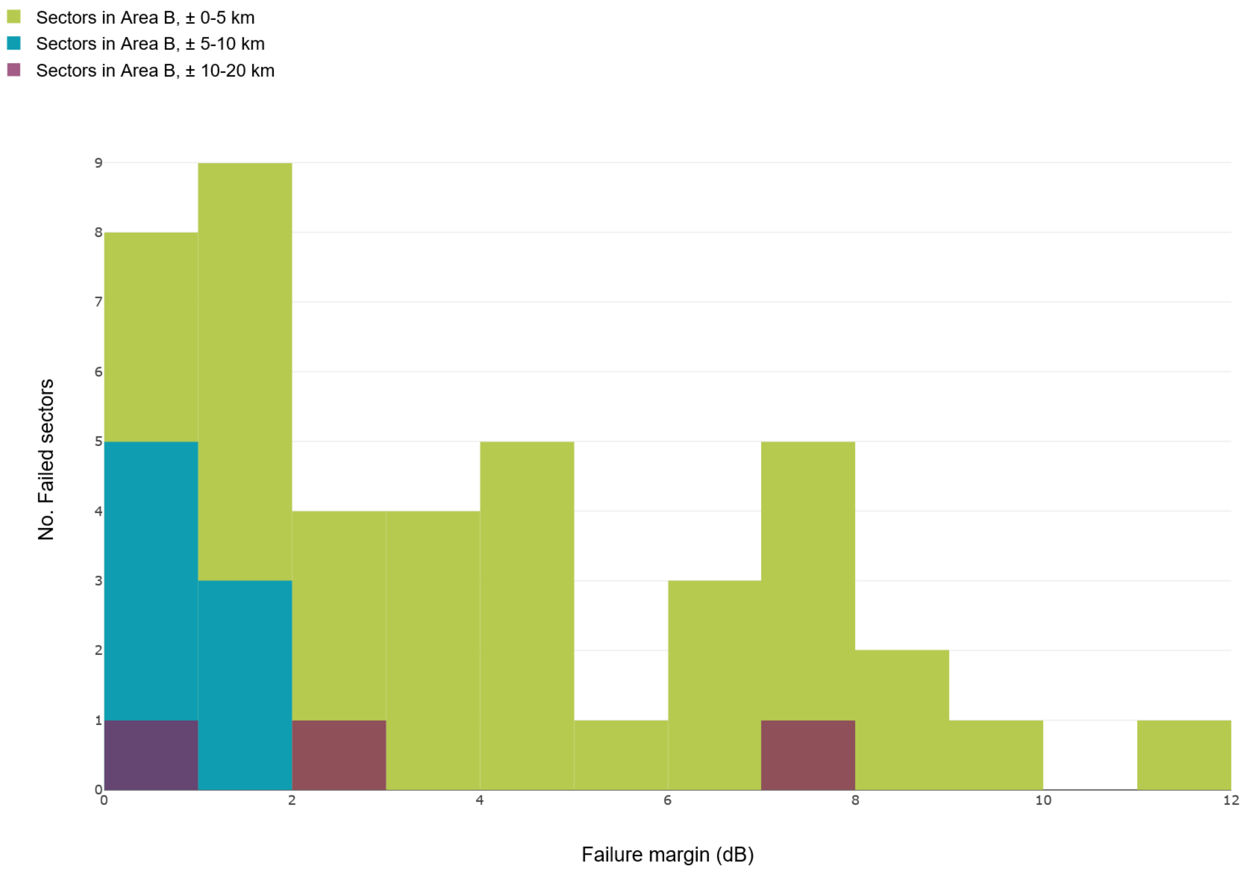
A8.39 Table A8.3 provides more details on the results for sectors located within Area B, i.e. for sectors located ±0-5 km, ±5-10 km and ±10-20 km either side of the extended boresight line. Note that sectors in Area A are not included in these results.

Table A8.3: 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	9 %	~ 3 dB
±5-10 km	412	8	2 %	~ 1 dB
±10-20 km	615	3	0.5 %	~ 3 dB

A8.40 Figure A8.4 shows the distribution of the failure margin.

Figure A8.4: Histogram of the interference failure margin values for sectors in Area B



A8.41 Sectors located further away from line of the extended boresight presented a lower likelihood of exceeding the interference threshold.

Conclusions

A8.42 Based on the in-band analysis that was described above, we have concluded that the relevant spectrum will be useable across a significant proportion of the UK both during and after the interim period.

Coexistence with services above 3.8 GHz

Our approach to coexistence modelling considered both a single dominant potential interferer and aggregate emissions from a nationwide mobile network

A8.43 We 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.

A8.44 We assessed the interference risk using two approaches as follows:

1. **Analysis considering a single dominant source of potential interference**: with this approach we have assessed the interference risk from a hypothetical mobile base station (BS) under two sets of assumptions:

1.1 **Worst case:** where we assessed the area around each satellite earth station or fixed link receiver over which a base station transmitting at maximum power and pointing in boresight to the satellite earth station or fixed link could cause interference above a specific threshold. We then determined the interference contour (i.e. the geographic boundary within which a base station could cause interference) around the location of each satellite earth station or fixed link receiver.

1.2 **Conservative case:** where we assumed an additional margin of 15 dB relative to our worst case assumptions based on our knowledge of current mobile network deployments. This margin takes account of a combination of factors that increased the overall losses towards the satellite earth station or fixed link receivers, such as antenna down tilt, azimuth pointing offsets, beamforming losses as well as a transmit power which is lower than the maximum regulatory limit. These are all more in line with values we observe in real networks, but still represent a conservative case when taken together.

2. **Analysis considering single entry and aggregate emissions from a potential nationwide macrocell deployment**: in a similar way to 3.6-3.8 GHz the December 2018 consultation, we modelled a potential future UK-wide macrocell deployment, based on our understanding of the likely characteristics of potential 5G networks in the band.[429] We then assessed the interference within a radius of 70 km from each satellite earth station and fixed link receiver, to produce an estimate of the number of base station sectors that could potentially cause interference to these satellite earth stations and fixed links.

A8.45 For the two approaches, we have conducted analysis for base stations using active antenna systems (AAS) and those using non-active antenna systems (non-AAS).

Our analysis considered both worst case and conservative assumptions

Table A8.4: Assumptions: worst case analysis considering a single dominant source of interference

	Values for non-AAS BS	Values for AAS BS
Base station 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.
In-block EIRP	65 dBm/ 5 MHz[430]	64 dBm/ 5 MHz[431]
Bandwidth	20 MHz[432]	

[429] See also Annex 5 in Ofcom, “Improving consumer access to mobile services at 3.6GHz to 3.8GHz”, July 2017.
[430] See also Annex 19 “Award of the 700MHz and 3.6-3.8 GHz spectrum bands”
[431] See also Annex 19 “Award of the 700MHz and 3.6-3.8 GHz spectrum bands”, EIRP based on assumption of an 4x8 antenna
[432] The bandwidth of 20MHz was assumed as a reference bandwidth for the coexistence studies. In practice out of band emissions from modern broadband radio technologies do not depend on the carrier bandwidth because of improvements in power amplifier linearisation techniques.

	Values for non-AAS BS	**Values for AAS BS**
EIRP OOB emissions 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 values are calculated based on the generic formula specified in ECC Report 281[433]. We have used *Pmax* = 71 dBm / 20 MHz EIRP for non-AAS and *Pmax* = 70 dBm / 20 MHz EIRP for AAS systems. The OOBE EIRP emission levels for AAS 5G BS were calculated assuming a 20 dBi system antenna gain when on boresight.	
BS antenna	Recommendation ITU-R M.2101[434] 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	
Antenna tilt	-2 degrees	
Antenna height	20m	
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 Use	Ofcom 50m terrain and land use databases.[435] 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 A8.5: **Assumptions for single entry and aggregate emissions from a potential nationwide macrocell deployment**

	Value for non-AAS and AAS 5G BS
Base station position and deployment	Deployed in an area centred on each SES or FL within a radius of 70km
In-block EIRP	A range of In-block EIRP values were 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.

[433] See also Table 18 ECC Report 281: https://www.ecodocdb.dk/download/5ffb56c9-9c78/ECCRep281.pdf
[434] See ITU-R Recommendation M.2101-1, February 2017, https://www.itu.int/rec/R-RECM.2101/en
[435] We used a legacy terrain/clutter database developed from the Technical Computing team of the Radiocommunications Authority in 2013.

	Value for non-AAS and AAS 5G 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.[436] As input for the *Pmax* parameter of the formula, we used the in-block EIRP value.
ECC AAS mask:	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 in-block TRP value which we derived for each BS, based on our knowledge of existing mobile network deployments and converting this to a TRP value for AAS by assuming that AAS might typically have a gain of 20 dBi.
Flat 60 dBc AAS mask:	In our analysis for the potential risk of interference to FL above 3815 MHz, we used an OOB emission mask for AAS BS, based on our knowledge from discussions with equipment manufacturers. This mask assumed a flat 60 dBc attenuation above 3815 MHz.
Bandwidth	20 MHz
BS antenna	Recommendation ITU-R M.2101[437] 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.

[436] See also Table 18, ECC Report 281: https://www.ecodocdb.dk/download/5ffb56c9-9c78/ECCRep281.pdf
[437] 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

A8.46 As we did in our previous consultations on this band (see for example our October 2016 consultation and our July 2017 statement[438]), we have assessed coexistence accounting for both 'long term'[439] interference (single-entry and aggregate) and interference during anomalous propagation periods, referred to as 'short term' interference[440] (single-entry)[441]. We have used the same interference thresholds[442] that we currently use to provide benchmark spectrum quality. Being consistent with our in-band analysis for the 3.6-3.8 GHz band[443], the propagation models used are: Recommendation ITU-R P.1812-4[444] to assess coexistence against the long-term interference criterion; and Recommendation ITU-R P.452-16[445] to assess coexistence against the short-term interference criterion.

A8.47 It should be noted that our main analysis focussed 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.

Adjacent band coexistence analysis with Satellite Earth Stations (SES)

A8.48 In the following paragraphs, we present the results of our interference assessment analysis for satellite earth stations. We analysed four of the thirteen satellite earth stations in the band and we chose these four stations because they have assignments at the 3.8 GHz band edge and therefore they would most likely be affected by adjacent band coexistence issues.

[438] "Improving consumer access to mobile services at 3.6 to 3.8 GHz", Ofcom, 6 October 2016, https://www.ofcom.org.uk/__data/assets/pdf_file/0035/91997/3-6-3-8ghz-consultation.pdf; and "Improving consumer access to mobile services at 3.6GHz to 3.8GHz", Ofcom, 26 October 2017, https://www.ofcom.org.uk/__data/assets/pdf_file/0019/107371/Consumer-access-3.6-3.8-GHz.pdf

[439] Long term interference thresholds are used to manage the interference conditions for a receiver that will occur most of the time.

[440] 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.

[441] We note that in our analysis for the interim protection zones we only considered the single-entry interference risk. This is because the existing coordination processes and tests that are followed using the in-house tool do not include assessment of aggregate interference.

[442] 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 protection criteria for fixed link licences are detailed in OfW446.

[443] 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

[444] https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.1812-4-201507-I!!PDF-E.pdf

[445] https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.452-16-201507-I!!PDF-E.pdf

Satellite earth station modelling parameters

A8.49 The satellite earth station parameters for the assignments we considered have been taken directly from the relevant licences and are presented in Table A8.6 below.

Table A8.6: Satellite Earth Station modelling parameters

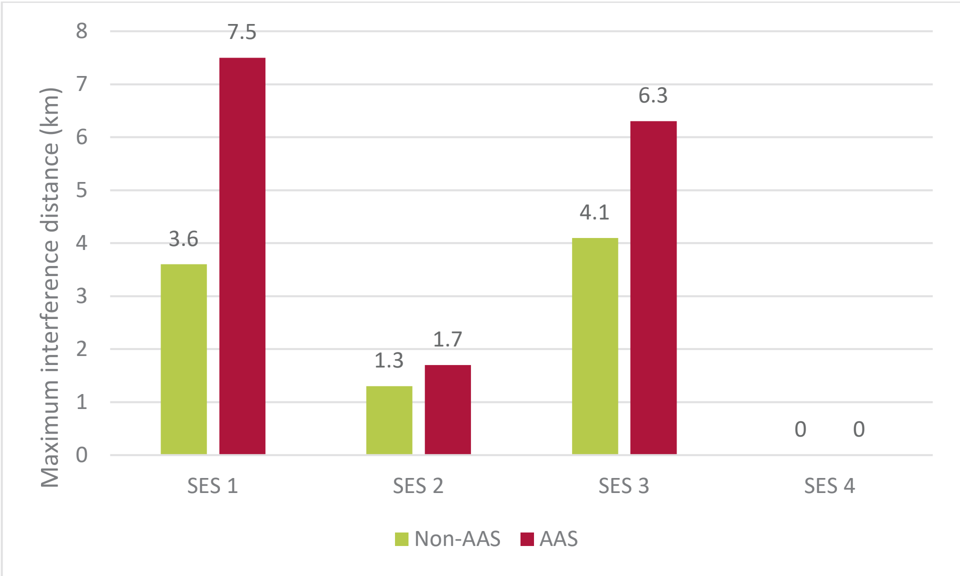
Satellite Earth Station	SES 1	SES 2	SES 3	SES 4
Antenna Gain (dBi)	54.9	49.2	54.2	48.1
Beamwidth (°)	0.28	0.51	0.44	0.58
Antenna pattern[446]	ITU-R S.580-6	ITU-R S.580-6	ITU-R S.580-6	ITU-R S.580-6
Antenna height (m)	16	5	9	2
Noise Temperature (K)	[✂ REDACTED]	[✂ REDACTED]	[✂ REDACTED]	[✂ REDACTED]
Elevation angle (°)	6	19	24	20
Azimuth (°)	110	217	218	227
Centre Frequency (MHz)	3830.5	3800.256	3801.25	3810.5
Bandwidth (MHz)	61	0.512	1.1	21

Analysis considering a single dominant source of potential interference

A8.50 In the figure below, we summarise the results obtained with a worst case area analysis when assessing coexistence against long-term interference

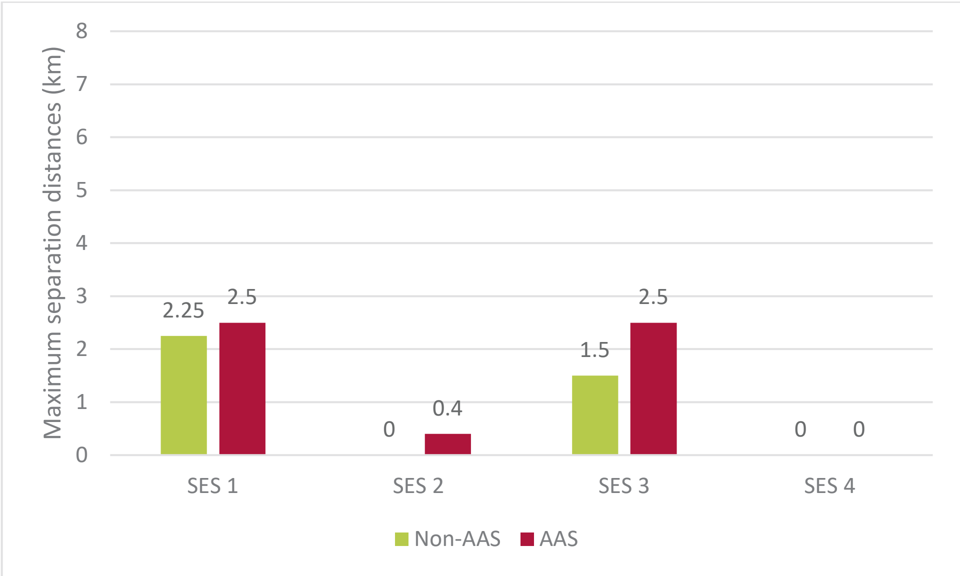
[446] See also Recommendation ITU-R S.580-6: Radiation diagrams for use as design objectives for antennas of earth stations operating with geostationary satellites https://www.itu.int/dms_pubrec/itu-r/rec/s/R-REC-S.580-6-200401-I!!PDF-E.pdf

Figure A8.5: Chart of the satellite earth station worst case area analysis results using long term protection criteria



A8.51 We also considered a conservative scenario, where we assumed a reduction of 15 dB in received power, to represent a combination of mitigating factors which are more representative of real mobile networks. These factors include increased antenna down tilt and azimuth pointing offset, beamforming gain and reduced transmit power, as well as a more realistic out-of-band emissions levels. Based on our knowledge of the parameters of existing mobile deployments, as well as our knowledge of typical out-of-band emissions values from equipment vendors, we estimate that the strength of the signals from real 5G base station deployments, into satellite earth station or fixed link receivers could be up to 20-25 dB less power compared to our worst case assumption. We therefore consider that a reduction of 15 dB compared with the worst case scenario still represents a conservative scenario. The results for the analysis considering this conservative scenario are summarised in Figure A8.6 below.

Figure A8.6: Chart of the SES conservative case area analysis results using long term protection criteria



A8.52 In Figures A8.6 and A8.7 we show the interference contours for SES 1 and SES 3 when considering base stations using active antenna systems. On the left side of each of the two Figures we show the interference contour under worst case assumptions (corresponding to the results in Figure A8.5), whereas on the right side we consider the conservative scenario (corresponding to the results in Figure A8.6).

Figure A8.7: SES 1 worst case (left) and conservative case (right) interference contour for AAS

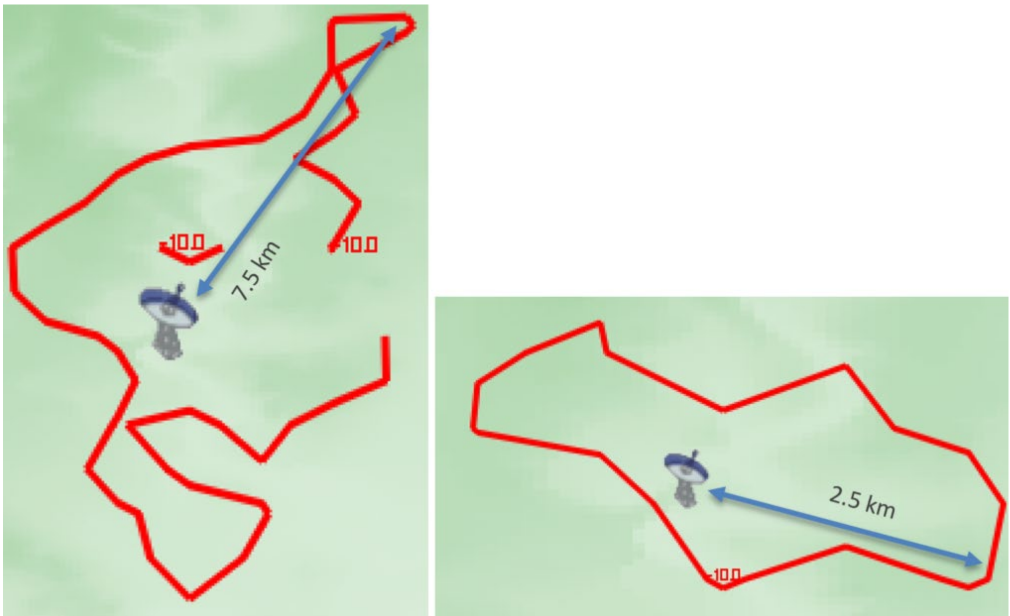
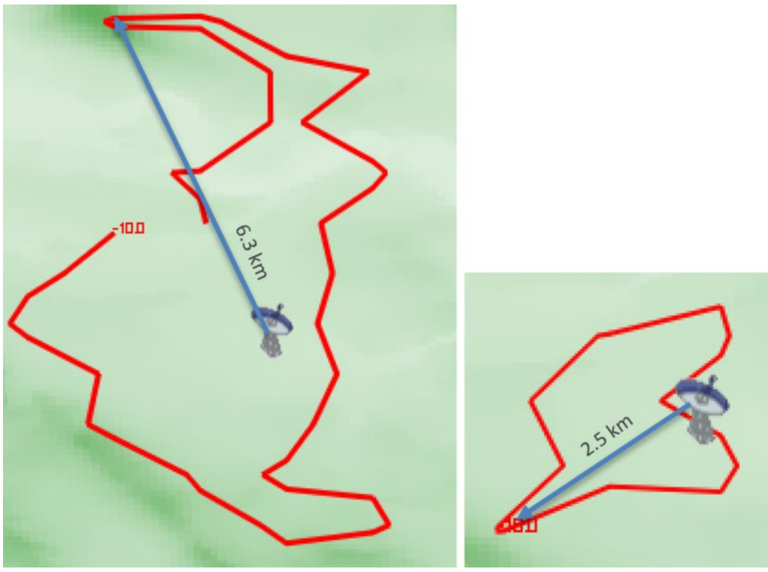


Figure A8.8: SES 3 worst case (left) and conservative case (right) interference contour for AAS



Analysis considering aggregate emissions from a potential nationwide macrocell deployment

A8.53 We assessed interference considering a potential macrocell deployment and the results for both non-AAS and AAS are presented in Table A8.7 below, showing the number of base station sectors causing interference above the threshold.

Table A8.7: Number of interfering BS sectors within 70km of each SES

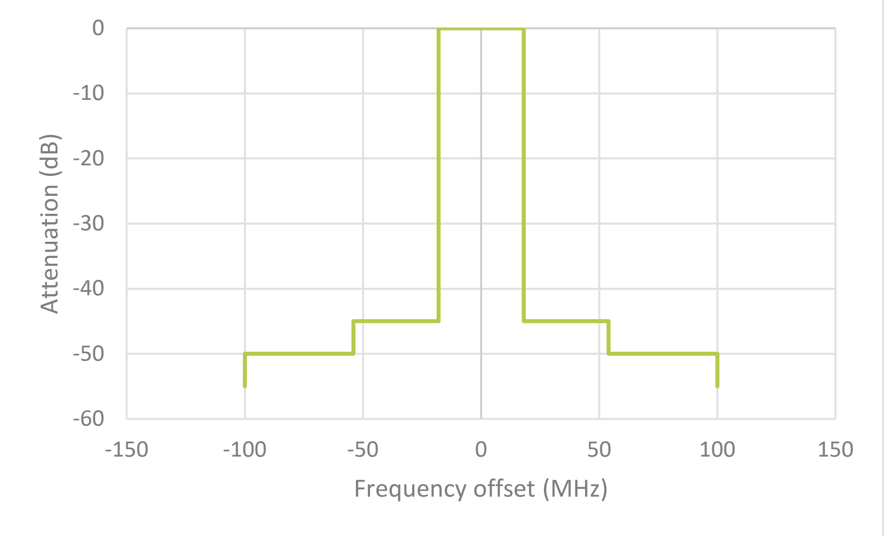
Satellite **Earth Station**	Long-term single entry		Short-term single entry		Long-term aggregate	
	Non-AAS	AAS	Non-AAS	AAS	Non-AAS	AAS
SES 1	1	3	1	6	1	3
SES 2	0	0	2	4	0	0
SES 3	0	0	0	0	0	0
SES 4	0	0	0	1	0	0

Analysis considering satellite earth station receiver blocking and the selectivity of satellite earth station receivers

A8.54 To provide a more complete assessment of the interference risk as well as to consider the potential benefits of receiver filtering, we also conducted a sensitivity analysis taking into account the effect of receiver selectivity.

A8.55 The results in Table A8.8 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 an area analysis and one considering a typical macrocell deployment. We are unaware of any standards for the adjacent channel selectivity performance of satellite earth station receivers so we have considered the ACS mask shown in Figure A8.9. This mask is taken from ITU-R SG04 contribution 78[447] and we believe it is a reasonable approximation of satellite earth station receiver selectivity. All other parameters are the same as those used under the conservative case assumptions of our area analysis and typical macrocell deployment.

Figure A8.9: Assumed adjacent channel selectivity performance for C-band SES receivers.



A8.56 Comparison of the results in Table A8.7 with Table A8.8 shows that there is a small increase in the interference impacts when the effect of receiver selectivity is taken into account.

Table A8.8: Analysis including the effect of receiver sensitivity

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

[447] 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

We consider that satellite earth station operators can protect themselves from blocking by installing suitable filters to improve the selectivity of their receivers.

A8.57 We carried out a blocking analysis at the 3.6 GHz boundary as part of the previous 2.3/3.4 GHz award[448] and we consider the result of that analysis also applies to the 3.8 GHz boundary.

A8.58 The analysis previously carried out for the 3.6 GHz boundary suggested that there was some potential risk of interference to satellite earth stations above 3.6 GHz with separation distances up to about 8 km from a base station operating below 3.6 GHz.

A8.59 We identified several commercially available high pass filters with a pass band above 3.8 GHz. We also identified several commercially available filters with a pass band above 3.7 GHz which appear to be more commonly available and all the 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.

A8.60 Therefore, we consider it reasonable to assume that satellite earth station operators can protect their receivers from blocking by retro-fitting filters appropriate for their protection requirements.

A8.61 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 filter can mitigate the interference effect. Examples of such filters are listed in the table below.

Table A8.9: 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

Conclusions

A8.62 Based on our analysis, we concluded that satellite earth station operators can protect their services from blocking using filters available in the market.

[448] Ofcom, Public Sector Spectrum Release, Technical coexistence issues for the 2.3 and 3.4 GHz award, February 2014.

Fixed links modelling parameters

A8.63 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 3.8 GHz band edge. We considered fixed links where the receivers were located near populated areas. The modelling parameters for the fixed link assignments were taken directly from the relevant licences and are presented in Table A8.10.

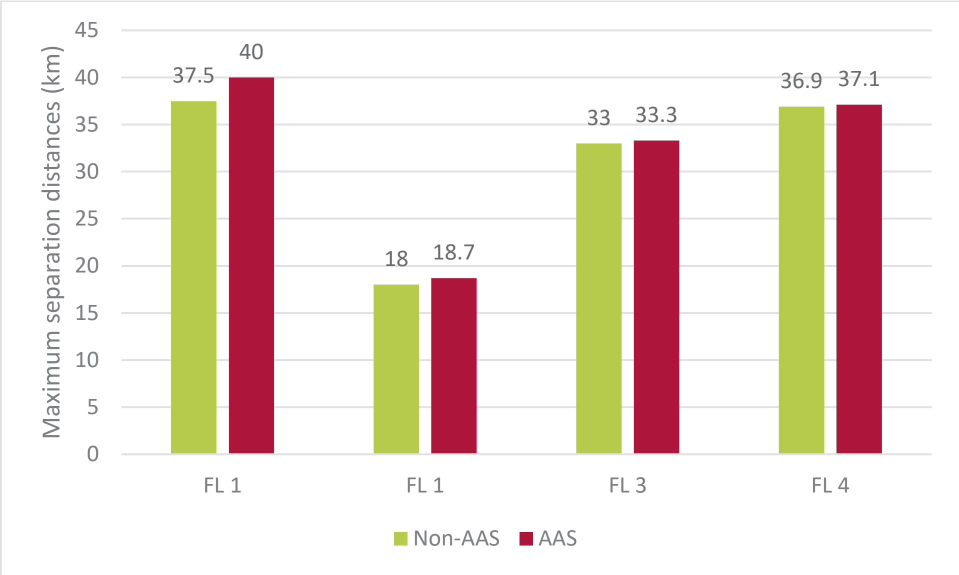
Table A8.10: Fixed Links modelling parameters

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[449]	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

[449] 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

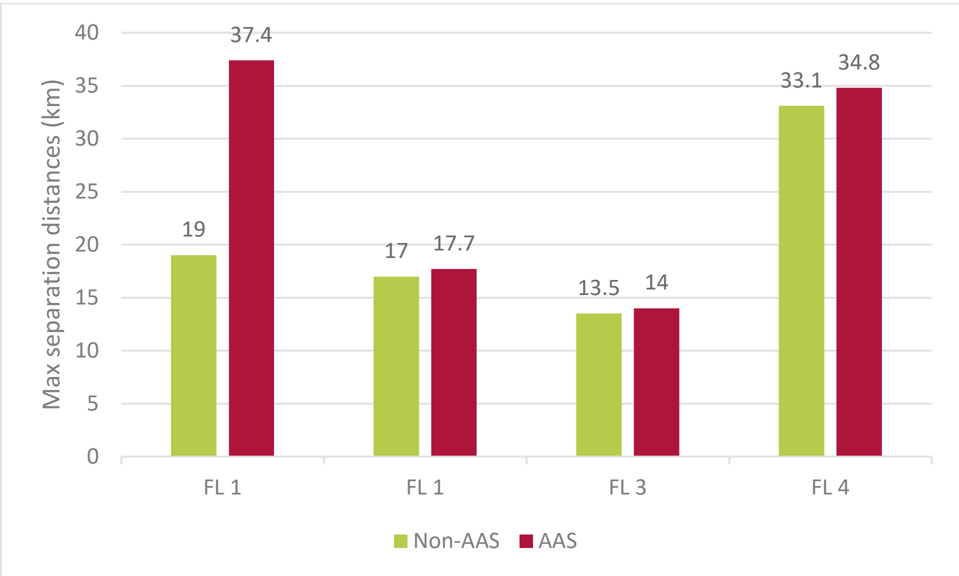
Analysis considering a single dominant source of potential interference

Figure A8.10: Chart showing fixed link area analysis results - worst case - long term criteria for a single dominant source of interference



A8.64 Following the same approach as our analysis for satellite earth stations, we also conducted an area analysis for the scenario using conservative parameters and the results are shown in Figure A8.11.

Figure A8.11 Chart showing FL area analysis results – conservative case - long term criteria for a single dominant source of interference



A8.65 The maximum interfering distances shown in Tables A8.9 and A8.10 are larger than those we observed for satellite earth stations. This is because the fixed link antennas cannot benefit from elevation angle like satellite earth stations can to reject terrestrial interfering signals. We can see that the interference contour follows the fixed link receiver boresight in Figures A8.12 and A8.13.

Figure A8.12: FL 1 worst case (top) and conservative case (bottom) interference contour for AAS

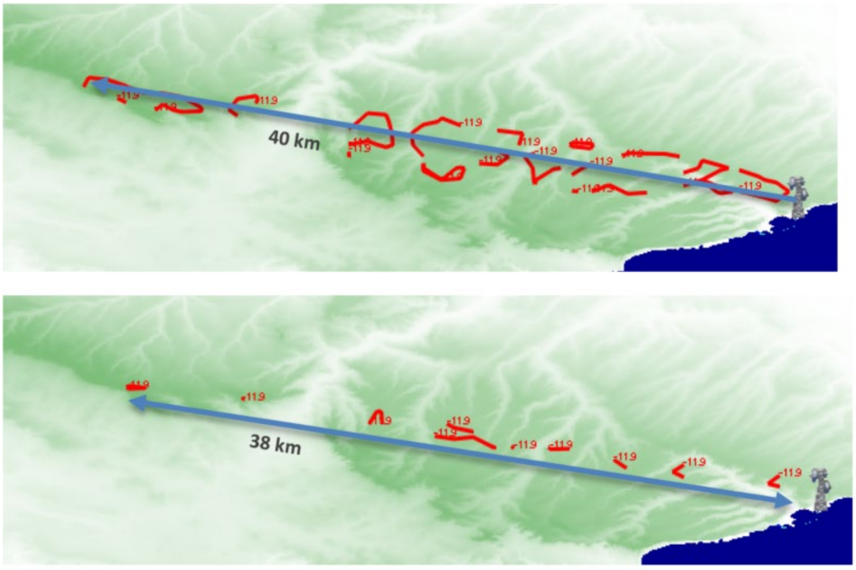
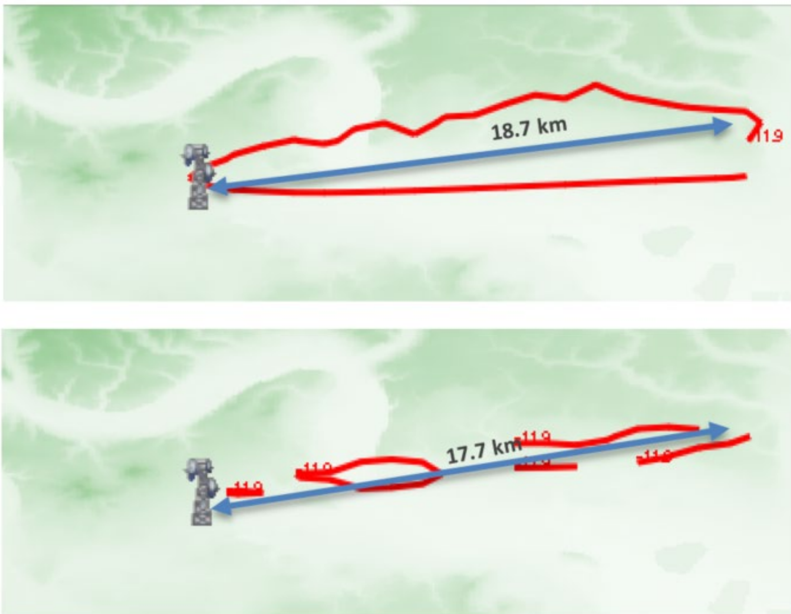


Figure A8.13: FL 2 worst case (top) and conservative case (bottom) interference contour for AAS



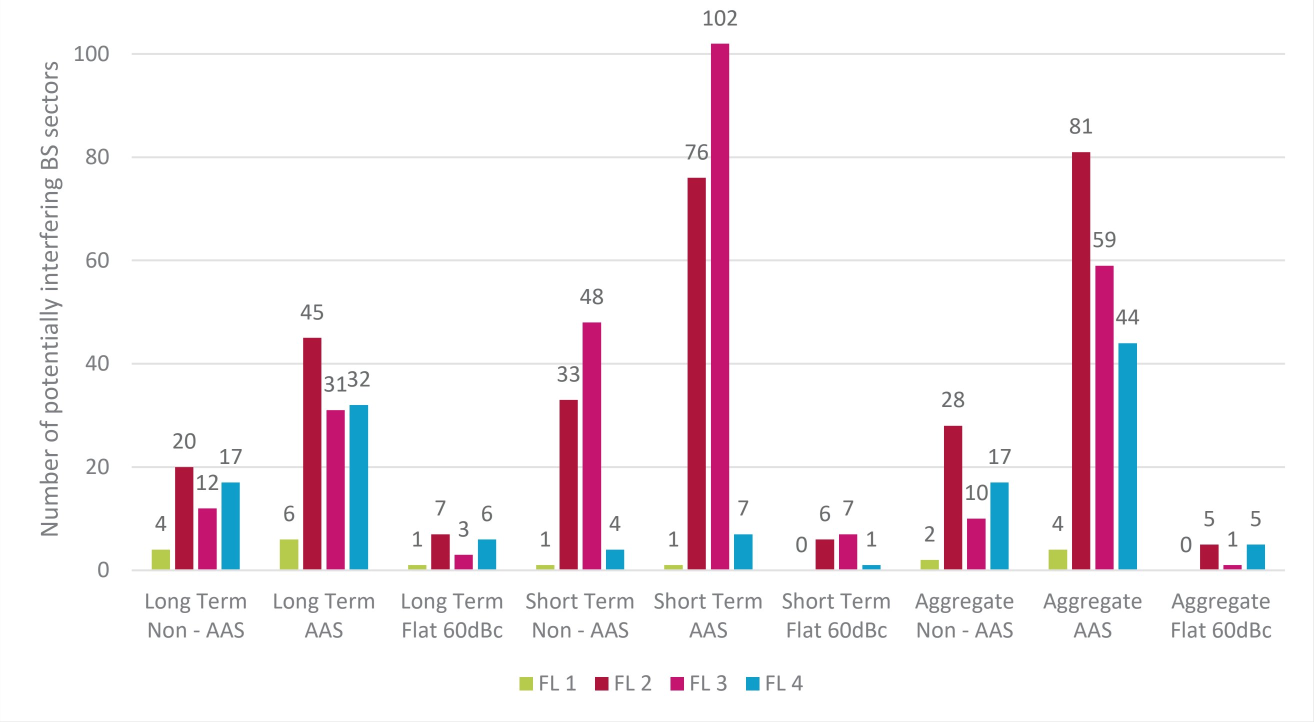
Analysis considering single entry and aggregate emissions from a potential nationwide macrocell deployment

A8.66 We then assessed interference against our example macrocell deployment and a summary of the results for both non-AAS and AAS systems is presented in Figure A8.14 below, showing the number of base station sectors causing interference above the threshold.

A8.67 We considered two different cases for the OOB emissions levels for AAS, as set out in Table A8.4: a worst case based on the ECC mask and a more realistic case, using the 'flat 60 dBc

AAS' mask, which is a mask derived from data we received from various equipment manufacturers.

Figure A8.14: Chart showing the number of potentially interfering BS sectors 70km around each FL receiver



Analysis considering potential risks of interference from a single dominant interferer and potential nationwide network to fixed link receiver

A8.68 Finally, following the same approach as for satellite earth stations, we assessed the impact of receiver selectivity.

A8.69 The results in Table A8.11 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 fixed link receivers is based on ETSI EN 302 217[450] specifications and is also used in our frequency coordination software tool. All other parameters were the same as those used in the area analysis and example macrocell deployment.

A8.70 Comparison of the results in Table A8.11 with Figure A8.11 "Chart showing FL area analysis results – conservative case - long term criteria for a single dominant source of interference" and Figure A8.12 "Chart showing the number of potentially interfering BS sectors 70km around each FL receiver" show that there is a small increase in the interference impact when the effect of receiver selectivity is taken into account.

---

[450] 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

Table A8.11: 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

A8.71 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.

Conclusions

A8.72 Based on our analysis, the potential risk of adjacent channel interference is minimal. Where the protection criteria are exceeded, the exceedance is small and so a change of the operational parameters of mobile network deployments can reduce interference to levels below the thresholds.

A9. Interface requirements for the 700 MHz band

IR 2xxx - UK Interface Requirement 2xxx

Terrestrial systems capable of providing electronic communications services in the 700 MHz band

Interface Requirement	2015/1535/EU Notification number	Date
IR 2xxx	2020/xxx/UK	xxx 2020

Contents

1. References

1.1 Decision (EU) 2017/899 of the European Parliament and of the Council of 17 May 2017 on the use of the 470-790 MHz frequency band in the Union.

1.2 Commission Implementing Decision (EU) 2016/687 of 28 April 2016 on the harmonisation of the 694-790 MHz frequency band for terrestrial systems capable of providing wireless broadband electronic communications services and for flexible national use in the Union.

1.3 ECC Decision (15)01 (06 March 2015) which harmonised technical conditions for mobile/fixed communications networks (MFCN) in the band 694-790 MHz including a paired frequency arrangement (Frequency Division Duplex 2x30 MHz) and an optional unpaired frequency arrangement (Supplemental Downlink).

1.4 CEPT Report 53 (28 November 2014) Report A from CEPT to the European Commission in response to the Mandate “To develop harmonised technical conditions for the 694 -790 MHz ('700 MHz') frequency band in the EU for the provision of wireless broadband and other uses in support of EU spectrum policy objectives”.

1.5 CEPT Report 60 (01 March 2016) Report B from CEPT to the European Commission in response to the Mandate “to develop harmonised technical conditions for the 694 -790 MHz ('700 MHz') frequency band in the EU for the provision of wireless broadband and other uses in support of EU spectrum policy objectives”.

1.6 ETSI EN 301 908: IMT cellular networks; Harmonised EN covering the essential requirements of article 3.2 of the Radio Equipment Directive (Directive 2014/53/EU).

2. Foreword

2.1 The Radio Equipment Directive (Directive 2014/53/EU) was implemented in the United Kingdom (UK) by the Radio Equipment Regulations 2017. In accordance with Articles 8 and 7 of Directive 2014/53/EU, this UK Interface Requirement contains the requirements for the licensing and use of terrestrial systems capable of providing electronic communications services in the specified frequency bands.

2.2 Nothing in this UK Radio Interface Requirement shall preclude the need for equipment to comply with Directive 2014/53/EU.

2.3 It is required by the Wireless Telegraphy Act 2006 that no radio equipment is installed or used in the UK except under the authority of a licence granted by or otherwise exempted by regulations made by Ofcom. It is a condition of such a licence or exemption regulations as appropriate that, in order to be installed or used in the UK, the equipment must meet the minimum requirements specified in this UK Interface Requirement for the stated equipment types and for the stated frequency bands. Nothing in this UK Interface Requirement shall preclude equipment from being placed on the market in the UK that complies with the 'essential requirements' specified in Directive 2014/53/EU.

2.4 The requirements given in the main body of this UK Radio Interface Requirement will apply to the licensing of terrestrial systems capable of providing electronic communications services in the 700 MHz band (694 – 790 MHz).

2.5 This UK Radio Interface Requirement will be revised as necessary, for example to follow:

i) current technology developments for reasons related to the effective and appropriate use of the spectrum in particular maximising spectrum utilisation; and

ii) changes to the available spectrum allocated for terrestrial systems capable of providing electronic communications services in the 700 MHz band.

2.6 All UK Radio Interface Requirements notified under Directive 2015/1535/EU will be published and will be made available free of charge from the Ofcom website at www.ofcom.org.uk.

2.7 Further information on this UK Radio Interface Requirement can be obtained from the technical enquiry contact given at the back of this document.

3. Minimum requirements for operation within the UK

3.1 The minimum requirements in this document are made for reasons related to the effective and appropriate use of the radio spectrum, in particular maximising spectrum utilisation.

3.2 This UK Radio Interface Requirement gives a high level description of how the spectrum in the UK is used for terrestrial systems capable of providing electronic communications services in the 700 MHz band. It does not prescribe technical interpretation of the ‘essential requirements’ of Directive 2014/53/EU.

3.3 This UK Radio Interface Requirement therefore stipulates the necessary equipment parameters for the authorisation of terrestrial systems capable of providing electronic communications services in the 700 MHz band in the UK. Tables 3.1, 3.2 and 3.3 contain the relevant equipment parameters. These, taken together with the ‘essential requirements’ detailed in Article 3(3) of Directive 2014/53/EU, constitute the minimum requirements for terrestrial systems capable of providing electronic communications services in the 700 MHz band within the UK. Nothing in this UK Interface Requirement shall preclude equipment from being placed on the market in the UK that complies with the ‘essential requirements’ specified in Directive 2014/53/EU.

3.4 The technical parameters specified in the UK Radio Interface Requirement are applied to achieve the desired level of compatibility within the spectrum for terrestrial systems capable of providing electronic communications services in the 700 MHz band and with other radiocommunications services, whilst promoting enterprise, innovation and competition.

3.5 This UK Radio Interface requirement provides the necessary technical information which facilitates access to the 700 MHz spectrum by making clear the assumptions that are made in planning the use of the spectrum for terrestrial systems capable of providing electronic communications services in the 700 MHz band in the UK. It is not the intention of this UK Radio Interface Requirement to duplicate or impose any additional ‘essential requirements’ of Directive 2014/53/EU on products. Any specified parameters within this document are for the purpose of identifying product options and not as a national de facto product requirement.

IR 2xxx.1

Table 3.1: Minimum requirements for the use of: - terrestrial systems capable of providing electronic communications services operating in the 758 – 788 MHz band		
Mandatory (1-10)		
1	Frequency band(s)	758 – 788 MHz
2	Radiocommunication Service	Mobile or Fixed service
3	Application	TRA-ECS (Terrestrial radio applications capable of providing electronic communication services)
4	Channelling	N/A
5	Modulation / Occupied bandwidth	N/A
6	Direction / Separation	Base station transmit Repeater downlink transmit Uplink / downlink separation: 55 MHz
7	Maximum Mean Transmit Power	Radio equipment must have a maximum mean power no greater than: 64 dBm / (5 MHz) EIRP per antenna
8	Channel access and occupation rules	N/A
9	Authorisation regime	WT Act licence required for base stations. repeaters and fixed installations.
10	Additional essential requirements	None
Informative (11-13)		
11	Frequency planning assumptions	EU Decision 2017/899/EU EU Decision 2016/687/EU ECC DEC (15)01 CEPT Report 53 CEPT Report 60
12	Planned changes	
13	Reference	ETSI EN 301 908
14	Notification	2020/xxx/UK
15	Remarks	

IR 2xxx.2

Table 3.2: Minimum requirements for the use of: - terrestrial systems capable of providing electronic communications services operating in the 703 – 733 MHz band		
Mandatory (1-10)		
1	Frequency band(s)	703 – 733 MHz
2	Radiocommunication Service	Mobile or Fixed service
3	Application	TRA-ECS (Terrestrial radio applications capable of providing electronic communication services)
4	Channelling	N/A
5	Modulation / Occupied bandwidth	N/A
6	Direction / Separation	Terminal station transmit Repeater uplink transmit Uplink / downlink separation: 55 MHz
7	Maximum Mean Transmit Power	Mobile or nomadic terminal stations or repeaters must have a maximum mean power no greater than: 23 dBm TRP per device* Fixed or installed terminal stations or repeaters must have a maximum mean power no greater than: 23 dBm EIRP per device* * The maximum mean power relates to the EIRP or TRP of a specific piece of Radio Equipment irrespective of the number of transmit antennas. This value is subject to a tolerance of up to + 2 dB, to take account of operation under extreme environmental conditions and production spread.
8	Channel access and occupation rules	N/A
9	Authorisation regime	Network user equipment meeting the minimum requirements outlined in this Interface Requirement is exempt from licensing provided that it meets the requirements of the relevant exemption regulations WT Act licence required for repeaters
10	Additional essential requirements	None
Informative (11-13)		
11	Frequency planning assumptions	EU Decision 2017/899/EU EU Decision 2016/687/EU ECC DEC (15)01

		CEPT Report 53 CEPT Report 60
12	Planned changes	
13	Reference	ETSI EN 301 908
14	Notification	2020/xxx/UK
15	Remarks	

IR 2xxx.3

Table 3.3: Minimum requirements for the use of: - terrestrial systems capable of providing electronic communications services operating in the 738 – 758 MHz band		
Mandatory (1-10)		
1	Frequency band(s)	738 – 758 MHz
2	Radiocommunication Service	Mobile or Fixed service
3	Application	TRA-ECS (Terrestrial radio applications capable of providing electronic communication services)
4	Channelling	N/A
5	Modulation / Occupied bandwidth	N/A
6	Direction / Separation	Base station transmit Repeater downlink transmit
7	Maximum Mean Transmit Power	Radio equipment must have a maximum mean power no greater than: 64 dBm / 5 MHz EIRP per antenna
8	Channel access and occupation rules	N/A
9	Authorisation regime	WT Act licence required for base stations. repeaters and fixed installations.
10	Additional essential requirements	None
Informative (11-13)		
11	Frequency planning assumptions	EU Decision 2017/899/EU EU Decision 2016/687/EU ECC DEC (15)01 CEPT Report 53 CEPT Report 60
12	Planned changes	
13	Reference	ETSI EN 301 908
14	Notification	2020/xxx/UK
15	Remarks	

4. Additional performance parameters

(informative)

None specified

5. Contact details

Ofcom Spectrum Licensing, PO Box 1285 Warrington, WA1 9GL

- Tel: 020 7981 3131
- Fax: 020 7981 3235
- Email: spectrum.licensing@ofcom.org.uk
- Website: http://www.ofcom.org.uk

A10. Interface requirements for the 3.6-3.8 GHz band

IR 2097 - UK Interface Requirement 2079

Terrestrial systems capable of providing electronic communications services in the 3.4 to 3.8 GHz band

Interface Requirement	2015/1535/EU Notification number	Date
IR 2097.1	2015/291/UK	February 2016
IR 2097.2	2015/291/UK	February 2016
	Date amended	January 2018
	Date amended	xxxx 2020

Contents

1. References

1.1 European Commission Decision of 21 May 2008 on the harmonisation of the 3400- 3800 MHz frequency band for terrestrial systems capable of providing electronic communications services in the Community (2008/411/EC)

1.2 Commission Implementing decision of 2 May 2014 on amending Decision 2008/411/EC on the harmonisation of the 3400 - 3800 MHz frequency band for terrestrial systems capable of providing electronic communications services in the Community (2014/276/EU)

1.3 ECC/DEC (11)06 (December 2011) which harmonised the frequency arrangements for mobile/fixed communications networks (MFCN) operating in the bands 3400 to 3600 MHz and 3600 to 3800 MHz

1.4 CEPT Report 49: Technical conditions regarding spectrum harmonisation for terrestrial wireless systems in the 3400-3800 MHz frequency band

1.5 ECC Report 203 on Least Restrictive Technical Conditions suitable for Mobile/Fixed Communication Networks (MFCN), including IMT, in the frequency bands 3400-3600 MHz and 3600-3800 MHz

1.6 ECC Report 216 on Practical guidance for TDD networks synchronisation

1.7 ETSI EN 301 908: IMT cellular networks; Harmonised EN covering the essential requirements of article 3.2 of the Radio Equipment Directive (Directive 2014/53/EU)

1.8 ECC Report 281: Analysis of the suitability of the regulatory technical conditions for 5G MFCN operation in the 3400-3800 MHz band

1.9 Commission Implementing decision (EU) 2019/235 of 24 January 2019 on amending Decision 2008/411/EC as regards an update of relevant technical conditions applicable to the 3 400-3 800 MHz frequency band

2. Foreword

2.1 The Radio Equipment Directive (Directive 2014/53/EU) was implemented in the United Kingdom (UK) by the Radio Equipment Regulations 2017. In accordance with Articles 8 and 7 of Directive 2014/53/EU, this UK Interface Requirement contains the requirements for the licensing and use of terrestrial systems capable of providing electronic communications services in the specified frequency bands.

2.2 Nothing in this UK Radio Interface Requirement shall preclude the need for equipment to comply with Directive 2014/53/EU.

2.3 It is required by the Wireless Telegraphy Act 2006 that no radio equipment is installed or used in the UK except under the authority of a licence granted by or otherwise exempted by regulations made by Ofcom. It is a condition of such a licence or exemption regulations as appropriate that, in order to be installed or used in the UK, the equipment must meet the minimum requirements specified in this UK Interface Requirement for the stated equipment types and for the stated frequency bands. Nothing in this UK Interface Requirement shall preclude equipment from being placed on the market in the UK that complies with the 'essential requirements' specified in Directive 2014/53/EU.

2.4 The requirements given in the main body of this UK Radio Interface Requirement will apply to the licensing of terrestrial systems capable of providing electronic communications services in the 3.4 to 3.8 GHz band (3400 – 3800 MHz).

2.5 This UK Radio Interface Requirement will be revised as necessary, for example to follow:

i) current technology developments for reasons related to the effective and appropriate use of the spectrum in particular maximising spectrum utilisation; and

ii) changes to the available spectrum allocated for terrestrial systems capable of providing electronic communications services in the 3.4 to 3.8 GHz band.

2.6 All UK Radio Interface Requirements notified under Directive 2015/1535/EU will be published and will be made available free of charge from the Ofcom website at www.ofcom.org.uk.

2.7 Further information on this UK Radio Interface Requirement can be obtained from the technical enquiry contact given at the back of this document.

3. Minimum requirements for operation within the UK

3.1 The minimum requirements in this document are made for reasons related to the effective and appropriate use of the radio spectrum, in particular maximising spectrum utilisation.

3.2 This UK Radio Interface Requirement gives a high level description of how the spectrum in the UK is used for terrestrial systems capable of providing electronic communications services in the 3.4 to 3.8 GHz band. It does not prescribe technical interpretation of the 'essential requirements' of Directive 2014/53/EU.

3.3 This UK Radio Interface Requirement therefore stipulates the necessary equipment parameters for the authorisation of terrestrial systems capable of providing electronic communications services in the 3.4 to 3.8 GHz band in the UK. Tables 3.1 and 3.2 contain the relevant equipment parameters. These, taken together with the 'essential requirements' detailed in Article 3(3) of Directive 2014/53/EU, constitute the minimum requirements for terrestrial systems capable of providing electronic communications services in the 3.4 to 3.8 GHz band within the UK. Nothing in this UK Interface Requirement shall preclude equipment from being placed on the market in the UK that complies with the 'essential requirements' specified in Directive 2014/53/EU.

3.4 The technical parameters specified in the UK Radio Interface Requirement are applied to achieve the desired level of compatibility within the spectrum for terrestrial systems capable of providing electronic communications services in the 3.4 to 3.8 GHz band and with other radiocommunications services, whilst promoting enterprise, innovation and competition.

3.5 This UK Radio Interface requirement provides the necessary technical information which facilitates access to the 3.4 to 3.8 GHz spectrum by making clear the assumptions that are made in planning the use of the spectrum for terrestrial systems capable of providing electronic communications services in the 3.4 to 3.8 GHz band in the UK. It is not the intention of this UK Radio Interface Requirement to duplicate or impose any additional 'essential requirements' of the Directive 2014/53/EU on products. Any specified parameters within this document are for the purpose of identifying product options and not as a national de facto product requirement.

IR 2097.1

Table 3.1: Minimum requirements for the use of: - terrestrial systems capable of providing electronic communications services operating in the 3400-3800 MHz band		
Mandatory (1-10)		
1	Frequency band(s)	3400 to 3800 MHz
2	Radiocommunication Service	Mobile or Fixed service
3	Application	TRA-ECS (Terrestrial radio applications capable of providing electronic communication services)
4	Channelling	N/A
5	Modulation / Occupied bandwidth	N/A
6	Direction / Separation	N/A
7	Maximum Mean Transmit Power	Non-AAS base station transmit Repeater downlink transmit 65 dBm / 5 MHz EIRP per cell AAS base station transmit 44 dBm / 5 MHz TRP per cell Mobile or nomadic repeater uplink transmit 28 dBm TRP * Fixed or installed terminal stations or repeaters uplink transmit 35 dBm / 5 MHz EIRP * * The maximum mean power relates to the EIRP or TRP of a specific piece of Radio Equipment irrespective of the number of transmit antennas.
8	Channel access and occupation rules	Licensee shall ensure that the Radio Equipment is operated in compliance with any Inter-operator synchronisation requirements according to the relevant Licence provisions.
9	Authorisation regime	WT Act licence required for base stations, repeaters and fixed installations.
10	Additional essential requirements	None
Informative (11-13)		
11	Frequency planning assumptions	EU Decision 2019/235/EU EU Decision 2014/276/EU

		ECC/DEC (11)06 ECC Report 203 ECC Report 216 ECC Report 281
12	Planned changes	
13	Reference	ETSI EN 301 908
14	Notification	2020/xxx/UK
15	Remarks	

Table 3.2: Minimum requirements for the use of: - terrestrial systems capable of providing electronic communications services operating in the 3400-3800 MHz band		
Mandatory (1-10)		
1	Frequency band(s)	3400 to 3800 MHz
2	Radiocommunication Service	Mobile or Fixed service
3	Application	TRA-ECS (Terrestrial radio applications capable of providing electronic communication services)
4	Channelling	N/A
5	Modulation / Occupied bandwidth	N/A
6	Direction / Separation	N/A
7	Maximum Mean Transmit Power	Mobile or nomadic terminal stations 28 dBm TRP per device* * Irrespective of the number of transmit antennas
8	Channel access and occupation rules	Licensee shall ensure that the Radio Equipment is operated in compliance with any Inter-operator Synchronisation Procedures as notified within the Licence
9	Authorisation regime	The use of mobile / nomadic terminal stations meeting the minimum requirements outlined in this Interface Requirement is exempt from licensing provided that it meets the requirements of the relevant exemption regulations.
10	Additional essential requirements	None
Informative (11-13)		
11	Frequency planning assumptions	EU Decision 2019/235/EU EU Decision 2014/276/EU ECC/DEC (11)06 ECC Report 203 ECC Report 216 Draft ECC Report 281
12	Planned changes	
13	Reference	ETSI EN 301 908
14	Notification	2020/xxx/UK
15	Remarks	

4. Additional performance parameters

(informative)

None specified

5. Contact details

Ofcom Spectrum Licensing, PO Box 1285 Warrington, WA1 9GL

- Tel: 020 7981 3131
- Fax: 020 7981 3235
- Email: spectrum.licensing@ofcom.org.uk

Website: http://www.ofcom.org.uk

A11. Illustrative auction procedures

A11.1 The illustrative procedures set out in this annex are intended to provide a description of how the spectrum award auction process will work for the proposed Simultaneous Multiple Round Ascending auction design. In the event of any discrepancy or inconsistency between this description and the rules set out in the Regulations, the Regulations will take precedence. Once the Regulations have been enacted by Ofcom and entered into legal force, they will constitute enacted UK legislation and as such will also, in the event of any discrepancy or inconsistency, take precedence to anything in this description or in the Information Memorandum.

A11.2 The language we use throughout this annex is close to the one we use in the Regulations, for ease of reference.

Lot structure

Use of frequency generic lots

A11.3 The award mechanism will consist of two distinct bidding stages. In the first stage (the 'principal stage'), the spectrum available will be offered as 'frequency-generic' lots grouped into three 'lot types'; one for each of the paired 700 MHz, unpaired 700 MHz and 3.6-3.8 GHz. Each lot will be frequency generic and will correspond (respectively) to a 2x5 MHz, 5 MHz and 5 MHz block of spectrum in the relevant frequency band. During this stage, bids will relate to a number of lots in each lot type, but not to specific frequencies within the lot type's frequency range. This first stage will allow Ofcom to determine the number of lots (i.e. the total bandwidth) to be assigned to each bidder in each band.

A11.4 The specific frequencies assigned to each winner of frequency-generic lots will then be determined in a follow-up 'assignment stage'. Ofcom will determine, for each frequency band, the potential assignment options that guarantee all winning principal stage bidders receive contiguous assignments. In the 3.6-3.8 GHz band, bidders that have won 20 MHz or less will be restricted to bidding for assignments at either the top or bottom of the band. Winning principal stage bidders in the 3.6-3.8 GHz band will also have an opportunity to negotiate their assignments, as an alternative to assignment stage bidding determining the outcome.

A11.5 In the event there are several assignment band plans in which some bidders will be assigned different frequencies, such bidders will be invited to bid for their preferred option. Winners of 3.6-3.8 GHz spectrum will also have the opportunity to negotiate their assignments, as an alternative to assignment stage bidding determining their location. Further details on the selection of assignment stage outcomes are provided in the subsection on the assignment stage below.

Lot types and spectrum packaging

A11.6 The spectrum available will be offered in three generic lot types:

a) 700 MHz paired frequency lots: This lot type will contain six 2x5 MHz lots of FDD spectrum in the frequency ranges 703-733 MHz and 758-788 MHz (700 MHz FDD);

b) 700 MHz individual frequency lots: This lot type will contain four 5 MHz lots of unpaired spectrum, suitable for providing supplemental downlink, in the frequency range 738-758 MHz (700 MHz SDL); and

c) 3.6-3.8 GHz lots: This lot type will contain twenty-four 5 MHz lots of TDD spectrum within the frequency range 3680–3800 MHz.

Eligibility points

A11.7 As explained in more detail below, the principal stage will include a rule that the number of eligibility points used by a bidder in a round cannot exceed the bidder's eligibility limit for that round.

A11.8 For this purpose, each 700 MHz FDD lot will be assigned four eligibility points, while each 700 MHz SDL and 3.6-3.8 GHz lot will be assigned one eligibility point.

A11.9 The number of eligibility points used by a bidder in a round is equal to the sum of the eligibility points associated with all the lots for which the bidder submits or maintains a bid in the round. As 700 MHz FDD lots have double the eligibility points of 700 MHz SDL and 3.6-3.8 GHz lots on a per MHz basis, bidders may increase their demand in MHz when switching from 700 MHz FDD to 700 MHz SDL or 3.6-3.8 GHz lots. If they do not increase their demand in MHz when switching from 700 MHz FDD to 700 MHz SDL or 3.6-3.8 GHz, then they will lose eligibility. Conversely, bidders switching from 700 MHz SDL or 3.6-3.8 GHz to 700 MHz FDD may have to reduce their overall demand in MHz.

A11.10 Information on how to determine a bidder's eligibility limit, and the number of eligibility points used by a bidder, is provided from paragraph A11.57 below.

Applications, initial deposit, overall bid constraint and qualification

A11.11 Applicants will be required to provide Ofcom with a range of information, by a deadline specified by Ofcom, in order to apply to participate in the auction. Amongst other things, applicants will be required to specify their existing spectrum holdings in their application, as this information will be required for the implementation of the overall spectrum cap (leading to an "overall bid constraint" for each bidder).

A11.12 Along with their application, applicants will be required to submit an initial monetary deposit of £100,000, which might be forfeited in whole or in part if the applicant subsequently breaches the Regulations.[451] Any interest on deposits will be retained by Ofcom and passed to HM Treasury.

A11.13 After the deadline for applications, Ofcom will notify each applicant of the name of every other applicant and its associates. Applicants will then need to ensure they meet bidder association rules, which will not allow for two or more associated applicants to participate in the auction. They will need to do so by a deadline specified by Ofcom, and it may be the case that some applicants have to withdraw their application to prevent another applicant from failing to qualify in the auction. Other qualification criteria to ensure that applicants are suitable to hold a licence will also apply. The provisions for qualification are similar to those used in recent awards by Ofcom, and are specified in the Regulations.

A11.14 After the deadline for complying with the bidder association rules (referred to above), Ofcom will determine which applicants qualify to participate in the auction.

A11.15 To do so, Ofcom may require additional information from specific applicants, which will need to be provided before a deadline specified by Ofcom.

A11.16 Following the last day for withdrawals from the award, Ofcom will determine the list of qualified applicants (i.e. bidders), and return the initial deposit to any applicants who fail to qualify. Only qualified applicants will be allowed to participate in the auction.

A11.17 Before the first round of the auction takes place, each bidder will need to provide an additional deposit to Ofcom of at least £900,000, which will determine the bidder's initial eligibility limit. This is in addition to the initial monetary deposit of £100,000 referred to above. The initial eligibility limit will determine the maximum number of bids that the bidder may submit in the first round of the auction.

The Electronic Auction System

A11.18 The auction will be run over the internet using an Electronic Auction System (EAS). No specialist hardware or software will be required on bidder's terminals, as the EAS interface will run on a standard web browser. However, bidders will need to install authentication credentials, provided by Ofcom only to qualified applicants who are confirmed as bidders, on any computer they wish to use to access the system. As in previous auctions, Ofcom will allow bidders to submit bids by alternative means in the event that they experience technical difficulties with the EAS, subject to Ofcom granting permission to the bidder to do so and provided that the bids by alternative means are authenticated in accordance with the Regulations for the auction.

[451] If the applicant simply chooses to withdraw its application by the last day for withdrawal, or fails to qualify in the auction, then that bidder’s initial deposit of £100,000 will not be forfeited for that reason.

A11.19 Ofcom also expects to make a stand-alone version of the software available to applicants, a few days after application. Applicants will be able to login both as bidders and as the auctioneer, allowing them to run internal mock auctions as part of their training.

The principal stage

A11.20 The purpose of the principal stage is to determine the number of lots to be assigned to each bidder in each band, and the 'base price' that each winner of spectrum will be required to pay for the lots it has won.

A11.21 Bidding in the principal stage will proceed in rounds, which consist of time windows scheduled by the auctioneer during which bidders are invited to submit 'bid decisions'. We refer in this document to 'bid decisions' in order to reflect the fact that bidders are entitled, on their principal stage form(s), to do more than submit a new bid. In particular, bidders may indicate that they wish to request that their eligibility limit be carried forward to the next round.

A11.22 The submission of bid decisions is only accepted while a round is in progress, and is only processed once the round has finished. At the end of each round, bidders will be notified whether the auction will proceed to the next stage or a further bidding round is needed, and given certain information about the results of the completed round (as detailed below).

Overview of the bidding process

A11.23 During the principal stage, bidders may submit bids for the (generic) lots available at prices announced by the auctioneer. These prices are known as the 'round price'. At the end of each round, Ofcom determines provisional winning bids for each lot. We refer to these provisional winning bids as 'bids with standing high bid status', or 'standing high bids' in this document. [452] These are bids which will become the winning principal stage bids unless they are replaced in subsequent rounds.

A11.24 The principal stage will end when there are no 'round events' in a round. This means that, in a round, no bidders have submitted any new bids and no waivers have occurred (explained below beginning at paragraph A11.74).

A11.25 When the principal stage ends, standing high bids will ordinarily become winning principal stage bids. Standing high bidders will be required to pay the round price of their winning principal stage bids for the lots they have won (plus, following the assignment stage, any additional price incurred).

Bids

A11.26 The bid submission process requires bidders to select the number of lots they wish to bid for at the price specified by the auctioneer (i.e. at the round price). However, this is not a package

[452] In the draft Regulations we refer to these as "bids with standing high bid status".

bid. Formally, where a bidder opts to bid for a number of lots this will be treated as separate bids for individual lots from that bidder. However, the principal stage is structured so that new bids will be subject to a common round price applying to all lots in a frequency band; this facilitates the making of bids through the EAS, as bidders will simply need to specify the number of lots sought in each category.

A11.27 Each bid must specify:

- the frequency band to which the bid applies; and
- the price that the bidder will pay for the lot if the bid is selected as a winning bid by virtue of being a standing high bid. We note that this price is the round price, as determined by the auctioneer for the round in which the bid was submitted.

A11.28 Submitting a bid establishes a commitment to acquire, in the event that the bid is selected as a winning bid, a lot in the specified frequency band at a price equal to the round price.

A11.29 Bidders may bid for several lots simultaneously. However, it is possible that only some of these bids may be selected as winning bids. Notwithstanding this, the process for selecting standing high bids has been designed with the intention of minimising the number of potential bidders who win some, but not all, of the bids they made simultaneously for lots in a lot category. We refer to such bidders in this document as 'partial standing high bidders'.

A11.30 A bid is only valid if it is submitted during a round in accordance with the Regulations.

Minimum bid in 3.6-3.8 GHz

A11.31 There is a minimum bid of two lots for the 3.6-3.8 GHz band. This means that any bidders that wish bid in 3.6-3.8 GHz must specify a bid for a minimum of two lots (10 MHz) in the band.

A11.32 Bidders may still be made partial standing high bidder on fewer than two lots. If a bidder is partial standing high bidder on one lot in the final round of the principal stage, it will win that lot.

The overall bid constraint

A11.33 On the basis of a bidder's recorded spectrum holdings (which are determined shortly after the deadline for payment of the additional deposit, but before the start of the principal stage), Ofcom will determine the overall bid constraint that will apply to each bidder.

A11.34 The overall bid constraint will establish a limitation on the combination of the number of new bids made in the round and standing high bids assigned at the end of the most recent round[453] that the bidder can submit for lots of the three lot types (700 MHz FDD, 700 MHz SDL and 3.6-3.8 GHz).

[453] In the bands where the bidder does not submit new bids.

A11.35 A bidder's overall bid constraint is irreversible and will apply throughout the auction. This means that, if a bidder subsequently divests all or part of its recorded spectrum holdings, its overall bid constraint will not be increased. Further, where a bidder's existing spectrum holdings are changed after they have been recorded (other than as a result of a divestment), this may be grounds for Ofcom to exclude that bidder from the award process and to forfeit its deposit if that change will affect that bidder's overall bid constraint.

The bidding process

A11.36 The bidding process in the principal stage will require one or more rounds, each round consisting of a fixed time window during which bidders may submit bid decisions in accordance with prices announced by the auctioneer.

A11.37 As explained above, a bid decision is only valid if it is submitted during a round in accordance with the Regulations.

Scheduling of rounds

A11.38 When a round is scheduled, the following information will be made available to each bidder:

- the start and the end time of the round;
- the round price for each lot type for that round;
- the bidder's own eligibility limit;
- the number of waivers the bidder has left (explained below);

A11.39 Ofcom expects rounds to last 30 minutes, but we may choose different durations. We intend to provide bidders with around 15 minutes notice before the start of a round.

Bid submission during a round

A11.40 In each round, bidders can make a single submission of bid decisions using the EAS. Therefore, bidders should submit all of the bids they wish to submit in a given round simultaneously in the same submission, or alternatively request to carry forward their eligibility limit. When a round is in progress, each bidder's EAS interface will provide a bid form.

A11.41 To make a submission, a bidder will need to:

a) specify, using the principal stage form provided by the EAS:

   i) the number of lots in each lot type for which they wish to submit a bid at the round price for that lot type. We note that:

      - bidders may not specify a bid amount for a lot that differs from the round price for that lot type;
      - in the first round, each bidder must submit a bid for at least one lot. Any bidders who do not do so will be excluded from the auction and will not receive a refund of

any of their deposit. In subsequent rounds, however, bidders may decide to not place any bids for any lots;

- any bid submitted by a bidder must not breach the overall bid constraint set for that bidder.

ii) if it wishes to request to carry forward its eligibility limit (this is only possible if a waiver has not occurred on three occasions, if the bidder is using a number of eligibility points which is smaller than the bidder's eligibility limit in the round and if it is not submitting any bids). This will also not be available for bidders in the first principal stage round;

b) send the completed bid form to the auction server, so that the bid can be checked for validity against the Regulations;

c) provided that the submission is valid according to the Regulations, confirm the submission using the confirmation form provided in the bidder interface of the EAS.

A11.42 The submission process is only completed when the bidder confirms its submission. Submissions sent to the server to check validity but not confirmed will be discarded by the EAS.

A11.43 Upon receipt of a valid submission, the EAS interface will provide a confirmation page. Conversely, if the submission process fails, the EAS interface will revert to the bid form. It is the responsibility of the bidder to check (through its bidder interface) that its submission has been successfully received by the auction server, and to alert Ofcom if it suspects any problems have occurred.

A11.44 Once the auction server has received a confirmation of a valid submission in a round, the bidder will not be able to revise or withdraw this submission, or submit any further bid decisions in respect of that round.

Round prices

A11.45 For each round, Ofcom will specify the round price per lot for each lot type.

A11.46 In the first round, the round price for each lot type will be the respective reserve price. These are £100m per 700 MHz FDD lot, £1m per 700 MHz SDL lot, and £20m per 3.6 GHz lot.

A11.47 In subsequent rounds:

a) the round price for a lot type will increase if the number of standing high bids for that lot type at the most recent round price is equal to the total number of lots available in that lot type;

b) otherwise, the round price for the lot type will remain unchanged.

A11.48 Therefore, round prices will not decrease over the course of the rounds.

A11.49 The amount of the increase in round prices, when applicable, will be determined at Ofcom's discretion and may vary across lot types and across rounds.

A11.50 Round prices will be specified in whole thousands of pounds.

Determination of standing high bids

A11.51 At the end of each round, the EAS will determine which bids for each lot type have standing high bid status. Standing high bids are determined for each lot category independently.

A11.52 To do so, the EAS will firstly consider the following bids:

a) the standing high bids in the lot type at the beginning of the round that have not been replaced by a standing high bidder submitting new bids in respect of that lot type; and

b) the new bids in respect of that lot type submitted during the round.

A11.53 Secondly, the EAS will order the bidders who made those bids as follows:

a) first, take in random order those bidders whose bids are at the current round price (regardless of whether they maintained previous standing high bids or submitted new bids in the current round);

b) next, take in random order those bidders who (i) maintained standing high bids with a bid amount lower than the current round price and (ii) are standing high bidder on the number of lots they bid for in that lot type when they submitted these bids;

c) finally, if there is a bidder who (i) maintained its standing high bids with a bid amount lower than the current price and (ii) is a partial standing high bidder, that bidder is placed last.

A11.54 The EAS will then select the standing high bids by taking the bids submitted by each of these bidders in the order established in the previous step, until there are no more lots available.

A11.55 This approach ensures that:

a) there can be at most one partial standing high bidder in each lot type; and

b) bids at the same price level are treated equally (regardless of whether they have been submitted in an earlier or later round), except for standing high bids from a partial standing high bidder, which is outbid first.

Bidding for lots when the bidder holds standing high bids

A11.56 After the first round, a bidder holding standing high bids in a lot type may submit further bids for that lot type. However:

a) If the round price for that lot type has increased relative to the round price of the bidder's standing high bids, that bidder may only submit bids at the new round price if it is bidding for at least as many lots as it holds standing high bids on (other than where the minimum bid of two lots in 3.6-3.8 GHz applies). If a bidder submits bids at the new price level, then the bidder's standing high bids at the earlier price level will be discarded (regardless of whether the new bids become standing high bids, and independently of the bids submitted by other bidders); or

b) Conversely, if the round price for that lot type has not increased relative to the round price of the bidder's standing high bids, that bidder may only submit bids for strictly more lots than the number of lots on which it holds standing high bid status. If a bidder submits new bids for that lot type, any standing high bids held by the bidder will be cancelled. Therefore:

    i) the bidder must specify the total number of lots it wishes to bid for at the prevailing round price; and

    ii) as previous standing high bids are cancelled, there is no guarantee that the bidder will hold any standing high bids after bids for the round have been processed.

Box 1: Example of the determination of standing high bids

The example below illustrates how standing high bidders and partial standing high bidders are determined at the end of each round. Consider the 700 MHz lot category, with six lots available and four bidders (Bidders A, B, C and D). Prices and bids are purely illustrative.

Round	Price	Number of lots bid for				Order	Standing high bids at the end of the round [price]			
		A	B	C	D		A	B	C	D
1	150	4	2	3	1	BACD	4[150]	2[150]	-	-
2	160	-	-	3	1	DCAB	2[150]	-	3[160]	1[160]
3	160	waiver	2			CBDA	-	2[160]	3[160]	1[160]
4	170	3	-	-	-	ADCB	3[170]	-	2[160]	1[160]
5	170	-	2	-	-	BADC	3[170]	2[170]	-	1[160]

In round 1, all bidders submit bids at the current round price. The EAS generates a random order for this group of bidders (BACD). There are no other bidders to consider. The first bidder in the order, Bidder B, bid for 2 lots and becomes standing high bidder on its full bid of 2 lots. We refer to this as being a "full standing high bidder". The next-ranked bidder, Bidder A, bid for 4 lots and also becomes full standing high bidder on 4 lots. There are no residual lots available, so Bidders C and D do not become standing high bidders.

In round 2, the price increases to 160, as all standing high bids at the end of round 1 were at the previous round price of 150. Bidders C and D submit new bids at the higher current round price. Bidders A and B do not need to submit new bids as they are full standing high bidders at the previous round price (although they may do so if they want). Bidders A and B therefore "maintain" their standing high bids from the previous round.

First, the EAS will consider the bids at the current round price and generates a random order for the corresponding group of bidders (DC). Second, the EAS will consider the full standing high bidders that have maintained their standing high bids at a price lower than the current round price, and randomly order these bidders (AB).

Therefore, the overall order of bidders is DCAB. Bidders D and C become full standing high bidders on 1 and 3 lots respectively at the current round price. There are only 2 residual lots available, so the next-ranked bidder, Bidder A, becomes standing high bidder on 2 lots at the previous round price of 150. This is fewer than the 4 lots it originally bid for in round 1. We refer to bidders that are standing high bidder on strictly fewer lots than it bid on as "partial standing high bidders". Bidder B has no standing high bids at the end of round 2.

In round 3, the price does not increase as Ofcom was unable to assign all standing high bids at the round 2 price of 160. Bidder B bids for 2 lots at 160. Bidder A submits a waiver, which maintains bidder A's current eligibility limit to the next round and prevents the bidder from submitting a bid in this round (we explain how waivers work in more detail from paragraph A11.61).

The EAS first ranks and randomly orders bidders that have submitted bids at the current round price of 160, which includes Bidder B, C and D (CBD). The EAS then considers any full standing high bidders that have maintained their standing high bids at a previous round price. There are no bidders in this category. The EAS lastly considers any bidders that maintained standing high bids at a previous round price and were partial standing high bidders – this applies to Bidder A.

Therefore, the overall order of bidders is CBDA. Bidders B, C and D become full standing high bidders at the current round price of 160. Bidder A has no standing high bids.

In round 4, the price increases to 170 as all standing high bids at the end of the previous round were allocated at the round price of 160. Bidder A submits a bid for 3 lots at 170.

The EAS first considers the bids submitted at the current round price, from Bidder A. The EAS then randomly orders full standing high bidders at a lower round price (DCB).

Therefore, the overall order of bidders is ADCB. Bidders A and D become full standing high bidder on 3 lots at the price of 170, while Bidder D becomes full standing high bidder on 2 lots at the lower round price of 160. Bidder C becomes partial standing high bidder on 1 lot at 160. Bidder B does not have standing high bids.

In round 5, the price does not increase, as there are still standing high bids left at a lower round price. Bidder B makes a bid for 2 lots at the current round price of 170.

The EAS first considers and randomly ranks the bids at the current price (BA). Then the EAS considers full standing high bidders from previous rounds at a price lower than the current round price, which applies only to D. Lastly, EAS considers the partial standing high bids from the previous round with a price lower than the current round price, which applies only to C.

Therefore, the overall order is BADC. Bidders B and A become full standing high bidders on 3 lots and 2 lots respectively at 170. Bidder D also becomes full standing high bidder on 1 lot, but at the previous round price of 160. Bidder C has no standing high bids.

In the next round, there are no new bids or waivers submitted. Let us suppose there are also no bids either in 700 MHz SDL or 3.6-3.8 GHz. As will be explained later in the annex, this means the principal stage ends. Any standing high bids become winning bids. The base price for the lots won by bidders A and B is 170, and for Bidder D is 160.

Eligibility rule

A11.57 The number of eligibility points used by a bidder in a round cannot exceed the bidder's eligibility limit for that round. To assess a bidder's compliance with the eligibility rule, we need to firstly calculate that bidder's eligibility limit in the relevant round.

A11.58 Each bidder will start each round with a given eligibility limit. In the first round, this will be determined by the amount of the bidder's 'additional deposit'. In subsequent rounds, the bidder's eligibility limit will be equal to the number of eligibility points used by the bidder in the most recent round provided that a waiver did not occur in that round.

A11.59 The number of eligibility points used by a bidder in a round is calculated as:

a) the sum of the eligibility points assigned to all lots for which the bidder submits bids in the round; plus

b) where the bidder does not submit bids for a particular lot type in that round, the sum of eligibility points assigned to all lots in that lot type for which the bidder held a standing high bid at the end of the most recent round.

A11.60 As explained at paragraph A11.8 above, each 700 MHz FDD lot will be assigned four eligibility points, while each 700 MHz SDL and 3.6-3.8 GHz lot will be assigned one eligibility point. Accordingly, where a bidder submits three bids in a round for 3.6-3.8 GHz lots and does not submit any bids for 700 MHz FDD lots, but has standing high bids for two 700 MHz FDD lots from the previous round, then that bidder will have used 11 eligibility points in that round (i.e. (3x1) + (2x4)).

Waivers

A11.61 Bidders can preserve their eligibility limit from one round to the next by using a waiver, even though they used a number of eligibility points which is smaller than their eligibility limit. Waivers are referred to in the draft regulations and the EAS as 'eligibility events'. There is a limit of three waivers per bidder in the course of the principal stage.

A11.62 A waiver may occur as a result of either:

a) A bidder submitting a valid request to carry forward its eligibility limit in its principal stage form; or

b) The EAS automatically carrying forward the bidder's eligibility limit when a bidder:

i) does not submit a valid principal stage form within a round; and

ii) the number of eligibility points used by the bidder from standing high bids is less than its eligibility limit for the round; and

iii) the limit of three waivers is not met.

A11.63 The EAS will not make any other default submissions.

A11.64 In turn, a bidder's request to carry forward its eligibility limit will be valid only if:

a) the number of eligibility points used by the bidder from standing high bids is less than its eligibility limit for the round;

b) the bidder does not submit any new bids in the same round;

c) the limit of three waivers is not met.

A11.65 A waiver cannot happen in the first round.

A11.66 To prevent the EAS from carrying forward the bidder's eligibility limit automatically, bidders may submit a decision not to place any new bids in the round. When they check the selection containing no new bids, the EAS will inform that they will lose eligibility if they submit it.

Information released at the end of each principal stage round

A11.67 At the end of each round, the EAS will process the submissions in the round and determine whether a further round is needed. In the event that a further round is needed, the EAS will determine which lot types require a price increase. Information about a completed round will be made available to bidders only after the auctioneer approves the results for the round.

A11.68 The 'active bids' in each lot type in a given round are defined to be, for the purposes of the description in this document:

a) the standing high bids in that category at the beginning of the round that have not been replaced by the standing high bidder submitting new bids in that category; and

b) the new bids for lots in that category submitted in the round.

A11.69 'Excess demand' is a concept defined in the Regulations. Excess demand for lots in a lot type in a given round is the total bandwidth corresponding to all active bids in that category minus the total bandwidth corresponding to all the lots available in that category.

A11.70 If a further round is needed, the following information will be made available to each bidder on the EAS interface:

a) the number of bids submitted by the bidder in the most recent round;

b) the number of bids with standing high bid status currently held by the bidder and the respective round prices;

c) the number of times a waiver can occur in respect of that bidder;

d) the bidder's eligibility limit for the next principal stage round;

e) the bidder's financial exposure[454] after the end of the most recent round;

f) for each lot type, after the first round, the following information about excess demand

i) For 700 MHz FDD and 3.6-3.8 GHz, the smallest positive multiple of 20 MHz that is strictly greater than excess demand in that lot type in the most recent round (i.e. whether excess demand for that lot type in the round was less than 20 MHz, 40 MHz, 60 MHz, 80 MHz, etc.).

---

[454] A bidder's financial exposure is the sum of the number of standing high bids held by the bidder in each lot type at the end of the round, multiplied by the round price at which the bids were made.

ii) For 700 MHz SDL, the smallest positive multiple of 10 MHz that is strictly greater than excess demand in that lot type in the most recent round (i.e. whether excess demand for that lot type in the round was less than 10 MHz, 20 MHz, 30 MHz, 40 MHz, etc.).

A11.71 At this stage, no further information will be released about the bids submitted by other bidders.

A11.72 If the principal stage has ended, the following information will be made available to each bidder on the EAS interface:

a) a message informing the bidder that the principal stage has ended; and

b) the names of the winning principal stage bidders and, in respect of each of them, the number of lots won in each lot type and the associated round price for those winning bids.

A11.73 The EAS will allow bidders to view and download the information provided after each completed round, once approved by the auctioneer.

End of the bidding process

A11.74 The bidding process ends after the first round in which no bids are submitted, and where no waiver occurs.

Determination of winning principal stage bids

A11.75 At the end of the bidding process, bids with standing high bid status will become winning principal stage bids.

Determination of base prices

A11.76 The Regulations introduce the concept of the 'base price' for winning principal stage bids. This is intended to reflect a bidder's total liability for those bids, as at the end of the principal stage. For each standing high bid that became a winning principal stage bid, the base price will be equal to the round price at which the winning bid was submitted. A bidder's total base price for a lot type will be the number of winning principal stage bids multiplied by the base price for that lot type.

Box 2: Worked example of principal stage

The example below illustrates how eligibility points, switching lot categories and waivers work in the principal stage. For simplicity we use only two lot categories in this example, instead of the three lot categories in the auction. This example takes the point of view of a particular bidder and assumes: the same lot structure of the award for the 3.6-3.8 GHz and 700 MHz FDD bands (24 lots available in 3.6-3.8 GHz and 6 lots in 700 MHz FDD), price increases in all rounds and the principal stage progressing as shown. The bids and prices are purely illustrative.

Round	700 MHz FDD			3.6-3.8 GHz			Financial exposure	Eligibility points used
	Price	Decision	Outcome	Price	Decision	Outcome		
1	150	Bid, 4 lots	PSHB, 1 lot	30	No bid	No SHB	150	16
2	160	No bid (maintain SHB)	No SHB	32	Bid, 8 lots	SHB, 8 lots	256	12
3	170	waiver	No SHB	34	waiver	PSHB, 2 lots	64	12
4	180	No bid	No SHB	36	Bid, 10 lots	SHB, 10 lots	360	10

In **round 1**, the bidder bids for 4 lots of 700 MHz FDD and becomes standing high bidder on 1 lot. It doe
In **round 1**, the bidder bids for 4 lots of 700 MHz FDD and becomes standing high bidder on 1 lot. It does not bid for any lots of 3.6-3.8 GHz. In total, the bidder used 16 eligibility points, and so its eligibility limit for round 2 will be 16. The bidder's financial exposure is given by the number of standing high bids multiplied by the round price when those bids were submitted. With 1 standing high bid at the price of 150, the financial exposure is therefore 150 (i.e. 1 x 150).

In **round 2**, the bidder does not submit new bids for 700 MHz, as it wishes to switch its demand to 3.6-3.8 GHz. It therefore maintains its partial standing high bid from the previous round, and bids for 8 lots of 3.6-3.8 GHz. At the end of the round, it no longer has any standing high bids for 700 MHz FDD, and becomes standing high bidder on 8 lots of 3.6-3.8 GHz. Its financial exposure is 256 (8 x 32). In total, the bidder has used 12 eligibility points (8 points for the 8 bids on 3.6-3.8 GHz and 4 points for maintaining its standing high bid on 1 lot in 700 MHz FDD). Its eligibility limit for the next round is 12.

In **round 3**, the bidder submits a waiver, which maintains its eligibility limit (12) to the next round and prevents the bidder from submitting a bid in this round. We explain how this request works from paragraph A11.61 above. The bidder's eligibility limit for round 4 will therefore be equal to its eligibility limit in this round, 12. The bidder ends the round as partial standing high bidder on 2 lots of 3.6-3.8 GHz. Its financial exposure is 64 (2 x 32).

In **round 4,** the bidder bids for 10 lots of 3.6-3.8 GHz and becomes standing high bidder on 10 lots. The bidder does not submit new bids for lots in 700 MHz FDD. It used 10 eligibility points and so its eligibility limit for round 5 will be 10. The bidder's financial exposure is 360 (10 x 36)

In the next round, the bidder does not submit any new bids or a waiver. Let us suppose there are also no bids or waivers from the other bidders. As will be explained later in the annex, this means the principal stage ends. Any standing high bids become winning bids. The bidder has won 10 lots of 3.6-3.8 GHz at a price of 360.

The assignment stage

A11.77 The specific frequencies assigned to bidders who have won lots in the principal stage will be determined in the assignment stage.

A11.78 The assignment of specific frequencies will be determined independently for each band.

A11.79 Winning bidders in the 3.6-3.8 GHz band will also have the opportunity to negotiate the outcome of the assignment stage, as an alternative to the outcome being determined solely by assignment stage bidding.

Possible combinations of assignment stage options

A11.80 For each of the three bands, Ofcom will only consider combinations of assignment stage options in which each bidder is assigned a contiguous frequency block that corresponds to the bandwidth it won in the principal stage, and in which any unallocated spectrum forms a contiguous frequency block.

A11.81 For the 3.6-3.8 GHz band, bidders that have won 20 MHz or less of 3.6-3.8 GHz spectrum will have the additional restriction of only bidding for the top or bottom of the 3.6 GHz. Subject to the outcome of any negotiation period (set out from paragraph A11.103 below), Ofcom will only consider combinations of the assignment stage options in which a bidder that has won 20 MHz or less is either assigned the top or bottom of the band, or the adjacent frequencies where more than one bidder has 20 MHz or less. This is set out in more detail below.

A11.82 If there is only one assignment that meets these requirements, then bidders will be assigned the frequencies corresponding to the spectrum they won in the relevant lot type in accordance with this assignment. If there are multiple assignments that meet these requirements, then bidders who will be assigned alternative frequencies in different assignments will be invited to submit bids for these alternative options.

A11.83 If a bidding process for the assignment stage is needed, Ofcom will schedule a single round of bidding (the 'assignment round') in which the relevant bidders may submit bids (the 'assignment stage bids') for their preferred assignment stage options.

A11.84 After bidders have submitted their assignment stage bids, if at least two winning bidders of 3.6-3.8 GHz spectrum agree to participate in a negotiation period, they will have the opportunity to negotiate assignments on the 3.6-3.8 GHz band following submission of bids. If negotiations are successful, this will be reflected in the assignment stage outcome in 3.6-3.8 GHz.

A11.85 Ofcom will then determine the assignment that will maximise the value of accepted bids for the 700 MHz FDD, 700 MHz SDL, and (subject to the outcome of the negotiation period) 3.6-3.8 GHz bands. Bidders may then be required to pay a price (the 'additional price'), on top of their prices from the principal stage, for the frequencies they are assigned (if they submitted a winning bid for this option and other bidders had expressed a preference for an option that was not compatible). Bidders do not have to submit assignment stage bids to be assigned spectrum they won in the principal stage. Participation in the bidding process of the assignment stage is optional.

Restriction of assignment stage options for bidders that have won 20 MHz or less of 3.6-3.8 GHz spectrum

A11.86 Any bidder that has won 20 MHz or less of 3.6-3.8 GHz spectrum (‘small 3.6-3.8 GHz winners’) in the principal stage will be restricted to bidding for the top or bottom of the 3.6-3.8 GHz band. Subject to the placement of any unsold spectrum, the assignments stage options for any small 3.6-3.8 GHz winners must satisfy one of the following conditions:

a) the assignment is at the top of the band;

b) the assignment is immediately below only other winners of 20 MHz or less (provided that one of the winners in this series is assigned the top of the band);

c) the assignment is at the bottom of the band; or

d) the assignment is immediately above only other winners of 20 MHz or less (provided that one of the winners in this series is assigned the bottom of the band). [455]

A11.87 Any bidder that has won 20 MHz or less and that is party to a successful negotiation agreement will no longer be restricted to being placed at the bottom or top of the band (see ‘Negotiation period and determination of winning assignments in 3.6-3.8 GHz’ below).

[455] These conditions apply where there is no unsold 3.6-3.8 GHz spectrum following the principal stage. Where there is unsold 3.6-3.8 GHz spectrum, the unsold spectrum may be placed in any location in the band, provided it is assigned in a contiguous block. This includes being placed at the bottom or top of the band, and next to or between small 3.6-3.8 GHz winners.

Assignment stage bids

A11.88 The 'assignment stage options' for each bidder are determined by Ofcom in accordance with our determination of possible combinations of assignment stage options.

A11.89 If there are several possible assignment stage options for a band, then at least two bidders will have multiple assignment stage options in that band. Any such bidders will have the opportunity to express their preferences within those options in the form of assignment bids.

A11.90 An assignment stage bid consists of:

a) an assignment stage option; and

b) a bid amount, specified in pounds, and which must be in whole thousands of pounds and at least zero.

A11.91 Submitting an assignment stage bid establishes a commitment to pay an additional price that will not exceed the bid amount in the event that the bidder is assigned the frequencies specified in the corresponding option.

Scheduling of the assignment stage round

A11.92 When the assignment stage round is scheduled, the following information will be made available to each bidder:

a) the start and the end time for the round;

b) the assignment stage options that the bidder may bid for.

Bid submission

A11.93 When the assignment stage round is in progress, participating bidders may submit a single list of assignment stage bids using the EAS.

A11.94 The interface of the EAS will provide an assignment stage form that lists all assignment stage options available to the bidder.

A11.95 To submit its list of assignment stage bids, a bidder will need to:

a) enter the bid amount for each one of the assignment stage options it wishes to bid for in its assignment stage form (the bid amount for any options left blank will be set to zero);

b) send the bid form to the auction server, so that it can be checked for validity against the Regulations;

c) provided that all bids in the list are valid according to the Regulations, confirm submission of its assignment stage bids using the confirmation form provided by the bidder interface of the EAS.

A11.96 The submission process for a bidder will be blocked if any of the assignment stage bids in the list are invalid. In such a case, none of the assignment stage bids made by that bidder will be accepted, unless the bidder amends its list and completes the submission process of a valid list of assignment stage bids.

A11.97 The process of submitting a list of assignment stage bids is only completed when the bidder confirms the submission. A list sent to the server to check for validity but not confirmed will be discarded by the EAS.

A11.98 Upon receipt of a valid submission of a list of assignment stage bids, the EAS interface will display a confirmation page, listing the assignment stage bids received by the EAS. Conversely, if the assignment stage bids submission process fails, the EAS interface will revert to the assignment stage form. It is the responsibility of the bidder to check (through its bidder interface) that its list of assignment stage bids has been successfully received by the auction server, and to alert Ofcom if it suspects any problems have occurred.

A11.99 Once the auction server has received a confirmation of a valid submission of a list of assignment stage bids in the assignment round, the bidder will not be able to revise or withdraw this submission, or submit any further assignment stage bids.

A11.100 Any bidder who fails to submit a list of assignment stage bids before the end of the assignment stage round will lose the opportunity to submit assignment stage bids. In this case, the bid for all of its assignment stage options will be set to zero by default.

Determination of winning assignments in 700 MHz FDD and 700 MHz SDL

A11.101 The determination of winning assignments stage bids will be calculated independently for each frequency band of 700 MHz spectrum.

A11.102 For each of the 700 MHz FDD and 700 MHz SDL frequency bands, the EAS will sum the bid amounts of the bids that can be accepted in each alternative possible assignment plan. The winning assignment plan will be the one that yields the greatest value of accepted bids. If there are multiple assignment plans that yield the greatest value, one of these will be selected as the winning assignment plan at random.

Negotiation period and determination of winning assignments in 3.6-3.8 GHz

A11.103 For the 3.6-3.8 GHz band, bidders that have won spectrum in the 3.6-3.8 GHz band will have an opportunity to negotiate an alternative outcome to the assignment stage. If at least two winning principal stage winners of 3.6-3.8 GHz spectrum consent to a negotiation period, Ofcom will pause the auction after assignment stage bidding for a period of up to four weeks. Ofcom will not process or reveal the assignment stage bids during this period.

A11.104 If all bidders unanimously agree the assignments in the 3.6-3.8 GHz band during this period, they must notify Ofcom of this agreement by submitting a 'full adjacency agreement form'. Ofcom will then proceed to assign the 3.6-3.8 GHz spectrum in accordance with this agreement. Under these circumstances, bidders will not pay any 'additional prices' for their 3.6-3.8 GHz assignments. We refer to this as a 'unanimous agreement'. [456]

A11.105 If all bidders are unable to come to a unanimous agreement, but a subset of bidders successfully agree to be assigned adjacent frequency locations in the 3.6-3.8 GHz band, they must notify Ofcom of this agreement by submitting a 'partial adjacency agreement form'. Ofcom will reflect this agreement in the outcome as set out below. We refer to this as a 'partial agreement'. [457]

A11.106 This subset of bidders must notify Ofcom by the specified deadline of:

a) which bidders have agreed to be part of the subset; and

b) the order of the bidders' assignments in the subset.

A11.107 There will be two phases of the negotiation period. Ofcom will accept notifications of a unanimous agreement in both the first and second phasers of the negotiation period. However, Ofcom will only accept notifications of any partial agreement between subsets of bidders in the second phase of this period, which is expected to be the last week of the four-week negotiation period.

A11.108 Ofcom will treat the 3.6-3.8 GHz spectrum won by these bidders as a single contiguous block for the purpose of determining the assignment stage outcome, and will invalidate any bids submitted by these bidders during the assignment stage bidding. This single contiguous block will have a bid value of zero. Ofcom will then determine the assignment that will allow us to maximise the value of accepted bids as set out above, subject to the bidders in the subset receiving adjacent assignments. Bidders that are included in the subset will not pay additional prices for its assignments. Bidders that are not included in the subset may pay an additional price, calculated as set out in the following section.

A11.109 Any bidder that has won 20 MHz or less and that is part of a successful unanimous or partial agreement will no longer be restricted to being placed at the bottom or top of the band.

A11.110 If no agreements are reached in the negotiation period or the negotiation period is not activated (i.e. fewer than two bidders agree to participate), Ofcom will determine the assignment in 3.6-3.8 GHz in the same way as for 700 MHz FDD and 700 MHz SDL. That is, Ofcom will determine the assignment that maximises the value of accepted bids, and bidders may be required to pay an additional price for their 3.6-3.8 GHz assignment.

A11.111 We have set out two worked examples of how the outcome and prices are determined, in the event of a partial agreement between bidders in paragraphs A11.118-A11.139 below

[456] The draft Regulations refer to a unanimous agreement among all winning bidders in 3.6-3.8 GHz as a 'full adjacency agreement'.

[457] The draft Regulations refer to an agreement among a subset of winning bidders in 3.6-3.8 GHz as a 'partial adjacency agreement'

Determination of additional prices

A11.112 The determination of additional prices is calculated independently for each frequency band. The total additional price to be paid by a bidder will be equal to the sum of its 700 MHz FDD, 700 MHz SDL, and 3.6-3.8 GHz additional prices (if any) it has to pay. If bidders have successfully unanimously agreed assignments or have agreed to be part of a subset receiving adjacent assignments in the 3.6-3.8 GHz band, these bidders will not have to pay additional prices for their 3.6-3.8 GHz assignments.

A11.113 Additional prices to be paid by winning bidders for the specific frequencies awarded to them in the assignment stage are based on the concept of opportunity cost.

A11.114 For each band, the opportunity cost of assigning a subset of bidders their frequencies in the winning assignment plan is calculated as the difference between:

a) the highest value of bids that could be achieved across all alternative assignment plans (subject to the outcome of any partial agreement in 3.6 -3.8 GHz) if all the bids from the bidders in the subset were set to zero; and

b) the sum of bid amounts of bids that are accepted from bidders that are not included in the subset in the winning assignment plan.

A11.115 The standalone opportunity cost of a bidder is the opportunity cost of the subset of bidders that includes only this bidder.

A11.116 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 amount specified by the bidder for the assignment option it is assigned in the winning assignment plan;

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.

A11.117 If there are multiple combinations of prices (one for each winning bidder) that satisfy the conditions above, then the additional prices will be the unique combination of prices that minimises the sum of squares of the differences between each bidder's additional price and their standalone opportunity cost across all sets of prices that satisfy all four the conditions above.

Worked examples of a partial agreement

A11.118 In order to give a better understanding of how the partial agreement negotiation option will work, we have set up two hypothetical examples. We first give an example where there are 3 principal stage winners in the 3.6 – 3.8 GHz band and then an example where there are 4 principal stage winners. In both examples, for simplicity we assume that each bidder has won the same amount of spectrum.

Example 1 – three winning principal stage bidders in the 3.6 – 3.8 GHz band

Step 1: Assignment stage bids

A11.119 In example 1, there are 3 principal stage winning bidders (called A, B and C) in the 3.6-3.8 GHz band. They have all won the same amount of spectrum in the band (40 MHz). In the assignment stage they all place bids for specific frequencies in the band. Here we examine bidder A's bids.

Figure A11.1: Bidder A's bids in the assignment stage of 3.6-3.8 GHz

3680 - 3720 MHz	3720 - 3760 MHz	3760 - 3800 MHz
100	50	0

A11.120 Bidder A submits its highest bid of 100 for the bottom of the band, which is its preferred frequency location. Its next preference is to be in the middle of the band and therefore it submits a bid of 50 for this location. The bidder does not wish to be at the top of the band and therefore submits a bid of 0 (or equivalently, makes no bid) for this location.

A11.121 Bidders B and C also submit bids for the assignment stage, but we do not need to detail these for this example.

Step 2: Notification to participate in the negotiation

A11.122 At least two winning bidders of 3.6-3.8 GHz spectrum notify Ofcom that they wish to enter the negotiation period. Ofcom therefore announces that there will be a negotiation period of up four weeks, but no shorter than three weeks.

Step 3: Outcome of first phase of the negotiation period

A11.123 All bidders negotiate but they are unable to reach unanimous agreement (within the first phase of the period allowed for achieving unanimity).

Step 4: Outcome of second phase of the negotiation period

A11.124 By the end of the four-week period, bidders B and C decide that they wish their spectrum to be considered as one contiguous block for the assignment stage, with bidder B being assigned the lowest frequencies of the contiguous block.

Step 5: Eliminating assignment stage outcomes that are no longer relevant

A11.125 Ofcom therefore eliminates all possible assignment stage outcomes where bidders B and C are not assigned adjacent blocks of spectrum, and considers these two bidders as one contiguous block. The possible assignment stage options are therefore reduced to the two shown in Figure A11.2 below. As can be seen, bidder A can no longer be placed in the middle of the band. Eliminating assignment stage options that are no longer relevant therefore has the effect of eliminating some bids from all bidders, including bidder A's bid of 50 for the middle of the band.

Figure A11.2: Remaining assignment stage possibilities

	3680 - 3720 MHz	3720 - 3760 MHz	3760 - 3800 MHz
Assignment 1	A	B	C

	3680 - 3720 MHz	3720 - 3760 MHz	3760 - 3800 MHz
Assignment 2	B	C	A

A11.126 For completeness, the assignment stage options that are eliminated are shown in Figure A11.3 and A11.4. Figure A11.3 shows the assignment stage options that are eliminated due to bidders B and C deciding that they wish their spectrum to be considered as one contiguous block.

Figure A11.3: Assignments that are no longer possible as B and C are not adjacent

	3680 - 3720 MHz	3720 - 3760 MHz	3760 - 3800 MHz
Assignment 3	B	A	C

	3680 - 3720 MHz	3720 - 3760 MHz	3760 - 3800 MHz
Assignment 4	C	A	B

Figure A11.4: Assignments that are no longer possible as the negotiated parties have decided that B should have the lower frequency

	3680 - 3720 MHz	3720 - 3760 MHz	3760 - 3800 MHz
Assignment 5	A	C	B

	3680 - 3720 MHz	3720 - 3760 MHz	3760 - 3800 MHz
Assignment 6	C	B	A

Step 6: Bids for the remaining assignment stage options

A11.127 For the remaining assignment stage options in Figure A11.2, Ofcom reduces bidders B and C's assignment stage bids to zero. The bids (after this modification) for each of bidder A and the combination of bidders B & C are shown in brackets in Figure A11.5 below.

Figure A11.5: Remaining assignment stage possibilities after bidders B and C are treated as a contiguous block

	3680 - 3720 MHz	3720 - 3800 MHz
Assignment 1	A (100)	B & C (0)

	3680 - 3760 MHz	3760 - 3800 MHz
Assignment 2	B & C (0)	A (0)

Step 7: Determining the band plan outcome

A11.128 Ofcom now processes the assignment stage bids. Given that only two combinations are possible, and that setting the bids of bidders B and C to zero means that they are treated as if they state no preference for the location of their one contiguous block, bidder A receives its preferred location. Assignment 1 is the winning combination as this has a total bid value of 100, as opposed to assignment 2 which has a total bid value of 0. Due to the second price rule, none of the bidders pays any amount in the assignment stage in this scenario. The band plan that is the outcome of the assignment stage is shown in Figure A11.6.

Figure A11.6: Final 3.6-3.8 GHz band plan

3680 - 3720 MHz	3720 - 3760 MHz	3760 - 3800 MHz
A	B	C

Example 2 – four winning principal stage bidders in the 3.6 – 3.8 GHz band

Step 1: Assignment stage bids

A11.129 In example 2, there are four principal stage winning bidders (called D, E, F and G) in the 3.6-3.8 GHz band. They have all won the same amount of spectrum in the band (30 MHz). In the assignment stage they all place bids for specific frequencies in the band. Here we examine bidder D and E's bids.

Figure A11.7: Bidder D's bids in the assignment stage of 3.6-3.8 GHz

3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
100	50	0	0

Figure A11.8: Bidder E's bids in the assignment stage of 3.6-3.8 GHz

3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
40	10	0	0

A11.130 Bidder D submits its highest bid of 100 for the bottom of the band which is its preferred frequency location. Its next preference is to be second from the bottom in the band and therefore submits a bid of 50 for this location. The bidder does not wish to be in the top half of the band and therefore submits bids of 0 for the top two locations. Bidder E has similar preferences, although at lower valuations. It therefore submits bids of 40 for the bottom location, 10 for the assignment 3710 – 3740 MHz, and zero for the other locations.

A11.131 Bidders F and G also submit bids for the assignment stage, but we do not need to detail these for this example.

Step 2: Notification to participate in the negotiation

A11.132 At least two winning bidders of 3.6-3.8 GHz spectrum notify Ofcom that they wish to enter the negotiation period. Ofcom therefore announces that there will be a negotiation period of up to four weeks.

Step 3: Outcome of the first phase of the negotiation period

A11.133 All bidders negotiate but they are unable to reach unanimous agreement (within the first phase of the negotiation period allowed for achieving unanimity).

Step 4: Outcome of the second phase of the negotiation period

A11.134 By the end of the four-week period, bidders F and G decide that they wish their spectrum to be considered as one contiguous block, with bidder G being assigned the lowest frequencies of the contiguous block.

Step 5: Eliminating assignment stage outcomes that are no longer relevant

A11.135 Ofcom therefore eliminates all possible assignment stage outcomes where bidders F and G are not assigned adjacent blocks of spectrum, and considers these two bidders as one contiguous block. The possible assignment stage options are therefore reduced to the six shown in Figure A11.9 below. In this example, the remaining options include all of bidders D and E (who are not party to the partial agreement) zero and non-zero bids. The elimination of assignment stage outcomes has not led to the elimination of any of bidder D or E's bids in this example.

Figure A11.9: Remaining assignment stage possibilities

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 1	D	E	G	F

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 2	E	D	G	F

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 3	D	G	F	E

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 4	E	G	F	D

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 5	G	F	D	E

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 6	G	F	E	D

A11.136 Figure A11.10 shows the assignment stage options that are eliminated due to bidders F and G deciding that they wish their spectrum to be considered as one contiguous block.

Figure A11.10: Assignments that are no longer possible as F and G are not adjacent

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 7	D	G	E	F

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 8	D	F	E	G

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 9	E	G	D	F

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 10	E	F	D	G

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 11	F	E	D	G

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 12	F	E	G	D

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 13	F	D	E	G

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 14	F	D	G	E

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 15	G	E	F	D

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 16	G	E	D	F

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 17	G	D	F	E

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 18	G	D	E	F

A11.137 Figure A11.11 shows the assignment stage options that are eliminated due to bidders F and G deciding that bidder G should be assigned the lowest frequencies of the contiguous block.

Figure A11.11: Assignments that are no longer possible as the negotiated parties have decided that G should have the lower frequency

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 19	D	F	G	E

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 20	E	D	F	G

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 21	E	F	G	D

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 22	F	G	D	E

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 23	F	G	E	D

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 24	D	E	F	G

Step 6: Bids for the remaining assignment stage options

A11.138 For the remaining assignment stage options, Ofcom also reduces bidders F and G's assignment stage bids to zero. The bids (after this modification) for each of bidders D, E and the combination of bidders F & G are shown in brackets in Figure A11.12 below.

Figure A11.12: Remaining assignment stage possibilities after bidders F and G are treated as a contiguous block

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3800 MHz
Assignment 1	D (100)	E (10)	G & F (0)

	3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3800 MHz
Assignment 2	E (40)	D (50)	G & F (0)

	3680 - 3710 MHz	3710 - 3770 MHz	3770 - 3800 MHz
Assignment 3	D (100)	G & F (0)	E (0)

	3680 - 3710 MHz	3710 - 3770 MHz	3770 - 3800 MHz
Assignment 4	E (40)	G & F (0)	D (0)

	3680 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 5	G & F (0)	D (0)	E (0)

	3680 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
Assignment 6	G & F (0)	E (0)	D (0)

Step 7: Determining the band plan outcome

A11.139 Ofcom now processes the assignment stage bids. Assignment 1 is the winning combination as this has the highest total bid value of 110. Due to the second price rule, only bidder D is required to pay for its location, due to outbidding bidder E for the bottom location. Bidder D is therefore required to pay 30 for this location, which is the difference between E’s value of 40 to be at the bottom location and E’s value of 10 to be at location 3710 – 3740 MHz. The band plan that is the outcome of the assignment stage is shown in Figure A11.13.

Figure A11.13: Final 3.6 GHz band plan

3680 - 3710 MHz	3710 - 3740 MHz	3740 - 3770 MHz	3770 - 3800 MHz
D	E	G	F

Deposits

Top up deposits during principal stage

A11.140 At any point during the principal stage, Ofcom may require a bidder to increase its deposit up to an amount equal to the highest financial exposure of the bidder from previous rounds.

A11.141 In the event of a deposit call, Ofcom will specify a deadline for bidders to make any additional deposits, and provide details of how to make the additional deposit.

A11.142 If the bidder does not provide Ofcom with the top up deposit as required, it will not be allowed to submit a principal stage form in the next principal stage round nor in any subsequent principal stage round. In addition, the bidder will also be unable to submit an assignment stage form in the assignment stage and shall be deemed to have made a valid bid for a value of zero pounds for each of its assignment stage options. The bidder will also not be able to participate in the negotiation period.

A11.143 The bidder will not be excluded from the award process for not having provided the sufficient top up deposit, and it will still win any bids that become winning bids. However, the bidder will not be granted a licence for its winning bids unless it provides Ofcom with the total auction sum payable, following the end of the assignment stage.

Required final principal stage deposit

A11.144 At the end of the principal stage, by a deadline to be specified by Ofcom, bidders need to have on deposit at least the sum of the total base price in 700 MHz FDD, 700 MHz SDL, and 3.6 GHz.

A11.145 If the bidder does not provide Ofcom with the required final principal stage deposit, it will not be excluded from the award process. However, it will not be allowed to submit assignment stage bids and will be deemed to have made valid assignment stage bids with a value of zero pounds for all of its assignment stage options.

Required assignment stage deposit

A11.146 During the assignment stage, by a deadline to be specified by Ofcom, bidders need to have on deposit at least the sum of the required final principal stage deposit (see above) and the amount which is the sum of the bidder’s highest assignment stage bid for its 700 MHz FDD, 700 MHz SDL, and 3.6-3.8 GHz assignment stage options.

A11.147 If the bidder does not provide Ofcom with the assignment stage deposit, all the assignment stage bids submitted by the bidder (if any) will be deemed to be invalid.

A11.148 As a result, the bidder will be deemed to have made a valid assignment stage bid with a value of zero pounds for all available assignment stage options.

Total auction sum

A11.149 After the end of the assignment stage, Ofcom shall notify bidders of their total auction sum payable.

A11.150 Where a bidder's total auction sum is less than the amount it has on deposit, Ofcom will specify a deadline by which it must pay the difference between the two amounts.

A11.151 A bidder that does not provide the total auction sum payable by the deadline shall not be entitled to the grant of any licences, nor a refund of its deposit. It shall also remain liable to pay the difference between its deposit and its total auction sum payable.

Extraordinary events

A11.152 Ofcom retains powers to address extraordinary events that might otherwise compromise the auction, including:

a) rescheduling a round that has been scheduled and has not yet started;

b) rescheduling the end of a round in progress;

c) cancelling a round in progress;

d) cancelling one or more completed rounds and rolling back to a previous round;

e) suspending the auction;

f) cancelling the auction;

g) cancelling some or all bids submitted by one or more bidders in earlier rounds; and

h) excluding one or more bidders from the auction.

A11.153 Bidders who breach the Regulations may forfeit part or all of their deposit.

Information released at the end of the auction

A11.154 The auction ends with the completion of the grant stage. At this point, the following information will be released to all bidders:

a) the frequencies assigned to each bidder that has been awarded spectrum; and

b) the price paid by each bidder that has been awarded spectrum, including a breakdown of that bidder's base price and any additional prices.

A11.155 Ofcom will also publish a range of information on its website, including:

a) the names of the winning bidders and the frequencies won by those bidders (and licence fees paid);

b) the names of those winning bidders (if any) that failed to pay their total auction sum on time and who therefore failed to obtain licences under the auction, despite making winning bids; and

c) details of all valid principal stage bids, valid assignment stage bids for the 700 MHz frequencies, and occurrences of a waiver during the auction.

A12. Glossary of terms

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.