making communications work
for everyone

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

Further consultation on modelling and technical matters

UPDATE NOTE AND CONSULTATION:

Publication date: 15 May 2020
Closing date for responses: 12 June 2020

1. Overview

Purpose of this update note and consultation

In our statement of 13 March 2020 on the "*Award of the 700 MHz and 3.6-3.8 GHz spectrum bands*"[1] (the "**13 March Statement**") we made reference to modelling derived from use of a "single user throughput" model (the "**SUT Model**"). We referred to the SUT Model in support of our view that operators were likely in the longer term to be able to support a wide range of 5G services without 80-100 MHz of spectrum bandwidth in the 3.4-3.8 GHz band (whether contiguous or not). The modelling post-dated, and so was not referred to in, Ofcom's consultations prior to the 13 March Statement.

A stakeholder has raised concerns that it did not have the opportunity to comment on our reference to the SUT Model in advance of publication of our statement.

This document sets out the context for our use of the SUT Model. It includes revised results in light of certain errors we have identified in the results shown in the 13 March Statement.

Our assessment remains that the results of the SUT Model, as revised, support our view that it is likely to be technically feasible for MNOs to support a wide range of 5G services with channel bandwidths in their current holdings smaller than 80 MHz, including 40 MHz, though we recognise that the new results differ from those we presented in the 13 March Statement.

In conjunction with other parts of our competition assessment, this contributes to our overall conclusion that there is a low risk of competition concerns related to 3.4-3.8 GHz spectrum from any auction outcome.

We invite any comments on the matters set out in this update and further consultation, by 12 June 2020. We will review the position set out in the 13 March Statement in light of any comments we receive and will publish our conclusions.

Introduction

1.1 In December 2018, we published a consultation document setting out our proposals for the award of 80 MHz in the 700 MHz band and 120 MHz in the 3.6-3.8 GHz band (the "**December 2018 consultation**").[2] One of the issues that we considered as part of our competition assessment was whether an operator needs 80-100 MHz of spectrum in the

[1] Ofcom's statement of 13 March 2020 (https://www.ofcom.org.uk/consultations-and-statements/category-1/award-700mhz-3.6-3.8ghz-spectrum).
[2] Ofcom's consultation of 18 December 2018 (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).

3.4-3.8 GHz band in the longer term to provide and compete in 5G services. We reached the provisional view that this is not necessary. We reached the same conclusion in the 13 March Statement[3], following two further consultations on the auction design.[4]

1.2 On 9 April 2020, a stakeholder raised with us a concern that Ofcom had not given stakeholders an opportunity to comment on the use of the SUT Model in supporting Ofcom's position. It also raised a concern about our reference to the availability of dynamic spectrum sharing to facilitate refarming of 4G spectrum for 5G. Ofcom wishes to ensure that all stakeholders have had an opportunity to make any observations they would wish to make on these matters.

1.3 In order to address any charge of unfairness, and to avoid the risk of further delay, we are publishing this short consultation to afford any interested party the opportunity to comment on the matters set out in this consultation. We will review the position reached in the 13 March Statement in light of any comments we receive.

The role of the SUT Model

Context

1.4 Our decisions in the 13 March Statement included a cap of 416 MHz on the total amount of mobile spectrum any single operator may hold, no sub-cap on holdings in the wider 3.4-3.8 GHz band, and measures in the assignment stage of the auction to facilitate defragmentation of the MNOs' holdings in that band.

1.5 In our competition assessment, we considered a number of potential competition concerns which might arise as a result of different outcomes of the auction. We identified two main potential competition concerns which could arise in relation to asymmetry of MNOs' ultimate holdings in the 3.4-3.8 GHz band:[5]

a) first, there could be an asymmetry in the relative scale of holdings if H3G won a large share of the remaining 120 MHz available in the 3.4-3.8 GHz band; and

b) second, fragmented holdings in the band could prevent one or more MNOs from realising the benefits of contiguity or proximity.

[3] Ofcom's statement of 13 March 2020 (https://www.ofcom.org.uk/consultations-and-statements/category-1/award-700mhz-3.6-3.8ghz-spectrum).
[4] Ofcom's consultation of 11 June 2019 (https://www.ofcom.org.uk/consultations-and-statements/category-3/defragmentation-spectrum-holdings) and Ofcom's consultation of 28 October 2019 (https://www.ofcom.org.uk/consultations-and-statements/category-2/award-700-mhz-3.6-3.8-ghz-spectrum-revised-proposals).
[5] 13 March statement, paragraph 4.219.

1.6 We considered two time periods in our assessment[6]:

a) the short term lasting until around 2021, in which the 3.4-3.8 GHz band will be the main spectrum useable for 5G; and

b) the longer term from around 2022, when Ofcom considers technological developments are likely to enable other bands to be used for 5G.

1.7 Having considered both the short and longer term, we concluded that there is a low risk of competition concerns related to 3.4-3.8 GHz spectrum from any auction outcome.[7] We reached this conclusion for three main reasons:[8]

a) In the longer term, spectrum in other bands in which Vodafone, O2 and BT/EE have holdings will be available for 5G, which the operators can "re-farm" for 5G use;

b) If MNOs really need more spectrum in the 3.4-3.8 GHz band to compete, they are likely to be able to acquire some 3.6-3.8 GHz spectrum in this auction; and

c) Noting the uncertainty over what future 5G services are likely to be important for consumers, and what the technical requirements for those services might be, we had not seen clear evidence suggesting there are likely to be future 5G services which would be of significant commercial importance and which would require 80-100 MHz of contiguous spectrum.

Ofcom's reference to the SUT Model in the 13 March Statement

1.8 We referred to the SUT Model in the context of one element of our reasoning relating to the third point set out at paragraph 1.7 (c) above. We considered three areas: (i) key 5G services for competition (and when they will become important), (ii) the need for 80-100 MHz of 3.4-3.8 GHz bandwidth, contiguous or otherwise, and (iii) capacity.

1.9 Having considered (in relation to point (i)) that there was very little certainty over which 5G services would be important and when,[9] we went on to consider point (ii) above.

1.10 First, we recognised at paragraph 4.258 that, in principle, large bandwidths could assist in delivering some hypothetical use cases (such as augmented/virtual reality, or very high-resolution professional quality video streaming).[10]

1.11 However, we noted that stakeholders had not provided clear evidence of use cases which are likely to require 80-100 MHz of 3.4-3.8 GHz bandwidth (contiguous or otherwise) and which are likely to be of significant commercial and competition importance.[11] We noted

[6] 13 March Statement, paragraphs 4.205 and 4.225-4.226.
[7] 13 March Statement, paragraph 4.203.
[8] 13 March Statement, paragraphs 4.208-4.211.
[9] 13 March Statement, paragraphs 4.257, A.7.6 and A.7.19.
[10] 13 March Statement, paragraph 4.258.
[11] 13 March Statement, paragraphs 4.211, 4.258, 4.290(b) and A7.39.

that at this stage any assessment of the commercial and competitive importance of hypothetical services would be inherently speculative.

1.12 Finally, we noted that if some new and important service that requires 80 MHz does emerge, then in our view there is a low risk that the necessary performance could not be achieved by alternative means including dual connectivity, carrier aggregation, Wi-Fi/Wi-Fi offload, or mmWave spectrum without too great a loss in quality of service.

1.13 In light of the lack of clear external evidence, we checked whether our own modelling – using the SUT Model – suggested that 80-100 MHz bandwidth in the 3.4-3.8 GHz band would be necessary to support a range of potential future 5G services.

The SUT Model

1.14 The SUT Model calculates an approximate theoretical maximum of the data throughput which a radio link in a cell of a 5G mobile network could support, given an assumed bandwidth of the radio carrier and an assumed received signal quality, expressed as signal to interference and noise ratio (the "**SINR**").[12] Data throughput is the rate at which data can be successfully transmitted in a cell of a network, and as such is one measure of the performance of a network.

1.15 The data throughput calculated by the SUT Model can be thought of as the maximum data throughput which a single user could experience at a location at which the assumed SINR applies, if all the data-carrying resources of the radio carrier were dedicated to that user, i.e. if there were no other users active on that carrier in the cell. Hence, we refer to the theoretical maximum data throughput calculated by the model as single user throughput (the "**SUT**"). We have used the SUT Model to calculate separately SUTs in the downlink (base station to user's terminal) and uplink (terminal to base station).

1.16 The SUT Model allows us to calculate the SUT for various modelled scenarios. We defined each scenario as a combination of an assumed carrier bandwidth (modelled in each scenario explicitly either as a single contiguous block or as two non-contiguous blocks) and an assumed multiple input multiple output ("**MIMO**") antenna configuration. The MIMO configurations are defined by the number of antennas and how they are used in the user's terminal (e.g. a handset) and at the mobile network base station. We modelled a configuration known as single-user MIMO, or "**SU-MIMO**". For example, a 4x4 SU-MIMO configuration would use four antennas at the user's terminal and four antennas at the base

[12] Although there are other considerations that also affect signal quality, since the SUT Model focuses on the aspect related to SINR, we refer to SINR and signal quality interchangeably for ease of discussion in this document.

station. We chose the minimum configuration for the scenarios we modelled, so as not to risk overstating the performance indicated[13].

1.17 The SUT Model is described in detail in Annex A1 of this document. Its calculations are based on guidance defined by the 3rd Generation Partnership Project (the "**3GPP**").[14]

Ofcom's use of the SUT Model

1.18 Using the SUT Model we estimated the throughput which a theoretical mobile cell could offer across its coverage area with different carrier bandwidths.[15] We used these results to gain insight into the quality of service a mobile user would experience with carriers of different bandwidth if all the available resources of the carrier were assigned to offer each of a set of potential future 5G services to that single user.

1.19 We recognised in the 13 March Statement that the SUT Model is a simplified theoretical model and that in an actual deployment many users would share the resources of a carrier, but considered its results could nonetheless give us some indication of what services carriers of different bandwidths might technically be capable of supporting.

1.20 The results we set out in the 13 March Statement suggested MNOs were likely to be able to support a wide range of 5G services with their current holdings (i.e. with channel bandwidths smaller than 80 MHz, including 40 MHz), in combination with massive MIMO (mMIMO).[16] That is to say, the results suggested that it would be technically feasible for operators to support such services with smaller bandwidths than 80 MHz: Ofcom drew no conclusions as to the associated commercial incentives or the competitive significance of future hypothetical services.

Revised Results

1.21 Since we published the 13 March Statement, we have identified certain errors in the original SUT modelling. We have corrected these, and set out below the revised results.

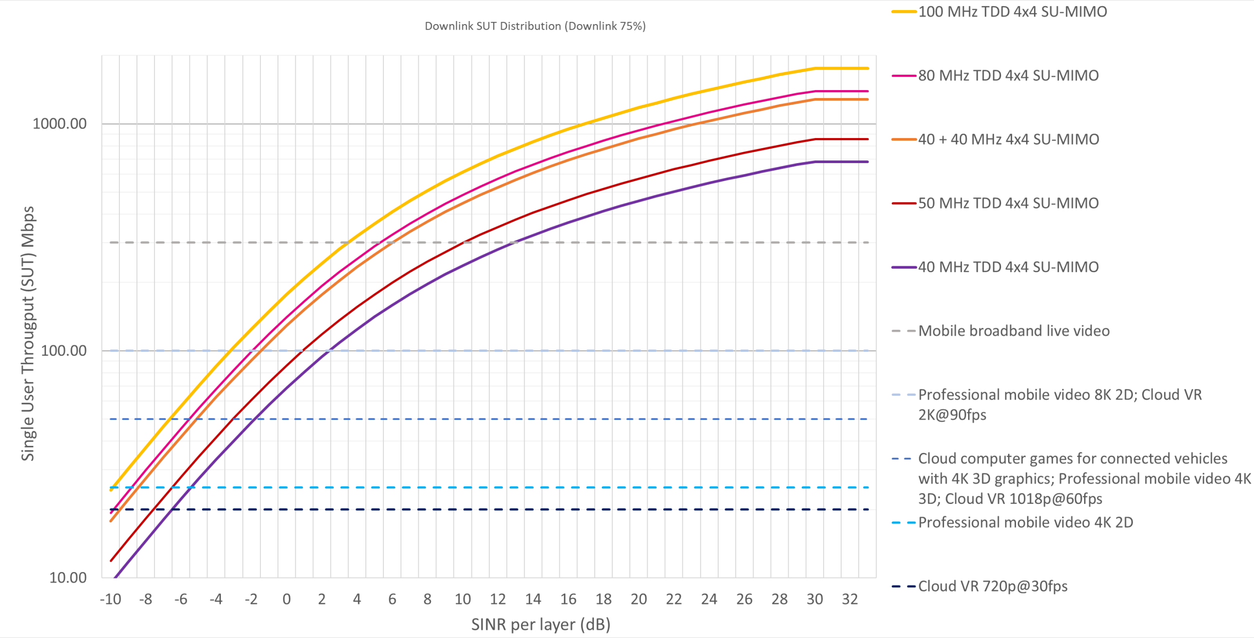
---

[13] 4x4 SU-MIMO in the downlink is the minimum configuration required by 3GPP document TS 38.306, which specifies the capabilities required of 5G user equipment, and 2x2 MIMO in the uplink is the minimum configuration likely to be supported in most devices. The small size of mobile handsets is a key constraint – larger terminals are likely to be able to support a greater antenna configuration (e.g. something the size of a laptop would have space for more antennas - so for example 8x8 SU-MIMO is more likely to be supported in larger devices).
[14] The 3GPP is a global consortium of standards organisations which develop protocols for mobile telecommunications.[15] 13 March Statement, paragraph A7.56.
[15] 13 March Statement, paragraph A7.56.
[16] mMIMO is a new antenna technology which MNOs are likely to deploy in many 5G base stations. Two of the key benefits of mMIMO are improved capacity by utilizing multi-user MIMO (MU-MIMO) and improved coverage by utilizing beamforming, which, for example, allows coverage from a network using 3.x GHz spectrum to approximately match that of a network using 1800 MHz. Note that we did not include mMIMO in the SUT modelling. This is because we would expect mMIMO to be used in addition to the SU-MIMO configurations that we did include, as it is unlikely that an operator would deploy mMIMO across all the cells in its network. Also, we have modelled SUT which assumes that there is only one user in a cell and that user receives all the carrier resources.

We note that these results differ from those we published in the Figures A7.26 and A7.27 of Annex 7 of the 13 March Statement. The differences are due to some adjustment to the modelled spectrum scenarios and to corrections of the errors identified.[17] We have also modelled two different downlink to uplink Time-Division Duplex (TDD) ratios.

1.22 The results are plotted in Figures 1, 2 and 3 below. Figure 1 depicts the downlink SUT for a TDD downlink (DL) to uplink (UL) ratio of 3:1. The downlink to uplink ratio is the ratio between the carrier's resources devoted to downlink and uplink transmissions respectively. Figure 2 depicts the uplink SUT for the same ratio, which is typical of a macro cell network and approximates the 3:1 Frame Structure A (also known as the "Preferred Frame Structure") in the 3.6-3.8 GHz example licence.[18] Figure 3 depicts the uplink SUT for a TDD downlink to uplink ratio of 1:1 which might be representative of some indoor small cell scenarios.[19]

Figure 1: Results of SUT Model – Downlink (for a DL/UL ratio of 3:1)



[17] For a description of the changes made to the model please see paragraph A1.54 in Annex A1.
[18] See paragraph 12, Schedule 1 to the example 3.6-3.8 GHz licence, Award of the 700 MHz and 3.6-3.8 GHz spectrum bands Information Memorandum, Ofcom, 13 March 2020, https://www.ofcom.org.uk/__data/assets/pdf_file/0019/192412/information-memorandum-award-700mhz-3.6-3.8ghz-spectrum.pdf
[19] See paragraph 15, Schedule 1 to the example 3.6-3.8 GHz licence, Award of the 700 MHz and 3.6-3.8 GHz spectrum bands Information Memorandum, Ofcom, 13 March 2020, https://www.ofcom.org.uk/__data/assets/pdf_file/0019/192412/information-memorandum-award-700mhz-3.6-3.8ghz-spectrum.pdf

Figure 2: Results of SUT Model – Uplink (for a DL/UL ratio of 3:1)

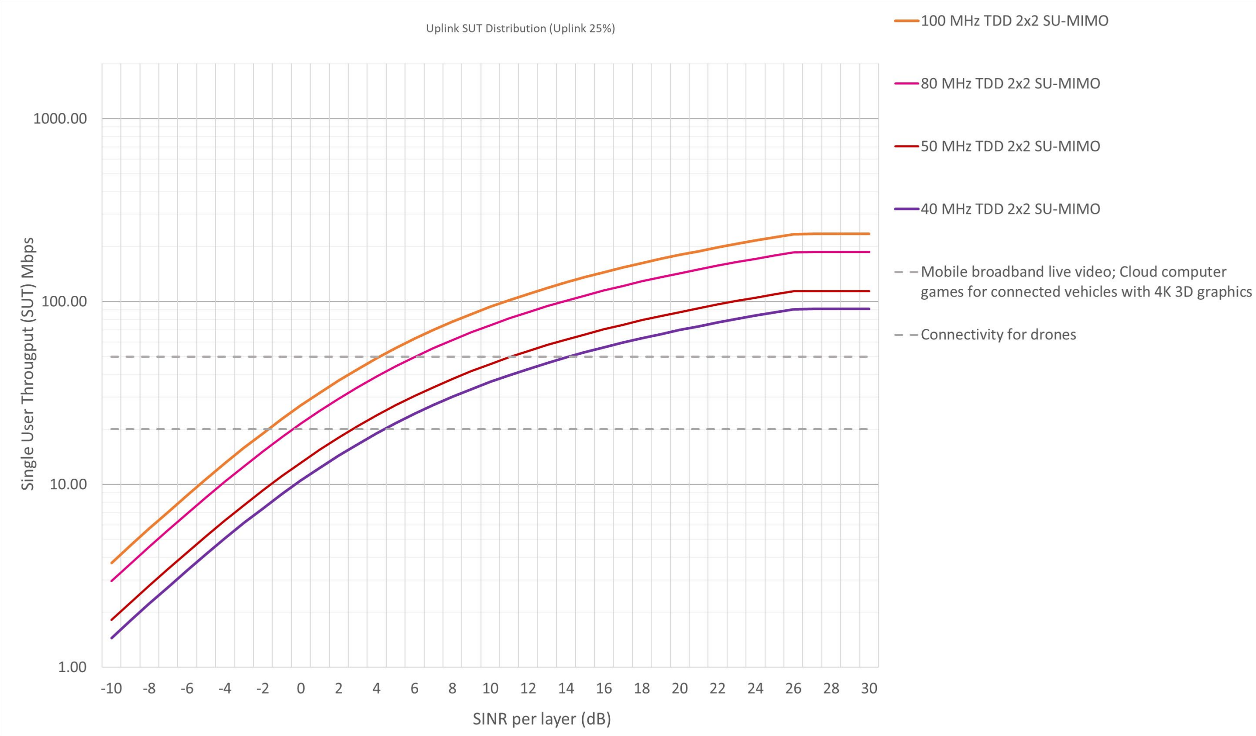
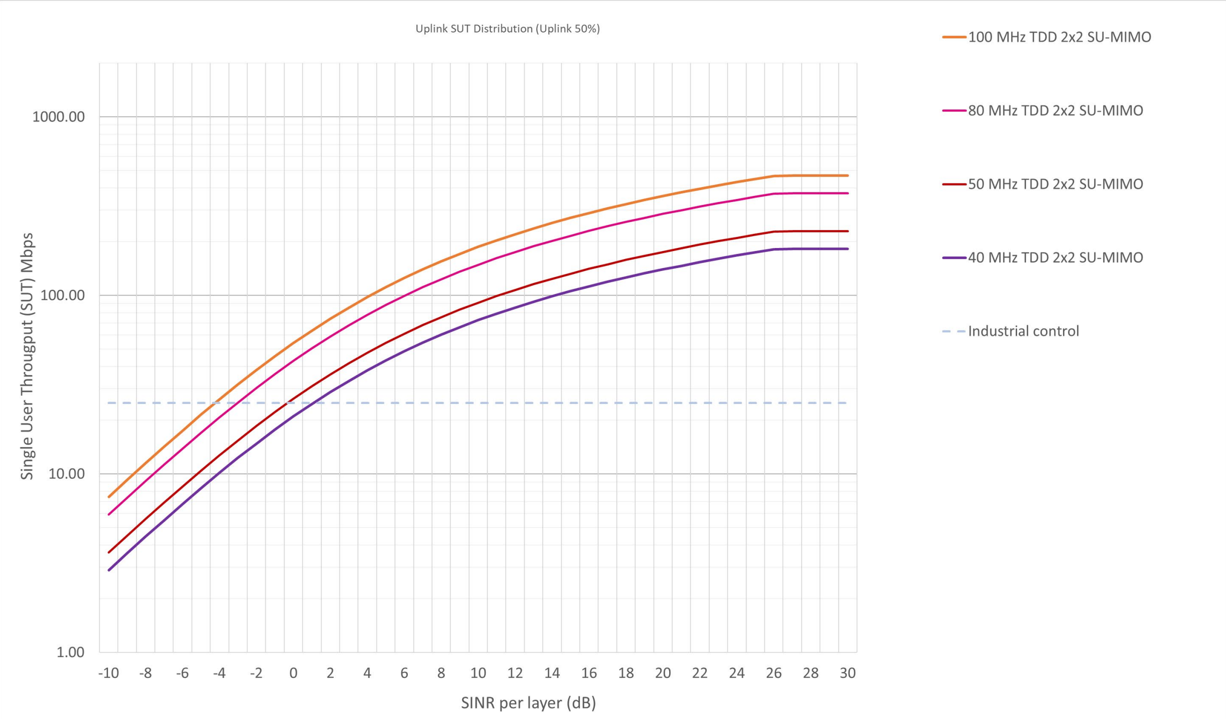


Figure 3: Results of SUT Model – Uplink (for a DL/UL ratio of 1:1)



How the results can in principle inform our assessment

1.23 Users' perception of the quality of a service generally improves as the data rate they experience increases, although the perceived improvement diminishes at higher data rates. Some services, such as streamed video, require a minimum data rate delivered to any user to work at all.

1.24 In a real network, the data rate (or throughput) available to a user, all other things equal, falls as SINR or signal quality declines.

1.25 The plots of SUT in Figure 1, Figure 2 and Figure 3 represent how a user's throughput would vary with SINR in an idealised situation, in which no other users share the resources of the radio carrier. The different curves in solid lines represent this in the various spectrum scenarios we have chosen. The horizontal dotted lines represent the minimum data rates required by the future 5G services we have selected from those described by 3GPP in a feasibility study on new services and markets technology enablers, in 3GPP document TR 22.891. The range of SINR values on the horizontal axis of the plots is representative of those that may be encountered in a real mobile network.[20] A SINR as low as -5dB might be encountered in environments such as at the edge of a macro cell in a rural area. Very low SINR can also occur where either fixed or moving objects, such as buildings or buses respectively, obstruct reception of the signal, although we note that MIMO antenna configurations are designed to minimise the impact of such obstructions. Higher SINR values might be expected nearer a base station in a rural area and at many locations in macro cells in urban and suburban areas, except in harder to reach locations such as deep indoors.

1.26 For a service to be technically feasible at all in a given scenario, the maximum throughput achievable in that scenario must exceed the minimum data rate of the service. All the services shown in Figure 1, Figure 2 and Figure 3 fulfil this criterion in all the spectrum scenarios modelled. These services are representative of some of the most demanding services (in terms of user data rates) of the much larger set of possible future 5G services described in 3GPP document TR 22.981 (see Annex A1 for further details).

1.27 The SINR value at the point the dotted horizontal line of a service meets the solid curve of a scenario is the SUT Model's prediction of the minimum signal quality necessary to deliver the service in that scenario. For example, the point at which the horizontal line for "Cloud

[20] The scale of the horizontal axis of SINR values in Figures 1, 2 and 3 is marked in decibels (dB). A dB is a logarithmic way of expressing a ratio between the power of two signals. Mathematically, the ratio r expressed in dB is 10 x log10(r). SINR values of 10 dB, 20 dB and 30 dB mean that the wanted signal is 10, 100 and 1,000 times stronger respectively than the unwanted interference and noise signals. A SINR value of 0 dB means that the wanted signal is of the same strength as the unwanted signals (a ratio of 1:1). A negative SINR value means that the wanted signal is weaker than the unwanted signals, e.g. a SINR value of -10 dB means that the strength of the wanted signal is one tenth of the strength of the unwanted signals.

VR 1018p @60fps" meets the purple solid line in Figure 1 has a SINR value of about -2 dB.[21] This is the SUT Model's prediction of the minimum signal quality necessary to deliver this service with a 40 MHz radio carrier and with 4x4 SU-MIMO antenna configuration. In other words, in this example, the SUT Model predicts that, with this combination of carrier bandwidth and MIMO configuration, we cannot expect the service to work in locations in a cell at which the SINR is lower than -2 dB, i.e. a signal quality less than the minimum necessary SINR that is shown in Figure 1.

1.28 However, in general, while the minimum SINR predicted by the SUT Model is likely to be necessary, it may not be sufficient, because in real situations in any scale deployment a user of the service is likely to have to share the radio carrier's resources with other users active in the cell at the same time, using the same service and/or other services. This means that any user of the service is likely to require a higher SINR than the minimum.

1.29 Signal quality can vary considerably across the coverage area of a cell due to a variety of factors and tends to reduce as the user's distance increases from the base station antennas serving the cell. In a real network deployed at scale, a particular service is therefore only likely to be experienced satisfactorily at locations in which the SINR exceeds the minimum by some margin. The greater the margin, the more of the radio carrier's resources can be allocated to other users in the same cell to provide the same and other services. The results of the SUT Model cannot tell us what margin would be appropriate (not least because it is limited to modelling the maximum throughput to a single user).

1.30 In designing its network, a MNO would need to consider, among other things, how to deploy its network to achieve sufficiently high signal quality across its coverage area to realise its quality objectives for all services it intends to offer.[22]

1.31 The results of the SUT Model can therefore only inform our assessment insofar as they provide insight into the technical feasibility of delivering each of a range of potential future 5G services in the scenarios we modelled.

1.32 We draw no inference from this analysis about the commercial incentive on an MNO to provide any particular service, either in the scenarios in which the results indicate the service is likely to be supported technically or in other scenarios. In addition, we remain of the view set out in the 13 March Statement that, at this stage, any assessment of the commercial and competitive importance of these services would be inherently speculative.[23] Nevertheless, we consider the results, as amended, continue to provide a helpful input to assist our regulatory judgement, as explained below.

[21] "Cloud VR" or "Cloud Virtual Reality" is an example of the "virtual presence scenario" described in section 5.11 of 3GPP document TR 22.891. An example would be a virtual or augmented reality video being generated on a remote computer (i.e. in the cloud) and relayed to a user's VR headset.

[22] One factor MNOs may consider is specification of terminals. There may be cases where some terminals exceed the minimum SU-MIMO configurations we have modelled. This is especially likely for larger terminals. In these cases, more carrier resources may be available to serve users receiving at the SINR limit for the service in question calculated assuming 2x2 or 4x4 SU-MIMO.

[23] 13 March Statement, paragraph 4.258.

What the results tell us

1.33 The results of our revised SUT Model differ from those we published in Figures A7.26-7 in the 13 March Statement. Notably the minimum SINR required for each of the services is higher in the new results, and some services are likely to be particularly constrained in the uplink in all bandwidth scenarios.

1.34 We used 3GPP document TR 22.891 as the primary source of information about potential future 5G services. TR 22.891 sets out 74 potential use cases (services). TR 22.891 does not specify the type of spectrum expected to carry the services. We consider that in a number of cases it is likely that use of a large bandwidth of mmWave spectrum was anticipated rather than spectrum in the 3.4-3.8 GHz band. A number of the services are also specific to indoor or hot spot usage. See Annex A, paragraphs A1.17 to A1.33 for a discussion of all the services in TR 22.891.

1.35 As noted in paragraph 1.26 above, and as Figure 1, Figure 2 and Figure 3 show, none of the services is strictly infeasible technically in any of the scenarios. The services we have included in Figures 1, 2 and 3 represent some of the most demanding throughput from those described in 3GPP TR 22.981. There are 74 broad use cases defined in that specification and our analysis in Annex A1, in conjunction with the modelling results discussed here, indicate that the majority of those cases are likely to be technically feasible to be delivered by a network with 40 MHz of spectrum.

1.36 To explain this conclusion, we consider what the SUT Model's results tell us about technical feasibility in different types of network deployment, first by discussing macro cells and then considering services that may involve other patterns of deployment, such as small cells.

1.37 Considering that MNOs are likely to deploy mMIMO antennas for spectrum in the 3.4-3.8 GHz band in the busiest areas, the results indicate that deployment of any of the scenarios in a network of macro cells is likely to support any of the services except those described as "mobile broadband live video", "cloud computer games for connected vehicles with 4k 3D graphics" and "industrial control".[24, 25] This is because, apart from these excepted services, applying our technical judgement, we consider the minimum necessary SINR for a single user for all bandwidths modelled, including 40 MHz, is at a signal quality level that it is reasonable to expect an operator to be able to achieve across a significant proportion of the cell, providing a margin allowing carrier resources to be allocated to other users, especially taking into account the throughput boost from mMIMO (where available). For the first of the excepted services, "mobile broadband live video", this judgement may not

---

[24] mMIMO antennas would tend to increase the SINR levels across locations in cells in which MNOs deploy them.

[25] We include connectivity for drones in those services likely to be supported by macrocells in any of the bandwidth scenarios we modelled, even though the minimum necessary SINR predicted for this service by the SUT Model of about 4dB in the 40 MHz scenario in the uplink, as can be seen in Figure 2, is relatively high. We consider that this service is likely to be supported nevertheless because the drone would be airborne, and the base station would therefore receive a significantly stronger uplink signal than it would from an equivalent transmitter on the ground directly below.

apply to a macro cell deployment, due to both the downlink and uplink requirements (in Figure 1 and Figure 2), whilst for the other two services it is because of the uplink requirements (in Figure 2), noting that it may not be optimal to deploy these services in macro cells, irrespective of carrier bandwidth.

1.38 For those excepted services we make the following observations.

1.39 **"Mobile broadband live video"** is an example of "on demand networking" described in section 5.7 of 3GPP document TR 22.891. This service is defined for a hot spot environment (e.g. a football stadium) and an example is the audience in a stadium sharing ultra-high definition (UHD) live video with friends who are not at the scene. The potential service requirements set out in TR 22.891 include a user experienced downlink data rate of 300Mbps and uplink rate of 50Mbps. The results shown in Figures 1 and 2 indicate that coverage is likely to be constrained to locations within a cell with good signal quality in the 40 MHz scenario, but also, to a lesser extent, in the 80 MHz and 100 MHz scenarios. We reached a similar conclusion in relation to the downlink with a 40 MHz carrier in the 13 March Statement. Given that it is a service defined for a hot spot environment, it is perhaps unsurprising that it would be challenging to provide using macro cells, as discussed above. However, we would expect that these signal qualities are likely to be available within the coverage footprint of a small cell designed for this type of hot spot.

1.40 **"Cloud computer games for connected vehicles with 4k 3D graphics"** is a type of service described in section 5.32 of 3GPP document TR 22.891. An example is video/gaming services to cars or buses in a city centre. User terminals would either be directly connected to the mobile network through a wireless radio link or through a relay in the car or bus. The mobile network deployment to deliver this service is described as either macro or micro cellular, or ultra-dense network (UDN). The potential service requirement set out in TR 22.891 includes an average end user throughput greater than [50-120] Mbps (downlink or uplink) and in Table 5.32-1 a KPI (minimum data rate) of < 50 Mbps is specified. The results shown in Figure 1 and 2 indicate that coverage of this service may be constrained by uplink performance in the scenarios modelled. Coverage is likely to be limited to locations within a cell with good signal quality in the 40 MHz scenario, but also, to a lesser extent, in the 80 MHz and 100 MHz scenarios.

1.41 The new results indicate a greater limitation in the potential coverage of this service with a 40 MHz carrier, due to the throughput attainable in the uplink. However, the difference in provision of this service between 40 MHz and larger bandwidths should not be exaggerated, because there is also a potentially significant limitation with 80 MHz bandwidth and some limitation even with 100 MHz. Even if these limitations are smaller than for 40 MHz, we consider they are still likely to be significant.[26] In our view, as

[26] In comparing uplink performance between different bandwidths, we take into account that the SINR in the uplink, i.e. at the base station receiver, may be limited by the maximum power which the user's terminal would be licensed to transmit. This means that the uplink SINR received at the base station from a user using a narrower carrier might be higher than the uplink SINR received at the base station from a user using a wider carrier in the same location. The results shown in Figure 2 do not reflect this. We explain this further in paragraphs A1.49-A1.53 in Annex A1.

indicated in TR 22.981, there are alternative ways to deploy these services with small cells (e.g. micro cells and ultra-dense networks) and use of carriers with very wide bandwidths (wider than 100 MHz), which are likely to become possible in future with mmWave spectrum. We would expect MNOs to use such different methods, especially if these services proved to be of competitive importance.

1.42 **"Industrial control"** is described in section 5.13 of 3GPP document TR 22.891. A specialised industrial service of this type is likely to be delivered using small cells in indoor environments, such as factories, warehouses and distribution centres, and is not likely to be delivered using an MNO's macro cell network. The potential service requirement set out in TR 22.891 includes support for high uplink data rate (tens of Mbps per device in a dense environment). Figure 3 shows that, with a 1:1 downlink to uplink ratio, the SINR values required to support this service appear unlikely to present a significant challenge using any of the bandwidths we modelled, from 40 MHz upwards. A downlink to uplink ratio of 1:1 might be appropriate in an "industrial control" indoor small cell scenario like this, where uplink traffic demand may equal or exceed downlink traffic. This downlink to uplink ratio is likely to be practicable in controlled indoor environments, in which wireless networks can be built and operated without interference with outdoor macro cell networks, which are likely to operate with a downlink to uplink ratio of 3:1.

1.43 Overall, the new results of the SUT Model indicate that it would be technically feasible to provide a wide range of potential future 5G services with bandwidths lower than 80 MHz, including 40 MHz. The results show that, in macro cells, the coverage of two of the services – "mobile broadband live video" and "cloud computer games for connected vehicles with 4k 3D graphics" – may be constrained by uplink performance, most severely in the case of a 40 MHz carrier bandwidth. In the case of the "mobile broadband live video" service, this is intended to be delivered using small cells where such constraints are likely to be less relevant. In the case of the "cloud computer games for connected vehicles with 4k 3D graphics" service, this service may also be better provided using small cells. Similarly, it is likely to be practicable to deliver the "industrial control" service using small cells in controlled indoor environments.

Our view in the 13 March Statement and with the revised SUT Model results

1.44 In the 13 March Statement we set out three main reasons for our overall view that there is a low risk of competition concerns arising from the potential asymmetries in MNOs' ultimate holdings in the 3.4-3.8 GHz band, that could result from different outcomes of the auction.[27] One of those reasons concerned the question of what 5G services and capabilities will become important for competition, and how much bandwidth they will require. The SUT Model informed Ofcom's assessment of the latter question, by modelling how much bandwidth is technically necessary to provide various possible types of 5G

[27] See paragraph 1.7 above.

service, based on particular assumptions. We set out our conclusion on this point in the 13 March Statement in paragraph 4.258.

1.45 The SUT Model results we set out in the 13 March Statement indicated that all of the services modelled could comfortably be provided to a single user in both downlink and uplink and at an acceptable signal quality (expressed as SINR), while allowing significant margin to accommodate multiple users. The one exception was mobile broadband live, for which we included a specific discussion.[28]

1.46 The revised SUT Model results in all bandwidth scenarios, when compared to the corresponding results we presented in the 13 March Statement, show lower throughputs in the downlink and significantly lower throughputs in the uplink. This has led us to ask ourselves whether the revised results suggest we should be drawing different conclusions from those we reached in the 13 March Statement.

1.47 In considering the revised results, we have examined in more detail the nature of some of the services for which we modelled results (those for which the minimum necessary SINR values look more demanding) and have considered their plausible network deployment patterns, to understand in more detail the nature of the technical feasibility challenge in providing those services using different bandwidths in the 3.4-3.8 GHz band.

1.48 This analysis suggests to us that in the three cases we identified for which deployment on a macro cell network at 3.4-3.8 GHz looked challenging (at 40, 80 or even 100 MHz bandwidths), a different network deployment pattern - such as small cell deployment at a hot spot for mobile broadband live video, or deployment indoors with a 1:1 uplink/downlink ratio for industrial control - would reasonably support the higher SINR values likely to be needed for these services. We might expect operators to deploy such alternatives if these services proved to be commercially important.

1.49 Having examined the results following the revisions we have made to the SUT Model, and taking into account the considerations set out above, we consider that the results of the modelling remain consistent with our view that it is likely to be technically feasible for MNOs to support a wide range of 5G services with channel bandwidths in their current holdings smaller than 80 MHz, including 40 MHz, though we recognise that the new results differ in material respects from those we presented in the 13 March Statement.

Dynamic spectrum sharing

1.50 Dynamic spectrum sharing (DSS) is a technology which 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.

1.51 In the 13 March Statement, at paragraph A7.36 of Annex 7, we said that we understand that DSS could facilitate refarming of 4G bands to 5G. We added that although we

[28] 13 March Statement, paragraph A7.61, final bullet.

understand that DSS might reduce capacity by 7 to 10% when compared with a 4G-only carrier, its benefits may improve the overall spectrum efficiency of the network when compared with assigning static 4G and 5G carriers. We noted that DSS is already being used by some operators (such as AT&T and Swisscom).

1.52 A stakeholder has raised a concern about our reference to the use of DSS to facilitate re-farming of 4G spectrum. In particular, it highlighted that a technical solution for DSS is not available in the 2.3 GHz band (which is licensed for use with time-division duplex technology).

1.53 We did not suggest in the 13 March Statement that DSS was necessarily available in all 4G bands. It is our position, however, that it is likely to be available in a number of current 4G FDD bands including 800 MHz, 900 MHz, 1800 MHz, 2.1 GHz and 2.6 GHz. Our view remains that DSS could facilitate refarming of most 4G bands to 5G, and so is likely to be an option for operators to consider. We will consider any observations stakeholders wish to make on this view.

Consultation

1.54 If stakeholders have any comments on the matters considered in this consultation, they should please send them by email to radiospectrum.award@ofcom.org.uk **by 12 June 2020**. We will review our position on these issues in light of any comments received and consider whether we need to make any changes to our conclusions as set out above and in the 13 March Statement. If stakeholders think that any of their comments should be kept confidential, they should please identify them and explain why.

A1. SUT Model details

Introduction

A1.1 In Section 1 of this document we set out the context for our use of the SUT Model and provide a high-level description of it. In this Annex we describe it in more detail.

We have considered potential future 5G services which have been identified by 3GPP

A1.2 The 5G services that we have considered in the SUT Model come from a feasibility study published by 3GPP (the 3GPP document TR 22.891[29]) which aims to identify the market segments and verticals which might be supported by future mobile networks. It identifies groups of related use cases and service requirements to be supported in the future in various scenarios (for example, connectivity for drones).

A1.3 In general, the data rates for services are specified in TR 22.891 for a single user (for example, high definition video streaming). However, it is not clear whether all of the services are defined in this way, and some may represent an aggregate from multiple users. Therefore, we have taken a conservative approach and interpreted them for a single user. We observe that the data rate requirements for some of these services are very high and might be expected to be delivered in only some areas and not everywhere; for example, many of the services are defined for small cells, hot spots or indoors and, as such, we would not expect these to be delivered using a network of macro cells. We also observe that TR 22.891 is spectrum agnostic and as such many of the services identified may, in practice, be intended to be carried using large bandwidths of mmWave spectrum rather than 3.4-3.8 GHz or other sub-6 GHz bands.

We have calculated the SUT using the 4G SINR to throughput mapping equation which we have extended for 5G and carrier aggregation

A1.4 We have modelled the SUT for a range of SINR (signal-to-interference-plus-noise ratio) values to reflect the fact that a user further from the base station (or in a hard to reach area such as indoors) will receive a poorer quality signal than a user closer to the base station.

[29] 3GPP TR 22. 891: "Technical Specification Group Services and System Aspects; Feasibility Study on New Services and Markets Technology Enablers" version 14.2.0
https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2897

A1.5 We have used the mapping function from Annex A to TR 36.942 to calculate SUT. Because TR 36.942 was originally developed for LTE (i.e. 4G), we have made adjustments to the calculation for 5G. The modifications we have made are:

- We have extended the model to support spatial multiplexing because a typical 5G mobile device might support four downlink spatial layers and two uplink spatial layers under SU-MIMO[30] conditions;[31]
- We have extended the maximum throughput to account for higher adaptive modulation and coding orders because at the time TR 36.942 was published, LTE had a maximum modulation order of 64QAM in the downlink and 16QAM in the uplink, however, 5G NR supports up to 256QAM in the downlink and up to 64QAM in the uplink; and
- We have calculated the maximum throughput using the maximum throughput equation for 5G NR from §4.1.2 in 3GPP TS 38.306.

A1.6 We have also extended the model to calculate total throughput when aggregating carriers in some spectrum scenarios; and we have added a downlink to uplink ratio to account for TDD networks transmitting in either uplink or downlink for only part of the time.

There are some factors that the SUT Model does not take into account

A1.7 This is a simplified model which is not intended to predict the throughput a user could expect at a specific location within a cell, but can illustrate the relative throughputs of carriers with different bandwidths (for example, a 40 MHz carrier when compared with a 80 or 100 MHz carrier)[32]. Higher values of SINR would be typical for a user close to the base station whilst lower values of SINR would be typical for a user who is at the edge-of-cell or in a hard to reach area (e.g. indoors).

A1.8 There are a number of additional factors that we have not modelled that could mean that the simplified model is likely to underestimate the throughput achievable at a particular signal quality. There are also some other factors that could mean that the SUT Model is likely slightly to overestimate the throughput achievable at a particular signal quality. We describe these additional factors below.

A1.9 We would expect additional improvements in the attenuation factor, α, that 5G brings when compared with 4G. The attenuation factor represents real-world implementation losses because real communications technologies will never quite reach the theoretical maximum spectral efficiency of a channel as calculated by the Shannon bound. We would expect 5G to have an improved attenuation factor because it has several physical layer

[30] Single User MIMO.
[31] 3GPP TS 38.306 “NR; User Equipment (UE) radio access capabilities”, version 15.5.0 https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3193
[32] Noting however that SINR may not be a simple proxy for location especially in the uplink for mobile and nomadic terminals where there is an absolute power limitation, see paragraphs A1.48 - A1.52 for further details.

improvements over 4G including a "lean carrier". This means that this aspect of the calculation may tend to slightly underpredict the throughput that can be achieved.

A1.10 There are additional benefits associated with massive MIMO beamforming which would tend to improve the received SINR at a given location and therefore improve the throughput a user might receive at that location. For example, it is generally expected that massive MIMO (64T64R) will allow for 3.4-3.8 GHz networks to have a similar downlink coverage footprint to 1800 MHz networks[33] and that the gain of massive MIMO networks might be 6 dB greater than 2x2 MIMO systems in the downlink.[34] Massive MIMO beamforming can be applied to 5G NR carriers of various bandwidths and we expect that the uplift in performance would be the same for all bandwidths.

A1.11 Multi-user MIMO (MU-MIMO) can bring capacity benefits when enabled by massive MIMO systems. We have not taken this into account as we are considering SU-MIMO only. One reason is because we would expect massive MIMO to be used in addition to the SU-MIMO configurations that we do model, as it is unlikely that an operator would deploy massive MIMO across all the cells in its network. Also, we have modelled SUT which assumes that there is only one user in a cell and that user receives all the carrier resources.

A1.12 Some 5G terminals with a larger form factor might also be able to support higher than 4x4 SU-MIMO in the downlink and 2x2 SU-MIMO in the uplink. It is possible that larger 5G terminals, typically larger than a smartphone, could support up to 8x8 SU-MIMO in the downlink and up to 4x4 SU-MIMO in the uplink.[35,36] These higher order MIMO layers will lead to a higher overall throughput than we have taken account of in our modelling.

A1.13 At lower SINR, the SU-MIMO order might be reduced as the antennas within a device are used for SIMO spatial diversity range enhancement instead of SU-MIMO spatial multiplexing throughput enhancement. In this mode, a user device will switch to spatial diversity range enhancement in order to maximise throughput. We expect that any impact on throughput would be proportional to carrier bandwidth (e.g. in absolute terms, any change in throughput would be approximately twice as much for an 80 MHz carrier as for a 40 MHz carrier) because antenna mode selection is dependent on SINR and is not dependent on carrier bandwidth.

A1.14 The SUT Model assumes that each MIMO layer can independently support throughput. However, in some downlink scenarios, the channel may not generate sufficient multipath

[33] §2.5.2, "5G Implementation Guidelines: NSA Option 3", GSMA, February 2020, https://www.gsma.com/futurenetworks/wp-content/uploads/2019/03/5G-Implementation-Guidelines-NSA-Option-3-v2.1.pdf

[34] §2.1, "5G deployment below 6 GHz", Nokia, 2017, https://www.rrt.lt/wp-content/uploads/2018/10/Nokia_5G_Deployment_below_6GHz_White_Paper_EN.pdf

[35] Table 4.1A-1, 3GPP TS 36.306 V16.0.0 (2020-03) https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3193

[36] § II-E.1.2 5 and Table 10, *PRELIMINARY EVALUATION REPORT FROM THE 5G INFRASTRUCTURE ASSOCIATION ON IMT-2020 PROPOSAL*, Independent Evaluation Group 5G Infrastructure Association, Document 5D/11-E, Received: 27 November 2019, https://5g-ppp.eu/wp-content/uploads/2020/01/5G-IA-5G-PPP.pdf

to gain the full spectral efficiency improvements from 4x4 SU-MIMO spatial multiplexing, thus the achievable SUT may be overstated in those scenarios. For example, the downlink for a drone is likely to be a line-of-sight scenario which means that there is likely to be little multipath and so the maximum SU-MIMO that might be supported is two spatial layers from polarisation diversity (N.B. “downlink” means from the base station to the drone). We have calculated uplink throughput considering two layer SU-MIMO only, which may be supported even in line-of-sight scenarios using polarisation diversity. We expect that any reduction in downlink throughput from using two layer SU-MIMO instead of four layer SU-MIMO in certain scenarios would be proportional to carrier bandwidth (e.g. in absolute terms, any reduction in throughput would be approximately twice as much for an 80 MHz carrier as for a 40 MHz carrier) because the spectrum efficiency improvements from spatial multiplexing are dependent on the multipath generation of the channel.

A1.15 We have not modelled some of the limitations associated with using carrier aggregation in devices. It may be that some devices, particularly lower cost devices, may only be able to make use of SU-MIMO on a single component carrier and support only a single spatial layer on any other aggregated carriers. We also understand that intra-band carrier aggregation in the uplink in 3.4-3.8 GHz may not be available soon and it is uncertain whether it would be developed in the longer term.

A1.16 Some operators with 100 MHz may face greater practical restrictions on the base station transmit power spectral density than operators with 40 or 50 MHz on some sites, meaning that the downlink transmit power per spatial layer will be reduced for the wider bandwidth carriers. This will lead to a lower SINR for wider carriers at a given location and therefore throughput may be overstated in our model in these cases. The 3.6-3.8 GHz licences have power limits which are defined in terms of transmit power spectral density for the base station, however, we understand that there are other factors that could constrain the total transmit power of a base station including the power rating of base station equipment and ICNIRP limits. These factors might limit the power that can be transmitted on some sites; however, we do not think that these constraints would be significant for most sites, so we have not included this in the SUT Model.

5G Services

Our assessment considers potential future 5G services

A1.17 The services we have looked at are based on use cases identified by 3GPP in TR 22.891[37] for future mobile networks. We have considered the 74 use cases set out in the document, some of which detail multiple services.

A1.18 For the purposes of this analysis, we have grouped the use cases into four of the categories set out in section 6.2 of TR 22.891: enhanced mobile broadband (eMBB), Critical communications (CriC)[38], Massive Internet of Things (MIoT) and Network Operation (NEO). In order to avoid repetition, where a use case is included in more than one of these categories, we have removed the duplications by including the use case in the first category it is listed in based on the above order of categories. We have not included vehicle-to-everything (V2X) as a separate category and have included these use cases under eMBB.

A1.19 We have identified example services which are representative of some of the most demanding use cases (in terms of data rates) from these categories, to assess to what extent they might be supported by different carrier bandwidths. These representative services are:

- Mobile broadband live video;
- Cloud VR;
- Professional mobile video;
- Connectivity for drones;
- Cloud computer games for connected vehicles; and
- Industrial control

The use cases we have considered

A1.20 The below table lists all of the use cases we have considered, including their relevant category.

[37] "Technical Specification Group Services and System Aspects; Feasibility Study on New Services and Markets Technology Enablers;", 3GPP TR 22.891 V14.2.0 (2016-09) https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2897

[38] We usually refer to this category of use cases as 'Ultra-reliable low latency communications (URLLC)' however for the purposes of this exercise we have aligned our terminology with that used in TR 22.891

Table A1: 5G use cases listed in 3GPP document TR 22.891, including the section number of each one

Enhanced mobile broadband (eMBB)	5.5 Mobile broadband for indoor scenario
	5.6 Mobile broadband for hotspots scenario
	5.56 Broadcasting Support
	5.71 Wireless Local Loop [AKA. Future Fixed Wireless Access]
	5.7 On-demand networking
	5.32 Improvement of network capabilities for vehicular case
	5.10 Mobile broadband services with seamless wide-area
	5.11 Virtual presence
	5.30 Connectivity Everywhere
	5.66 Broadband Direct Air to Ground Communications
	5.72 5G Connectivity Using Satellites
	5.29 Higher User Mobility
	5.53 Vehicular Internet & Infotainment
	5.33 Connected vehicles
Critical communications (CriC)	5.1 Ultra reliable communication
	5.18 Remote control
	5.44 Cloud Robotics
	5.45 Industrial Factory Automation
	5.46 Industrial Process Automation
	5.50 Low-delay speech coding
	5.54 Local UAV Collaboration
	5.68 Telemedicine Support
	5.12 Connectivity for drones
	5.13 Industrial control
	5.65 Moving ambulance and bio-connectivity
	5.14 Tactile internet
	5.15 Localized real-time control
	5.17 Extreme real-time communications and the tactile Internet
	5.43 Materials and inventory management and location tracking
	5.55 High Accuracy Enhanced Positioning
	5.2 Network Slicing
	5.3 Lifeline communications / natural disaster
	5.31 Temporary Service for Users of Other Operators in Emergency Case
Massive Internet of Things (MIoT)	5.19 Light weight device configuration
	5.21 IoT Device Initialization
	5.22 Subscription security credentials update
	5.24 Bio-connectivity
	5.25 Wearable Device Communication

	5.40 Devices with variable data
	5.41 Domestic Home Monitoring
	5.59 Massive Internet of Things M2M and device identification
	5.63 Diversified Connectivity
	5.67 Wearable Device Charging
	5.20 Wide area monitoring and event driven alarms
	5.42 Low mobility devices
	5.60 Light weight device communication
Network operation (NEO)	5.8 Flexible application traffic routing
	5.37 Routing path optimization when server changes
	5.48 Provision of essential services for very low-ARPU areas
	5.49 Network capability exposure
	5.57 Ad-Hoc Broadcasting
	5.65 User Multi-Connectivity across operators
	5.69 Network Slicing – Roaming
	5.70 Broadcast/Multicast Services using a Dedicated Radio Carrier
	5.73 Delivery Assurance for High Latency Tolerant Services
	5.74 Priority, QoS and Policy Control
	5.9 Flexibility and scalability
	5.35 Context Awareness to support network elasticity
	5.51 Network enhancements to support scalability and automation
	5.34 Mobility on demand
	5.47 SMARTER Service Continuity
	5.36 In-network & device caching
	5.38 ICN Based Content Retrieval
	5.39 Wireless Briefcase
	5.52 Wireless Self-Backhauling
	5.61 Fronthaul/Backhaul Network Sharing
	5.23 Access from less trusted networks
	5.26 Best Connection per Traffic Type
	5.27 Multi Access network integration
	5.28 Multiple RAT connectivity and RAT selection
	5.58 Green Radio
	5.62 Device Theft Preventions / Stolen Device Recovery
	5.4 Migration of services from earlier generations
	5.16 Coexistence with legacy systems

Enhanced mobile broadband (eMBB)

A1.21 For each eMBB service in TR 22.891, we have listed the throughput requirements, where they are specified, in the table below. Where it is not explicit in TR 22.891, we have made a judgement on whether the specified throughput is required for the uplink or downlink. Based on the information provided we have either quoted or made a judgement on whether the use case would be indoors, outdoors, or both, and whether its use would be localised (e.g. campus), or over a wide area (e.g. national). In many cases, the document does not include any specific information on network deployment, therefore where there is sufficient information to make an assumption about the type of base station that would serve that use case, we have done so.

A1.22 As can be seen in Table A2, the services range from having download requirements of less than 1 Mbps (vehicular infotainment scenario 1), to up to gigabit per second user experienced throughput (wireless local loop (fixed wireless access); mobile broadband for indoor and hotspot scenarios). For the scenarios requiring Gbps throughput we consider that operators would likely need to deploy mmWave spectrum and/or small cells to deliver these kinds of download throughput to multiple users, and therefore we have not included them in our analysis.

A1.23 Regarding wireless local loop or fixed wireless access (FWA) services, the table notes that throughput of "up to Gbps" will be required. In future, FWA may reach Gbps throughput, however services available today are providing around 300 Mbps throughput. For example, Verizon's fixed wireless access service uses 400 MHz of mmWave spectrum to provide typical download throughput of 300 Mbps and peak download throughput of 940 Mbps.[39] H3G is currently providing 5G home broadband using its 3.4-3.8 GHz spectrum. It does not currently provide an advertised throughput for the service,[40] however, for a postcode within its advertised coverage area (Finsbury Park, London) its coverage checker predicts an average download throughput of 200 Mbps.[41] BT/EE also provides 5G FWA with its 5GEE product. For an address in Southwark, London it quoted an average download throughput of 300 Mbps.[42] We therefore consider that it is unlikely that Gbps FWA throughput can be supported on existing mobile networks using sub-6 GHz spectrum and that Gbps FWA might only be supported by future networks with access to several hundred MHz of spectrum, probably in the mmWave bands. For this reason, we have excluded FWA from our analysis, which only considers bandwidths of 40 to 100 MHz.

A1.24 For the services that require 250-300 Mbps throughput, we assume that the virtual presence in an office or a school scenario would occur indoors and would likely be served by an indoor base station rather than the macro coverage layer. The example given in TR 22.891 for the on demand networking live video use case considers how operators can

---

[39] *Early 5G fixed-wireless access retail offers have yet to truly disrupt the fixed broadband market*, Analysis Mason, 21 January 2020, https://www.analysysmason.com/Research/Content/Comments/5g-fwa-retail-rdmb0/, accessed 10 May 2020

[40] *Broadband speeds*, Three http://www.three.co.uk/broadband-speeds (accessed 11 May 2020)

[41] H3G also notes along with the 200 Mbps average throughput figure that "Speed and coverage can vary depending on location and number of users", *5G Home Broadband Coverage Checker*, H3G http://www.three.co.uk/store/broadband/home-broadband/5ghomebroadband, accessed 12 May 2020

[42] BT/EE broadband checker, https://shop.ee.co.uk/broadband, results for Ofcom, 2a Riverside House, London SE1 9HA (accessed 11 May 2020)

flexibly meet the changing requirements of users in an area, for example, 90,000 users in a stadium. To meet the 300 Mbps per user throughput requirement, our view is that an operator would need to deploy sub-6 GHz spectrum using small cells rather than to rely on a macro site covering the area. For example, in Germany, Vodafone partnered with the Deutsche Fußball Liga and built additional 5G antennas at Wolfsburg's stadium to provide connectivity using its 3.6 GHz spectrum, to support services including augmented reality. [43] These services are captured in our representative services under 'mobile broadband live video' as set out in Table A5.

A1.25 We have assumed that the wide area coverage use cases would require macro layer connectivity, and the associated services have throughput requirements which vary from less than 0.5 Mbps up to 100 Mbps, with the majority of the scenarios requiring less than 50 Mbps. The wide area use cases for vehicles might also be supported by small cells, ultra-dense networks, or dedicated roadside infrastructure in some cases. These are captured in our representative services under 'cloud computer games for connected vehicles' as set out in Table A5. There are no services specified which require 100-250 Mbps.

Table A2: Table showing eMBB use cases and service throughput requirements as set out in TR 22.891 and likely network deployment characteristics

Case study and scenario	Deploy-ment	Cell	Area	UL	DL
5.5 Mobile broadband for indoor scenario	Indoor	Small	Local		up to Gbps experience
5.6 Mobile broadband for hotspots scenario	Both	Small	Local		up to Gbps experience
5.56 Broadcasting Support	Indoor	Small	Local	N/A	300 Mbps
5.71 Wireless Local Loop [AKA. Future Fixed Wireless Access]	Both	Macro	Wide area	N/A	up to Gbps
5.7 On-demand networking: live video	Both	Small	Local	50 Mbps	300 Mbps
5.7 On-demand networking: terminals in area	Both	Both	Local	25 Mbps	50 Mbps
5.32 Improvement of network capabilities for vehicular case: high definition video 8k streaming	Outdoor	Both	Road network		< 100 Mbps
5.32 Improvement of network capabilities for vehicular case: high definition (conversational)	Outdoor	Both	Road network	< 10 Mbps	< 10 Mbps
5.32 Improvement of network capabilities for vehicular case: Cloud Computer Games with 4K 3D graphics	Outdoor	Macro, Micro, Ultra dense	Road network	< 50Mbps	< 50 Mbps

[43] *An industrial 5G spectrum policy for Europe*, Vodafone, November 2019 https://www.vodafone.com/content/dam/vodcom/files/public-policy/5g-report/an-industrial-5g-spectrum-policy-for-europe.pdf (accessed 11 May 2020)

5.10 Mobile broadband services with seamless wide-area: seamless connectivity	Outdoor	Macro	Wide area		100 Mbps
5.10 Mobile broadband services with seamless wide-area: train	Outdoor	Macro	Wide area		'sufficient'
5.11 Virtual presence: 360 degree video in office or school	Indoor	Small	Local	high	high
5.11 Virtual presence: 8k video stream	Indoor	Small	Local	250 Mbps	250 Mbps
5.30 Connectivity Everywhere: Connectivity for commercial or recreational UAVs	Both	Both	Wide area		
5.30 Connectivity Everywhere: Connectivity on flights	Both	Both	Wide area		
5.30 Connectivity Everywhere: Connectivity to ships at sea	Outdoor	Both	Wide area		
5.66 Broadband Direct Air to Ground Communications			Dedicated air-to-ground network[44]		
5.72 5G Connectivity Using Satellites			Satellite network		
5.29 Higher User Mobility: passengers accessing high quality mobile internet (HD video and browsing) on high speed train	Outdoor	Both	Wide area (rail network)		5 Mbps
5.29 Higher User Mobility: remote computing	Outdoor	Both	Wide area		
5.29 Higher User Mobility: 3D connectivity (aircrafts)	Outdoor	Both	Wide area		
5.53 Vehicular Internet & Infotainment: browsing	Outdoor	Both	Road network		< 0.5 Mbps
5.53 Vehicular Internet & Infotainment: high quality music streaming	Outdoor	Both	Road network		< 1 Mbps
5.53 Vehicular Internet & Infotainment: standard quality video streaming	Outdoor	Both	Road network		< 5 Mbps
5.53 Vehicular Internet & Infotainment: high quality video streaming (up to UHD)	Outdoor	Both	Road network		< 15 Mbps
5.33 Connected vehicles: connected vehicle connectivity and video between vehicles and infrastructure for safety and efficiency	Outdoor	Both	Road network		tens of Mbps

Critical communications (CriC)

[44] For example, the European Aviation Network uses a dedicated complementary ground component *In-flight WiFi battle over Europe takes off*, Financial Times, 5 March 2018, https://www.ft.com/content/924e706c-164c-11e8-9376-4a6390addb44, accessed 13 May 2020

A1.26 In the table below we have listed all of the throughput and latency requirements noted in TR 22.891 for the CriC use cases. We have made a judgement on the network deployment scenarios for some of these use cases though there was typically less information in TR 22.891 on which to base these judgements than for the eMBB scenarios which is why we have made fewer judgements than we did for the eMBB scenarios..

A1.27 Many of the use cases in this category have very low latency requirements or very high network resilience requirements for which there is unlikely to be a large dependence on channel bandwidth. This is because, in general, we consider the latency of CriC services are more dependent on factors other than peak throughput, including network capacity and backhaul latency. Only a few of the scenarios had specified throughput requirements. Where there are gaps in the table, we have not attempted to take a judgement on the required characteristics.

A1.28 As can be seen in the table, the use case with the most substantial throughput requirement is the 'moving ambulance and bio connectivity' use case, which requires 100 Mbps to send data and video to the hospital. We have not included this in our analysis because it is a niche use case with potentially advantageous terminal characteristics, for example an ambulance may typically have more space to make use of higher uplink MIMO with more than two spatial layers, will be able to mount the antenna higher than a handset device, and will have fewer power restrictions than a user handset.

A1.29 We have removed any duplication where one service sits in multiple categories. We recognise there are other services which do have significant throughput requirements which could be classed as 'Critical Communications' (and are included in this category in TR 22.891), for example virtual presence, however for this analysis we have already included those in the eMBB category.

Table A3: Table showing CriC use cases, including service throughput and latency requirements as set out in TR 22.891, and likely network deployment characteristics

Case study and scenario	Deploy-ment	Cell	Area	UL	DL	Latency requirements
5.1 Ultra reliable communication: substation protection and control	Indoor		Localised	~12.5 Mbps per Merger Unit		1 ms end-to end
5.1 Ultra reliable communication: smart grid system with distributed sensors and management	Both		Wide area	200 to 1521 bytes reliably delivered in 8 ms		8 ms end to end
5.1 Ultra reliable communication: public safety	Outdoor		Wide area			
5.1 Ultra reliable communication: Multimedia Priority Service (MPS)	Outdoor		Wide area			

5.18 Remote control	Outdoor		Wide area			<150 ms round trip
5.44 Cloud Robotics			Localised			< 10 ms end to end
5.45 Industrial Factory Automation	Indoor	Small cells	Localised		Each transaction should support a payload of 50 to 100 Bytes	1-10 ms cycle time
5.46 Industrial Process Automation	Indoor	Small cells	Localised			50-100 ms transaction latency
5.50 Low-delay speech and video coding						10 ms one way
5.54 Local UAV Collaboration	Outdoor		Localised			10 ms
5.68 Telemedicine Support			Localised			
5.12 Connectivity for drones: transmit 4K live broadcast	Outdoor	Macro	Localised	> 20 Mbps		<150 ms round trip
5.13 Industrial control	Indoor		Localised	tens of Mbps		~1 ms
5.65 Moving ambulance and bio-connectivity	Outdoor		Wide area	100 Mbps		1-10 ms end to end
5.14 Tactile internet	Indoor		Localised			~1 ms
5.15 Localized real-time control	Indoor		Localised			1-10 ms
5.17 Extreme real-time communications and the tactile Internet	Both		Localised			~1 ms one way
5.43 Materials and inventory management and location tracking	Both	Marco	Wide area	Very small uplink requirement		
5.55 High Accuracy Enhanced Positioning (ePositioning)	Both		Wide area			
5.2 Network Slicing	-	-	-	-	-	-
5.3 Lifeline communications / natural disaster	Outdoor		Wide area			
5.31 Temporary Service for Users of Other Operators in Emergency Case	Both		Localised			

Massive IoT (MIoT)

A1.30 As can be seen in the table below, very few of these use cases have specified service throughput requirements. Many of the services included in the MIoT category are to do with operational aspects of connectivity, for example subscription security credentials update focuses on the requirement of the network to be able to identify a IoT devices and determine whether it requires a subscription security credential update. This means that we consider that there is unlikely to be a high throughput requirement for many of these services. Where there are gaps in the table, we have not attempted to take a judgement on the required characteristics.

A1.31 There are some higher throughput services within the use cases. Taking bio connectivity as an example, we consider that the 'sensors sending data to doctors/nurses' scenario would only require very low throughout. However, 'surgery supported by video stream' would likely require a very high throughput in a very local area (e.g. an operating theatre), and we consider that we have addressed this service case as a subset of the 'mobile broadband live video' scenario in Table A5.

Table A4: Table showing MIoT use cases, including service throughput requirements as set out in TR 22.891, and likely network deployment characteristics

	Deployment	Cell	Area	UL	DL
5.19 Light weight device configuration	-	-	-	-	-
5.21 IoT Device Initialization	-	-	-	-	-
5.22 Subscription security credentials update	-	-	-	-	-
5.24 Bio-connectivity: surgery supported by video stream				High data rates	
5.24 Bio-connectivity: sensors sending data to doctors/nurses					
5.25 Wearable Device Communication	-	-	-	-	-
5.40 Devices with variable data					Flexible between low and high data rates
5.41 Domestic Home Monitoring	Localised				low volume low frequency
5.59 Massive Internet of Things M2M and device identification	-	-	-	-	-
5.63 Diversified Connectivity	-	-	-	-	-
5.67 Wearable Device Charging	-	-	-	-	-
5.20 Wide area monitoring and event driven alarms					
5.42 Low mobility devices					
5.60 Light weight device communication	-	-	-	-	-

Network Operation

A1.32 As these use cases are related to operation of the network, TR 22.891 does not set out any service throughput requirements or deployment characteristics for these use cases. We consider they are, therefore, not relevant for the purposes of this analysis.

We consider the following services to be representative of some of the most demanding services from those identified by 3GPP

A1.33 We consider the following services to be representative of some of the most demanding services (in terms of data rates) from those identified by 3GPP. Where information about downlink and uplink rates were not available, we have supplemented the information from TR 22.891 with information from other sources.

Table A5: We have considered a wide range of some of the most demanding 5G services

Service	UL (Mbps)	DL (Mbps)	Description
Mobile broadband live video *Very high data rate, local services*			This category is based on the video streaming in a stadium scenario given in §5.7 of TR 22.891. This scenario considers video streaming to/from users in a stadium connecting to the mobile network through small cells installed in the stadium. This category is representative of some of the highest data rate services that we consider might be provided on mobile networks in a particular area using sub-6 GHz spectrum. These include mobile broadband for indoor and hotspot scenarios.
4K @ 50 fps[45]	50	300	

[45] §5.7.2 and §5.56.3, 3GPP TR 22.891 V14.2.0 (2016-09)

Service	UL (Mbps)	DL (Mbps)	Description
Cloud VR *Very high data rate local services and high data rate wide area services*			This category is based on the virtual presence scenario in §5.11 of TR 22.891. This scenario considers use in "high data rate zones (e.g. office environments)" which we might expect to be supported using indoor small cells. This category is representative of some of the highest data rate services that we consider might be provided on mobile networks using sub-6 GHz spectrum in a local area. We might expect that some lower data rate virtual reality and augmented reality services might be supported over a wider area, for example, to support field operatives.
2K @ 90 fps[46]	N/A	100	
1080p @ 60 fps[47]	N/A	50	
720p @ 30 fps[48]	N/A	20	
Professional mobile video *High data rate, wide area services*			This category is representative of several video services from TR 22.891 including low delay speech and video coding[49], guaranteed video delivery through network slicing[50] and mobile broadband services with seamless wide-area coverage.[51] We have used the throughput requirements from another source which are representative of the throughput that might be required for a wide range of video services.[52] This category is representative of high data rate services that might be provided across a wide area, for example, news crews or other professional content creators sending footage back to the studio.
8K 2D video[53]	N/A	100	
4K 3D video[54]	N/A	50	
4K 2D video[55]	N/A	25	

[46] Slide 21, "5G Spectrum Awards: Views on 3400-3800 MHz in Europe", GSA, April 2019, https://gsacom.com/paper/5g-spectrum-awards-april-2019/
[47] Ibid., Slide 21
[48] Ibid., Slide 21
[49] §5.50, 3GPP TR 22.891 V14.2.0 (2016-09)
[50] Ibid., §5.2
[51] Ibid., §5.10
[52] Slide 21, "5G Spectrum Awards: Views on 3400-3800 MHz in Europe", GSA, April 2019, https://gsacom.com/paper/5g-spectrum-awards-april-2019/
[53] Slide 21, "5G Spectrum Awards: Views on 3400-3800 MHz in Europe", GSA, April 2019, https://gsacom.com/paper/5g-spectrum-awards-april-2019/
[54] Ibid., Slide 21
[55] Ibid., Slide 21

Service	UL (Mbps)	DL (Mbps)	Description
Connectivity for drones *Medium data rate, wide area high mobility services*			This category is based on §5.12 of TR 22.891 which considers wide range of drone services. For example, this category includes smart farming systems where drones are used to monitor, through the use of cameras and sensors, the state of fields and crops. The mobile network will need to support uplink from a drone at altitudes of 10-1000 meters with a maximum speed of 300 km/h.
video, sensors etc.[56]	20	N/A	
Cloud computer games for Connected vehicles *Medium to high data rate, wide area high mobility services*			This category is based on §5.32 of TR 22.891 which considers several passenger services for connected vehicles with a large range of throughput requirements. TR 22.891 observes that "The mobile network deployment can be either macro or micro cellular, or ultra-dense network (UDN)." TR 22.891 describes the UL and DL throughput requirements as "<50 Mbps" but we have taken a conservative approach and plotted 50 Mbps in our results.
Cloud computer games with 4K 3D graphics[57]	50	50	
Industrial Control *Medium data rate, high density, local services*			This category is based on §5.13 of TR 22.891 for industrial control applications which require high reliability and very low latency (~1ms). In some cases, high data rates may be required, e.g., in the uplink, to deliver live video stream to an operator or automated system controlling the equipment (10s of Mbps per user in a dense environment). We have used 25 Mbps as a more precise figure from a secondary source.[58] 3GPP does not specify a downlink throughput requirement. These services might typically be supported by small cells within an industrial complex.
live video per user[58]	25	N/A	

[56] §5.12, 3GPP TR 22.891 V14.2.0 (2016-09)
[57] §5.32, 3GPP TR 22.891 V14.2.0 (2016-09)
[58] Slide 21, "5G Spectrum Awards: Views on 3400-3800 MHz in Europe", GSA, April 2019, https://gsacom.com/paper/5g-spectrum-awards-april-2019/

Calculating SUT

A1.34 We have calculated the SUT using the equations from 3GPP with some additional modifications to adapt them from 4G to 5G and also to modify them for carrier aggregation. In this section we consider:

- 3GPP TR 36.942 which describes how to map SINR for SUT for 4G and how we have extended this for our 5G spectrum scenarios based on the equation from §4.1.2 in 3GPP TS 38.306; and
- a range of spectrum scenarios to understand the impact on throughput when using several combinations of carrier bandwidths, SU-MIMO order, and carrier aggregation.

The SINR to SUT mapping equation from 3GPP TR 36.942 provides the overall approach to our model

A1.35 The mapping function in TR 36.942 calculates how the spectral efficiency of a modem with link adaptation can be approximated by an attenuated and truncated form of the Shannon bound. The Shannon bound defines the theoretical maximum spectral efficiency that can be achieved over a communication channel and this upper bound is a function of the available bandwidth and the SINR.[59] TR 36.942 was developed for LTE but this approach is also valid for 5G NR because the Shannon bound is common to all communications technologies.

Equation A1: Spectral efficiency estimation from Annex A of TR 36.942

$$Throughput, Thr, \frac{bps}{Hz} = \left\{ \begin{matrix} 0\ for\ SINR < SINR_{min} \\ \alpha * S(SINR)\ for\ SINR_{min} < SINR < SINR_{max} \\ Thr_{max}\ for\ SINR > SINR_{max} \end{matrix} \right\}$$

A1.36 Where:

S(SINR)	is the Shannon bound: *S(SINR) = log2(1+SINR)* (bps/Hz);
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); and
$SINR_{max}$	is the SINR at which max throughput is reached $S^{-1}(Thr_{max})$ (dB)

A1.37 We note that the terminology used in TR 36.942 refers to this as a calculation of “throughput”, but we would normally refer to a number with units bps/Hz (bits per second per Hz) as a “spectral efficiency” and we use these terms in this way throughout the rest of

[59] Original paper from C.E. Shannon “A mathematical theory of communication” http://people.math.harvard.edu/~ctm/home/text/others/shannon/entropy/entropy.pdf

this document. We also consider that the calculation of $SINR_{max}$ should take α into account.

We have extended this equation for 5G NR

A1.38 TR 36.942 was developed for LTE and so we have extended this for 5G NR using the 5G NR throughput calculation in section 4.1.2 of 3GPP TS 38.306.[60] The data rate for a given number of aggregated 5G NR carriers in a band or band combination is computed as:

Equation A2: Maximum supported downlink and uplink data rate that a 5G NR UE must support

$$\text{data rate (in Mbps)} = 10^{-6} \cdot \sum_{j=1}^{J} \left(v_{Layers}^{(j)} \cdot Q_m^{(j)} \cdot f^{(j)} \cdot R_{\max} \cdot \frac{N_{PRB}^{BW(j),\mu} \cdot 12}{T_s^{\mu}} \cdot \left(1 - OH^{(j)}\right) \right)$$

A1.39 Where:

J	is the total number of aggregated carriers in a frequency band;
$V^{(j)}_{layers}$	is the number of layers in the MIMO configuration: 2 in the case of 2x2 SU-MIMO and 4 in the case of 4x4 SU-MIMO;
$Q^{(j)}_{m}$	refers to the modulation order (8 for 256QAM and 6 for 64 QAM as the highest downlink and uplink modulation order respectively);
R_{max}	is the is the maximum code rate of 948/1024;
$F^{(j)}$	is a scaling factor, to ensure slots and symbols of different modulations and numerologies align in the time domain. The SUT model uses a scale factor of 1;[61]

[60] 3GPP TS 38.306 V16.0.0 (2020-03) https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3193

[61] The default scaling factor is $f_{(j)} = 1$. $f_{(j)}$ is the scaling factor used to reflect the capability mismatch between baseband and RF capability for both standalone and non-standalone user equipment. Its use is also proposed to scale down the maximum throughput of NR user equipment in dual connectivity scenarios where there is LTE and NR hardware sharing within the user equipment.
Page 9, PRELIMINARY EVALUATION REPORT FROM THE 5G INFRASTRUCTURE ASSOCIATION ON IMT-2020 PROPOSAL, Independent Evaluation Group 5G Infrastructure Association, submitted 27 November 2019 ITU WP 5D, https://5g-ppp.eu/wp-content/uploads/2020/01/5G-IA-5G-PPP.pdf

$N_{PRB}^{BW.j}$ is the number of resource blocks given for a given carrier bandwidth and numerology (μ). The numerology refers to the subcarrier spacing and for 5G NR; the SUT model uses numerology value of 1, which refers to a subcarrier spacing of 30 kHz with a normal cyclic prefix[62] which is typical of current deployments for 5G NR deployed at 3.4-3.8 GHz.[63] The values of $N_{PRB}^{BW.j}$ that were only considered in the 13 March Statement are in square brackets below whereas the values of $N_{PRB}^{BW.j}$ considered in both the 13 March Statement and this document are presented below without square brackets.[64]

Bandwidth (MHz)	$N_{PRB}^{BW.j}$
100	273
80	217
[70]	[189]
50	133
40	106
[20]	[51]

T_s^{μ} is the OFDM[65] symbol duration, $T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$, which equals 3.57×10^{-5} seconds for μ = 1. We use μ = 1 for the same reason that we use μ = 1 for $N_{PRB}^{BW.j}$

$OH^{(j)}$ is the signalling overhead for the relevant frequency range.[66] For sub-6 GHz frequencies the downlink and uplink overhead values are 0.14 and 0.08[67] respectively according to TS 38.306.

A1.40 We have calculated the throughput for 5G NR into the SUT Model in the following ways.

A1.41 **We have accounted for a TDD downlink to uplink ratio.** TDD systems only transmit in the uplink or downlink for part of the time so we have used a TDD factor to reflect this. We have considered two cases: the first uses a TDD factor of 0.75 for the downlink and 0.25 for the uplink, which approximates the 3:1 Frame Structure A (also known as the "Preferred

[62] The cyclic prefix provides a guard internal to prevent inter-symbol interference.
[63] Table 19, *National synchronisation regulatory framework options in 3400-3800 MHz: a toolbox for coexistence of MFCNs in synchronised, unsynchronised and semi-synchronised operation in 3400-3800 MHz*, ECC Report 296, 8 March 2019, https://www.ecodocdb.dk/document/9067
[64] Table 11, *Guidance on defragmentation of the frequency band 3400-3800 MHz*, ECC Report 287, 26 October 2018, https://www.ecodocdb.dk/document/7245
[65] Orthogonal Frequency-Division Multiplexing is a digital communication scheme used in LTE and 5G NR.
[66] This overhead is calculated as a ratio of the 5G NR resources designed for signalling (control synchronisation, reference signals, guard bands, etc.) and the total available 5G NR resources in the 5G NR bandwidth.
[67] From 3GPP TS 38.306 V16.0.0 (2020-03), Section 4.1.2 Supported max data rate: OH is the overhead and takes the following values 0.14; for frequency range FR1 for DL 0.18; for frequency range FR2 for DL 0.08; for frequency range FR1 for UL and 0.10 and for frequency range FR2 for UL.

Frame Structure") in the 3.6-3.8 GHz example licence[68]; and the second uses a TDD factor of 0.5 for both the downlink and uplink which might be representative of some indoor small cell scenarios[69].

A1.42 **We have used attenuation factors appropriate for TDD networks.** We use attenuation factors of α = 0.6 in the downlink and α = 0.55 in the uplink which come from the attenuation factors for E-UTRA (4G) TDD given in TR 36.942.[70] We consider these attenuation factors to be conservative because 5G NR has improvements to the physical layer when compared with 4G which means that we might expect the implementation factors to have improved in 5G NR.

A1.43 **We have added SU-MIMO.** TS 38.306 introduces the term $V^{(j)}_{layers}$ to describe the number of layers supported by the SU-MIMO spatial multiplexing. We have applied this to the SUT Model by multiplying the calculated per layer throughput by the total number of SU-MIMO spatial multiplexing layers. We consider that typical 5G NR devices with a smartphone form factor will support two spatial layers in the uplink and four spatial layers in the downlink.[71, 72]

A1.44 **We have calculated throughput on the basis of the transmission bandwidth occupying the whole transmission bandwidth configuration.** TR 36.942 does not distinguish between channel bandwidth and the transmission bandwidth configuration (see Figure A1), so we have taken a conservative approach and calculated throughput based on the transmission bandwidth occupying the whole transmission bandwidth configuration instead of the transmission bandwidth occupying the whole channel bandwidth. This means that we have taken the internal channel guard bands into account.

---

[68] See paragraph 12, Schedule 1 to the example 3.6-3.8 GHz licence, *Award of the 700 MHz and 3.6-3.8 GHz spectrum bands Information Memorandum*, Ofcom, 13 March 2020, https://www.ofcom.org.uk/__data/assets/pdf_file/0019/192412/information-memorandum-award-700mhz-3.6-3.8ghz-spectrum.pdf

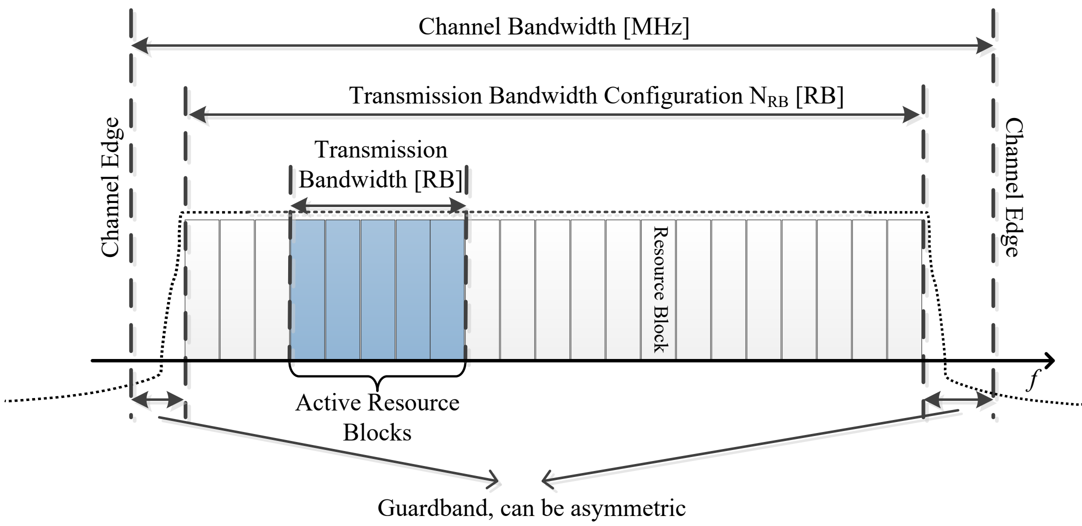
[69] See paragraph 15, Schedule 1 to the example 3.6-3.8 GHz licence, *Award of the 700 MHz and 3.6-3.8 GHz spectrum bands Information Memorandum*, Ofcom, 13 March 2020, https://www.ofcom.org.uk/__data/assets/pdf_file/0019/192412/information-memorandum-award-700mhz-3.6-3.8ghz-spectrum.pdf

[70] Table A.5, Annex A4, 3GPP TR 36.942 V15.0.0 (2018-06) https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2592

[71] The Qualcomm x50, x55 and x60 modems support 4x4 MIMO in the downlink for sub-6 GHz carriers https://www.qualcomm.com/products/snapdragon-x50-5g-modem; https://www.qualcomm.com/products/snapdragon-x55-5g-modem; and https://www.qualcomm.com/products/snapdragon-x60-5g-modem.

[72] "5G devices will require 4x4 downlink MIMO and most will support 2x2 uplink MIMO, at least in the 2.5 GHz to 6 GHz spectrum."
Page 4, *5G White Paper*, Skyworks Solutions Inc, 2018, https://www.skyworksinc.com/-/media/SkyWorks/Documents/Products/2901-3000/5G-White-Paper-Part-2.pdf

Figure A1: Diagram illustrating channel bandwidth, transmission bandwidth configuration and transmission bandwidth[73]



A1.45 **We have added carrier aggregation.** We have calculated the SUT for some scenarios considering the aggregation of multiple carriers. We calculated this by extending the model to sum the transmission bandwidths from all carriers and to account for the additional signalling overheads associated with aggregating carriers. We factor in an extra 6% signalling overhead when aggregating two carriers compared with using a single contiguous carrier of the same total aggregate transmission bandwidth.[74]

A1.46 **We use the maximum throughput equation for 5G NR.** We have calculated the maximum SUT using Equation 2 above, which is from TS 38.306 and is for calculating the maximum throughput of 5G NR. This allows us to ensure that the throughput curves are truncated appropriately when considering that 5G NR supports up to 256QAM 9/10 (DL) and 64QAM 9/10 (UL). This equation also takes account of the general overhead factor and we multiply by the appropriate TDD downlink to uplink ratio to give the maximum throughput that the curves truncate at.

A1.47 These modifications update the throughput model from TR 36.942 as shown below in Equation A3.

[73] Figure 5.3.1-1, 3GPP TS 38.101-1 V16.3.0 (2020-03), https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3283

[74] The ECC C-band defragmentation report notes that carrier aggregation across two 50 MHz carriers might require signalling overheads of around 12% (depending on the precise implementation) compared with signalling overheads of 6.3% for a single contiguous carrier of 100 MHz. See:
Table 13, “Guidance on defragmentation of the frequency band 3400- 3800 MHz”, ECC Report 287, 26 October 2018 https://www.ecodocdb.dk/document/7245

Equation A3: Modified throughput estimation equation

$$SUT\_Throughput, (bps) = \begin{Bmatrix} 0 \; for \; SINR < SINR_{min} \\ \begin{bmatrix} TBW * \alpha * S(SINR) * F_{TDD} * v_{Layers} * (1 - CA) \\ for \; SINR_{min} < SINR < \; SINR_{max} \end{bmatrix} \\ SUT\_Thr_{max} \; for \; SINR > \; SINR_{max} \end{Bmatrix}$$

A1.48 Where:

TBW	is the total aggregate transmission bandwidth.[75] This is the total bandwidth occupied by resource blocks across one or more carriers (see A1.44 above);
S(SINR)	is the Shannon bound: *S(SINR)* = $\log_2(1+SINR)$ (bps/Hz) for a single spatial layer;
α	is the attenuation factor, representing implementation losses, which are 0.6 for the downlink and 0.55 for the uplink (see A1.42 above);
$SINR_{min}$	is the minimum SINR of the codeset (dB), for this analysis we assume it is -10 dB;
SUT_Thr_{max}	*is* the maximum throughput of the codeset (bps) as calculated using Equation 2 which calculates the maximum data rate for 5G NR (see A1.46 above);
$SINR_{max}$	is the SINR at which max throughput (SUT_Thr_{max}) is reached (dB);
F_{TDD}	is the TDD factor which, depending on the scenario, is either 0.75 in the downlink and 0.25 for the uplink or 0.5 in the downlink and 0.5 in the uplink (see A1.41 above);
v_{Layers}	is the number of SU-MIMO spatially multiplexed data layers which depends on the scenario, (e.g. four in the downlink and two in the uplink) (see A1.43 above); and
CA	is the additional signalling overhead for carrier aggregation. This value is 0 for single carrier scenarios and 0.06 for scenarios with two carriers (see A1.45 above).

[75] For carrier aggregation scenarios TBW is the total bandwidth of all aggregated carriers.

We consider spectrum scenarios which reflect MNOs current spectrum holdings and are representative of possible future auction outcomes

Table A6: We have investigated several spectrum scenarios to understand the impact on throughput when using a wide range of combinations of carrier bandwidths; SU MIMO order; and carrier aggregation

#	Uplink Carriers	Downlink Carriers	Comment
1	40 MHz 2x2 SU-MIMO	40 MHz 4x4 SU-MIMO	This is representative of the largest single carrier which could be deployed in O2 and BT/EE's existing holdings in 3.4-3.6 GHz
2	50 MHz 2x2 SU-MIMO	50 MHz 4x4 SU-MIMO	This is representative of the largest single carrier which could be deployed in Vodafone's existing holdings in 3.4-3.6 GHz
3	80 MHz 2x2 SU-MIMO	80 MHz 4x4 SU-MIMO	This is the minimum contiguous spectrum that some operators have claimed is necessary for providing 5G services
4	-	2 x 40 MHz both 4x4 SU-MIMO	This is representative of downlink carrier aggregation between two 40 MHz carriers in 3.4-3.8 GHz.
5	100 MHz 2x2 SU-MIMO	100 MHz 4x4 SU-MIMO	This is representative of the largest single carrier that H3G could deploy in its existing holdings in 3.4-3.8 GHz.

Figure A2: Example of downlink results for the spectrum scenarios modelled

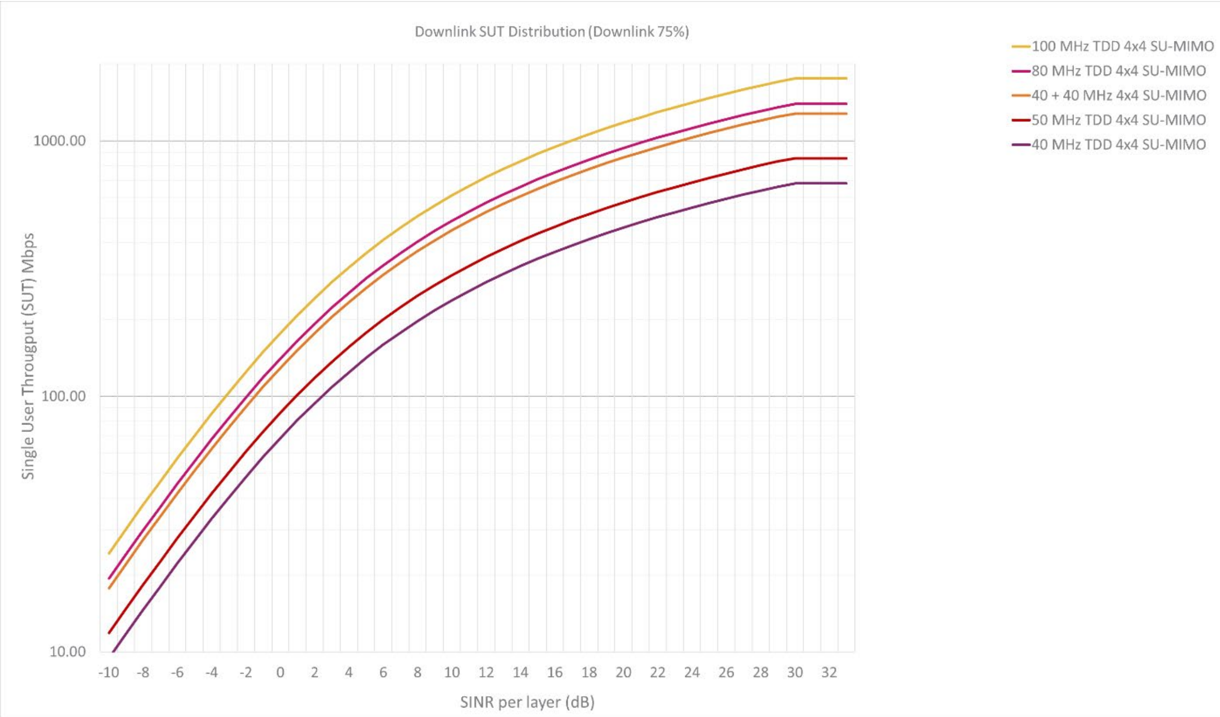
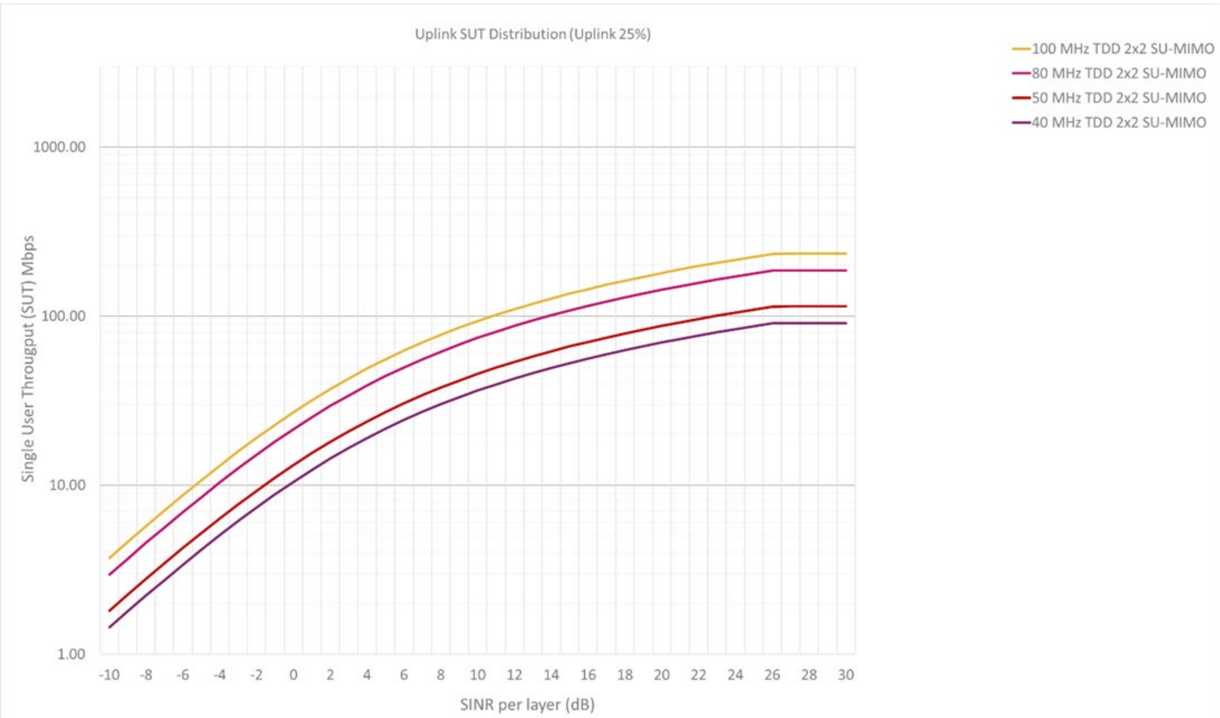


Figure A3: Example of uplink results for the spectrum scenarios modelled



We have also considered the potential impact of the power limits for mobile and nomadic devices

A1.49 The maximum power for mobile and nomadic terminals in the 3.6-3.8 GHz examples licences is 28 dBm TRP[76] which is equivalent to 3GPP power class 2 user equipment.[77] This is a total power limit so a terminal transmitting over 40 MHz will have a higher maximum transmit power spectral density than a terminal transmitting over 100 MHz. User devices will only use the bandwidth necessary to provide the service and will operate at less than the maximum transmit power when link conditions allow. This means that the uplink SINR received at the base station from a using a narrower carrier might be higher than the uplink SINR received at the base station for a user using a wider carrier in the same location.

A1.50 To assess the potential impact of this difference in power spectral density between carriers of different bandwidths, we have considered the pathloss between a user and the base station if that user were using a range of carrier bandwidths at maximum transmit power at the same location. For example, in a noise-limited edge-of-service scenario[78], the signal received at a base station from a user using a 40 MHz carrier will have approximately 3 dB higher SINR than the signal received at the base station from a user stood at the same location and using an 80 MHz carrier.

A1.51 We have explored this effect by extending the SUT vs. SINR model as described above to plot SUT vs. pathloss. This means that the SUT is calculated for a range of pathloss values between the user device transmit antenna and the base station receive antenna. We have mapped SINR to pathloss using the following equation:

[76] Paragraph 8, Schedule 1 to the example 3.6-3.8 GHz licence, *Award of the 700 MHz and 3.6-3.8 GHz spectrum bands Information Memorandum*, Ofcom, 13 March 2020, https://www.ofcom.org.uk/__data/assets/pdf_file/0019/192412/information-memorandum-award-700mhz-3.6-3.8ghz-spectrum.pdf

[77] 3GPP power class 2 specifies mobile and nomadic terminal power limit of 26 dBm +2 dB to take tolerances resulting from temperature and manufacturing variation into account.
§6.2D.1, *NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone*, 3GPP TS 38.101-1 V16.3.0 (2020-03),
https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3283

[78] Note that the edge-of-cell will be different for different services. For more demanding services, e.g. those requiring higher minimum data rates, the edge of cell will require a higher signal quality (SINR) and hence will be closer to the base station than a service requiring a lower data rate.

Equation A4: SINR to pathloss equation

$$Pathloss(dB) = P_{UE} - SINR - N_{SYS\_BS} + G_{BS}$$

A1.52 Where:

P_{UE} is the power radiated power by the user equipment which is 23 dBm / spatial layer EIRP. We have calculated this by converting the 26 dBm TRP terminal power limit as described in A1.49 considering two spatial layers and a terminal antenna gain of 0 dBi;

$SINR$ is the signal to noise ratio in a noise-limited scenario and so is equivalent to SNR (dB);

N_{SYS_BS} is the system noise of the base station (dBm). This is calculated as follows:

$$N_{SYS\_BS} = N_{TH} + 10 \cdot \log_{10} TBW + NF_{BS}$$

Where:

N_{TH} is the thermal noise power spectral density at 20°C. This is -114 dBm / MHz;

TBW is the transmission bandwidth (MHz); and

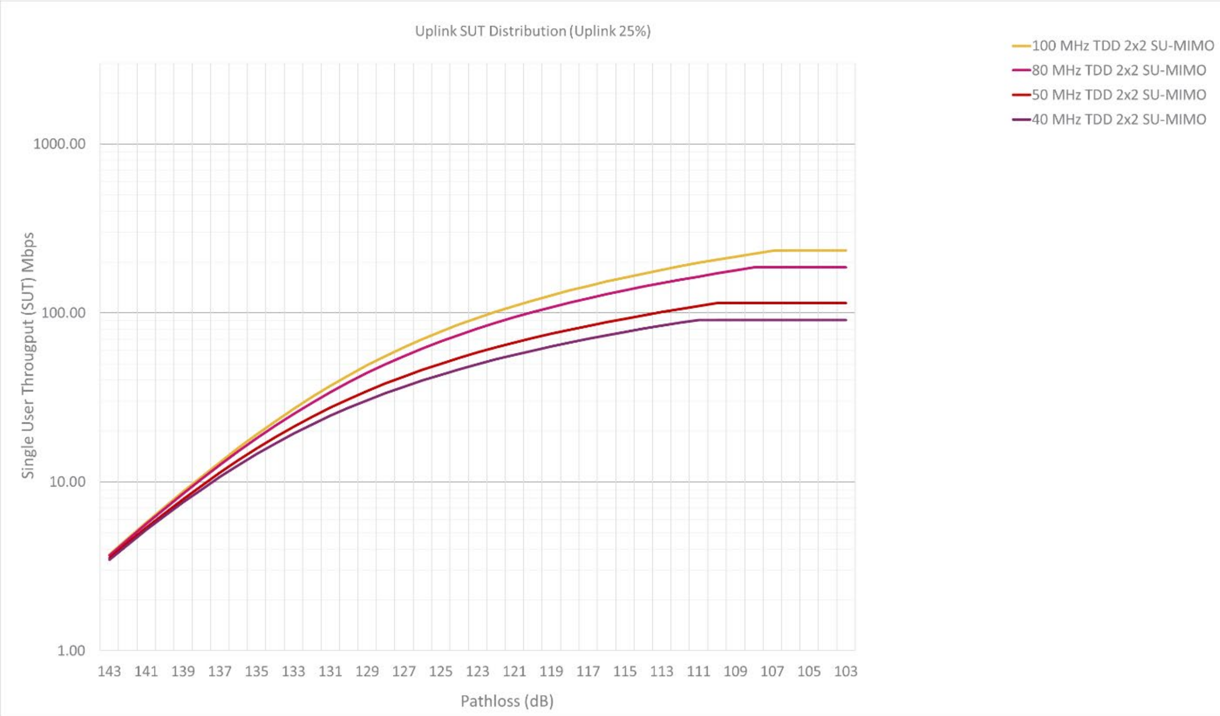
NF_{BS} is the base station noise figure. Typical noise figures might be 5 dB for a macro cell, 7 dB for a micro cell[79] and 9 dB for an indoor small cell.[80]

G_{BS} is the receive antenna gain of the base station. Typical base station antenna gains might be 21 dBi for a macro cell,[81] 3 dBi for a micro cell and 0 dBi for an indoor small cell.

A1.53 Figure A4 illustrates the impact of the potential impact of the power limits for mobile and nomadic devices in a typical marco cell.

[79] The reference sensitivity for mobile phone base stations is calculated assuming a noise figure of 5 dB plus an additional 2 dB implementation margin. See: Equation 14.6, §14.4, "LTE for UMTS: Evolution to LTE-Advanced", Harri Holma and Antti Toskala, Wiley, Second edition, 2011.
[80] We have assumed that an indoor small cell might have a similar noise figure to user equipment.
[81] Para 11.31, *Consultation: Award of the 700 MHz and 3.6-3.8 GHz spectrum bands*, Ofcom, December 2018, 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

Figure A4: Example the potential impact of the power limits for mobile and nomadic devices in a typical macro cell



We have made several changes compared to the 13 March Statement

A1.54 In this consultation we have made a number of adjustments to the model used to calculate the results presented in the 13 March Statement. In particular:

a) We had intended to represent the 3:1 downlink to uplink ratio in the throughput curves, however the uplink results incorrectly reversed this ratio. This has now been corrected. Note that in the main body of this consultation we additionally present uplink results using a downlink to uplink ratio of 1:1 as this may be more representative of some indoor scenarios.

b) We have now taken account of the signalling overhead when considering the maximum cell throughputs, which now consider the data payload throughput only. Previously, we had included the total cell throughput irrespective of whether it was data payload or overhead. The downlink and uplink signalling overhead values we have used are 0.14 and 0.08[82] respectively according to TS 38.306.

[82] From 3GPP TS 38.306 V16.0.0 (2020-03), Section 4.1.2 Supported max data rate: OH is the overhead and takes the following values 0.14; for frequency range FR1 for DL 0.18; for frequency range FR2 for DL 0.08; for frequency range FR1 for UL and 0.10 and for frequency range FR2 for UL.

c) We have identified an error in the way that the truncated Shannon bound curves were previously calculated. The point at which the curves truncated should have been at a higher SINR to account for the increased modulation orders in 5G NR whereas in fact the whole curve had been offset to match the maximum rate.

d) We now use an attenuation factor, α, of 0.55 in the uplink which is appropriate for TDD systems.[83] We had used a value of 0.4 previously, which is appropriate for FDD systems.[84]

e) We now use the transmission bandwidth configuration for all calculations involving bandwidth whereas we previously used the full channel bandwidth.

A1.55 In addition, we have modelled some different spectrum scenarios in this consultation. Those spectrum scenarios used in the Statement are shown below.

Table A7: Spectrum scenarios used in the 13 March Statement

#	Uplink Carriers	Downlink Carriers	Comment
1	1 x 40 MHz 2x2 SU-MIMO	1 x 40 MHz 4x4 SU-MIMO	This case is representative of the holdings of MNOs with less than 100 MHz of contiguous spectrum in 3.4-3.8 GHz.
2	1 x 100 MHz 2x2 SU-MIMO	1 x 100 MHz 4x4 SU-MIMO	This case is representative of the throughput that could be provided with 100 MHz of contiguous spectrum.
3		1x100 MHz 2x2 SU-MIMO	This case shows how the downlink throughput of a 100 MHz carrier will be halved when using 2x2 SU-MIMO instead of 4x4 SU-MIMO. This could be representative of a line-of-sight scenario with polarisation diversity but poor multipath generation.
4	1 x 80 MHz 2x2 SU-MIMO		This case is representative of the uplink throughput that could be provided with 80 MHz of contiguous spectrum.
5	1 x 20 MHz + 1 x 70 MHz both 2x2 SU-MIMO	1 x 20 MHz + 1 x 70 MHz both 4x4 SU-MIMO	This is carrier aggregation of a 20 MHz and a 70 MHz carrier. The calculated throughput takes into account the 6% throughput reduction when compared with a single contiguous carrier of 90 MHz.

[83] Table A.5, Annex A4, 3GPP TR 36.942 V15.0.0 (2018-06) https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2592
[84] Figure A6.20, *Statement on the award of the 700 MHz and 3.6-3.8 GHz award – annexes*, Ofcom, March 2020, https://www.ofcom.org.uk/__data/assets/pdf_file/0017/192410/annexes-award-700mhz-3.6-3.8ghz-spectrum.pdf

#	Uplink Carriers	Downlink Carriers	Comment
6	2 x 40 MHz both 2x2 SU-MIMO	2 x 40 MHz both 4x4 SU-MIMO	This is carrier aggregation of 2x40 MHz carriers. The calculated throughput takes into account the 6% throughput reduction when compared with a single contiguous carrier of 80 MHz.

A1.56 Figure A5 and Figure A6 below show results from the corrected SUT model for the spectrum scenarios in the 13 March Statement.

Figure A5: Results of SUT Model – Downlink (for a DL/UL ratio of 3:1) – 13 March Statement – Corrected

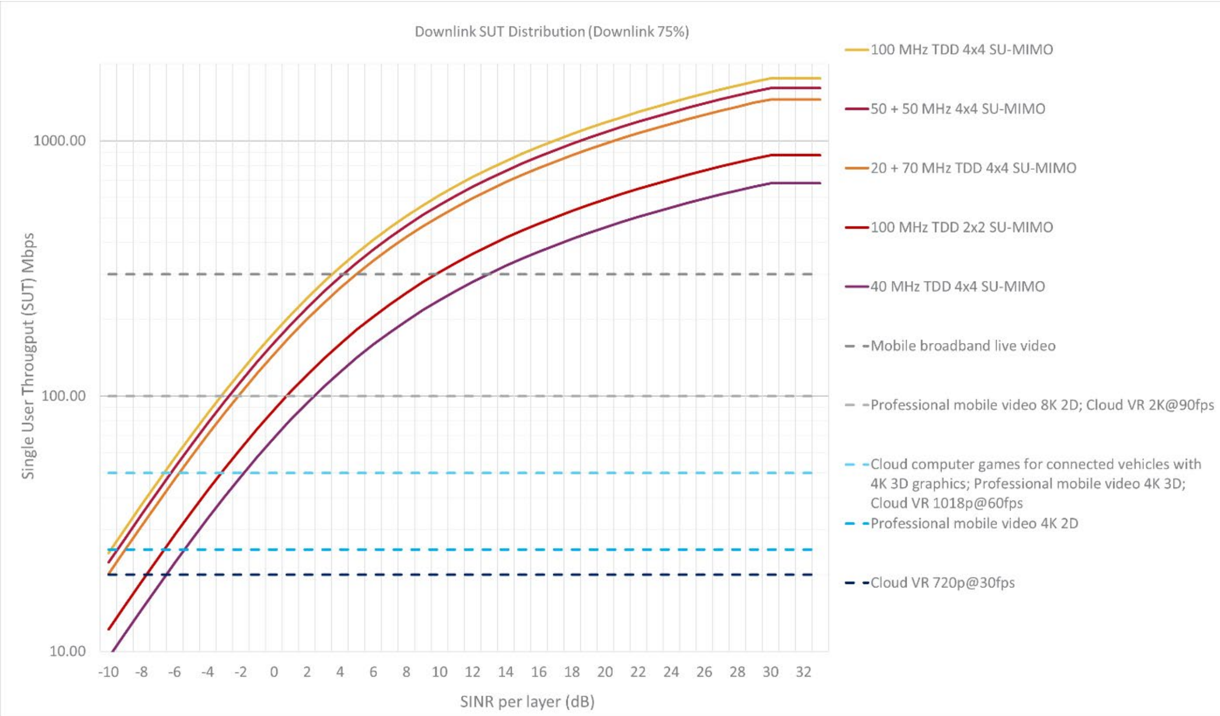


Figure A6: Results of SUT Model – Uplink (for a DL/UL ratio of 3:1) – 13 March Statement – Corrected