Response to the consultation "Award of the 700 MHz and 3.6-3.8 GHz spectrum bands: Further consultation on modelling and technical matters"

*Prepared by Professor William Webb on behalf of Telefónica UK Limited ("**TUK**")*[1]

*This report has been prepared in response to the "Update Note and Further Consultation" issued by Ofcom on 15 May 2020 ("**Consultation Paper**") concerning the use of Single User Throughput ("**SUT**").*

Executive Summary

1. In this Consultation Paper and in Annex 7 to Ofcom's March 2020 statement "Award of the 700 MHz and 3.6 – 3.8 GHZ spectrum bands" (the "**Statement**"), Ofcom used the SUT analysis to attempt to show that 40MHz of spectrum in the 3.4-3.8GHz band is sufficient to offer 5G services. That SUT analysis has been further developed in the Consultation Paper, in which Ofcom conclude that:

   > "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." (Consultation Paper, page 1)

2. This then informs their subsequent auction design process for the 3.6-3.8GHz band where they conclude that:

   > "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". (Consultation Paper, page 1)

3. The SUT analysis is not sufficient for this purpose. Ofcom themselves point to this. They say:

   > "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." (Consultation Paper, paragraph 1.28)

4. The probability of there being just one user in a cell is extremely small – typically there are hundreds or thousands of users. This means a user is near-certain to have to share the resources of the cell, and it is the reduction in cell resources caused by sharing that is the key factor in determining whether 5G services can be offered, regardless of what would be possible for a single user. Hence, to be sufficient for their purposes, Ofcom should have also undertaken capacity modelling to understand the impact of resource sharing.

[1] I have been instructed by TUK to critique Ofcom's use of the Single User Throughput Model in its "Update Note and Further Consultation" published on 15 May 2020 and associated model. The opinions I have expressed represent my true and complete professional opinion on the matters to which they refer. I have made clear which facts and matters referred to in this report are within my own knowledge and those which are not. Insofar as I have relied on information provided to me by TUK, I have specifically identified that information.

5. It is perfectly possible to model a typical cell and estimate the number of simultaneous users and hence the data rates available to each user. If Ofcom had undertaken this, as demonstrated below, they would have found that it is far from certain that 40MHz is sufficient to meet the demands of subscribers and that there are plausible scenarios where services will need to be curtailed, and many might not be able to receive the 5G service that they would like.

6. While my main conclusion is that the use of SUT as the only analysis of whether 40MHz is sufficient is flawed, I also note a number of flaws with the way that the SUT concept has been applied.

The basics of network planning

7. To function correctly, a mobile network must have both sufficient coverage and sufficient capacity. If the coverage is deficient then some handsets will not be able to receive a signal and so will be unable to connect. If the coverage is sufficient but there is insufficient capacity then the handsets will be able to connect but not to provide certain services to the user such as streaming video.

8. Typically, networks in urban and suburban areas are “capacity constrained”. This means that provision of coverage is generally achieved but that there may be insufficient capacity. Conversely, networks in rural areas are often “coverage constrained” such that there is sufficient capacity but problems in receiving a signal in some places. Note that 5G is currently being deployed predominantly in urban areas[2] where capacity, not coverage, is the key issue.

9. Coverage planning is performed by those deploying networks such as the mobile network operators (“**MNOs**”) using a process somewhat akin to the SUT process Ofcom relied on. Using models of how far radio signals propagate, computer-based planning tools can estimate the resulting radio signal levels across an area. Using SUT models or a similar process known as link budgets[3], the necessary signal to deliver a service can be determined. The extent to which this signal level is provided can then be seen. However, as mentioned above, coverage planning is typically less important in the areas where 5G will be deployed in the early years, and where the majority of 5G subscribers will be, because base stations are already quite dense providing generally good coverage.

[2] O2 (https://5g.co.uk/coverage/o2/) say “O2 launched its 5G service […] in six major towns and cities, and since then it has boosted that number to 30. Looking ahead, O2 has also said that it will have brought 5G to at least 50 towns and cities in total by summer 2020.” Vodafone say (https://www.vodafone.co.uk/network/5g) “5G will be available in selected UK locations, such as large towns, and cities, but the network will be expanding across the UK as the technology is implemented.” EE say (https://ee.co.uk/why-ee/5g-on-ee/5g-uk-coverage) “We're leading the UK on 5G rollout, with our 5G live in 80 cities and large towns.” Three say (https://5g.co.uk/coverage/three/) “There are currently 91 major towns and cities with 5G coverage from at least one UK mobile network. EE 5G coverage is currently available in 62 major locations, Vodafone has 29 major locations, O2 has 26, and Three offers it in 41.”

[3] Link budgets calculate the amount of loss that can be tolerated in the radio signal in order to meet service design criteria.

10. Capacity planning is performed by those deploying networks such as the MNOs by assessing the total capacity of the cell, and then comparing this with the number of users in the cell and their typical data demands. Cell capacity is set by:

    a) The amount of spectrum available.
    b) The technical efficiency which in turn is set by the standards such as the 4G and 5G standards.

11. Cell demand is set by:

    a) The number of users in the cell.
    b) The data rate requirements per user.

12. MNOs can increase capacity by:

    a) Acquiring more spectrum.
    b) Using the latest technology.
    c) Making cells smaller such that there are fewer users in the cell. This implies deploying more cells to cover an area using a process sometimes called "cell splitting".

13. To recap. Delivering a mobile service requires both coverage and capacity. Where 5G is likely to be deployed it is capacity, and not coverage, that is typically the key constraint.

The Ofcom SUT concept

14. The SUT approach is one method which determines the minimum signal level that a handset would need to receive in order to be able to provide the user with specific services such as video calling. This process, or ones similar to it, are part of the coverage planning process – once the minimum level is determined then coverage planning tools can be used to understand whether it will be achieved.

15. In A7.56 of the Statement Ofcom say that:

    > "To inform our assessment about whether 5G services could be offered by a mobile network using different bandwidths we have modelled the Single User Throughput (SUT) that a theoretical cell site could offer across its coverage area. We use SUT as a proxy for the quality of service a mobile user would experience if all the available spectrum resources in the cell were assigned to offer a particular 5G service to that user (for example, to support high definition video streaming)."

16. The SUT methodology assumes that there is only one user in a given cell. By way of background, cells can vary in size from a radius of around 100m to about 20km, although those for 5G will more likely be between 100m and 1km radius. It is on existing cells in cities where 5G has predominantly been installed to date, alongside 4G. In many UK cities the population density[4] ranges from 5,000 to over 10,000 people per km^2 and during the day many more commuters, tourists and others travel into the city. Hence, for most cities it seems likely that day-time user density levels exceed 10,000 people per km^2. For a 5G cell with a radius of 1km, this would imply 30,000 people in the cell of whom on average a quarter will subscribe to a given MNO, hence 7,500 users per cell would be plausible. In

[4] See, for example, https://en.wikipedia.org/wiki/List_of_English_districts_by_population_density.

smaller cities or larger towns this might fall to perhaps 1,000-2,000 users per cell. Cells are typically divided into three sectors and it is actually the number in the sector that is relevant for the subsequent analysis – in cities, this might be around 2,500 per sector (assuming there are 7,500 users per cell).[5] The number of users will also vary with time, with many fewer users in the night-time.

17. The Ofcom SUT approach calculates the data rates that the nominal single user could expect according to the underlying signal strength, the interference from neighbouring cells and the relationship between signal levels and data rate.

18. In Figures 1, 2 and 3 in the Consultation Paper, potential 5G services are shown as horizontal lines equating to particular data rates or throughputs (the terms are synonymous).

19. Ofcom then consider what data rates a single user in the cell might expect and presents the results in Figures 1 to 3 based on three factors – the Signal to Interference and Noise Ratio ("**SINR**") which forms the x-axis of the figures, and the spectrum bandwidth and the type of antenna system expressed as "2x2 SU-MIMO" or "4x4 SU-MIMO" which define the various lines drawn on the figures. I explain these terms below.

20. The fact that a single user can achieve a data rate greater than that needed for a 5G service is a necessary element in delivering that 5G service. But it is far from sufficient as in the real world there are typically thousands of users in a cell and the data rate that a user can expect depends much more on the demands for data from all the other users in the cell, which causes the data rate for each user to be reduced from the maximum theoretically possible in order to equitably share access to the cell. I will explain this further in subsequent sections. This is a point pointed to by Ofcom in its Consultation Paper – in paragraph 1.19 of the Consultation Paper they say:

> "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."

21. While in 1.28 Ofcom say:

> "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."

22. This lack of sufficiency is my key criticism of the use of SUTs. Ofcom have used an approach which indeed is insufficient to be able to draw the conclusions they reach.

23. Before going further, I now explain the terms used.

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[5] I have been provided with data from TUK which suggests 665 residential users per sector per MNO share (i.e. 25%) on the basis of c.2.4 users per premises. Clearly many more workers and visitors travel into cities than live there as residents and my figure of 2,500 users per sector seeks to take that into account.

24. ***SINR***: The Signal to Interference and Noise Ratio is a measure of the quality of the radio signal received by the user. It is measured as the overall strength of all the radio energy within the frequency band of interest impacting on the user's terminal, less that energy that is unwanted such as interference from other cells using the same frequency, and less the noise caused by thermal effects within various components in the phone. The SINR therefore represents the size of the useful part of the radio signal from which the terminal can extract information. For example, if the overall signal level is high and the interference level low then the useful signal level is large and a high level of information can be extracted from it. However, if the overall signal level is only slightly more than the interference level or the noise level then the useful signal level is small, and the amount of information it can carry commensurately low. Typically, SINR would be very high close to the centre of the cell since the wanted signal is not travelling far, while neighbouring cells are further away and their interfering signals reduced. The SINR would be very low at the edge of the cell since the wanted signal has to travel further, and the interfering signals often near-equally far and so are almost as strong as the wanted signal. In any given cell, most of the users will be towards the edge of the cell because the volume of a concentric ring of given width is much greater at the cell edge than at the centre. This means that most users will experience relatively low SINR values.

25. ***SU-MIMO***: Single user, multiple-input multiple-output antennas refers to the antenna systems used. In 4G and 5G systems it is normal to use more than one antenna at both the base station and the handset or terminal. For example, a 2x2 SU-MIMO system uses two antennas at both the base station and the terminal, while a 4x4 SU-MIMO system uses four antennas at each. Using more antennas allows more information to be received. The way that this is achieved is complex and relies on the signals from one transmit antenna to one receive antenna following a slightly different path from that of, eg the same transmit antenna and a different receive antenna. These differences can be exploited with complex signal processing to extract additional information. Hence these antennas can increase the data rate within a given bandwidth. However, there is a cost to using them, and it is impractical to have a large number of antennas within a cellular handset, limiting the approach (for example 8x8 SU-MIMO would generally not be practical). In 5G my expectation is that 4x4 SU-MIMO might be common in all but the lowest-cost smartphones given the advantages it brings over 2x2 SU-MIMO. However, as I explain later, even if 4x4 SU-MIMO is present it cannot always be used.

26. ***Bandwidth***: This is the amount of radio spectrum in use in a cell. 5G operators might use all of their licensed spectrum bandwidth in each cell in dense areas.

27. Ofcom conclude (in paragraphs 1.41-1.49 of the Consultation Paper) that their analysis shows that almost all envisaged 5G services are "technically feasible" in 40MHz, albeit with many caveats around whether they would be available at cell edge and whether small cells might be needed to meet demand. Of course, being "technically feasible" is quite different from being practically realisable. In the next section I show why their SUT analysis is flawed, while in subsequent sections I discuss the additional capacity modelling that is essential in determining whether 5G services could be delivered even where SUTs predict that they are possible with only a single user in the cell.

Flaws with the application of SUTs

28. Ofcom have made a number of omissions, simplifications and invalid assumptions that make their results overly optimistic. These are:

    a) The use of a 1:1 downlink:uplink ratio for industrial control[6].
    b) The lack of discussion as to how likely the SINR values they determine necessary are to be realised, especially on the uplink[7].
    c) The assumption that small cells can be deployed to resolve issues whenever needed.[8]
    d) Simplification of the role of 4x4 SU-MIMO antennas.

29. These are discussed in turn below.

Downlink:uplink ratio

30. Spectrum is divided to allow for both the downlink transmissions (from the cell to the handset) and the uplink transmissions (from the handset to the cell). This division is called duplexing. Most current bands use frequency division duplexing ("**FDD**") where the band is split into two equal parts. The 5G bands discussed here use time division duplexing ("**TDD**") where the band is not split in frequency, but in time such that for part of the time it is used for downlink and for the remainder for uplink, rapidly moving from one to the other. This allows for more of the band to be dedicated to downlink which is currently much more heavily used than uplink since users tend to download much more than they upload. Typical ratios are 75/25 down/up[9].

31. Ofcom's SUT modelling suggests, correctly, that for a single user it will be the uplink that constrains the delivery of the most demanding 5G services. For example, Figure 1 shows that for five possible 5G services that Ofcom have chosen, the most demanding – mobile broadband live video – can be delivered in the downlink with an SINR of between 3dB and 13dB, depending on the bandwidth assigned. Figure 2 shows that for the most demanding 5G services Ofcom have selected – mobile broadband live video – a similar range of SINR is needed. However (and not mentioned or explained by Ofcom), the SINR on the uplink is weaker than that on the downlink due to the handset having a less powerful radio transmitter than the base station. I estimate this difference to be about 9dB. As a result, delivering the uplink services would require an equivalent downlink SINR range of 11 to 22dB. Ofcom note at paragraph 1.43 of the Consultation Paper that:

    > "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."

32. Ofcom suggest that the solution to the uplink constraint is to move to a 1:1 ratio in small cells deployed, for example, in industrial locations. This will, generally, not be possible. The same downlink:uplink ratio needs to be used across entire networks and entire bands,

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[6] See paragraph 1.42 of the Consultation Paper.
[7] There is very perfunctory discussion in paragraph 1.25 of the Consultation Paper.
[8] This is assumed for "Mobile broadband live video" (paragraph 1.39, Consultation Paper), "Cloud computer games" (paragraph 1.41, Consultation Paper) and "Industrial control" (paragraph 1.42, Consultation Paper).
[9] See paragraph A1.41 of the Consultation Paper where it references this ratio being the "Preferred Frame Structure".

otherwise the interference created dramatically reduces network capacity. It would only be viable to use a different ratio if the cells in question were well-isolated from the national network. Such isolation might be possible, for example, for a remote factory, well away from areas of 5G coverage, but not for any factories or buildings within, or close to, areas of 5G coverage. Hence, Ofcom cannot rely on the 1:1 ratio being available and should base all results on the 3:1 ratio that will be used across the national network. Further, as I explain below, the reliance on small cells is optimistic, meaning larger cells will often be used, which will have a greater likelihood of interfering with national networks, further weakening the case for the 1:1 ratio. TUK have confirmed that in their view 1:1 is unrealistic and should not be used in the Ofcom analysis.

Likely SINR values

33. There is a further problem with the Ofcom approach because the charts presented in their Figures 1 and 2 (ignoring Figure 3 for the reasons mentioned above) show how data rates vary with SINR but they do not show what SINR a user might expect to experience. As mentioned earlier, SINR will vary throughout a cell, being high near the centre and low at the edges. Because the area of a concentric ring of equal width is much greater towards the cell edge than the centre, most of the users will be located towards the edges. Further, many users will be indoors, experiencing lower levels than those outdoors, and so biasing the SINR experienced towards lower levels. Ofcom note in paragraph 1.25 of the Consultation Paper that at the cell edge an SINR of -5dB might be encountered. This appears to be based on the assumption that cell will transmit at the maximum power whereas TUK have advised me that equipment generally available uses slightly lower transmit powers with the result that cell-edge SINRs might be even lower than this.

34. Ofcom have not presented analysis showing how SINR levels are distributed across a typical cell and therefore in what fraction of the cell a user would be able to receive a sufficient SINR to enable a particular 5G data service. Even without further analysis it is clear that there may be issues – if the cell edge SINR is -5dB as Ofcom suggest, and if the majority of users are located towards the edge and experience levels of this sort, then if 40MHz bandwidth is available, these users will only be able to access two of the five 5G services Ofcom have chosen to illustrate in Figure 1. The Figure also shows that if 100MHz bandwidth is available then an SINR between 6-9dB less is needed to deliver these 5G services, which my simplified modelling suggests could result in as many as 60% more of the users in the cell being able to receive some of the more demanding 5G services. However, even if Ofcom had completed this analysis, it would still not have accounted for other users since they were only considering a single user.

Small cells

35. Ofcom accept that for some services 40MHz is insufficient. In paragraph 1.37 of the Consultation Paper Ofcom say:

> "[…] 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". 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 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."

36. In these cases, Ofcom suggest that the solution is the deployment of small cells, for example in paragraph 1.39 Ofcom say:

> "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."

37. Small cells are typically cells with a range of 100-150m, with low base station heights often of 3-5m. They are typically used in areas of very high demand such as train stations or major shopping streets. Ofcom's reliance on small cells as a solution to delivering 5G services, with no analysis as to their practicality, lacks evidence. There are many reasons why small cells may not resolve the problem[10], including:

    a) It may be very challenging logistically to deploy small cells because there may not be appropriate places along busy streets or in high footfall buildings to erect masts or existing structures that can be used to mount antennas, or permission to deploy within venues and similar might not be forthcoming.
    b) The MNO needs to dedicate some radio spectrum to the small cells. Typically, an MNO will deploy all of their 5G spectrum on their larger cells, so if the small cells sit within the coverage of a larger cell then spectrum must be "borrowed" from the larger cell in that it needs to be taken away from the large cell so it can be used in the small cell, since if both the small and large cell try to use the same spectrum at the same time there will be interference between them. Removing spectrum from the larger cell will reduce the capacity of this cell, making it harder to provide 5G services in the larger cells.
    c) Small cells may not have greater cell-edge signal levels than larger cells so the assumption that SINR values will be higher in small cells may not be valid. In particular, small cells tend to have relatively low base station antenna heights compared to large cells. These low heights are often below the height of the surrounding buildings, with the result that users in the small cell can be shadowed by these buildings or other similar obstacles, whereas due to its greater antenna height the larger cell can send signal over the obstacle. Hence, in some cases larger cells can lead to greater cell-edge SINR values and hence higher data rates than small cells.
    d) Small cells add significant expense to a network build since sites must be found, masts erected, rental paid, additional equipment deployed and maintained, power provided

[10] I have seen a confidential copy of TUK's "Note to Ofcom re. Small Cells" (26 June 2017). As Ofcom will be aware, I was also a member of the Project Team which produced the report titled "The case for spectrum caps that support efficient and pro-competitive outcomes in the award of PSSR spectrum" submitted by TUK in January 2017 in response to Ofcom's consultation on the award of the 2.3 and 3.4 GHz spectrum bands. That report addressed small cells.

and more. If small cells are essential to provide a service it might potentially make provision of the service uneconomic.

38. Without addressing these Ofcom cannot just cite small cells as a universal solution.

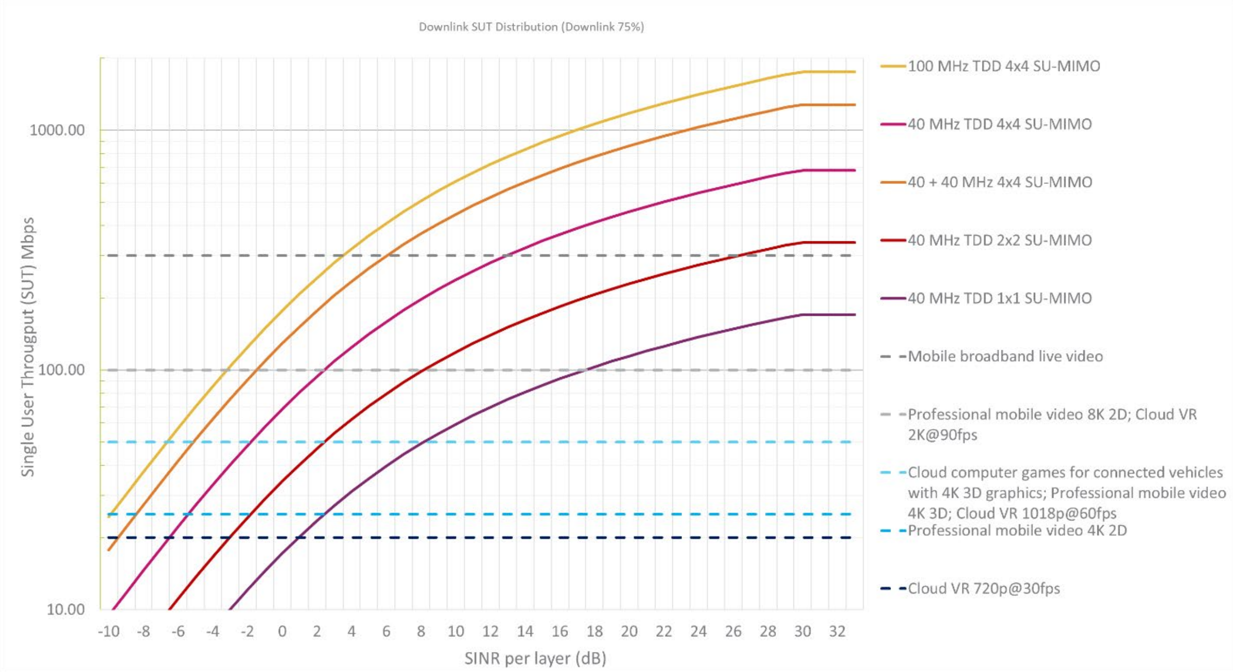
Simplification of the role of SU-MIMO antennas

39. Ofcom assume that 4x4 SU-MIMO antennas can be used in most situations and all of their results in their Figure 1 assume 4x4 SU-MIMO. However, there are two situations when this does not apply:

    a) As SINR values fall it is necessary to switch to 2x2 SU-MIMO and then eventually to single transmit antenna systems (which could be termed 1x1 SU-MIMO). This is because there is insufficient signal to accurately estimate the different radio signal paths in a 4x4 situation and hence to accurately decode the information. However, less signal is needed to accurately decode the 2x2 signal paths. Dropping to 2x2 will halve the data rate that can be provided for a given SINR (according to Ofcom's calculation methodology, see Equation A2, paragraph A1.38, Consultation Paper) and in dropping to 1x1 it will halve again. Using Ofcom's own model, I have illustrated the impact of this in Figure A below where the lower three curves relate to the 4x4, 2x2 and 1x1 variants. As can be seen, the impact is very substantial, making some 5G services impossible to receive and for others requiring a much higher SINR. Until 5G is widely deployed it will not be clear at which SINR values these changes to different SU-MIMO levels occur. TUK have told me that in their 4G network at least [✂] of the time subscribers are unable to use 2x2 SU-MIMO because the signal level is insufficient. This points to a substantial number of 5G subscribers - likely [✂] or more - being unable to use 4x4 SU-MIMO at any given point in time.
    b) If the terminal is using carrier aggregation across two bands, then the antennas need to be divided among the bands – so that a 4x4 SU-MIMO becomes a pair of 2x2 SU-MIMO antennas. Carrier aggregation is quite likely both in the 3.4-3.8GHz band, depending on the outcome of the auction process, and across multiple bands (eg 2GHz and 3GHz) in the future.

40. This suggests, at the very least, that Ofcom should have included curves for 2x2 SU-MIMO antennas in their Figure 1. Ideally, their conclusions should have been based on the more conservative assumption that 2x2 SU-MIMO antennas would be used by those towards the cell edge.

Figure A



Flaws with the use of SUTs

41. The Ofcom approach of using SINR, antenna configuration and bandwidth does show that one user, in isolation, could experience some 5G services according to the bandwidth allocated and their position in the cell. However, as explained above, there may be thousands of users in cells in urban areas with a greater than 10% probability[11] that a user is using their phone at any given time – so the chances of there being just one active user are extraordinarily low. It is the presence of these other active users that determine the data rates that can actually be delivered with a given bandwidth. Ofcom themselves acknowledge that they have not taken the density or number of devices into account in determining whether a 5G service can be offered where they say in Footnote 363 to paragraph A7.57 in Annex 7 to the Statement:

> "Whilst our assessment focuses only in data rates, 3GPP requirements to support these services are specified across a range of metrics including latency, packet loss, transmission frequency, data-rates and **device density**. However, **our assessment focus solely in providing a basic overview** about the data rates that could be offered using existing spectrum holdings with several antenna configurations without consideration of any other technical parameters that would impact these other requirements." (emphasis added)

42. In paragraph 1.19 (Consultation Paper) Ofcom say:

[11] This is my estimate, provided purely for illustrative purposes, based on data reported at https://www.theguardian.com/lifeandstyle/2019/aug/21/cellphone-screen-time-average-habits that the average user spends 3hrs and 15mins on their phone each day. Given a 16-hour waking day this corresponds to 20% of the day. However, the phone will not necessarily be transmitting or receiving throughout the active period hence the suggestion of a range between 10-20%. [✂].

> "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."

43. Ofcom do not explain why they say "We […] considered its results could nonetheless give us some indication". They do not explain how they came to this view. Nor do they qualify "some indication". They use a phrase "technically be capable" which they do not explain, but technical capability is not the same thing as practical plausibility.

44. In paragraph 1.28 (Consultation Paper), Ofcom say:

> "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."

45. However, Ofcom make no attempt to determine how much higher this SINR would need to be, and to what extent this is significant.

46. To understand the importance of capacity modelling, consider the typical case where there are thousands of users in a cell, some fraction of which are trying to access 5G services – eg to pick one of the less demanding services suggested by Ofcom[12] watching Professional Mobile Video at 4K/2D-resolution or delivering broadband to a connected vehicle. The cellular system will aim to accommodate all of these users – few would be satisfied with a system where the first user in a cell was granted all the data and subsequent users had to await their turn. To do so the cellular system will distribute the available data capacity among the users. Consider a simple situation where there are say 2,500 users in a sector of a cell of which only 10 users wish to watch 4K video – a service that could even be delivered over 4G - which requires around 25Mbits/s according to Ofcom (the second dashed horizontal line up from the bottom on Ofcom's Figure 1), and by chance these all had the same SINR of +5dB. While we do not know how many people might want to watch 4K video, if we assume that users spend around a hour a day watching some form of video on their phone,[13] it would suggest for a 16-hour waking day that there is around a 6% probability of a user is watching video at any given time. With around 2,500 users per sector of a cell, this suggests some 150 users in a cell might want to watch video of some form during the busier hours. While we do not know what the balance will be between different video resolutions in the coming years as 5G starts to be widely used, and this will likely change towards higher resolution over time, assuming that 10 of these approximately 150 video users might want high resolution does not appear unreasonable.

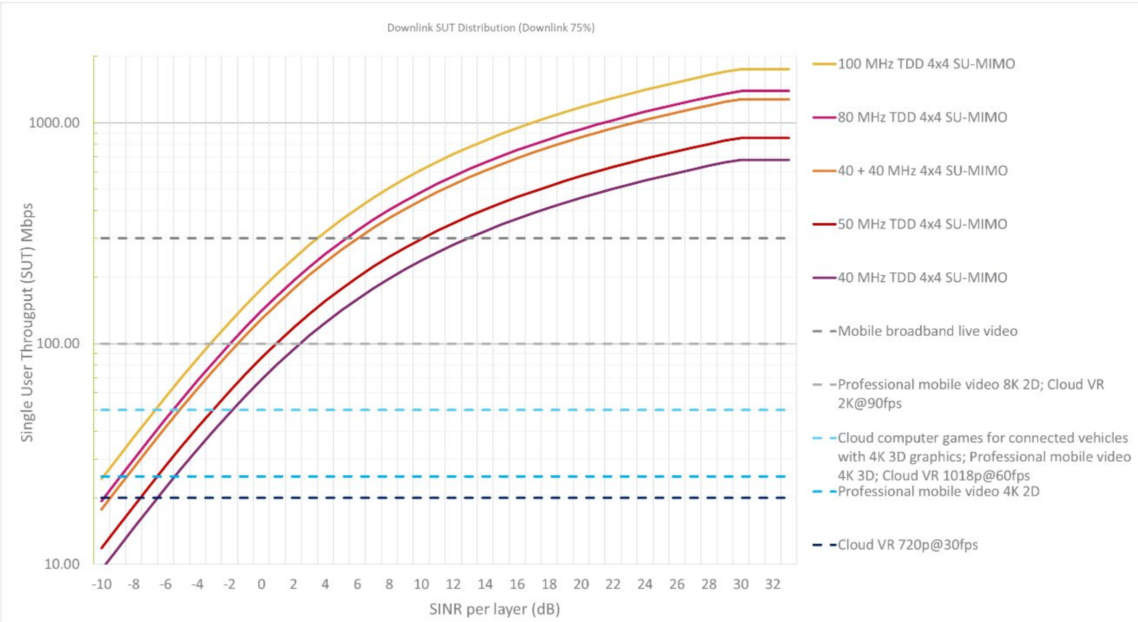
47. Imagine this is a cell with 40MHz bandwidth using 4x4 SU-MIMO. According to Ofcom's Figure 1, reproduced below for ease of reference, the lower curve shows that the SUT in this case is around 200Mbits/s. Hence, each user would be granted 20Mbits/s. This is less than

[12] Paragraph A1.33 of the Consultation Paper, Table A5.

[13] This might be watching a TV channel, streaming video or even a video clip embedded in a website, such as in the feed of Facebook.

the 25Mbits/s they would like for this particular 5G service (and much less than for some other 5G services shown on the figure) and so they would not be able to access this 5G service (in practice they would be downgraded to lower definition video, as currently available on 4G). Hence, despite the fact that the SUT shows that a single user could be granted a 5G service, in practice doing this would soon mean that most consumers who had elected to have a 5G service would only receive, at best, a 4G service. Of course, in practice different users will experience different SINRs according to their position in the cell, but this only complicates the analysis and does not negate the approach.

Figure 1



48. Now imagine the same situation as described above but with 100MHz bandwidth. In this case the uppermost curve in Figure 1 would apply leading to a SUT of about 550Mbits/s. This would enable each user to have up to 55Mbits/s, more than sufficient for the 5G 4K video service.

49. Note that this is only illustrative. In practice, many subscribers are simultaneously accessing many different services, and it is the total of all their data requirements that determines whether the cell is congested, and hence whether their requirements can be met.

50. It is this combination of SUT (or equivalent approaches) with the number of users in a cell that in practice will determine whether 5G services can be delivered. By failing to take account of the fact that there is more than one user in the cell Ofcom's analysis is flawed.

Capacity modelling

51. Capacity demands and whether they can be met can be determined by:

    a) Estimating the number of users in a cell.
    b) Assuming how often they wish to access 5G services and the data rates that they require when doing so which then leads to an estimate of the overall demand for data.

c) Calculating the capacity of the cell, which will be linearly related to the bandwidth available.
d) Hence, assessing whether the cell is able to meet the demand.

52. I have prepared a simplified and limited illustration which shows how this could have been done. I have constructed such a model which shows that in the dense urban areas where 5G is currently being deployed, that with 40MHz of spectrum only around 50% of users' 5G requirements could be met, whereas with 80MHz all could be met. The results depend on the assumptions made as to 5G user density and 5G requirements which I discuss further below. These are based upon my experience, industry forecasts and extrapolations of 4G usage, and so the results derived should be seen as purely illustrative and only be taken as indicative of the sort of assessment that should have been performed by Ofcom.

53. The model I have used to estimate the amount of spectrum needed for 5G services concentrates on the dense urban and suburban areas since this is where 5G is being deployed and in my view is likely to be the focus of 5G deployments for many years.

54. For each area, the model calculates a typical cell radius based on existing cells. For example, in dense urban areas the cell radius is typically around 800m.

55. The model then segments the cell into 50 "slices" of concentric circles. For each slice it calculates the percentage of cell area within the slice. It calculates the likely signal level (the SINR as discussed earlier) in the slice based on standard engineering models[14], and then converts the signal level into data rate using standard formula in much the same manner as the Ofcom SUT approach. Up to this point the model follows essentially the same approach as the Ofcom SUT model.

56. The model assumes the user density, that I discussed earlier of 10,000 people per km^2 in dense urban areas and that 25% of these will be on one of the four mobile networks. It assumes cells are divided into three sectors. It assumes that users will generate around 6GBytes/month of traffic in these 5G bands (in addition to the levels of around 3GBytes/month of traffic they currently generate in the 4G bands). It assumes that 5G will also, over time, be offered in some of the other frequency bands that the MNOs own. All of these 5G assumptions are unknowns, and are open to differing views as to their values, I have used these numbers purely for illustrative purposes and have not cross-referenced them to predictions made by others.

57. For each slice of the cell the model then determines the number of active 5G users in the segment and hence their total bandwidth demands as a percentage of the overall bandwidth available in the slice of the cell. The bandwidth demands can then be totalled across the entire cell and scaled according to the actual bandwidth. This then shows whether the cell can meet the spectrum demand.

58. This is a conservative approach. It assumes interference from neighbouring cells is minimal whereas in practice in dense areas inter-cell interference can significantly reduce capacity.

[14] Specifically, I have used the "Hata propagation formulas" – a set of empirical curves widely used in the industry to estimate signal strength at a given distance from the cell site. I have assumed indoor penetration losses in line with those used by Ofcom and 5G enhancements such as MIMO antennas also in line with those used by Ofcom.

However, there is much uncertainty as to what 5G will be used for, so any model of this sort is necessarily speculative.

59. If there is insufficient capacity in a cell, the MNO has to decide how to ration the available capacity among those demanding service. There are many ways it might choose to do this, including, for example:

a) All subscribers might see their data rates reduced by the same percentage.

b) Those subscribers using the highest data rate services may have their usage blocked.

c) Those users with the lowest priority use, perhaps because they have not opted for high “quality of service” tariffs may be blocked.

d) Those users near the cell edge, who use a disproportionate amount of the cell capacity because of their weaker connections, might have their usage blocked.

60. Hence, it is not possible to be definitive as to what the impact of insufficient capacity will be, but in all cases some 5G subscribers will not receive the services that they desired.

Conclusions

61. As Ofcom themselves note, the SUT approach may demonstrate the technical feasibility of implementing 5G services to a single user in a cell but this may be insufficient for showing that 5G services can actually be delivered. Ofcom should have undertaken the additional capacity modelling work which is needed to provide a sufficient assessment to draw conclusions as to the spectrum requirements of MNOs in delivering real-world 5G services when there are thousands of users in a cell.

62. Such capacity modelling is well within the capabilities of Ofcom. I have illustrated this by undertaking simplified and illustrative modelling of the demand for data in a cell compared with its ability to supply this data which suggests that there are plausible scenarios where 40MHz is not enough bandwidth to deliver 5G services to the number of simultaneous users likely to demand them.

63. Ofcom have concluded 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.” (Consultation Paper, paragraph 1.49)

64. ”Likelihood of technical feasibility” is not the same as being practically plausible and with only 40MHz there may be insufficient spectrum to meet the rapidly growing demands of subscribers with the result that services would need to be curtailed, and many might not be able to receive the 5G service that they would like, although exactly which subscribers and services will be curtailed depends on the policies adopted by the MNO.