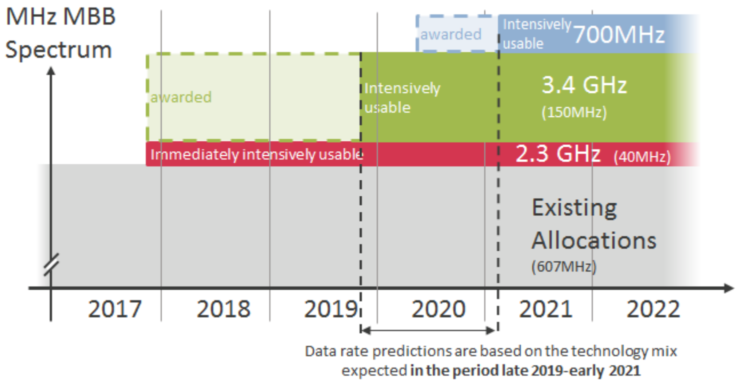
Annex 11 - UK MNO network capability: Present and future

Final report



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Real Wireless is a leading independent wireless consultancy, based in the U.K. and working internationally for enterprises, vendors, operators and regulators – indeed any organization which is serious about getting the best from wireless to the benefit of their business.

We seek to demystify wireless and help our customers get the best from it, by understanding their business needs and using our deep knowledge of wireless to create an effective wireless strategy, implementation plan and management process.

We are experts in radio propagation, international spectrum regulation, wireless infrastructures, and much more besides. We have experience working at senior levels in vendors, operators, regulators and academia.

We have specific experience in LTE, UMTS, HSPA, Wi-Fi, WiMAX, DAB, DTT, GSM, TETRA – and many more.

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Executive summary

Background

Real Wireless have been asked to perform an independent study to evaluate the potential benefits of operating services utilising the 2.3 GHz and 3.4 GHz spectrum bands that are to be released in the near term in the UK. The study also evaluates the potential of existing spectrum holdings that has through legacy auction outcomes, mergers and acquisitions, resulted in significantly different spectrum holdings between the operators.

Release of the 2.3 GHz and 3.4 GHz spectrum, under the Government's Public Sector Spectrum Release (PSSR) programme, makes a total of 190 MHz available for mobile use. This will allow operators to launch new services in the UK, including future Mobile Broadband (MBB) services.

Ofcom has estimated that UK household consumer mobile spending in 2015 was £15.05Billion, and continues to grow. However, there are significant differences in the Mobile Network Operators (MNOs) spectrum holdings. There is the potential that new spectrum could imbalance spectrum holdings further, resulting in noticeable differences in the services that can be supported. This poses a risk to the level of competitive intensity in the UK market, which is potentially detrimental to UK consumers.

This study has therefore investigated the types of services that are anticipated to be supported by the UK MNOs likely to be deliverable by around mid-2020. According to a recent Government report, 80% of traffic in this timeframe will be video; HD video support is likely to be a necessary but not sufficient performance requirement to address customer needs. HD video will require MNOs to support a minimum data rate of 4Mbps everywhere (i.e. contiguous coverage) and a recommended data rate of 8Mbps to guarantee the service. Additionally all operators have to support higher average data rates which will improve the experience of users performing other file transfer or cloud synchronisation functions.

This study then considered, first, the capability of MNOs to provide the services demanded by consumers in the following years with existing spectrum holdings and, then, different MNO capability to provide these same services with alternative spectrum holdings consistent with alternative outcomes of the PSSR award.

Findings on service quality

In order to determine the ability of MNOs to provide a ubiquitous HD video service, we have measured the service they could provide at the cell edge (i.e. contiguous service availability) throughputs for a reference load of 10 active UE's per cell for different spectrum scenarios [3].

In practical terms, MNOs may be limited to aggregating only their spectrum across the 3 largest bands they hold over the relevant time period. However, the deployment of additional spectrum with small cells could help MNOs make full use of their spectrum holdings in dense areas and approach the upper limit. We have therefore presented both cell edge performance measures – throughput using all spectrum, and speeds achieved with deployment of an MNO's three largest bands, representative of likely real-life performance of macro cells over the timeframe.

While less relevant given the high proportion of traffic that HD video will represent within the relevant timeframe, higher typical average data rates (i.e. not just those at the edge of the cell) also allow users to transfer data quicker, and can be more convenient for interactive tasks that might otherwise cause frustration. We have assessed that users consider transfers of representative media files to be ‘instant’ if they are performed in less than 3 seconds, and ‘slower’ if they take less than 10 seconds. We found:

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1. Introduction

This report has been commissioned by Three, who have asked that Real Wireless carry out an independent study to compare the benefits of operating services using existing spectrum holdings of the four main operators and the new spectrum bands to be released in the near term; the 2.3 GHz and 3.4 GHz spectrum bands.

As a result of legacy auction outcomes, mergers and acquisitions, different operators in the UK own significantly different quantities of spectrum. The forthcoming release of the 2.3 GHz and 3.4 GHz spectrum [1] presents an opportunity for the UK operators to launch new services as well as significantly enhance existing services such as their Mobile Broadband (MBB) services. These bands, released by the Ministry of Defence as part of the Government's Public Sector Spectrum Release (PSSR) programme [1], will provide a total of 190 MHz of spectrum.

Mobile services in general, and MBB in particular, are of significant value to UK consumers. Ofcom has estimated that UK household consumer mobile spending in 2015 was £15.05 Bn. [2]. The introduction of new mobile services can have a significant impact upon this value, as can the level of competitive intensity in the market. A discrepancy in the amount of spectrum held by different operators could disadvantage some operators' competitive position, and potentially be detrimental to UK consumers.

Two questions we seek to answer in this study are:

1.1 Our approach

To answer the questions above we follow the steps shown in Figure 1-1.

Figure 1-1: The Analysis process steps

This analysis process is used as we focus on possible outcomes based on quantity of spectrum held by each of the mobile network operators (MNOs) and this dimension underpins the competitive forces.

Step 2: Expected user data rate evaluation: The achievable user data rate for a representative cell load is estimated based on technology capability anticipated in mid-

2020. We consider Long Term Evolution (LTE) technology release mix, device capability, carrier aggregation (CA) in a multi-user environment. This tells us what cell edge and average user data rates MNO's will be able to support, for the given spectrum scenario during the study period.

Step 3: Use case and services analysis: From the wide range of services anticipated to be used for 5G networks, we focus on those that may be offered on earlier generation technologies in the timeframe of the study period. We identify which of these services can be supported by different MNOs for each spectrum scenario.

1.2 Report Structure

The remainder of this report is based upon the analysis process steps and is organised as follows:

Chapter 2: Introduces the spectrum scenarios which consist of existing MNO spectrum holdings plus three different distributions of 2.4 and 3.4GHz spectrum.
Chapter 3: Provides the technology capability analysis (Step 2).
Chapter 4: Provides a use case and service analysis (Step 3).
Chapter 5: Summarises the findings and addresses the questions posed.

2. Spectrum scenarios and timeframe for this study

To derive technology and use case insights we frame the scenarios within a defined time window, as shown in Figure 2-1 – up to the end of 2020, the shortest period where no further spectrum will become available for mobile use other than 2.3GHz and 3.4GHz.

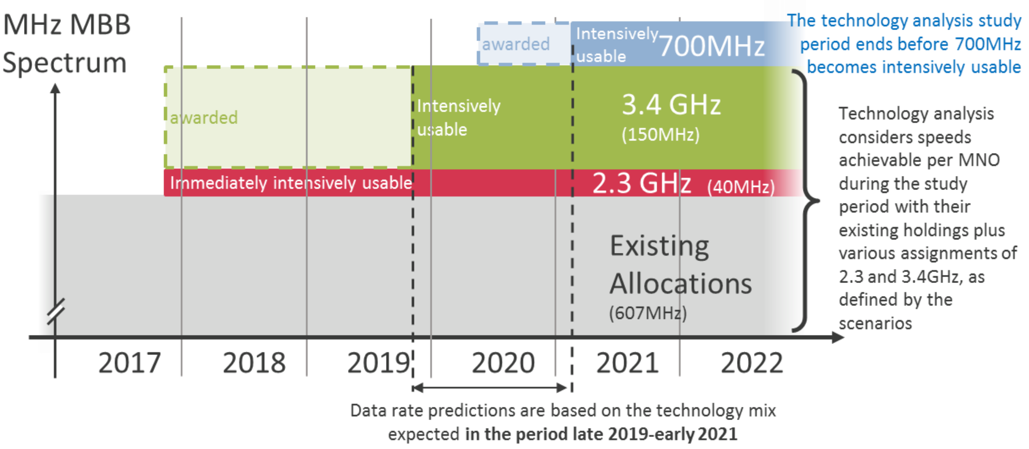


Figure 2-1: Spectrum timing diagram in the context of this analysis

In the foreseeable future, Ofcom plans to release spectrum in the 2.3 GHz, 3.4 GHz, 3.6 GHz and 700 MHz bands. We expect that:

- while 700 MHz is likely to be available from Q2 2020, the use case for this band will be predominantly coverage and the 2x30MHz that will be usable with certainty from this point will not make a significant difference to the performance of the 5G-type MBB services we evaluate in this study; and
- the availability of the 3.6 GHz band will be delayed, with earliest possible availability of 3.6 GHz in 2022 (though this is uncertain and may be later).

However, for the purpose of this study, we consider only the period where the supply of additional spectrum will be limited to the 190MHz (Table 2-1) in the 2.3 GHz and 3.4 GHz bands with high certainty.

Table 2-1: Spectrum band definitions

Band name	Spectrum range and notes
2.3 GHz	2350-2390 MHz
3.4 GHz	150 MHz of spectrum above 3410 MHz and below 3600 MHz, at 3410-3480 MHz and 3500-3580 MHz + 40 MHz held by UK Broadband (UKB). The auction will make available 150 MHz of spectrum in the 3.4 GHz band

This is in line with an estimated auction date in 2017 and reasonable assumptions on auction timing of all bands currently considered for mobile:

1. 2.3GHz spectrum is intensively useable by the end of 2017, owing to the use of a critical mass of compatible devices already held by UK consumers.
2. 3.4GHz is deployed in 2018, which enables an initial service launch, with a critical mass of consumers owning compatible devices for this to be intensively usable for capacity by the end of 2019
3. Other 5G bands will be intensively usable from 2021 onwards.

The current assignments of spectrum that are identified in Table 2-1 are detailed in Table 2-2.

Table 2-2: Current spectrum holdings per MNO

MNO	Spectrum band and BW(MHz)							
	800 FDD	900 FDD	1400 SDL	1800 FDD	2100 FDD	2600 FDD	2600 TDD	Total
BT / EE	10	0	0	90	40	100	15	255
Vodafone	20	34.8	20	11.6	29.6	40	20	176
O2 / Telefonica	20	34.8	0	11.6	20	0	0	86.4
Three	10	0	20	30	29.5	0	0	89.5
Total BW	60	69.6	40	143	119	140	35	

3. Expected User Data Rates

3.1 Method

We consider here the user data rates that MNOs will be able to support over the study period with the different spectrum scenarios. The method used for calculating user data rates from given spectrum holdings is defined by the following steps:

1. Take as an input the Total MHz MBB spectrum per MNO, per scenario
2. Calculate MHz available for downlink transmissions based on duplex type
3. Consider spectrum that could be deployed at a ‘capacity crunch’ cell site
4. Calculate spectral efficiencies for cell edge and average user DL throughputs
5. Calculate cell edge and average user data rates per MNO, per scenario

The following sections report the outcomes from the application of this method.

3.1.1 What our data rates represent

Figure 3-1 illustrates the key assumptions for our data rate predictions

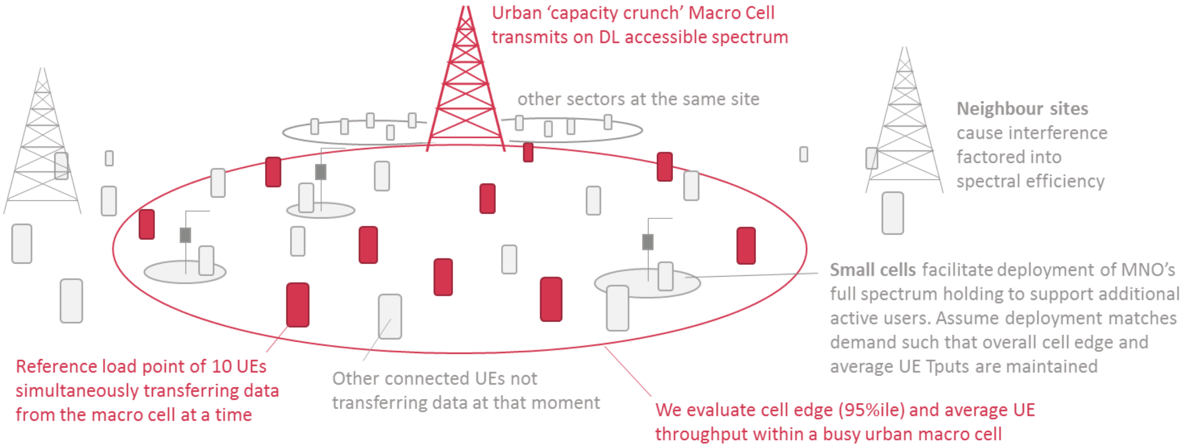


Figure 3-1: Data rates represent cell edge and average downlink user throughputs for a busy urban macrocell

To understand how different spectrum scenarios impact the service levels that MNOs can offer we focus on areas of the highest demand density. These areas, where spectrum holdings make the most difference between MNO holdings, are 'capacity crunch' sites in dense urban areas. We assume that services will be limited by speeds on the downlink and focus on those.

Cell Edge and Average User Throughputs: We wish to consider what speeds an MNO may be able to achieve given the spectrum holdings and dominant technology of the day. The appropriate metric depends somewhat on the type of service: For services with a 'hard' minimum speed requirement like a given video codec, the cell edge user throughput is used as this represents what can be supported to nearly all (95%) users in the cell. For services where Quality of Experience (QoE) increases with speed, such as file download, or cloud sync, the average user speeds are used to represent the users' 'typical' experience. Given the focus of this study on the MBB use case, we focus our assessment on cell edge measurements as the ability of MNOs to meet threshold use case values, though note that in addition to higher cell edge speeds, the deployment of more spectrum will also mean higher average speeds. These per-cell user throughput values reported take account of interference from neighbouring cells and therefore broadly represent the user throughputs achieved across the whole cellular network.

We calculate the cell edge and average user throughputs by multiplying the amount of down link spectrum with the cell edge and average spectrum efficiencies respectively. More details about the spectrum efficiency are presented in sub-section 3.1.3 and in Annex B.

10 UE/cell Reference load point: To compare different spectrum holdings, we assume a fixed reference load for all MNOs of 10 UEs per cell simultaneously transferring data at a given moment. Whilst there are likely to be many more than 10 UEs connected to or camped on an urban macro cell, they would not all be transferring data at that moment, and thus can be excluded for the evaluation of user throughputs. Our spectral efficiency figures assume the largest allowable control plane capacity, representing many connected users.

Whilst 10 UEs/cell may seem somewhat arbitrary, this has been agreed by the industry [3] to represent a typical load for the purposes of performance comparisons. Industry reference performance characteristics (consensus of equipment suppliers' performance) exist for this reference loading. This performance measure represents a "typical" load but actually; however, in practice, operators will have sites with higher (and lower) load than this so there would be many sites which do not achieve this "typical" performance.

Heterogeneous Networks: Small cells are being deployed in urban hotspots to densify the network and improve performance. Carrier aggregation and multi-point connectivity enable spectrum 'lit up' by small cells to be presented seamlessly to devices, and all MNOs to utilise disparate spectrum holdings. In this analysis, we assume each MNO deploys small cells in such a way as to keep up with localised increases demand density, to maintain the same cell edge achieved over the wide area coverage of the macro cell.

3.1.2 Spectrum available for downlink transmissions

Here we consider the amount of spectrum that each MNO will have available for downlink transmissions at the capacity crunch site.

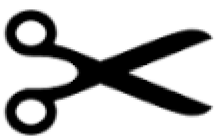
For duplex type, we align with Ofcom assumptions [1]:

- Frequency division duplex (FDD) bands: 50% available for downlink
- Supplementary DL (SDL) band: 100% available for downlink
- Time division duplex (TDD) bands: assume 3:1 DL:UL ratio, giving 75% available for downlink

For the amount of spectrum deployed at the busy site, we consider two possibilities:

1. We consider the case where an MNO can deploy all of their downlink accessible spectrum on the capacity crunch cell, representing an upper limit.
2. Recognising the complexity of deploying multiple sets of band specific hardware, such as antennas, duplexers, filters etc., we also present figures where an MNO limits their deployment to the three largest non-contiguous bands in their holding.

The resulting MHz of DL spectrum per site is shown in **Error! Reference source not found. Error! Reference source not found.**. As already mentioned, the deployment of additional spectrum with small cells will help the MNOs make full use of their spectrum holdings in dense areas and approach the upper limit.



Potential spectrum limitation on the device side and Carrier Aggregation
We have also checked whether the limitations of carrier aggregation on the mobile device could limit the bandwidth usable by a single device and the resulting impact on data rates.

Until release 13 there is a limit of 5x20MHz component carriers, so no one device can access more than 100MHz spectrum. At a load of 10UEs/per cell, we assume that the 95% percentile cell edge user is scheduled around 20% of the cell's spectrum. [4]. This is disproportionately higher than other devices to compensate for its lower signal quality and spectrum efficiency. Given the largest total downlink holding in any of our scenarios is under 200MHz, we do not expect any device could therefore be scheduled more than 40MHz downlink spectrum at a reference load of 10UEs/cell. We anticipate this 100MHz device limit would not impact user equipment (UE) speeds for loads of 4UEs/cell or more.

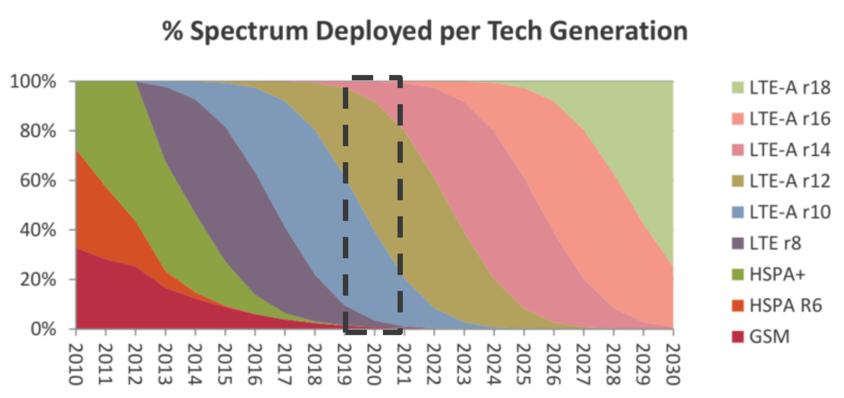
Devices may also be limited in the number of different bands from which carriers can be aggregated. Device support for different band combinations is market led and 3GPP standards are continually adding new combinations as driven by their members of the partner organisations. At the current time, premium devices such as the iPhone 7 can support 3 band carrier aggregation, so we assume that such support will be sufficiently prevalent by the time of the study period. In the future, more bands will be able to be aggregated and will be in general use. We therefore present the results of the performance assuming two configurations; that all bands can be used, and that only the 3 highest capability bands can be aggregated.

3.1.3 Spectral efficiencies of technology in use during the study period

3GPP LTE standards now dominate mobile broadband and are expected to continue to do so during the study period. LTE standards are being continually updated with new releases, which each increase the efficiency by which Hz of spectrum can be used to carry bits of information (the spectrum efficiency). Our expectations for the versions in use during the study period are based on the model used by Ofcom in [5]. This extrapolated the known 3GPP standards freeze dates out to 2030 and factored in lead times for infrastructure deployment and device availability to derive a "blended mix". Figure 3-2 shows the technology generations deployed during the study period.

Figure 3-2: Split of spectrum across technology generations during study period. Source: Real Wireless for Ofcom [5]

By this estimate, the majority of spectrum will be using Third Generation Partnership Project (3GPP) LTE releases 10-12, corresponding to 'LTE-Advanced' technology [6]. 'LTE-Advanced Pro' covers release 13 onwards [7] and will be emerging during this time, although we do not consider it to be sufficiently prevalent to significantly impact cell edge and average user throughputs. Expected speeds are therefore based on spectrum efficiencies achievable in the middle of the study period with LTE-Advanced, based on an extensive analysis by 3GPP members in their self-evaluation against the ITU's IMT-Advanced requirements [8].



Whilst in practice, spectral efficiency will increase continuously, we assume our midpoint rates represent the average of the study period for the purposes of spectrum comparison. Any changes will impact all MNOs equally, and thus not impact their relative performance.

We draw upon the 3GPP analysis of LTE-Advanced (Release 10-12) [9] to evaluate data rates during the study period. For our capacity crunch cell in a dense urban area, in addition to the assumptions above, we assume cell edge speeds available to consumers for enabling the MBB use case will be based on:

- Average spectrum efficiency (SE) taken over 3 base-station 4x2 MIMO transmit antenna configurations
- The control channel overhead, representing a large number of devices and associated signalling in the busy capacity crunch cell i.e. the control channel overhead parameter, L, equals to 3.
- We calculated the “weighted” average and cell edge spectrum efficiencies by considering the TDD and FDD band spectral efficiencies [see Annex B] and the amount of TDD and FDD spectrum.
- The SE values are based on full buffer and proportional fair scheduler [9,4]

Error! Reference source not found. shows the cell edge user spectral efficiencies used in the study. It is important to note that the metric of bps/Hz/user takes into account how spectral resources are shared between the assumed 10UEs in the cell. i.e. the bps represents the user data rate, but the Hz represents the spectrum used for all users in that cell, not just the Hz scheduled to that user.

4. Use cases and services supported

5G performance requirements have been defined in a series of 5G PPP projects, such as METIS-II, FANTASTIC-5G, 5G-XHaul and mmMAGIC for different use cases and services (see [10, 11, 12, 13]. Different performance targets exist for different services in different environments. This study is primarily interested in the service requirements of MBB – i.e. the provision of (primarily) outdoor services over a wide area by a mobile network to mobile devices. In addition, this study is less interested in true 5G services – but to investigate what services MNOs in the UK would be able to offer, based on different spectrum holding scenarios, in the timeframe where the only substantial increase in capacity spectrum is that made available in the PSSR award.

In the following we will identify the requirements to support some potential anticipated future services in different environments, before considering demanding services that are anticipated to be used in the study time period.

4.1 5G Requirements

The METIS-II project was established to provide the 5G collaboration framework within 5G-PPP for a common evaluation of 5G radio access network concepts. This was a high level study and established some of the early 5G service requirements, which have been augmented in related 5G-PPP studies. For example, the 5G-PPP project mmMagic seeks to identify 5G performance requirements for spectrum above 6GHz – which set much higher performance than those planned below 6GHz, based on the Metis-II project. The main KPIs identified in the Metis II project are shown in Table 4-1.

Table 4-1: 5G Service requirements identified in Metis-II project in different environments.

Use Case (UC)	Key Performance Indicator (KPI)	Key requirements
UC1 Dense urban information society	Experienced user throughput	300 Mbps in DL and 50 Mbps in UL, 95% availability and 95% reliability
	E2E RTT latency	Less than 5ms (augmented reality applications)
UC2 Virtual reality office	Experienced user throughput	5 (1) Gbps with 20% (95%) availability in DL 5 (1) Gbps with 20% (95%) availability in UL Both with 99% reliability
UC3 Broadband access everywhere	Experienced user throughput	50Mbps in DL and 25Mbps in UL, at 99% availability and 95% retainability
UC4 Massive distribution of	Availability	99.9%
	Device density	1 000 000 devices / km^2

Use Case (UC)	Key Performance Indicator (KPI)	Key requirements
sensors and actuators	Traffic volume/ device	From few bytes/day to 125 bytes per second
UC5 Connected cars	End to end (E2E) one-way latency	5ms (traffic safety applications)
	Experienced user throughput	100 Mbps in DL and 20 Mbps in UL (service applications) at 99% availability and 95% reliability
	Vehicle velocity	Up to 250 km/h

Several key points emerge from this summary table:

- Use Case 3: MBB environments are anticipated to support a ubiquitous 50Mbps (DL) and 25 Mbps (UL).
- Use Case 4: Machine to Machine type communications is expected to support a high number of low data rate devices, with extremely high levels of availability.
- Use Case 5: Connected cars are anticipated to support high data rate to moving vehicles, with low levels of latency[1] [14].
- Use Case 2: The virtual reality office is anticipated to support the highest data rates (5Gbps in both UL and DL at 95% availability, dropping to bi-directional 1Gbps with 20% availability). This environment will also need low latency.
- Use Case 1: Dense urban environments with data rates of 300 Mbps (DL) and 50 Mbps (UL), 5ms latency for augmented reality applications and high reliability.

These requirements, in terms of data rate, exceed the anticipated network capability described in Section 3. It is therefore of interest to identify what types of services are likely to be supported, in a MBB environment, with the more modest performance anticipated by the analysis in Section3.

4.2 Minimum ubiquitous data rates

A key requirement for 5G MBB is the provision of high data rates (50 Mbps DL) everywhere, with much higher coverage probability than today's networks. Typically, the requirements established for a mobile network generation are not achieved when that technology is initially introduced. An October 2016 report (The National Infrastructure Commission, NIC Report) for the UK government [15] on future use cases for mobile communications has investigated a wide variety of potential future uses in order to establish anticipated user needs up till 2025. Though not exhaustive, this report claims to "focus on [the services] that are likely to represent the majority of the 2025 mobile traffic demand and/or significant new value and be maturing in use by this timeframe". The report considered MBB, Machine Type Communication (MTC) and Mission Critical Communications (MCC) for connected cars, railways, healthcare, "utility and supply chain", and "media and cloud"

[1] It is noted that high latency results in 'sea-sickness' if the users' movement is inconsistent with the projection viewed by the user. This reduces the ability to use compression, requiring extremely high data rates – see [14].

market sectors. We will therefore base the requirements for these "towards 5G" services on this NIC report.

Based on the NIC report, the key service anticipated to drive the requirements for a MBB network in the short term is high quality video to mobile devices. The report also notes that "the consumer demand for video is forecast to be greater than 80% of content over wireless networks". Similarly, Cisco forecast that 75% of the world's mobile data traffic will be video by 2020 [16]. Based on [17, 18, 19] the minimum and recommended data rates for different streaming services[2] re shown in Figure 4-1, and listed in Table 4-2.

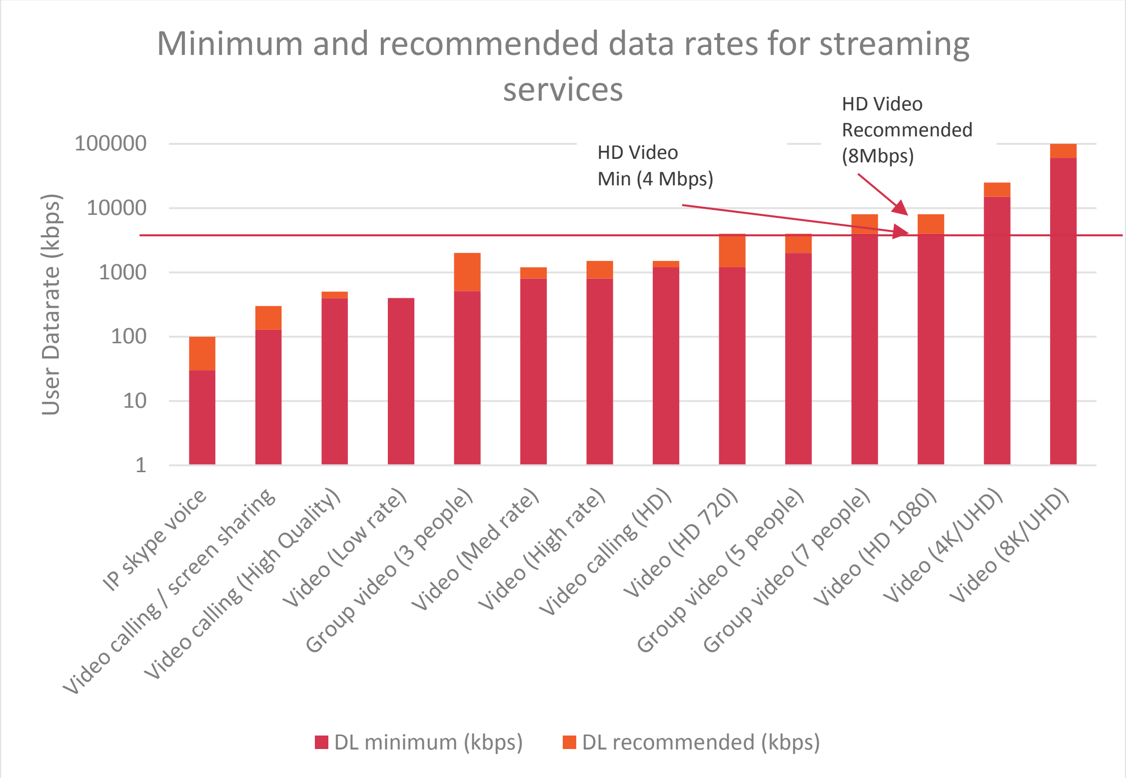


Figure 4-1: Minimum and recommended data rates for streaming services (NB: Logarithmic scaling of the user data rate).

A key requirement from 5G standard definition is ubiquitous availability of a minimum required data rate to allow support at all locations in the network. This sets the requirements for the cell edge that needs to be achieved in order for an operator to commit to ubiquitous service support.

In January 2016, Netflix [20] questioned the benefit of using 8K video for large domestic screens. This raises the question as to what the maximum useful video resolution to stream to a mobile device should be. Today's high end mobile devices are unlikely to benefit from this level of resolution (the iPad Pro has a physical screen resolution of 2048x2732 and the Samsung Galaxy S7 1440x2560). These resolutions are marginally above the HD pixel resolution, but do not achieve the resolution of UHD, and certainly not 8K. Whilst it is

[2] The figure for 8K video is extrapolated based on the number of pixels and the trend from HD to 4K. No additional improvement in compression is assumed.

possible to anticipate that higher resolutions may be possible in future mobile devices, within a few years it is difficult to anticipate that a large number of users would significantly benefit from a video resolution greater than HD video, to a mobile handheld device. Netflix anticipates that 8K may never be required for a large static screen in a home.

We can therefore assume that HD video support is likely to be a minimum performance requirement for MNOs seeking to offer high demand video services. To support this operators will need to support a minimum data rate of 4Mbps and recommended data rate of 8Mbps at the cell edge, to maintain ubiquitous availability. Since this is expected to be 80% of traffic, all operators will need to offer this.

Table 4-2: Minimum and recommended data rates to support different streaming service applications and resolutions.

Streaming Service	Minimum DL data rate (kbps)	Recommended DL data rate (kbps)
IP skype voice	30	100
Video calling / screen sharing	128	300
Video calling (High Quality)	400	500
Video (Low rate)	400	400
Group video (3 people)	512	2000
Video (Med rate)	800	1200
Video (High rate)	800	1500
Video calling (HD)	1200	1500
Video (HD 720)	1200	4000
Group video (5 people)	2000	4000
Group video (7 people)	4000	8000
Video (HD 1080)	4000	8000
Video (4K/UHD)	15000	25000
Video (8K/UHD)	60000	100000

4.2.1 Mapping ubiquitous data rates to spectrum scenarios

4.3 Benefits of higher average data rates

Other services, including cloud synchronisation, would benefit from data rates higher than the minimum data rates for video described above i.e. the quality of a higher speed network can provide higher quality of service to users for the purposes of data exchange, file download and data synchronisation. Higher data rates would simply reduce the time necessary to synchronise large amounts of data or to perform tasks that would otherwise "waste" time. Since these file transfers only need to be representative (rather than continuously available) it is appropriate to use the average data rate for these values (not the cell edge data rate).

Hence it is useful to determine what tasks can be done for representative[3] file types in different times. Typical files, their characteristics and data volume are shown in Figure 4-2.

Media type	Characteristics	Data Volume
Medium resolution photograph (maximum resolution on Galaxy S6)	Resolution: 5312x2988 JPEG compression	~5MB
Medium resolution Song	4 minute song, 176kbps constant bit rate, MP3 compression	~5MB
eBook		1 – 5MB
Ofcom 2011 CMR report – business report document	Pdf	~4MB

Figure 4-2: Typical data volumes of different media file types

We will use a nominal data volume of 5MB for either a song, a photograph, eBook or business report. The key question is how many of these files can be transferred in a timeframe that is acceptable to different users (interactive) or if they are background tasks, and perhaps deemed less suited to a mobile experience. We have assumed that users consider events requiring less than 3 seconds on a mobile device to be essentially "instant", and anything less than 10 seconds to be "slower" – i.e. since it is "slower" compared to an "instant" download and download users would wait for the task to be done. Anything more than 10 seconds is deemed to be a background task. Hence, we have three time periods of interest: <3s ("instant"), 3 ->10s ("slower"), and >10s ("background"). We can determine

[3] This analysis is illustrative – precise values would depend upon the nature of the media, and compression performance, resolution, sampling rate etc. However, these values are broadly representative.

the number of multimedia file transfers that can occur within the 3 and 10 second timeframes given different link rates (Figure 4-3).

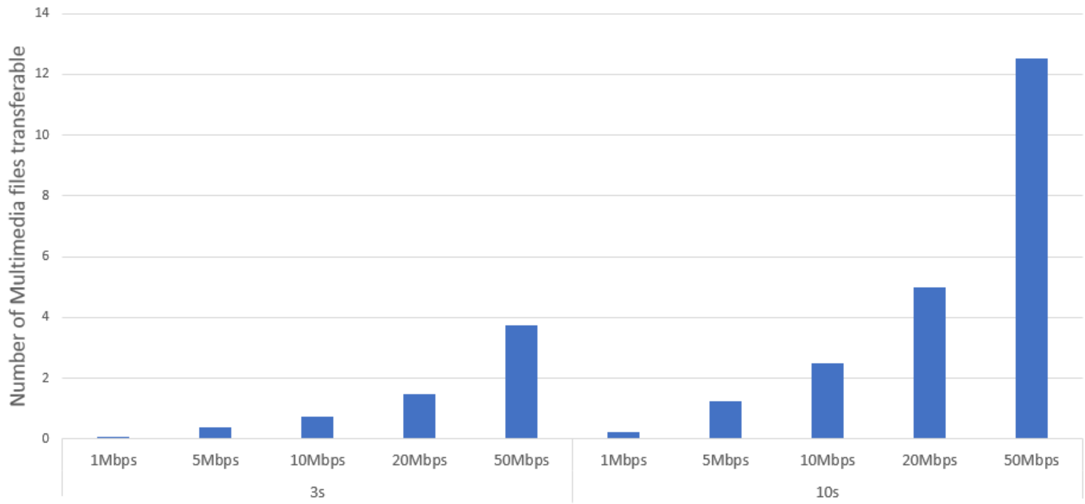


Figure 4-3: Number of multimedia files transfers in a 3sec and 10sec time interval

Further, we can further determine the data rate required to transfer one item or 10 (an album) in these different timescales as shown in Table 4-3.

Table 4-3: Data rate required to transfer individual or groups of media files ("Albums") in different timeframes

Media type	Timeframe	Average data rate (Mbps)
One Media file: (One Photograph, song, eBook or report)	Instant (<3 s)	13.3
	Slower (3 - >10s)	4.0
One Media Album: (10 Media files)	Instant (<3 s)	133.3
	Slower (3 - >10s)	40.0

We can therefore assess that in order for users to transfer a media file "instantly" a minimum data rate of 13.3 Mbps is required (and 133 Mbps for 10 media files). These data rates reduce to 4.0 Mbps and 40.0 Mbps respectively when a "slower" transfer is sufficient.

4.4 Mapping average data rates to users' timeframe

The above section has identified the data rates needed for different example file transfers to appear to be 'slower' or 'instant'. The time necessary to transfer an 'album' (i.e. 10 media files) exceeds the time that users are assessed to consider either 'instant' or 'slower'.

5. Conclusions and future work

5.1 Conclusions

The technology analysis considers LTE-Advanced (3GPP release 10-12) as the predominant technology, and establishes pertinent performance metrics to evaluation different spectrum holding outcomes from late 2018 to late 2021. For a 'capacity crunch' site utilising all an MNOs downlink accessible spectrum; cell edge user data rates vary between 4 - 13 Mbps for a reference load point of 10 active UEs per cell. This represents the rate that an MNO can 'guarantee' to nearly all of its users, and is the basis for offering a service with a hard minimum data rate requirement like HD video, for example. Average user throughputs at this load represent the 'typical' user experience, and are applicable to services like cloud sync or file transfer, where there is no hard minimum speed requirement. We expect these rates to be in the range 11-48 Mbps, depending on the MNO and spectrum scenario.

[redacted]

5.2 Future work

We make following the recommendations for further work beyond this project:

1. Current work is limited to MBB use cases. Consideration of other 5G use cases relevant to these spectrum bands such as IoT would enable a broader range of multi-service competition aspects to be evaluated.
2. [redacted].

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Annex A-Spectrum scenarios

Annex B: Spectrum Efficiency