Annex 7 to Three's response to PSSR auction consultation Jan 2017

Number of sites versus spectrum analysis

Technical annex

Contents

1. Summary of analysis and key findings

It is not physically possible to match speeds across all times and locations where there is an imbalance of spectrum between MNOs because peak speeds cannot be matched by the MNO with less spectrum.

Three has however run a simulation based on its network deployment in the Maidenhead area to estimate the number of sites required to *nearly* match speeds at locations and times of day where there is a *significant* amount of traffic (which is less demanding than attempting to match speeds at other locations and times of day). Three has estimated the numbers of sites required to nearly match speeds (at both busy hour and midday traffic levels[1]) on average across the network where one operator has 2.4 times the amount of Downlink (DL) spectrum of another. This is the ratio between BTEE (135MHz) and Three's spectrum (55MHz) holdings *ceteris paribus* for both operators.

- Three's network would require [✂] times sites *cf.* BTEE to nearly match speeds across the entire network at midday; i.e. [✂] sites (versus the existing ~[✂] MBNL sites).
- The number of sites Three would require to deploy to nearly match BTEE speeds on only the busiest 8,000 sites (i.e. not to attempt to match speeds at less busy sites), is approximately [✂] at midday.

Three has also run a simulation to estimate the number of users experiencing a minimum of 2, 4 and 8Mbps for networks with two different spectrum holdings[2]. This capacity analysis estimates the number of sites required for 95% of users to achieve the minimum target speed under fixed loading assumptions and where one operator has twice the amount of spectrum of the other. We concluded that:

- The network with smaller spectrum holding would require [✂] times the number of sites in order to match the competitor network in satisfying 95% of the users with the 2Mbps minimum speed

However:

- [✂] times site densification is needed to match the number of users with the minimum speed of 4Mbps; and
- a network with 2×10MHz of spectrum [✂] a competitor with twice the spectrum holding if the minimum speed was raised to 8Mbps or beyond.

[1] Based on traffic measurements across its sites in the Maidenhead and Slough area in 2015, Three found that traffic levels at midday were [✂]% lower than in the busy hour, representing moderate network loading (lower than in the busy hour but still substantially higher than at some other times of day).
[2] In its capacity analysis, Three models a network with 2×10MHz and a competitor network with twice the spectrum (2×20MHz) in the 1800MHz band.

To validate Three's findings, Three has also asked Qualcomm, Real Wireless and Samsung to perform similar independent studies to analyse the extent to which additional sites can be used to compensate for a lack of spectrum.

- Qualcomm ran a simulation using the same area in Maidenhead to quantify the required site densification to match the user speeds on a network with twice as much spectrum under different load conditions. Qualcomm concluded that [✂-Qualcomm's conclusions]. Qualcomm's findings were fully in line with Three's analysis.

- Real Wireless implemented a different methodology to independently quantify the required level of site densification and concluded that [✂-RW's conclusions]. In its analysis, Real Wireless modelled a network consisting of the 50% most densely populated areas in the UK served through [✂-number] sites. It found that [✂-RW's conclusions]

- Samsung followed a two-pronged approach whereby it simulated the number of video users that could be simultaneously supported by each MNO (with actual spectrum holdings) and then calculated the amount of spectrum Three would require in order to match the quality of experience (i.e. download speeds) available on EE's network. Samsung's findings agreed with Three on the number of video users supported with different spectrum holdings. [✂-Samsung's conclusions]

2. Introduction

It is well-known that to increase the volume of traffic supported and the user speeds on a network, there are 3 main potential options:

- Increase the amount of spectrum available;
- Increase the number of sites (densification); or
- Optimise the network and improve the spectral efficiency through advanced techniques.

In this work, we define **capacity** as **the combination of the total throughput of the network** (i.e. the total volume of data carried) **and the average user speeds delivered**.

Spectrum is a valuable and limited resource. Each UK operator holds licences for differing amounts of spectrum. All else being equal, user speeds are directly proportional to the amount of spectrum. Larger amounts of spectrum result in higher user speeds, i.e. the relationship between the amount of spectrum and the data speeds delivered is linear. Increasing the number of sites also increases the network capacity, meaning that it improves average user data speeds and increases the total volume of data that can be carried by the network. However, in this case, the relationship between increasing sites and increased capacity is not linear.

Adding more sites where they are most needed helps in offloading traffic from surrounding sites. However, additional sites do not lead to a proportionate increase in data speeds for two main reasons:

- adding more sites also raises the interference level in the area, which has a negative impact on the user speeds[3]. This constraint introduces a limit for the effectiveness of site densification.
- a user only connects to one site at a time, meaning that a user's peak speed is always limited by the amount of spectrum deployed on that site.

In this analysis, we quantify the following:

1. The required number of sites to come as close as possible to matching user speeds of a network with more spectrum (noting that fully matching the user speeds is not physically possible)
2. The number of sites needed to match the user speeds of a network with more spectrum in order to satisfy 95% of users with set minimum target speeds[4]

In the remainder of this annex we first highlight a previous theoretical piece of work that considers the benefits of additional spectrum versus additional sites. We then present our analysis, produced using our LTE simulator to evaluate different scenarios. Finally, we provide an overview of work carried out on Three's behalf by Qualcomm, Real Wireless and Samsung to verify our findings using their own simulation models.

3. Literature Review

Three has identified a recent paper[5] (Yang, Sung 2015) from KTH Royal Institute of Technology, Sweden that is directly relevant. The paper's abstract describes the research as follows:

"Abstract - Dense deployment which brings small base stations (BS) closer to mobile devices is considered as a promising solution to the booming traffic demand. Meanwhile, the utilization of new frequency bands and spectrum aggregation techniques provide more options for spectrum choice. Whether to increase BS density or to acquire more spectrum is a key strategic question for mobile operators. In this paper, we investigate the relationship between BS density and spectrum with regard to individual user throughput target. Our work takes into account load-dependent interference model and various traffic demands. Numerical results show that densification works better in sparse networks than dense networks. In sparse networks, doubling BS density results in almost twofold throughput increase. However, in dense networks where BSs outnumber users, more than 10 times of BS density is needed to double user throughput. Meanwhile, spectrum has a linear relationship with user throughput for a given BS density. The impact of traffic types is also discussed. Even with the same area throughput requirement,

[3] User data speed is inversely proportional to interference. This is because as interference increases, the signal to noise ratio (SINR), of the transmitted data, to which user speeds are directly proportional, decreases.
[4] Simulations were carried out for target speeds of 2, 4 and 8Mbps assuming low, medium and heavy loading on the network.
[5] Yang, Y., Sung, K W., (2015); "Tradeoff Between Spectrum and Densification for Achieving Target User Throughput"; IEEE VTC 2015; London (UK)

different combination of user density and individual traffic amount leads to different needs for BS density and spectrum.”

The authors calculate the number of sites required to achieve similar user throughput (i.e. data speeds) with half the spectrum holding. They categorise the networks they model as “sparse” and “dense”. A “sparse” network is one where there are fewer sites than active users, meaning that each site carries a high-level of traffic. Results for a sparse network are therefore reflective of what can be achieved where sites are heavily loaded. A “dense” network is one where there are more sites than active users and provides results reflective of the situation where traffic is low.

The paper concludes that the number of sites needs to be more than doubled in a sparse network (heavily loaded) and the number of sites needs to be increased between 10~20 times in a dense (lightly loaded) network in order to match the user speeds achievable with a larger amount of spectrum. The authors presented their finding in the following charts shown in Figure 1.

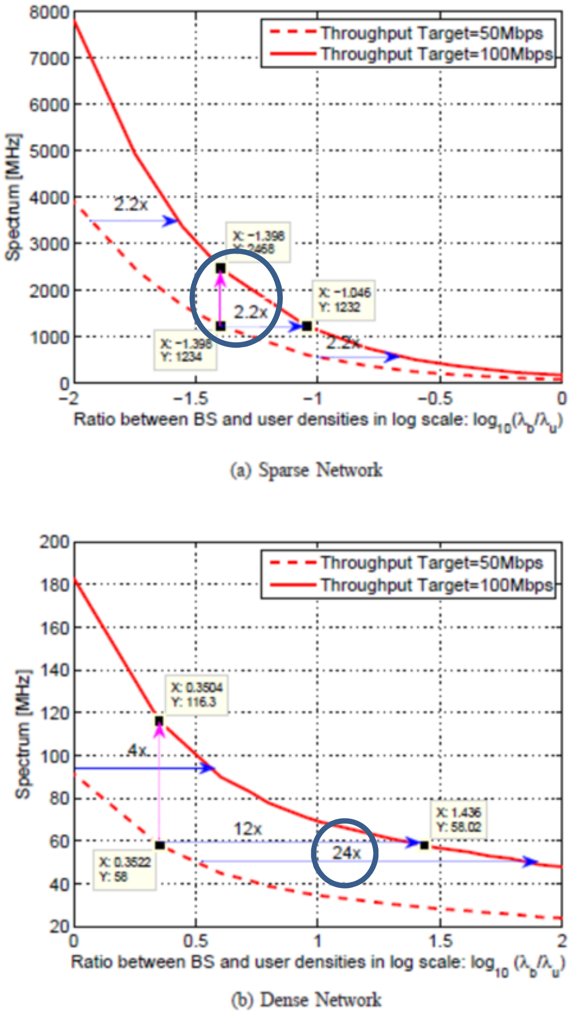

Fig. 5: Tradeoff in sparse and dense network regime.

Figure 1: Trade off in sparse and dense networks[6] (*Figure 5 in the paper by Yang and Sung, 2015*)

The authors conclude:

"User throughput increases almost linearly with the BS density in this [sparse network] regime. On the contrary, further densification is not effective in dense networks. More than 10 to 20 times of BS density is needed to double user throughput when the BS density is already very high. Meanwhile, twice spectrum always guarantees twofold increase in the user throughput for a given BS density. ***Spectrum is shown very effective in dense deployment where acquiring few more spectrum [sic] gives significant reward on user throughput.*** *We also demonstrated the importance of specifying user demand in the dimensioning of wireless networks by showing that different resources are needed in different traffic demand types even with the same area throughput. Spectrum has significant impact in a situation with few users and high individual requirements while densification plays a more important role in flat traffic conditions with many users."*

4. Three's analysis

In this section, we set out the basis for two simulation analyses run by Three on the relationship between site densification and spectrum with regard to:

1. Average User Throughput; and
2. Capacity, i.e. the number of users supported at a minimum user speed.

The analysis is carried out using our internally developed 3GPP compliant 4G simulator. We used the Mobile Broadband Network Limited (MBNL) network in Maidenhead and Slough as our reference network for distribution of data usage during the day and composition of traffic.

- Further detail on the approach to the simulation are provided in Section 4.1
- Validation of Three's simulation approach by comparison to results from academic literature and empirical data from drive test surveys is provided in Section 4.2
- The findings from the two main analyses carried out using Three's simulator model (described above) - the average user throughput analysis and the capacity analysis – are shown in Section 5 and Section 6.

4.1. Approach to the simulation

4.1.1. Maidenhead/Slough network

In order to compare the performance of two networks with different spectrum holdings, analysis was conducted in a section of the MBNL network in the Maidenhead and Slough area, which contains a total of 17 sites. Sites in the Maidenhead and Slough area are representative of a

[6] Note that the analysis conducted by Yang and Sung (2015) used as inputs large amounts spectrum as the analysis was aimed at 5G. This is why the top chart in Figure 1 shows results for high amounts of spectrum.

national network, containing a blend of different clutter types. Moreover, this area lies within the West London simulation area that was used by Ofcom for its technical analysis in its consultations on the combined award of 800MHz and 2.6GHz spectrum.

[✂]**Figure 2: Three UK analysis area using Maidenhead/Slough Network**[7]

4.1.2. Additional sites

In our simulations, user average speeds were calculated using the same set of MBNL sites within the simulation area but with two different sets of spectrum holdings, representing spectrum deployed by Three and BTEE. In order to simulate a network matching BTEE's network performance (with a larger spectrum holding) but with only Three's spectrum holdings, the number of sites in the chosen analysis area was gradually increased to nearly match the performance of the competitor network. New additional sites were placed at optimum locations where the interference is minimised and with increased/optimised antenna tilts although these optimised conditions may not be practically achievable in a real network. Figure 3 below shows examples of how site densification is simulated; shown are network configurations for when the number of sites in the chosen simulation area is densified by two (left) and five times (right) within the analysis area identified in Figure 2 above.

[✂]Figure 3: Three's analysis area in Maidenhead/Slough network (existing sites in red) and new random site locations (sites in blue) showing site densification at two times (left) and five times (right) within the analysis area.

4.1.3. Traffic Modelling

There are two types of traffic models used in this analysis, namely full buffer and bursty traffic models. Full buffer traffic model means that users will continuously download at whatever data rate they can achieve, i.e. there is always data in the buffer. This model can be used to simulate, for example, the downloading of a very large file. However, in a real-world mobile network, data traffic tends to be bursty, i.e. there is some low level of demand for data with sudden increases in different time periods, followed by periods of idle time where the user is reading the content downloaded.

[7] The analysis is concentrated in a sub-area (shown in red) consisting of 3 sites with the surrounding sites assumed to be fully loaded. Numbers in the diagram show the downtilts in each sector to control interference between neighbouring sites.

In order to model a realistic network, Three has developed a bursty mixed traffic model as defined by 3GPP[8] and IEEE[9]. The model focuses on traffic generated through video, web browsing and large file downloads in order to capture average customer usage profiles on Three's network, consisting of ~[✂]% video, ~[✂]% web browsing / messaging and ~[✂]% download of large files, as shown in Figure 4.

[✂]Figure 4: Traffic split in Three UK's network[10] (2015)

Whilst a full buffer model is applied to the small percentage of file download traffic (~[✂]%), the mixed traffic model has considered the characteristics of video streaming and web browsing traffic separately to create the bursty traffic model representing the overall profile of traffic on Three's network. The models used for web browsing and video streaming are described in turn below.

Web browsing

Web browsing was modelled through a web-page download consisting of a main page and embedded objects (e.g. pictures, advertisement etc.). After receiving the main page, the web-browser will parse for the embedded objects. After the web page has been fully transferred from the source, there will be a period where the user spends some time idle, for example reading the webpage before transitioning to another page as shown in Figure 5. During these reading/idle times for one user, another user could be downloading data through the same network.

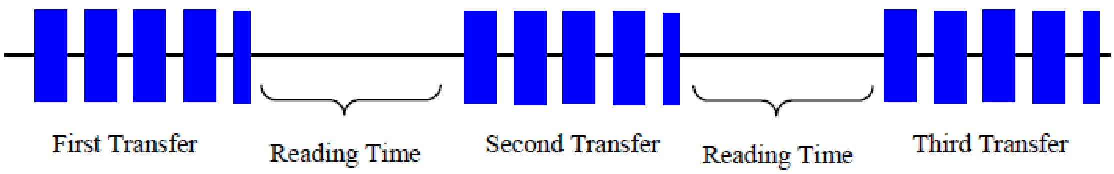

Figure 5: Web browsing modelling

Video streaming

The model used for video streaming traffic is constructed in a similar way.[11]. Each frame of video data arrives at regular intervals determined by the number of frames per second. Each frame is decomposed into a fixed number of slices, each transmitted as a single packet as shown in Figure 6. The size of each packet is a random number. The duration between two packets within one frame is also random. Our simulations assume an encoding speed of 1Mbps.

[8] Orange, China Mobile, KPN, NTT DoCoMo, Sprint, T-Mobile, Vodafone, Telecom Italia; "R1-070674: LTE physical layer framework for performance verification"; www.3gpp.org; 3GPP TSG RAN WG1, meeting 48; St Louis (USA); February 2007

[9] Srinivasan, R. *et al*; "IEEE 802.16m Evaluation Methodology Document (EMD)"; IEEE 802.16m-08/004r2; IEEE 802.16 Broadband Wireless Access Working Group; http://ieee802.org/16; July 2008

[10] [✂]

[11] See L. Plissonneau and E. Biersack. ''A Longitudinal View of HTTP Video Streaming Performance'', In MMSys, 2012

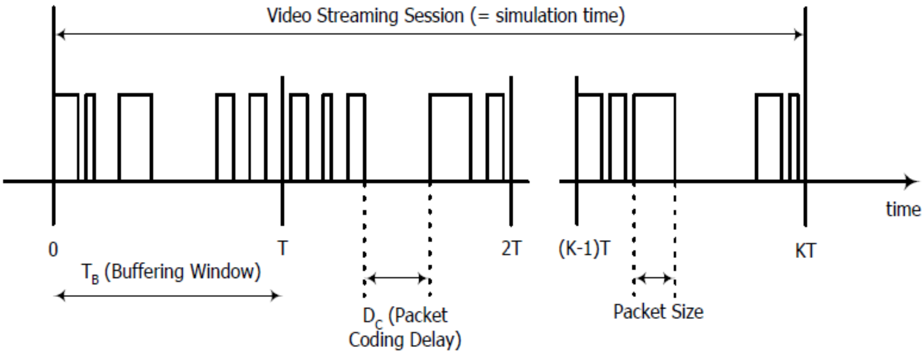

Figure 6: Video streaming modelling

4.1.4 Real and Average busy hour Users

Our simulation model considers the number of users on the network in two ways, namely real users (RUs) and the average number of users in the busy hour, also known as average busy hour users (ABHUs). RUs are the total number of users in a cell (known as eRABs by 3GPP) which consist of both idle and active users, whilst ABHUs are the average number of users who have data in the buffer, i.e. active users only during the busy hour. The number of ABHUs is always less than or equal to the number of RUs. The modelled values for ABHUs depend on the number of RUs, the spectrum bandwidth, traffic type and demand per RU.

4.1.5 Peak and Average Speed

The peak speed that a user is able to achieve is modelled to vary as a function of the operator's spectrum holding. For example, an LTE network with a bandwidth of 2×10MHz cannot deliver more than 75Mbps theoretical maximum user throughput. However, an operator which deploys an LTE network using 2×20MHz bandwidth is capable of offering user throughput of up to 150Mbps, which is double compared to a network with a 2×10MHz bandwidth.

Average user speeds are measured by the data volume that can be delivered during a period of time. The average user speed is modelled to be affected by a set of conditions:

1. the operator's spectrum holdings,
2. the path loss between the site and the user's location,
3. the number of active users sharing a site, and
4. the type and amount of traffic demanded by each user.

4.1.6 Amount of spectrum used in the simulation

All mobile operators in the UK commission P3[12] to perform quarterly benchmarking drive tests. These drive tests measure and record the average user throughputs for Three and BTEE (as well as the other MNOs). During the most recent P3 drive tests of June 2015, Three and BTEE used 2×10MHz and 2×20MHz bandwidth, respectively; in the 1800MHz band (both therefore have the same propagation characteristics). As a result of sharing the MBNL infrastructure, Three and BTEE also have the same site grid. This makes a direct comparison straightforward.

In order to compare results from Three's simulation to the empirical results of P3's drive tests, Three has setup a simulation assuming a spectrum holding of 2×10MHz for Three and 2×20MHz for BTEE on the same set of site locations. Results from this simulation are shown in Section 4.2.2. We note that, whilst this allows for straightforward comparison with the P3 results, the simulation is therefore likely to underestimate the actual speed advantage that BTEE will enjoy over Three's network. This is because BTEE, in reality, has around 2.4 times more spectrum than Three, rather than 2 times.[13]

4.2. Simulation Results: Average User Speed versus Number of Sites

This section presents results of using Three's simulation model for two related pieces of analysis, namely:

- Section 4.2.1 tests the ability of Three's simulation to reproduce the results of the analysis conducted by Yang and Sung (2015)[5],
- Section 4.2.2 shows the results of a similar simulation using the results of P3 drive tests (2015) as a starting point for identifying the speed differential between BTEE and Three's networks

Section 5 goes on to show the results of a more detailed simulation run using Three's modelling of Three's and BTEE's network performance assuming spectrum holdings representative of real spectrum bandwidths available to each operator at present.

4.2.1. Simulation results in comparison to the theory

Three has sought to compare its simulation results to the published results in the paper by Yang and Sung in 2015[51] described in Section 3 above. In Three's simulation analysis, the average user throughput for the simulations of both the Three and BTEE networks is calculated for low

[12] P3 is a global management consultancy which offers worldwide consulting and services for telecommunication industry; http://www.p3-group.com
[13] Three's analysis shown in Section 5 models a network with a spectrum holding of 2×10MHz and a competitor network with a spectrum holding of 2×24MHz, hence representing the ratio of spectrum holdings between Three and BTEE at present.

and high traffic scenarios, similar to Yang and Sung's analysis. Three then increased the number of sites in Three's network to match the profile of user speeds with the speed measured in BTEE's network. In this analysis, the spectrum bandwidth of BTEE was assumed to be double the spectrum bandwidth of Three (which is conservative because in reality BTEE has ~2.4 times more spectrum than Three) and therefore similar to the analysis by Yang and Sung[5].

Table 1 shows the results of Three's simulation for full buffer traffic (i.e. a simulation solely focussing on large file downloads – the same approach used by Yang and Sung).

Traffic volume	**Three (Mbps)** [2×10MHz without new sites]	**BTEE (Mbps)** [2×20MHz]	**Three's required site density to match BTEE speeds** [2×10MHz]
High	[✂]	[✂]	[✂]
Low	[✂]	[✂]	[✂]

Table 1: Resultant site densification required for Three to match BTEE data speeds with full buffer traffic modelling.

The results show [✂-Results of the analysis.] .

4.2.2. P3 Measurement Analysis with Bursty Traffic

The results from the P3 drive test performed in June 2015 are shown in Table 2 for both the Three and BTEE networks. [✂-P3 results.]

Three has used the P3 results to help it to quantify the number of sites required for Three (with 2×10MHz of spectrum) to match the speeds on the BTEE network (with 2×20MHz of spectrum) in the simulation.

In these simulations, mixed bursty traffic was used which represented the traffic mix as measured in Three's network i.e. [✂]% video, [✂]% web browsing / messaging and [✂]% large downloads. A test mobile was then randomly placed, a specified amount of data downloaded, and the user speeds recorded. This was repeated at 500 different locations, each iteration running for 5 seconds. The same traffic mix and number of active users for both the Three and BTEE networks was assumed in the simulations.

The number of sites on Three's network was then increased and the average user speed of the test mobile calculated. The results are shown below in Table 2. [✂-Results of the analysis.]

Three (Mbps) [2×10MHz without new sites]	BTEE (Mbps) [2×20MHz]	Three's site density to match BTEE throughput [2×10MHz]
[✂]	[✂]	[✂]

Table 2: P3 Average user throughput for Three and BTEE from drive tests, June 2015 and Three's simulation results to match BTEE's average user throughput based on P3's measurements.

5. Estimation of required number of sites to match BTEE's user speeds across Three's network

As detailed in Section 4.1.6 above, Section 4.2.1 and 4.2.2 describe the results of simulations modelling two networks: one holding 2×10MHz and a competitor's network holding 2×20MHz of spectrum, both in the 1800MHz band, so as to:

- match the test assumptions of the work by Yang and Sung (2015)[5] in Section 4.2.1, and
- match the spectrum deployed by Three and BTEE for 4G services at the time of the P3 drive tests in Section 4.2.2.

[✂-Results of earlier analysis.] Three has gone on to use its model to simulate network performance using spectrum amounts that reflect the ratio of 1.0 to 2.0. Three then estimated the required number of sites using the spectrum amounts that reflect the actual ratio of 1.0 to 2.4 between Three and BTEE's spectrum holdings.

In these simulations, mixed bursty traffic was used to represent the traffic mix as measured in Three's network i.e. [✂]% video, [✂]% web browsing / messaging and [✂]% large downloads. Three assumed the same traffic mix and number of active users in both the Three and the BTEE networks. A test mobile was randomly placed, a specified amount of data downloaded and the user speed recorded. This was repeated at 500 different locations (250 locations for the heavily loaded network scenario, which was more time consuming to run) with each iteration running for 5 seconds.

In order to define the simulation scenarios, Three studied the distribution of traffic load per site in its network. Three's active user distribution per site varies significantly throughout the network as shown in Figure 7.

[✂]Figure 7: Active busy hour User distribution in Three's network (continuous line) and values used in simulations (marked with *x*'s)

This ABHU distribution in the network is based on a forecast for the end of 2014[14] and represents peak ABHUs per site. The distribution of active user in the busy hour end of 2015 was similar to that shown in Figure 7.

The traffic profile (range of traffic load) in the network also varies during the day, as shown in Figure 8. Three's simulations consider both traffic in the busy hour and at midday, which is ~[✂]% less than the busy hour traffic.

[✂]Figure 8: Daily traffic profile in Three's network, showing the busy hour and the traffic levels at midday used in simulations.

Table 4 below shows the average user speeds experienced in the busy hour in each network for each (randomly selected) simulation point of ABHU (as shown in Figure 8). [✂-Results.] However, Three has also simulated the average user speeds for Three's network using a higher number of sites in order to match the speeds recorded for the simulation of BTEE's network for each simulation point of ABHU (as per Figure 8). Results are also shown in Table 3 below.

ABHU	**Three average user speed (Mpbs)** [2×10MHz without new sites]	**BTEE average user speed (Mpbs)** [2×24MHz]	**Three's site densification to match BTEE speeds**
[✂]	[✂]	[✂]	[✂]
[✂]	[✂]	[✂]	[✂]
[✂]	[✂]	[✂]	[✂]
[✂]	[✂]	[✂]	[✂][15]

Table 3: Site densification required on Three's network in order to match BTEE's throughput for corresponding ABHU simulations

[✂-Results]

By using the MatLab curve matching technique[16], Three has generated a formula to estimate the site densification (i.e. number of sites required in place of each existing site on Three's network) at different ABHUs as follows:

No. of sites = [✂-Formula]

Using the model, Three has developed a relationship between the ABHU and the required number of sites in order to match the benefits of holding 2.4 times the spectrum bandwidth. The cumulative distribution of the number of sites required in the busy hour and at midday were

[14] The forecast is based on 3G traffic in a bandwidth of 2×10MHz.
[15] [✂]
[16] "Data curve matching technique" by MatLab software; http://uk.mathworks.com/discovery/data-fitting.html?refresh=true; MathWorks, Matrix House, Cambridge Business Park, Cambridge, CB4 0HH

plotted over the ABHU and midday active users and are shown in Figure 9.

[✂]

Figure 9: Required sites at the busy hour and midday.

[✂ - Results]

6. Capacity Analysis: Estimation of required number of sites to match the ability of a network with more spectrum to serve 95% of users at or above target speeds

In Section 5, we presented Three's analysis of the impact of larger spectrum holdings upon the average user speeds and the amount of densification needed to match user speeds in BTEE's network. In this section, we describe Three's extension of the analysis to quantify the number of sites needed in order to match the capacity of a network with twice the spectrum bandwidth to ensure that 95% of the users achieve minimum target speeds.

In this analysis, we only simulate video traffic at different encoding speeds of 2, 4 and 8Mbps. Figure 10 illustrates the packet buffering and scheduling mechanisms used in this simulation.

The incoming video data frames arrive in the buffers in eNB at regular intervals. Each frame is decomposed into a fixed number of packets. The size of each packet and the duration between any two packets within one frame are random. The eNB scheduler empties the buffer over the air interface to the corresponding user. The amount of transmitted packets over the air interface for a user depends on the number of ABHU, radio channel quality the amount of spectrum and fairness of the scheduler. If the scheduler transmits data over the air interface to a user faster than the incoming packets, then this user will go to idle mode. This results in resources being available for other users as shown in Figure 11.

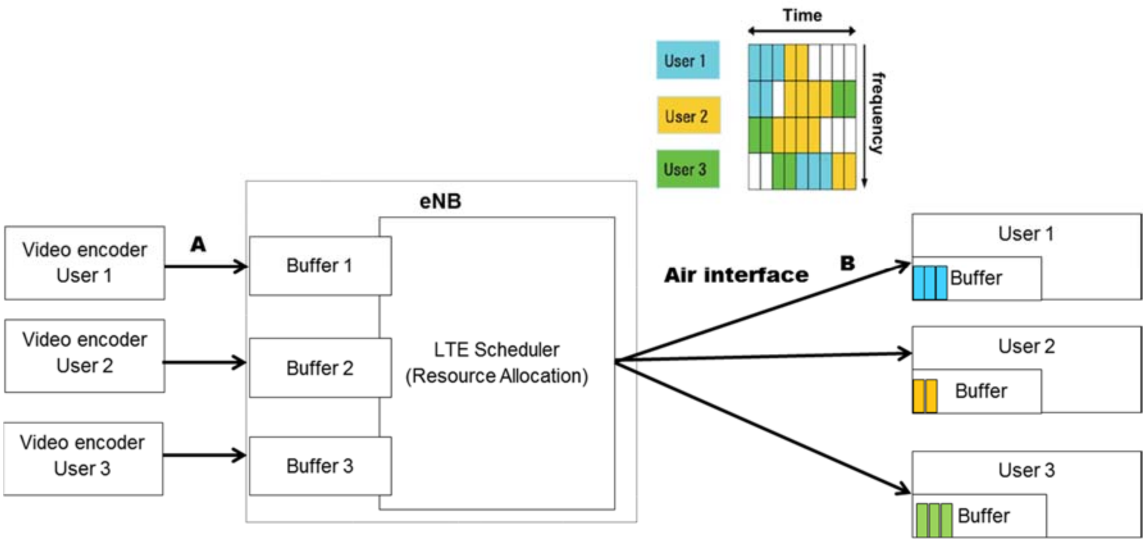

Figure 10: Illustration of packet buffering and scheduling mechanism used when simulating video traffic.

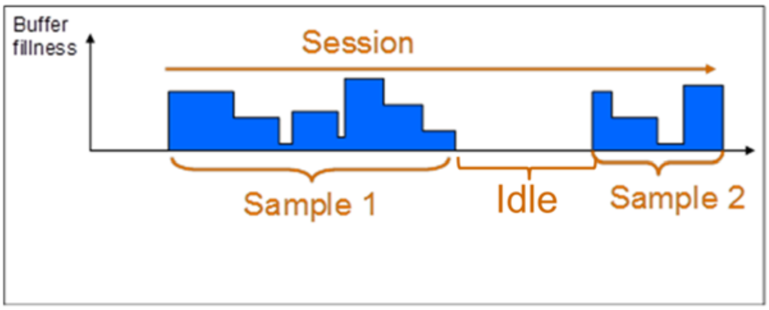

Figure 11: Illustration of traffic session in a buffer.

The offered speed over the air interface for each user, referred to in Figure 10 above, is calculated using the following formula:

$$\text{Offered speed DL} = \sum_{Samples} \text{buffered data} \Big/ \sum_{Samples} \text{active time}$$

The video encoding rates assumed in this analysis are at 2Mbps, 4Mbpsand 8Mbps, which represent HD (high-definition), FHD (full HD) and UHD (ultra HD), respectively. We model a network with a spectrum holding of 2×10MHz and compare to a competitor's network with a spectrum holding of 2×20MHz. The results are the average over 1000 iterations (using a Monte Carlo simulation).

Table 4 shows the maximum total number of users (RUs) for which the network is able to meet the condition of 95% of users achieving target speeds for video content in networks with 2×10MHz and 2×20MHz spectrum bandwidth. The analysis shows [✂-Results.]

Bandwidth	2Mbps	4Mbps	8Mbps
2×10MHz	[✂]	[✂]	[✂]
2×20MHz	[✂]	[✂]	[✂]

Table 4: The number of RUs that can support 2, 4 and 8Mbps in networks with 2×10 and 2×20MHz spectrum bandwidth.

It is important to note that if larger spectrum bandwidths were also analysed, e.g. 2×50MHz instead of 2×10MHz, we would see a proportionally larger maximum number of users in a cell. Table 5 illustrates that the ratio of users served at 2Mbps in a network with 2×10MHz vs. 2×20MHz is the same as the ratio of users in a network with 2×50MHz vs. 2×100MHz spectrum bandwidth.

Bandwidth	No of users achieving 2Mbps (95%)
2×10MHz	[✂]
2×20MHz	[✂]
2×40Mhz	[✂]
2×50MHz	[✂]
2×100MHz	[✂]

Table 5: The number of RUs achieving 2Mbps for networks with different spectrum holdings.

Figure 12 compares the cumulative distribution function (CDF) of the proportion of users achieving different speeds in two networks: MNO **A** holds 2×10MHz whiles MNO **B** has 2×20MHz spectrum, both in the 18000Mhz band. 30 users are simulated in both networks. [✂-Results.]

[✂]Figure 12: The CDF of average speed experienced by users for 2Mbps target user speed.

The same analysis was repeated for 4Mbps and 8Mbps video speeds. Figure 13 show the CDF for the minimum speed of 4Mbps. [✂-Results.]

[✂]Figure 13: The CDF of **average speed experienced by users** for 4Mbps target user speed.

As a summary, the number of sites required to match the capacity for different user speed targets are shown in Table 6 for different video speeds. [✂-Results.]

Video speed	2Mbps	4Mbps	8Mbps
Site densification required	[✂]	[✂]	[✂]

Table 6 - Video speed versus level of site densification required to match speeds for 95% of users.

7. Independent Analysis on site versus spectrum

Three commissioned three companies, Qualcomm, Real Wireless and Samsung, to each undertake an independent investigation on the replicability of the benefits offered by additional spectrum with additional sites. We summarise the findings from each of the investigations below, with the full reports from Qualcomm and Real wireless provided in Annexes 8 and 6 respectively. A Samsung presentation is also appended to this annex.

7.1. Summary of findings from Qualcomm

Qualcomm conducted an independent study modelling Three and a competitor which holds double the amount of spectrum compared to Three. Qualcomm performed LTE simulations using its QUEST simulator based on an existing macro network cluster of 7 sites located in proximity to Three's head office in Maidenhead. The competitor was modelled to hold 2×20MHz whilst Three held 2×10MHz of spectrum in the 1800MHz band. The main objective of this study was to verify Three's simulation results under a variety of site loading scenarios[17].

Qualcomm's analysis concluded the following:

[✂-Qualcomm's conclusions.]

These results are fully in line with Three's analysis presented in Section 5.

The full report for Qualcomm's investigation is provided in Annex 8.

7.2. Summary of findings from Real Wireless

Real Wireless's independent investigation used a different approach to that followed by Three and Qualcomm. Real Wireless compared the user experience for two different spectrum holdings and quantified the site densification required to match throughputs in the top 50% most densely populated areas in the UK, hence representing a mainly urban environment.

In order to simulate an 1800MHz mobile network in a densely populated area, Real Wireless used traffic measurements per site from Three's live network in Maidenhead. Real Wireless compared the user throughput curves of two networks with different bandwidths, specifically:

- 2×15MHz bandwidth deployed in the 1800MHz band for LTE services
- 2×30MHz bandwidth deployed in the 1800MHz band for LTE services
- both networks were modelled to be deployed across [✂] sites, which corresponds to the number of sites on Three's network serving approximately 50% of the UK population
- population served through each site and traffic demand at each site were modelled based on data from these [✂] sites.

The network with 2×15MHz bandwidth is then densified until its user throughput curve matches, as closely as possible, the user throughput curve of the network with 2×30MHz.

The figure below (Figure 11 in the report from Real Wireless, included in Annex 6) shows the benefits of larger spectrum holding vs. site densification for a new user entering each cell in a network with either 2×15MHz or 2×30MHz of spectrum. In order to compare the throughput that can be experienced by a new user entering a given cell in either of the two networks, both networks have the same number of sites initially. The number of sites in the network with the smaller spectrum holding is then increased (or densified) in increments. In each case, the

[17] Three site loadings were modelled assuming average video users per cell of 1, 5 and 24 for low, medium and high loading scenarios.

cumulative distribution function of the new user throughput is plotted. In this way, the level of densification where the network with the smaller spectrum holding can match the new user experience in the network with the larger spectrum holding can be determined, if a match is possible.

[✂]

[✂-RW's conclusions.]

The full report for Real Wireless's investigation is provided in Annex 6.

7.3. Summary of findings from Samsung

Samsung conducted an independent study, modelling traffic for all four UK MNOs based on real network measurements from Three's network[18]. Each MNO was modelled to utilise its actual and projected spectrum deployments[19][✂][20] Samsung's study consisted of three workstreams, which we summarise along with the key findings below.

In the first part of the study, Samsung calculated the number of simultaneous users receiving video content (defined as the video user capacity)[21] without stalling of playback[22] for all four MNOs, and repeated for three different qualities of video (HD, full HD and ultra HD). Findings from this work are shown in Figure 14 for the 2016 simulation. [✂-Samsung's results] Samsung further modelled the impact of increased spectrum bandwidth for each MNO in 2018 and 2021. [✂-Samsung's results] These findings are very similar to the results from Three's capacity analysis presented in Table 5 in Section 6.

[✂]Figure 14: The number of users making a 4min uninterrupted video call assuming different spectrum holdings for each MNO (2016).

In the second part of the study, Samsung calculated the amount of spectrum bandwidth that Three requires in order to match EE's quality of experience (QoE, defined as the perceived download speed of a large single file) across the busiest 20% of the modelled [✂]sites (i.e.

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[18] Data was collected from Three's current offering of 4G services through its 1800MHz spectrum across [✂] sites nationwide.
[19][✂]
[20][✂]
[21] Modelled through a 4min video call, with a 15min inter-arrival time, at a rate of 2.3Mbps for HD, 4Mbps for full HD and 8Mbps for ultra HD. The data rates are similar to those used by Three in its simulation, with the only difference being that Three used a rate of 2Mbps for HD.
[22] This is a slightly different approach to Three's own simulation, which assessed the number of simultaneous users that could receive a video service with 95% confidence but, unlike Samsung's simulation, did not take into account buffering of the video stream. The net effect of these differences in approach is not likely to be large.

[✂]sites). This was repeated for all three model years and findings are summarised in Table 7 below. [✂-Samsung's results]

Year	2016	2018	2021
EE's QoE (download speed)	[✂]	[✂]	[✂]
EE's spectrum bandwidth	[✂][23]	[✂][23]	[✂][23][✂]
Three's required spectrum bandwidth	[✂]	[✂]	[✂]

Table 7 – Three's required spectrum bandwidth in order to match EE's data speeds considering current and future traffic levels.

In the third part of the study, Samsung investigated how Three's spectrum requirements would change if Three also deployed additional sites in the locations served by the 20% of sites currently carrying the most traffic. The results of this work are shown in Figure 15. [✂-Samsung's results]

[✂]Figure 15: Three's required spectrum holdings to match EE's data speeds when Three deploys additional macros sites[24]

In summary, Samsung's findings are in line with results from Three's simulations and the findings from Qualcomm and Real Wireless.

The full presentation of Samsung's investigation is appended to this annex.

8. Conclusion

Three has carried out extensive analysis to compare the data speeds that can be achieved on its network during the busy hour and at midday with a given spectrum holding, and calculated the number of sites required to nearly match the user speeds experienced in a network with a larger spectrum bandwidth. Three's analysis of average user throughputs assumed matching of data speeds to a competitor's network with 2.4 times the spectrum bandwidth (i.e. representative of

23 [✂]

24 [✂]

BTEE’s spectrum holdings relative to Three’s). Three’s capacity analysis assumed matching of data speeds to a competitor’s network with twice the spectrum bandwidth.

Three concludes that:

i. [✂-Summary of all results and conclusions.]