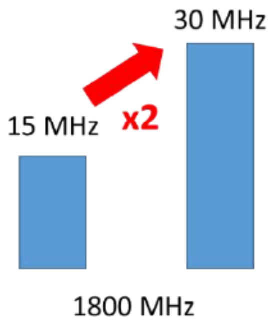
Site density vs spectrum investigation

Final report from Real Wireless



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independent wireless experts

About Real Wireless

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

Introduction and the objective

This report presents the outcome of an independent study conducted by Real Wireless on behalf of Three. It compares the user experience for two different spectrum holdings and also how user experience changes with site densification. The principal question we seek to answer in this project is: "Can the offered user experience of a mobile operator with a large amount of spectrum be matched by an operator with less spectrum by increasing the site density?"

In recent years, demand for mobile broadband service has risen dramatically, fuelled by devices providing increasingly convenient Internet access. This increase in demand comes with significant capacity challenges for mobile network operators (MNOs) to continue to offer a user experience that is acceptable to their subscribers. There are three principal elements available to an operator to increase the capacity of their network:
Spectrum, where the total bandwidth as well as the frequency bands and arrangement of those bands affect the capacity available;
Technology, where modulation schemes, antenna processing systems and interference mitigation techniques all can enhance the available spectrum efficiency per cell. However, the technology upgrade depends on availability and maturity of the technology in the market place and the cost. Therefore, the available capacity gain from the technology is limited for a given period.
Network topology, where the density, location and arrangement of cells all affect the density with which spectrum can be reused in a given area. Changing the network topology to increase the site count mainly refers to site densification.

Currently there is a considerable imbalance in mobile spectrum holdings among the UK MNOs. Operators with a smaller spectrum holding argue [1,2] that this significantly constrains the levels of services that can be offered to their subscribers.

In this study we explore if site densification can compensate for the lack of spectrum for a given technology.

Our approach

We answer this question based on:

1. qualitative analysis of the principal question by comparing the benefits, challenges, complexities and practical aspects. It compares the user experience enhancement based on additional spectrum vs. site densification. We provide our independent opinion on these issues based on the evidence from a literature review.
2. quantitative assessment of the principal question using a simulation methodology. We simulate a mobile network in a densely populated area i.e. area where 0-50% of the UK population lives, for an LTE network using 1800 MHz spectrum. We compare the user throughput curves of:

   - 15 MHz of LTE deployed in 1800 MHz spectrum band with 7000 sites.
   - 30 MHz of LTE deployed in 1800 MHz spectrum band with 7000 sites Outcomes.
   - Densification of the 15 MHz of 1800 MHz spectrum scenario until the user throughput curve matches the user throughput of the network with 30 MHz.

From our qualitative analysis, which examines evidence from published papers, concludes that it would not be feasible through network densification for an operator with substantially less spectrum to match the user experience of an operator with a larger spectrum allocation, even in theory. It is also evident that, even if network densification was able to provide the necessary improvement, to implement such a change to the network in a timely and cost effective manner entails significant commercial challenges that are likely to be detrimental to the competitiveness of the business.

The outcome of the quantitative assessment demonstrates that even if the site count is increased by 4 times, the user performance of a 15 MHz network operating at 1800MHz cannot be matched with the user performance of a 30 MHz network (also at 1800MHz).

We also see that the benefits of densification decrease gradually as the densification factor increases. For instance, site densification by a factor of 1.4 times results in user throughputs increasing by a factor of 1.5. However, 2.6 times more sites increase new user throughputs only by a factor of 1.9 times.

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1. Introduction

1.1 Scope of the study

Real Wireless were engaged by Three to carry out an independent study that compares the user experience for two different spectrum holdings and how the user experience changes with site densification.
The principal question we seek to answer from this project is:

Principal question
Can the user experience of a mobile operator with a large amount of spectrum be matched by an operator with less spectrum by increasing the site density?

1.2 Background

In recent years, demand for mobile broadband service has risen dramatically, fuelled by devices providing increasingly convenient internet access. This increase in demand comes with significant challenges for mobile operators to continue to offer a user experience acceptable by their subscribers. Operators are generally looking for cost-effective and flexible capacity solutions to allow their investment to be focused on the locations with the greatest need.
The three main elements available to increase the capacity for mobile operators are:
Spectrum, where the total bandwidth as well as the frequency bands and arrangement of those bands affect the capacity available;
Technology, where modulation schemes, antenna processing systems and interference mitigation technique all affect the available spectrum efficiency per cell;
Network topology, where the density, location and arrangement of cells all affect the density with which spectrum can be reused in a given area.

In this study we explore if site densification can compensate for the lack of spectrum if the same technology is available to both networks.

1.3 Our approach

We answer this question based on:

1. qualitative analysis of the principal question by comparing the benefits, challenges, complexities and practical aspects. It compares the user experience enhancement based on additional spectrum vs. site densification. We provide our independent opinion on these issues based on the evidence from a literature survey
2. quantitative assessment of the principal question using a simulation methodology. We simulate a mobile network in a densely populated area i.e. area where 0-50% of the UK population lives, for an LTE network using 1800 MHz spectrum. We compare the user throughput curves of:

    - 15 MHz of LTE deployed in 1800 MHz spectrum band with 7000 sites
    - 30 MHz of LTE deployed in 1800 MHz spectrum band with 7000 sites

- Densification of the 15 MHz of 1800 MHz spectrum scenario until the user throughput curves matches the user throughput of the network with 30 MHz.

1.4 Report Structure

Our report is organised as follows:

1. In Chapter 1 we introduce the study objectives and the background including the situation with mobile spectrum in the UK.
2. Chapter 2 provides a qualitative analysis of the principal question by comparing the challenges and complexities in providing capacity using site densification vs. additional spectrum. We provide our independent opinion on these issues based on the evidence from a literature survey.
3. Chapter 3 provides details about the quantitative assessment. It explains the simulation approach we have used together with assumptions, results and our interpretation of the findings.
4. Conclusions and suggestions for further work are presented in chapter 4.
5. Chapter 6 (Annex A) explains the capacity options available to operators based on spectrum, technology and network topology point of view.
6. Chapter 7 (Annex B) provides additional details of the literature search presented in the section 2 and practical aspects.
7. Chapter 8 (Annex C) provides an assessment of different methods that may be used to compare spectrum addition vs. site densification as a capacity solution. Based on this comparison we choose the methodology for our analysis.

2. Qualitative analysis: literature search for spectrum increase vs. site densification

Within this section we will consider the published documents that analyse the merits of spectrum versus site densification and whether operators with less spectrum can achieve the same levels of performance and user experience as those with greater spectrum resources. These are outlined below and will be covered in more depth in subsequent sections:

- Peak speed – ability to offer the highest peak speeds.
- Average user throughput – ability to deliver a reasonable level of data throughput per customer.

More details of these points and the practical aspects related to the ability, cost and timeliness of delivering network densification versus additional spectrum are available in 7 (in the Annex).

2.1.1 Peak Speeds

Larger spectrum allocations not only bring capacity benefits but they also enable higher average peak speeds to be achieved. For instance, carrier aggregation available in LTE-Advanced1 not only offers higher peak speeds but also an improved overall broadband experience within the coverage area because the benefits can be enjoyed across the entire cell. With carrier aggregation the data rates scale depending on the volume of spectrum that an operator has available.

The availability of high peak and average user speeds can bring significant marketing benefits to an operator. As shown in Table 1, within the UK market there is a considerable imbalance in the spectrum available to each operator. This significantly constrains the levels of carrier aggregation and hence speeds that some operators can offer. Table 1 below shows that only EE/BT can offer the highest levels of carrier aggregation with current frequency division duplex (FDD) spectrum allocations.

Carrier Aggregation	Peak Speed (Downlink)	UK Operator
10+5 (2x10MHz @ 800 + 2x5MHz @ 1800)	**110 Mbit/s**	O_2
15+5 (2x15MHz @ 1800 + 2x5MHz @ 800)	**150 Mbit/s**	3

[1] Carriers can be in the same band, or in different bands, or a combination of the two. Latest developments allow time division duplex (TDD) and FDD carriers to be aggregated.

Carrier Aggregation	Peak Speed (Downlink)	UK Operator
10+5+20 (2x10MHz @ 800 + 2x5MHz @ 1800 + 2x20MHz @2600)	260 Mbit/s	vodafone
20+20+20 (2x20MHz @ 1800 + 2x20MHz @ 2600 + 2x20MHz @2600)	450 Mbit/s	EE BT
In Future 20+20+20+20+20 (2x20MHz @ 1800 + 2x20MHz @ 2600 + 2x20MHz @ 2600 + 2x20MHz @ 2600 + 2x20MHz @2600)	750 Mbit/s	EE BT

Notes:

- *Assumes each operator retains at least 2x15MHz for UMTS and 2x12.5MHz for GSM (not '3').*
- *EE's allocation of 2x5MHz @800 is ignored.*
- *Only considers FDD spectrum, EE/BT and Vodafone also each have 25MHz of LTE 2600MHz TDD spectrum.*

Table 1: Maximum FDD Carrier Aggregation Combinations & Peak Speeds Available to UK Operators with Current Spectrum Allocations.

Heterogeneous LTE-Advanced Network Expansion for 1000x Capacity, Liang Hu et al, Aalborg University, DOCOMO, Nokia Siemens Networks - Vehicular Technology Conference (VTC) Spring 2013 [3]

The paper says, *"In terms of spectrum requirements, we have increased the total amount of spectrum to 300 MHz by re-farming and adding new spectrum in 3.5 GHz band. We conclude that a new spectrum of up to 200 MHz at 3.5 GHz is essential to reach the set target network capacity and performance."*

In drawing conclusions from this paper, it can be summarised that [redacted]

Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030. Produced by Real Wireless on behalf of Ofcom, April 2012 [32]

The report says *"In the urban area, Figure 1-36 indicates that the quantity of spectrum available plays a strong role in determining the number of both macrocells and small cells deployed. A spectrum 'crunch' starts to occur around 2018 with the low spectrum scenario and the number of macrocells starts to increase rapidly"*. It also says that *"The impact the low spectrum scenario has on cost in Figure 1-37 is striking compared to the mid and high cases. The requirement for both additional macrocells and small cells as well as other sites upgrades means a steep increase in network costs between 2019 and 2025 to relieve the* *capacity crunch"*. [redacted]

2.1.2 Average User Throughput

Tradeoff Between Spectrum and Densification for Achieving Target User Throughput, Yanpeng Yang and Ki Won Sung, VTC Spring 2015 [4]

This paper says *"... 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"*. [redacted]

Case Study: Reduction of spectrum holdings and its impact on the number of 2G cell sites [5] – and Part 2 [6]. Prepared for Ofcom by Red-M, July and August 2008

In 2008 Ofcom was considering recovering some 900MHz spectrum from UK operators Vodafone and O2 and re-allocating it for UMTS900. The simulated design exercise (carried out by Red-M) was repeated five times for each scenario with reducing amounts of spectrum. Starting with a baseline, with 14.2MHz of spectrum in London and 17.2MHz of spectrum in Burton, spectrum was removed in 2.5MHz blocks. Blocks of 2.5MHz, 5MHz, 7.5MHz and 10MHz of spectrum were removed and the network was re-designed to meet defined grade of service and coverage quality objectives. The results of this exercise for the first two areas is summarised in Table 2.

The results show that in the London scenario, the cells were predominantly capacity limited and any reduction in spectrum required significant volumes of additional sites to achieve the required capacity. The report says that "*... removal of 7.5MHz and 10MHz of spectrum require increasingly-large numbers of new sites, and a completely new frequency plan*". For the case where 10MHz was removed it was not possible to achieve the grade of service requirements with the existing grid of base station locations, and a completely new 'simulated regular grid' had to be applied. Further, even considering the substantial increase in the number of sites (330%) there is still a notable difference in the Grade of Service which can be offered. This indicates that the addition of the sites has not been able to fully compensate for the reduction in spectrum in terms of Grade of Service.

Simulation Results	Site Count Summary		
	Sites	Transceivers	Sites %
Burton Baseline	32	197	100%
Burton -2.5MHz	32	200	100%
Burton - 5MHz	32	205	100%
Burton - 7.5MHz	33	211	103%
Burton - 10MHz	37	216	116%
London Baseline	70	742	100%
London - 2.5MHz	83	791	119%
London - 5MHz	98	872	140%
London - 7.5MHz	156	1016	223%
London - 10MHz	231	1172	330%

Table 2: Results of GSM900 Spectrum Removal Planning Simulation for Burton and London 9 *(Source: Red-M Study - Reference [5]).*

Although this analysis relates to GSM and not MBB technologies like LTE, it does nevertheless provide some useful conclusions. [redacted]

<u>Conclusions from These Studies</u>

[redacted]

For further details see Annex B.

3. Quantitative assessment: spectrum increase vs. site densification analysis

In this section we provide details of the simulation methodology we adopted in this study to address the principal question.

In section 8 we provide an assessment of different methods that may be used to compare spectrum addition vs. site densification as a capacity solution. We then compare these methods by identifying strengths and weaknesses and propose a methodology, known as "optimised macrocell" method, for our analysis.

The optimised macrocell method implements a simple scheduler to give "fairness" to multiple concurrent users and at a high level provides the ability to perform multi-user throughput analysis of a capacity constrained network over a large geographic area. This simulation method has the additional merit of not requiring lengthy simulation times, providing the evaluation of the effects under study within a reasonable simulation run-time. For these reasons, we adopted the optimised macrocell model. Details of this modelling approach is explained in the following sub sections.

3.1 Description of the modelling methodology

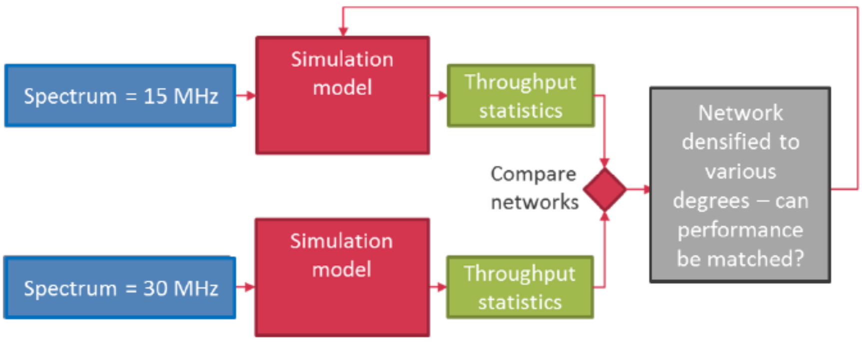

Figure 1: Modelling approach

The flow chart in Figure 1 shows the high level modelling approach taken in this study. Here we model the expected user throughput for a network with 15MHz of spectrum and then one with 30MHz of spectrum. Both networks have the same number of sites initially. We then increase the number of sites in (or densify) the network with the 15 MHz spectrum. In each case we plot the cumulative distribution function of the expected new user throughput for each site and spectrum portfolio to see if there is a level of densification where the network with 15 MHz spectrum can match the throughput of the network with the larger spectrum portfolio.

3.2 Modelling assumptions

3.2.1 Base station and user equipment configuration assumed

Our baseline simulation settings used to calculate the downlink signal strength from each site and noise at the receiver are shown in Table 3.

Parameter	Value	Notes
Maximum effective isotropic radiated power (EIRP) per 180 kHz LTE resource block	47 dBm	[40]
Antenna horizontal 3 dB beam-width	65 degrees	[7]
Antenna vertical 3 dB beam-width	7.5 degrees	[40]
Antenna down-tilt	Optimised for average distance to nearest neighbouring sites	
Antenna patterns	Based on theoretical equations	[8]
Site locations and heights	Taken from Three data	
UE antenna gain (mean effective gain)	0.0 dBi	[40]
UE antenna height	1.5m	[40]
Body loss (relative to free space)	5.0 dB	[40]
Receiver noise figure	10 dB	[40]
Location variability (outdoor)	Varies dependent on frequency and clutter	
Location variability (outdoor) cross-correlation coefficient	1.0 (inter-sector) 0.5 (inter-site)	[40]
Building penetration loss cross-correlation coefficient	1.0 (inter-sector) 0.5 (inter-site)	[40]
Propagation path loss model	Extended Hata	[9]
SINR cut-off (or $SINR_{min}$)	-5 dB	[10]

Table 3: Simulation parameters

3.2.2 Other parameters

- **Simulation area:** We have undertaken our analysis in areas where the 0-50% of the population lives. This will be predominantly urban areas, comprised of the most densely populated local authority districts in England, Scotland and Wales where 50% of the population live. Figure 2 shows the simulation area.

Figure 2: Simulation area i.e. area where 0-50% of the population lives

- **Bandwidth:** In line with the coverage results in the Ofcom publication [11], we used the bandwidth of 10 MHz for the single user case for the base line scenario. For the multi-user case, we carried out the simulations for a network deployed with the bandwidth of 15 MHz and 30 MHz. This is because the Three network provided the network statistics i.e. PRB utilisation, enhanced radio access bearers (eRABs) etc. from the 15 MHz LTE network deployed in the UK. Note that the LTE network with the bandwidth of 30 MHz can be deployed with 20 MHz + 10 MHz carrier aggregation.
- **Physical resource block utilisation**: PRB utilisation shows the fraction of the total number of resource blocks utilised for both data and overheads. We used actual PRB utilisation (in the down link direction) data taken from Three's network during the busiest hour of the day and 12 noon (midday). Figure 3 shows the average PRB utilisation distribution in 0-50% area during the midday hour.

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Figure 3: PRB utilisation distribution of LTE cells in Three network during the midday hour.

- **Site configurations:** We used Three's site locations and site heights during this work. [redacted]

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Figure 4: Site configurations of the Three network in an example area (Southwark, London)

- **Number of samples:** We sample the SINR from 10,000 user locations within the area where 0-50% of the population lives.
- **User distribution:** We combine the throughput estimates with the following proportions:
    - 40% users are outdoor
    - 30% users in shallow indoor
    - 30% users in deep indoor

  Building penetration loss (mean and standard deviation) varies according to the user location.
  Users in no coverage, i.e. SINR less than -5dB, are not considered in this study,
- **Traffic load:** We derived the number of users per cell from the network data provided by Three based on the measurements from their current network statistics.

3.3 Simulation methodology

3.3.1 Modelling user throughputs

Our simulation model for generating user throughput statistics for each network configuration consists of the following steps:

1. Step 1: single user performance calculation
2. Step 2: multi-user throughput calculation

Note that the single user performance calculation is based on the methodology used by Ofcom in [11]. We used the site locations from Three network to replace the synthetic base stations network used in [11]. The multi-user implementation is an enhancement to the simulation method to calculate the single user performance.

Step 1: single user performance calculation
As the first step, we calculate the single user throughput and spectrum efficiency of a user location as follows. For each user location:

1. Select the user location randomly within 0-50% area
2. Calculate SINR using PRB utilisation data (described in more detail later)
3. Calculate Single User Throughput (SUTP) and Spectral Efficiency (SE) for that user (described in more detail later)
4. Save SUTP and SE
5. Calculate the user throughput for each location
6. Repeat steps 1 to 5, 10,000 times.

As shown in Figure 5 the user location (hence the SINR) changes in each simulation run.

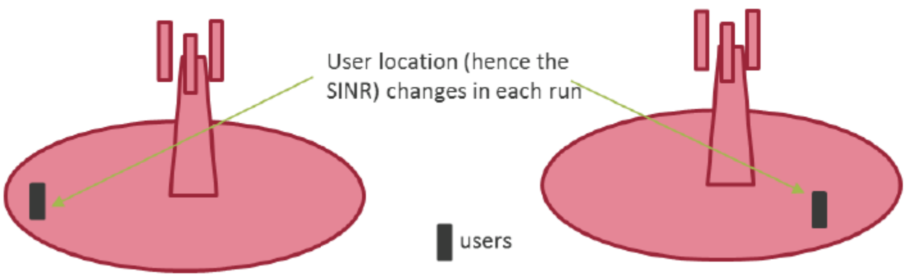

Figure 5: SINR calculation for a single user

Step 2: multi-user throughput calculation

Step 1 gives the probability distribution function (PDF) of the user SINRs and hence spectrum efficiency across the network. With a knowledge of the number of active users per site, PRB utilisation per site and this PDF of spectrum efficiency across users modelled, we can interpret what the SEs of a given drop of users in a given cell would be and use a proportional fair scheduler to translate these SEs to user throughputs in step 2.

Within step 2, for each site, we calculate the throughput of the users within the site by applying a proportional fair scheduling rule as follows:

1. Interrogate the site database to find the number of users in a selected cell. Number of users are derived from average number of simultaneous enhanced radio access bearers (E-RABs) per cell data obtained from Three (described in more detail later). The number of E-RABs is converted to the number of users using a constant activity factor, derived from the network statistics taken from [redacted] LTE sites that uses 15 MHz of spectrum within 0-50% area. The model uses an activity factor of 0.0416 (this is explained later)

   The simulation requires integer numbers of users per cell. The number of users are converted to integer values by calculating a cumulative sum of all the user count values, rounding this result and then using the difference between each point. This achieves the required rounding but does not alter the total number of users in the system.

   We use the spectrum efficiency (SE) values for the locations we have calculated. SE values for the remaining users within the cell are picked from the SE PDF curve of the network. This process is illustrated in Figure 6. The simulation uses a minimum and maximum SINR. A user below the minimum SINR will be denied service. The spectral efficiency of a user is limited by the maximum SINR set in the simulation. i.e. beyond this maximum SINR the system is limited by bandwidth rather than signal quality or modulation and coding scheme.

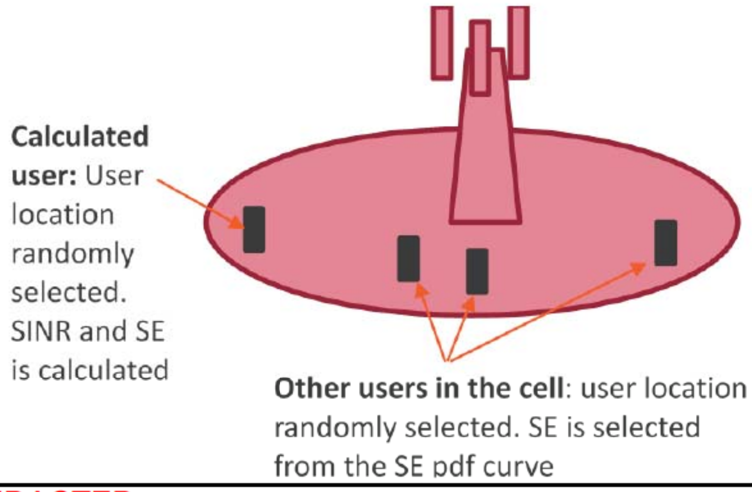

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Figure 6: calculation of SE for users in the cell

2. Calculate the weighing factor for the scheduler from the SE values (more details in the scheduler implementation section)
3. Calculate the PRBs assigned to users of this site. Fractional PRBs are permitted as in practice resource allocation is shared in both time and frequency. E.g. A user with 2.5 PRBs may be allocated 5 PRBs every other subframe (1ms).
4. Calculate throughput for the users of this site. The throughput is calculated by multiplying the number of resource blocks by 180kHz and the calculated spectral efficiency.

SINR generation:
The SINR at the user equipment (UE) location is calculated according to the following equation:

$$SINR = P_{\text{wanted}} / (P_{\text{other}} + P_{\text{noise}})$$

Where:

- The wanted power, Pwanted, at the UE location is the calculated power received per resource block from the serving sector
- The other power, Pother, is the total other cell interference power received during the same time period and at the same frequency as Pwanted

- The noise power, Pnoise, is the noise power at the UE given by kTB, multiplied by the noise figure where k is Boltzmann's constant, T is the temperature (290 K) and B the bandwidth (i.e. 180 kHz for one resource block)

The flow diagram for SINR calculation in each user location is shown in Figure 7. The steps in Figure 7 are repeated for each UE location (10,000 sample locations) within the simulation area (i.e. area where 0-50% of the population lives) to build up an SINR distribution for a given network size and spectrum portfolio.

An overview of the steps involved in each simulation run to generate the network's SINR distribution and in turn user throughput distribution is (shown in Figure 7) as follows:

- Establish a set of 10,000 sample locations within the sample area. These are taken from a random sample of postcode database within the simulation area.
- Using simple geometry, calculate the median outdoor path loss at each sample location from each of the three sectors of the 20 closest surrounding base stations (19 surrounding sites + 1 service site) using the Extended Hata [13] propagation model accounting for horizontal and vertical base station antenna patterns, antenna heights and the clutter at the sample location.
- Calculate the median BPL for the particular in-building depth under consideration (the median BPL at the sample location is assumed to be the same for transmissions from all surrounding base stations)
- For each sample location, generate a set of shadow fading values for each of the 20 closest surrounding base stations (assuming 50% shadow fading correlation). Shadow fading is assumed to have a log normal distribution with a zero mean and characteristic standard deviation σ.
- Combine the median BPL and median outdoor path loss figures together with the shadow fading and BPL variability figures to derive an overall path loss to each sample location from each of the three sectors of the 20 closest surrounding base stations.
- From the above, find the sector that provides the greatest received power at the sample location and designate this as the serving sector.
- The SINR at the sample location for a single resource block is calculated from the wanted power of the serving sector, the interference power from every other sector of the 19 closest surrounding base stations and the UE receiver noise. This calculation assumes that the resource blocks from the serving sector transmit at 47 dBm EIRP per resource block (i.e. the maximum allowed by our proposed technical licence conditions). Interference power from non-serving sectors is taken into account by weighting the calculated interference power by the probability that the interference is received during the same time period and at the same frequency as the wanted power from the serving sector.

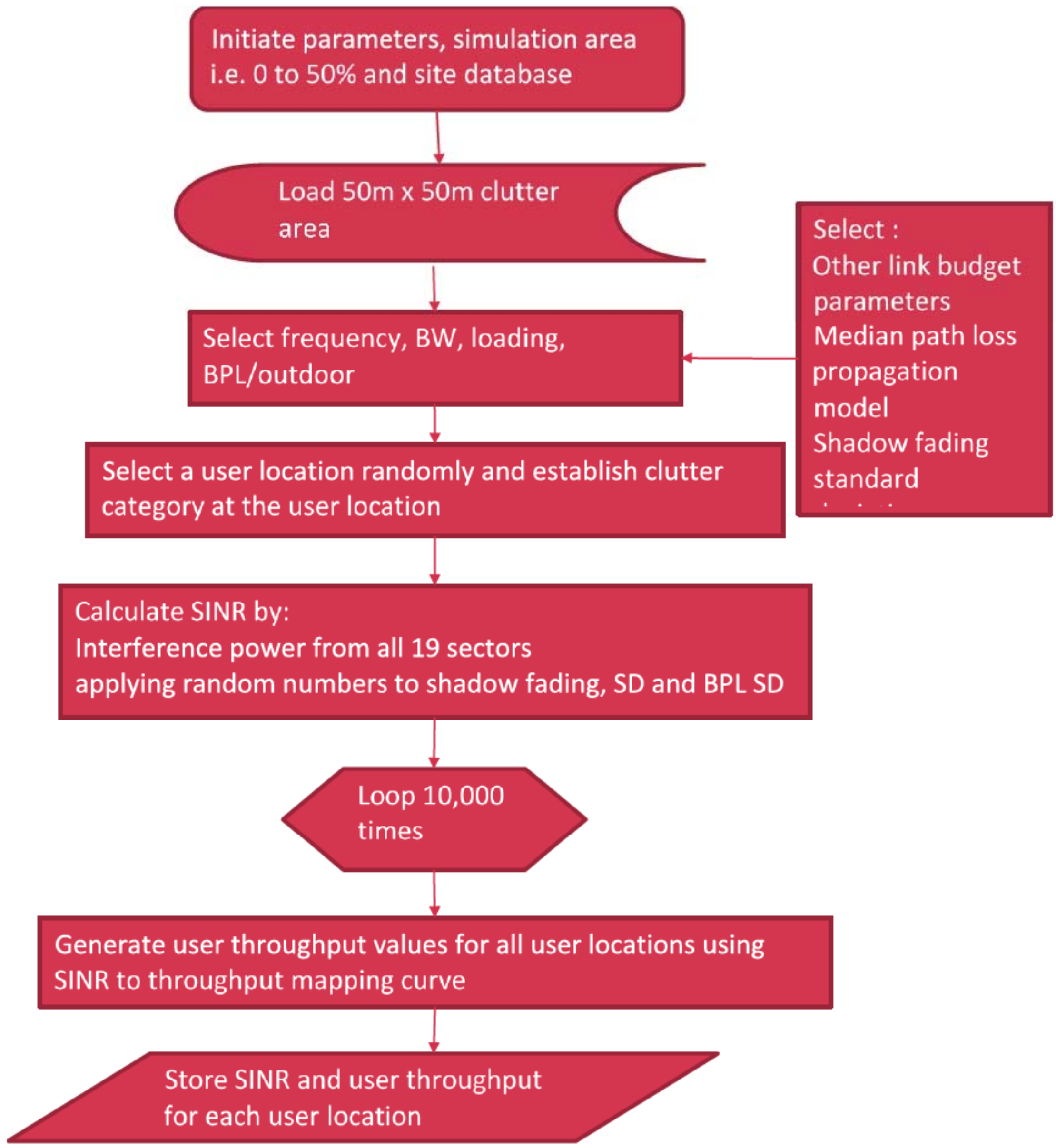

Figure 7: Steps used to generate SINR distribution of each network

A series of different SINR distributions are generated covering each particular base station network size and bandwidth. Figure 8 shows the comparison of user SINR values for [redacted] and [redacted] sites site densities for the network. This shows that the higher site count has about [redacted] increase in SINR at 60%. Note that when densifying the network our simulation model re-optimises the antenna down tilt settings and from Figure 8 it appears that optimisation works well to mitigate any additional interference due to the increased site number for these site densities and inter-site distances at least. Also the measured PRB utilisation is relatively low for some sites and so overlap between PRBs of neighbouring cells can be avoided via smart scheduling. Hence interference is kept controlled but the wanted signal improves across the cell due to the shorter ISD (hence the user is clear to the base station) at these loading levels.

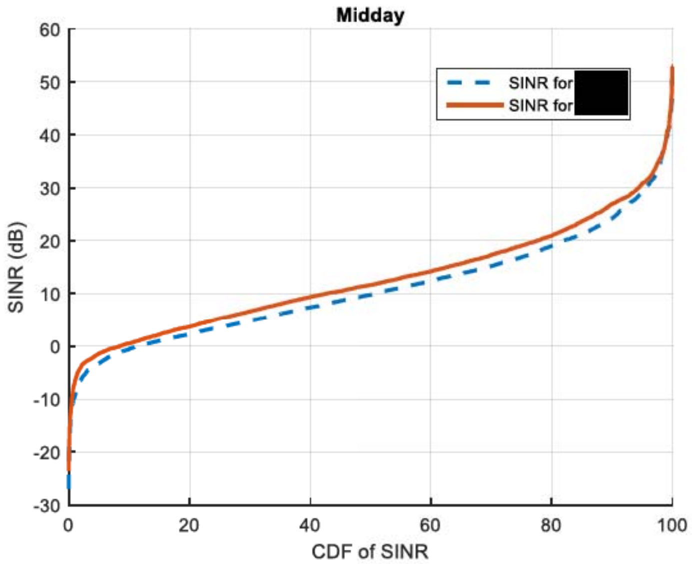

Figure 8: User SINR values versus traffic load

Spectrum efficiency calculation:

The spectrum efficiency (in bps/Hz) calculation function per sample location is expressed as follows:

$$Spectrum\ efficiency = \begin{cases} 0, & for\ SINR < SINR_{min} \\ \alpha.S(SINR), & for\ SINR_{min} < SINR < SINR_{max} \\ Spectrum\_efficiency_{max}, & for\ SINR > SINR_{max} \end{cases}$$

Where:

- S(SINR) is the Shannon bound (in bps/Hz) given by S($SINR$)=$\log_2(1+10^{SINR/10})$
- α is Attenuation factor, representing implementation losses. This is set to 0.6 in the simulation [40]
- $SINR_{min}$ is the minimum SINR of the codeset, dB
- $Spectrum\_efficiency_{max}$ is the maximum spectrum efficiency of the codeset, bps/Hz
- $SINR_{max}$ is the SINR at which max spectrum efficiency is reached, dB

The use of the appropriate SINR to SE mapping function as shown above, combined with a reduction of 20% [16] to account for overheads, gives us a net spectral efficiency (bps/Hz) vs SINR for the user data in a resource block.

Active user calculation:

To work out how the SE values per user map to throughputs we next need to understand the number of active users per cell who will be sharing the PRBs of that cell.
Three has provided a dataset with the number of eRABs, average user throughput and average PRB utilisation for each cell.

We used this information to derive the number of users concurrently active in each cell with the following methodology. We assessed the average spectral efficiency, E, for cells within the 0 to 50% area using the following formula:

$$E = \frac{TNa}{B}$$

where T is the average user throughput, N is the number of eRABs, a is the activity factor of an eRAB and B is the bandwidth of transmission, given by:

$$B = 180 \text{ kHz}$$

where M is the number of PRB in the 15 MHz channel dataset we received from Three, and 180 kHz is the bandwidth of one PRB. The number of users concurrently on the cell is then given by Na. For an expected spectral efficiency of an urban cell, E, we can then solve the equations to derive the activity factor, a. Three agreed with us to assume E=1.4 bps/Hz/cell, which results in a=4.16%.

The target average cell spectrum efficiency, i.e. E, of 1.4 bps/Hz/cell is based on Table 4.

Parameter	Value (bps/Hz/cell)	Notes
3GPP full buffer 100% PRB utilisation	2.23	[12]
65% factor to consider a realistic traffic mix (i.e. non full buffer)	1.4	2.23 * 0.65 [13]

Table 4: Spectrum efficiency

Scheduler implementation

In our multi user simulations we allocate the PRB resources depending on the SE distribution of the network and number of active users in a given cell based on a fairness scheduling rule.

- We recognise Round Robin scheduling does not give a fair user throughput distribution for Full Buffer UEs and under heavy congestion when even the fixed demand video UEs appear as full buffer UEs
- We consider fairness in terms of the data rates experienced by different users
- The weight set can initially be related to the UEs spectral efficiency to model some degree of fairness on a sliding scale between Round Robin and equal throughout:
- Resource weight of K^{th} UE: $W_{UEk}=1/SE^{\alpha}$
    - a=0 is Round Robin Resource allocation agnostic of channel conditions. This gives high cell throughput, but an unfair distribution of UE throughputs across the cell.
    - a=1 is Equal Throughput Resource allocated to completely compensate for the channel. All UEs achieve same throughput, but results in low aggregate cell throughputs, as more resources are assigned to inefficient UEs
    - a=0.5 is fair - A balanced middle ground between UE throughput distribution fairness and cell throughput

Site densification:

Site densification is a key part of the simulation process. During the site densification process, we ensure the number of users per site scales linearly: We look at the 6 surrounding sites and the active users on these when introducing a new site. The same number of active users are now spread across the sites so that the total number of users remains same but the users per site decreases due to the introduction of a new site. Site densification process is illustrated in Figure 9.

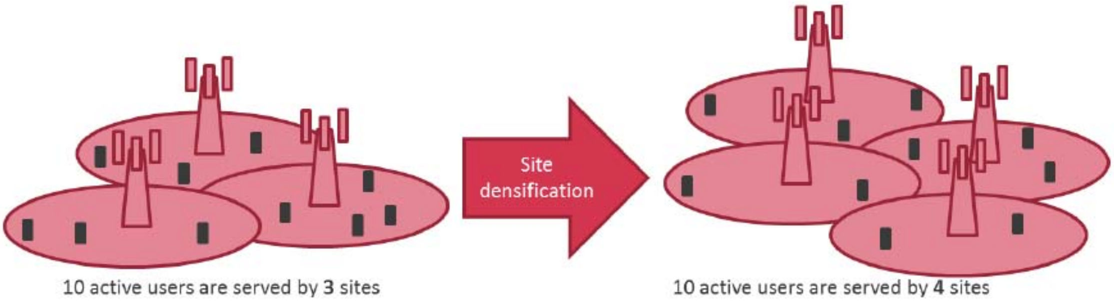

Figure 9: Illustration of site densification process

The first stage of the site placement processing in the model generates the base network data base.

- The base network was provided by two data sets which are first combined. The first data set contains the details of approximately [redacted] sites. The details for each site included the cell ID, the site coordinates and its height.
- The second data set contains the network data for the midday hour. It contains the average DL PRB usage (a percentage), the average number of eRABs and the average DL user throughput (Mbps).
- Since the model require data per sites, data from multiple sectors of the same site were combined to create one result per site.
    - The number of PRBs were combined by calculating the mean
    - The number of eRABs is calculated by summing all the sectors
    - The throughput value was calculated by calculating the mean
- Some entries of the second set included either missing or zero values. These entries were removed before further processing.
- The second data set did not have entries for all the sites. For the sites with missing data the missing data was calculated by combining the 6 nearest sites that did have data.

The second stage of the site placement process interpolates the base network to produce a densified network with the required number of sites.

- The first step uses a Delaunay triangulation algorithm [31] to divide the coverage area into a number of triangles with the cell site locations as the points of the triangles.
- The population within each triangle is calculated and the N highest values are selected. N is the number of additional sites required.
- N new sites are then located at the centre of the N triangles. The new coordinates (including height) are calculated from a simple mean of the surrounding points.
- As each new site is created the users of the surrounding sites is reduced by 25%. The users for the new site is calculated by summing the three surrounding sites and multiplying by 0.25. The net effect is no change in overall population.

Coverage area calculation:
To perform a fair comparison, we keep the number of users served by the network constant during the site densification. This way, we focus on the full benefit of new spectrum or adding new sites shared among the same number of users.
The simulation iterates through a set of increasingly dense networks starting from the base network size. For the base network the throughput of each of the 10000 users is calculated

and the users with zero throughput (those below the minimum SINR threshold) are noted. For each of the subsequent densified networks, those users that did not get service in the base network are automatically excluded in the denser network.

Network load during the site densification

To understand the PRB utilisation change with the number of users, we carried out a regression analysis. The PRB utilisation vs. the number of eRABs was plotted and a best fit curve was found as shown in Figure 10.

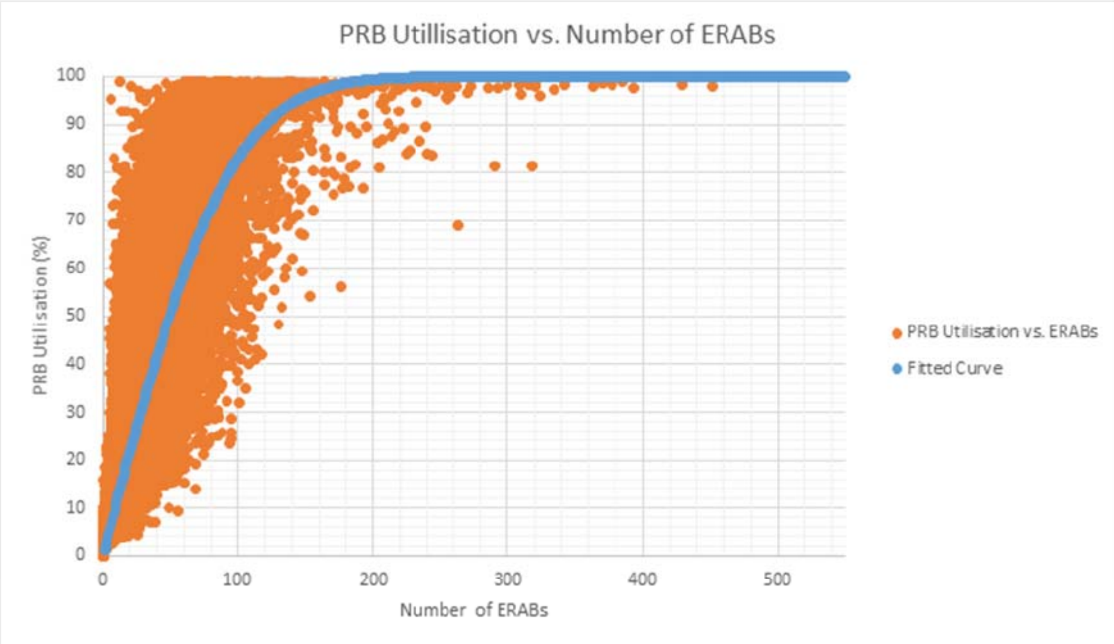

Figure 10: Relationship between PRB utilisation and number of users in the 0-50% area.

The fitted curve is *PRB_fitted = erf[0.01715 * ERAB / sqrt(pi)]* and this curve represents the relation between the number of eRABs in a cell and the PRB utilisation.

The densification process is achieved by placing a new site inside the triangle formed by its three neighbours. Therefore, traffic in the form of eRABs from these parent sites will be transferred into the new site.

We consider the 3 surrounding sites with eRAB values ERAB_i, where $i \in [1,3]$, representing the three parent sites of the new site, prior to the introduction of the new site. The new site is allocated with a small number of eRABs from the parent sites (that is, a quarter of the traffic from each site is transferred to the new site). The PRB utilisation of the new site is calculated according to the formula below:

$$ERAB\_NEW = 0.25 * (ERAB\_1 + ERAB\_2 + ERAB\_3) \quad (1)$$
$$PRB\_NEW = erf\{0.01715 * ERAB\_NEW / [3 * sqrt(pi)]\} \quad (2)$$

where *ERAB_NEW* is the number of eRABs of the new site and *PRB_NEW* is the PRB utilisation.

Note that the model requires site level data. To generate site level data, we:

- aggregate the number of eRABs from three sectors

- take the average PRB utilisation of three sectors as the PRB utilisation of the site

Since the fitted curve requires cell level data, we divide the number of eRABs by 3, as shown in the equation (2).

Due to the transfer of traffic to the new site, the parent sites will now have a smaller number of eRABs. Therefore, their PRB utilisation should also decrease accordingly. A similar approach to above is followed to calculate the decrease in the PRB utilisation. The number of eRABs of the 3 surrounding sites decrease to *ERAB_i_NEW*, where *i* represents each of the parent sites. Since a quarter of the traffic is transferred to the new site, each parent site will have three quarters of the traffic comparted to the traffic it carried prior to the densification:

$$ERAB\_i\_NEW = 0.75 * ERAB\_i, \forall I. \quad (3)$$

The PRB utilisation of these sites can also be calculated using the fitted formula above, i.e. for each parent site *i* the new PRB utilisation will be:

$$PRB\_i\_NEW = erf[0.01715 * ERAB\_i\_NEW / sqrt(pi)].$$

Using the fitted curve and the number of eRABs per site prior to the introduction of the new site, we deduce the PRB utilisation that corresponds to the initial number of eRABs. The PRB utilisation, PRB_i_FITTED, calculated by the fitted curve is:

$$PRB\_i\_FITTED = erf[0.01715 * ERAB\_i / sqrt(pi)]$$

whereas the actual PRB from the given data file from Three is *PRB_i*, and thus the corresponding error between the actual data and the fitted curve in this case is:

$$PRB\_i\_ERROR = PRB\_i - PRB\_i\_FITTED.$$

Combining all the above we derive the PRB utilisation for each parent site *i* as follows:

$$PRB\_i\_NEW = erf[0.01715 * ERAB\_i\_NEW / sqrt(pi)] + PRB\_i\_ERROR. \quad (4)$$

In the above analysis, we have bounded the PRB utilisation between 1/75 and 1. The former correspond to the utilisation of 1 PRB in 15MHz.

Example – reduction in the PRB utilisation case

Assume the three parent sites have the following:

ERAB_1 = 265 and *PRB_1* = 0.5177
ERAB_2 = 100 and *PRB_2* = 0.4879
ERAB_3 = 104 and *PRB_3* = 0.2609

Using Equations 1 and 2 we calculate the eRABs for the new site as follows:

ERAB_NEW = 117 and PRB_NEW = 0.4074

Using Equations 3 and 4, we calculate the eRABs for the parent sites as follows:

ERAB_1_NEW = 199 and PRB_1_NEW = 0.3799
ERAB_2_NEW = 75 and PRB_2_NEW = 0.4037
ERAB_3_NEW = 77 and PRB_3_NEW = 0.1744

3.4 Results

We use the current LTE network site count from Three as the base case for the simulations. For the base case we consider [redacted] sites deployed in the area where 0-50% of the population lives in the UK. This corresponds to approximately [redacted] sites at national level. We use midday hour network statistics such as average PRB utilisation from Three's network to make the simulation as close to the real world as possible. To evaluate the benefit of spectrum increase vs. site densification, we simulated the following scenarios:

1. 15 MHz LTE network with [redacted] sites
2. 30 MHz LTE network with [redacted] sites
3. We densified the site count of 15 MHz LTE network up to 4 times

Our site placement algorithm increases the national site count in steps of 3000 sites. Consequently, this will increase the site count in the area of analysis i.e. 0-50% area, as shown in

Table 5. Please note that due to the small increase in the number of sites within the 0-50% area for the 30,000 sites in the national level, this case was not considered in the simulations.

REDACTED

Table 5: Site densification

3.4.1 Presentation of results

The measurements from the network show that 68% of the sites have less than 5 users simultaneously connected to the network in 0-50% of the area. This scenario consists of [redacted] users simultaneously connected to [redacted] sites in 0-50% area. In this case the user throughput is not limited due to the lack of PRBs in most of the cells. Therefore, we keep the number of PRBs used by the users the same irrespective of the bandwidth i.e. 15 or 30 MHz. This results in the percentage of PRB utilisation decreasing by a factor of two when the spectrum is increased from 15 to 30 MHz.

The number of users in each cell is calculated (according to the number of eRABs as explained in "Active user calculation") and are distributed across each cell. We analyse and present the cumulative distribution function (cdf) of the user throughput across the network, for a new user entering each cell in the network. This is to present the throughput that can be experienced by a new user entering a given cell in the network in the presence of existing loading conditions. This new user throughput represents the throughput experienced during a drive test. We made the following assumptions in the new user throughput calculation:

- If the new user requests service from a sector that has PRB utilisation <90%, then the new user gets all the remaining PRBs.
- If the new user requests service from a sector that has PRB utilisation >90%, then the new user gets 10% of the PRB.

If a new user is admitted to a cell, depending on the available resources, the new user gets a fair allocation of resources. This is because the resource scheduler provides fairness to all active users depending on the scheduling algorithm. To reflect this concept, we assume some resources, i.e. at least 10% of the resources, are allocated to the new user

As described in Section 3.3, we derived a relationship between eRABs and the PRB utilisation using a regression analysis on Three data. We have used this relationship and reduced the PRB utilisation of the existing sites in cases where we densify the network to during the simulations to generate the following results.

3.4.2 Results

Figure 11 shows the new user performance vs. the percentage of new user test cases covered within the area where 0-50% users live.

REDACTED

Figure 11: [redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted] [redacted]

[redacted]

[redacted]

[redacted]

- [redacted]

[redacted]

- [redacted]

We also highlight that site densification in urban areas in the UK, where the network capacity is limited, is extremely challenging and time consuming. Our discussion with the other UK MNOs revealed that it is extremely challenging to deploy anything more than 30% of the sites in central London area. The deployment also usually takes up to 18 to 24 months [See Annex B 7.1.4].

4. Conclusions and further work

This chapter summarises our key findings from this study and recommendations for Three for further investigations which would enhance the arguments we presented.

4.1 Conclusions

In this study we assessed whether it would be possible for an operator with less spectrum to deliver an equivalent level of subscriber experience as one with a much larger spectrum holding through significant network densification.
We answer this question based on:

1. **qualitative analysis** by comparing the benefits, challenges, complexities and practical aspects. We provide our independent opinion on these issues based on the evidence from a literature survey.
2. **quantitative assessment** using a simulation methodology. We simulate a mobile network in a densely populated area i.e. area where 0-50% of the UK population lives, for an LTE network using 1800 MHz spectrum. We compare the user throughput curves of:

    - 15 MHz of LTE network deployed with 7000 sites
    - 30 MHz of LTE network deployed with 7000 sites
    - Densification of the 15 MHz network scenario until the user throughput curves match the user throughput of the network with 30 MHz.

Our findings from these assessments are presented below.

4.1.1 Qualitative analysis

This aspect of the study was conducted primarily through a literature review.
In section 2 we began by reviewing the options available to a mobile operator to grow capacity and improve user experience in a mobile network. Broadly the three main options are:

1. Add **spectrum** – either through additional spectrum acquisition or re-farming.
2. Enhance **technology** - to improve spectrum efficiency, e.g. with higher order MIMO, interference mitigation, increased modulation schemes, etc.
3. Change **topology** through network densification – through more macrocell rollout, higher order sectorisation and small cells / heterogeneous networks.

We noted in particular that in the UK market the mobile spectrum allocations are highly imbalanced with two players holding 71% of the available spectrum between them (EE/BT having the largest share at 43%) with the two remaining players holding just 29% (14% for O2 and 15% for Three). Such a disparity in spectrum holding creates a competitive advantage for the holders of the greater quantities of spectrum.
The impact of user experience was broken down into several categories. These points and the key conclusions are as follows:

- **Peak speed – ability to offer the highest peak speeds.** It was concluded that [redacted]

[redacted]

- **Average user throughput – ability to deliver a competitive data throughput per customer.** The evidence from the four papers that were reviewed all support the conclusion that [redacted]

We have also reviewed the practical aspects of network densification versus adding additional spectrum. Overall it was shown that there are numerous practical challenges with network densification. [redacted]

[redacted]

4.1.2 Quantitative assessment

To evaluate the benefits of spectrum increase vs. site densification we model the expected user throughputs for a network with 15MHz of spectrum and then one with 30MHz of spectrum. Both networks have the same number of sites initially. We then increase the number of sites in (or densify) the network with the smaller spectrum portfolio by various levels up to four times the number of sites. In each case we plot the cumulative distribution function of the expected user throughputs for each site and spectrum portfolio to see if there is a level of densification where the network with the smaller spectrum portfolio can match the throughputs of the network with the larger spectrum portfolio but less or equal site number.

We focus our simulation in the area of 0-50% of the UK population lives. Three's network currently deployed [redacted] sites in the area where 0-50% of the population lives in the UK and approximately [redacted] sites nationally. We used current Three network site count and carried out simulations with the measured traffic loading level.

We also highlight that site densification in urban areas in the UK, where the network capacity is limited, is extremely challenging and time consuming. Our discussion with the other UK MNOs revealed that it is extremely challenging to deploy anything more than 30% of the sites in central London area. The deployment also usually takes up to 18 to 24 months.

[redacted]

We also highlight that site densification in urban areas in the UK, where the network capacity is limited, is extremely challenging and time consuming. Our discussion with the other UK MNOs revealed that it is extremely challenging to deploy anything more than 30% of the sites in central London area. The deployment also usually takes up to 18 to 24 months [See Annex B 7.1.4].

Conclusions:

- [redacted]

4.2 Further work

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

1. **Detailed system level simulation**: We recommend carrying out a detailed system level modelling with "analytical microcell" approach presented in Chapter 8 (Annex C) for a wider area to investigate the tradeoff between spectrum and site densification.
2. **Simulation of detailed recommendations on spectrum usage** to try to maximise the capacity and user experience. This involves evaluating which spectrum to use for which technologies and which layers. This will provide a comparison among available spectrum bands and technologies geographically to find the optimum combination to maximise the user experience and network capacity.
3. **Spectrum migration strategies**. Solutions and recommended mechanisms for migrating traffic and spectrum from legacy technologies (i.e. 3G). Tradeoffs for compressing the 3G spectrum allocation (e.g. at 2100 MHz) and migrating to LTE.
4. **Recommendations/analysis on utilising additional TDD frequency bands** (e.g. 2300 and 3500 GHz) in conjunction with existing FDD bands. For example, is it better to deploy as a standalone overlay (potentially with a different vendor) or combine into the existing network with carrier aggregation.
5. **Developing spectrum strategy for 5G**. In particular building a case for future low band spectrum allocation (e.g. at 700MHz) to be reserved for operators without significant low band spectrum today.

5. Acronyms

3GPP 3rd Generation Partnership Project
BW Bandwidth
CA Carrier aggregation
CAGR Compound Annual Growth Rate
CEPT European Conference for Post and
CTN ComSoc (IEEE communications socirty) Technology News
Telecommunications/Electronic Communications Committee
EE Everything Everywhere
EIRP Effective isotropic radiated power
E-RAB Enhanced radio access bearers
ETSI European Telecommunications Standards Institute
FCC Federal Communications Commission
FDD Frequency division duplex
GSM Groupe Spéciale Mobile or Global System (or Standard) for Mobile
GSMA GSM (Groupe Spéciale Mobile) Association
KPI Key Performance Indicator
MBB Mobile Broadband
MIMO Multiple Input Multiple Output
MIP Mobile Infrastructure Project
MNO Mobile network operator
OSS Operation Support System
PDF Probability distribution function
PRB Physical resource block
QAM Quadrature amplitude modulation
QPSK Quadrature phase shift keying
RF Radio Frequency
SE Spectral Efficiency
SINR Signal to Interference Ratio
SUTP Single User Throughput
TDD Time division duplex
UE User equipment
VTC Vehicular Technology Conference

6. Annex A: Capacity options available to operators

6.1 Introduction

If operators are to meet this requirement for high and increasing demand density they need to find solutions which are both cost-effective and flexible to allow their investment to be focused on the locations with the greatest need.
Three generic sources of capacity are available to mobile operators:

1. **Spectrum**, where the total bandwidth as well as the frequency bands and arrangement of those bands affect the capacity available;
2. **Technology,** where modulation schemes, antenna processing systems and interference mitigation technique all affect the available spectrum efficiency per cell;
3. **Network topology,** where the density, location and arrangement of cells all affect the density with which spectrum can be reused in a given area.

The total network capacity can be expressed as the product of the contributions from these three sources:

Capacity [bits per second]	= *Quantity of spectrum [hertz]*	x *Cell Spectrum Efficiency [bits per second per hertz per cell]*	x *Number of cells [no units]*
Capacity	***Spectrum***	***Technology***	***Topology***

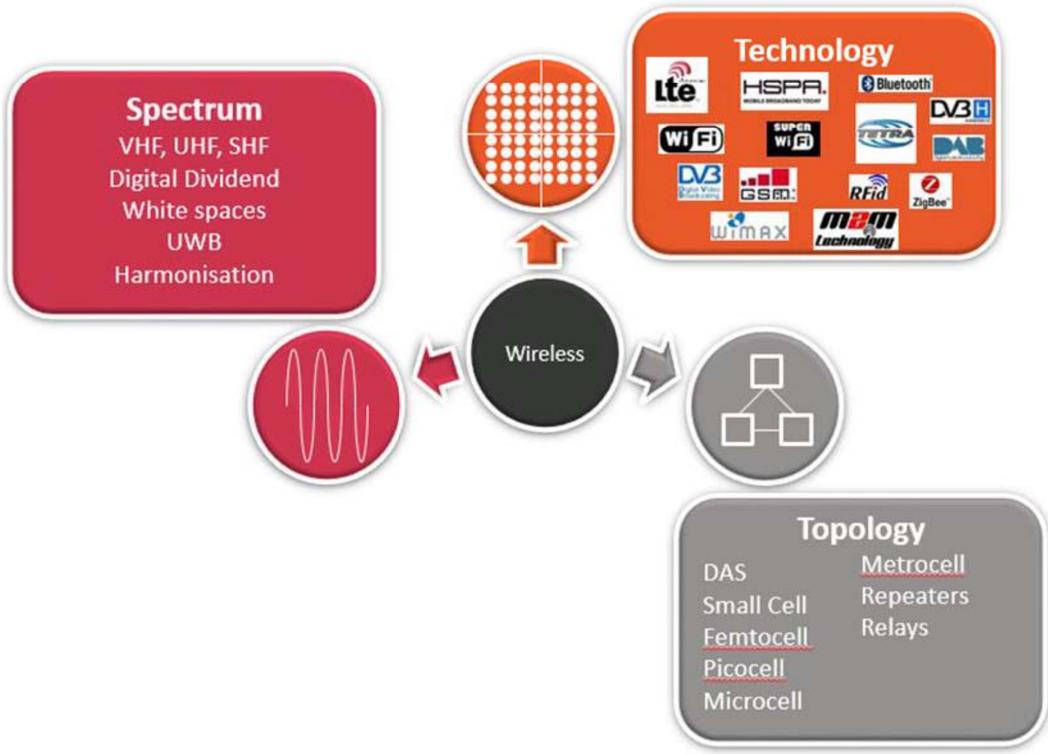

Figure 12: Capacity depends on a combination of spectrum, technology and topology of the network © Real Wireless

Three generic sources of capacity are available to mobile operators:

1. **Spectrum**, where the total bandwidth as well as the frequency bands and arrangement of those bands affect the capacity available;

2. **Technology,** where modulation schemes, antenna processing systems and interference mitigation technique all affect the available spectrum efficiency per cell;
3. **Network topology,** where the density, location and arrangement of cells all affect the density with which spectrum can be reused in a given area

6.1.1 Spectrum efficiency and its evolution

There are many ways in which existing macrocells can be upgraded to increase the capacity they can deliver with a given quantity of spectrum – i.e. their spectrum efficiency. Potential sources of improvement in spectrum efficiency include:

1. Increased modulation and coding efficiency (e.g. to 64 QAM from QPSK)
2. Increased sectorisation (e.g. from three- to six-sector)
3. Increased multiple input multiple output (MIMO) order (e.g. from 2 to 4 elements or more)
4. Introduction of Coordinated Multipoint Transmission
5. Introduction of Carrier Aggregation

All of these techniques can potentially increase capacity.
Figure 13 shows the projected timing of mobile technology evolution based on new standards available from the Third Generation Partnership Project (3GPP). 3GPP standards releases occur approximately every 18 months. Data points corresponding to the solid shapes are taken from [14] and [15] whereas the data points corresponding to empty shapes are Real Wireless extrapolations [16].

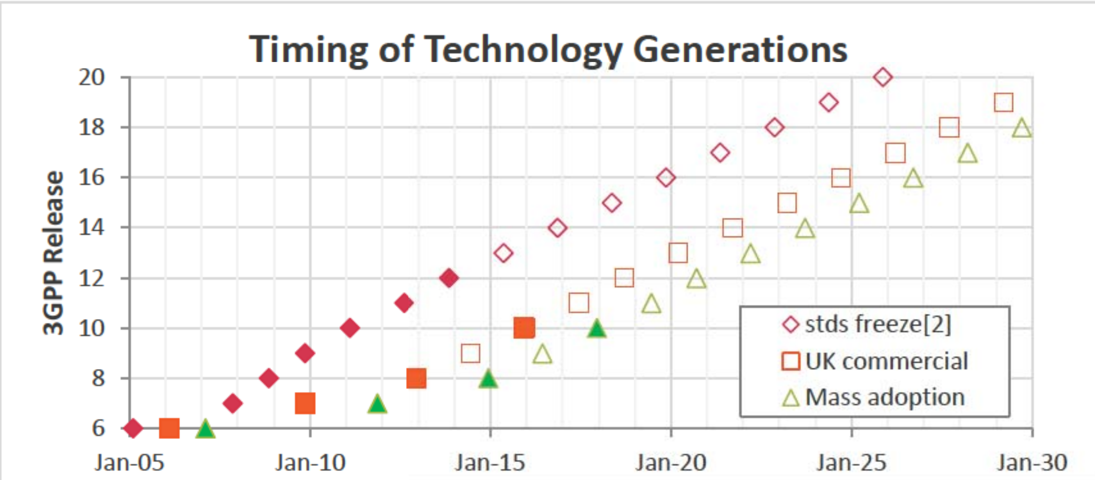

Figure 13: MBB technology evolution: 3GPP Releases deployed within the study period

We have considered the rate of spectrum efficiency growth over time which might arise from the above techniques embedded within mobile technologies, taking into account factors such as the availability of supporting features on mobile devices, constraints on site upgrades etc.

Figure 15Figure 14illustrates these resulting spectrum efficiencies for several growth scenarios for a 3 sector macrocell site with 2x2 MIMO. This shows that the site spectral efficiency in 2030 is increased by a factor of almost five times compared to the site spectral