efficiency in 2014. This gradual increase in spectral efficiency of macrocell sites translates to a similar increase in macrocell sitecapacity. Note that the real world spectral efficiency will be dominated by the actual device mix.

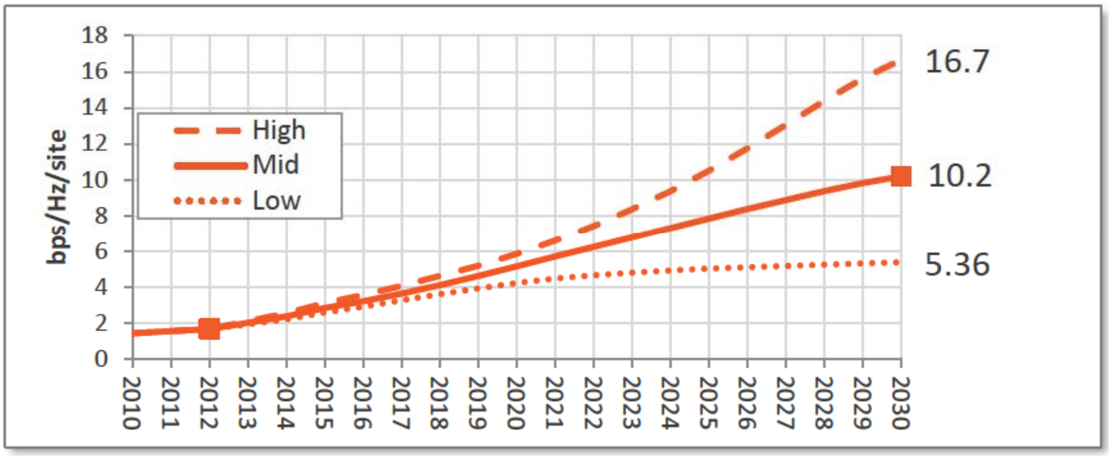


Figure 14: Spectral efficiency evolution for macrocell site (down link, 3 sector with 2x2 MIMO) [16]

Nevertheless, the increase in spectrum efficiency is not expected to be the same in the future. The evidence suggests that the rate of increase of spectrum efficiency is reducing over time as systems tend towards theoretical limits, this will have the effect of reducing the rate of improvement in capacity due to spectral efficiency.

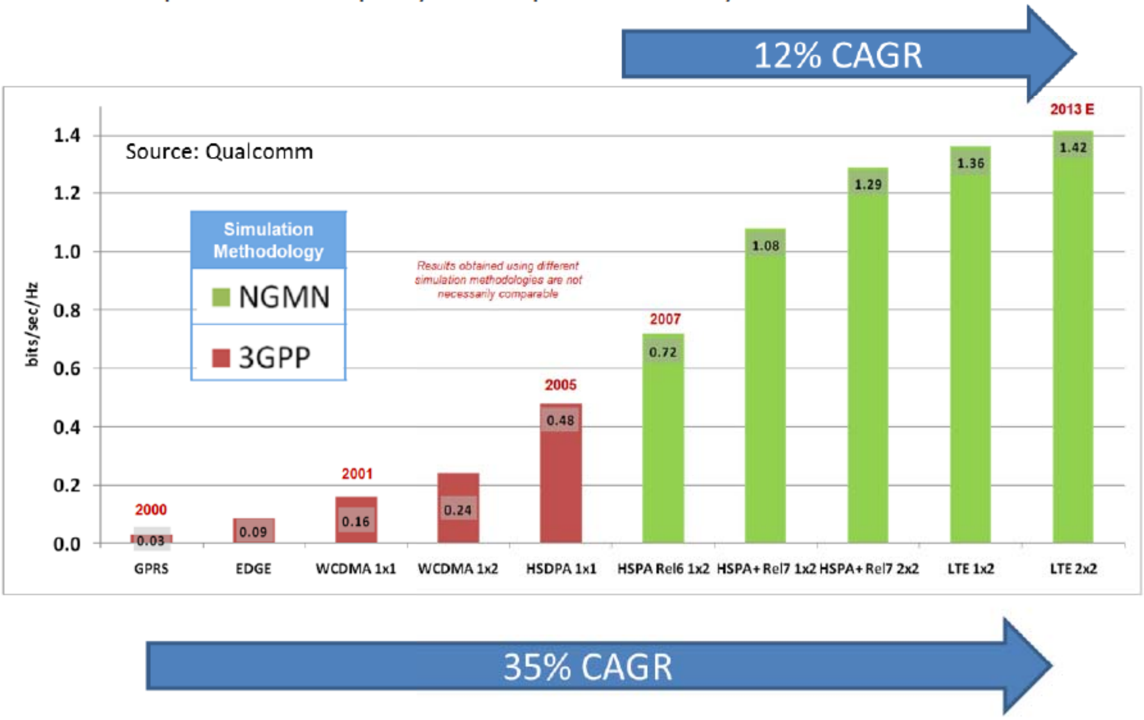


Figure 15: The rate of increase of spectrum efficiency is reducing over time (Source: Qualcomm)

6.1.2 Spectrum

Spectrum is a basic necessity for wireless systems. The capacity of a wireless system depends directly on the quantity of spectrum available and increasing the amount of spectrum can be a very cost-effective means of increasing capacity. However, such spectrum does not come for free: as well as the cost of initially acquiring the spectrum and maintaining ongoing license fees, there are costs in upgrading network equipment and ensuring mobile devices support the relevant spectrum bands.

Spectrum has a number of technical and economic characteristics which mean that specific spectrum bands may be more suitable – and hence more valuable – for certain applications. These characteristics include particularly:

1. The physical properties of spectrum change the coverage available from a given transmitter, with lower frequencies generally providing greater distances and deeper penetration into buildings. Also, the physical properties of the spectrum band affect the practical antenna sizes and transmitted powers.
2. The quantity of spectrum (the bandwidth) affects the numbers of users that can be served and the quality of service available to each user. Higher frequency bands generally provide greater bandwidth.
3. The international use of spectrum bands affects its attractiveness, both because interference must be coordinated between countries, and because the wide use of the same band for a given purpose drives economies of scale in the equipment available for those bands. Internationally harmonised spectrum allows it to be included in standards, typically those produced by 3GPP.

Given these constraints, there is clearly a limited supply of spectrum for mobile applications. Regulators internationally are engaged in locating additional spectrum for mobile broadband: for example, the US telecoms regulator, the FCC, has announced the availability of 11 GHz of high frequency spectrum has been made available for use by 5G [17]. The UK government announced in 2010 a commitment to find at least 500 MHz of public sector spectrum below 5 GHz over the next ten years for mobile communication uses [18]. The European Commission's Radio Spectrum Policy Programme published in 2012 includes an action to ensure that at least 1200 MHz of spectrum is identified to address increasing demand for wireless data traffic [19].

In practice this tends to limit useful mobile spectrum in the range 450 MHz – 3.5 GHz, although future generations of mobile technologies may effectively address higher ranges i.e. 5G is exploring the use of spectrum bands above 6 GHz.

The dominant source of spectrum for mobile applications is provided on a licensed, exclusive basis by the national regulator, Ofcom (in the UK). The UK spectrum management regime is also set by the European spectrum regulation process as managed particularly by the European Commission, CEPT2 and ETSI3. In 2014 Ofcom published its spectrum management strategy, giving its approach to, and priorities for, spectrum management over the next ten years [20].

Figure 16 shows the spectrum distribution across UK operators.

[2] European Conference for Post and Telecommunications/Electronic Communications Committee
[3] European Telecommunications Standards Institute

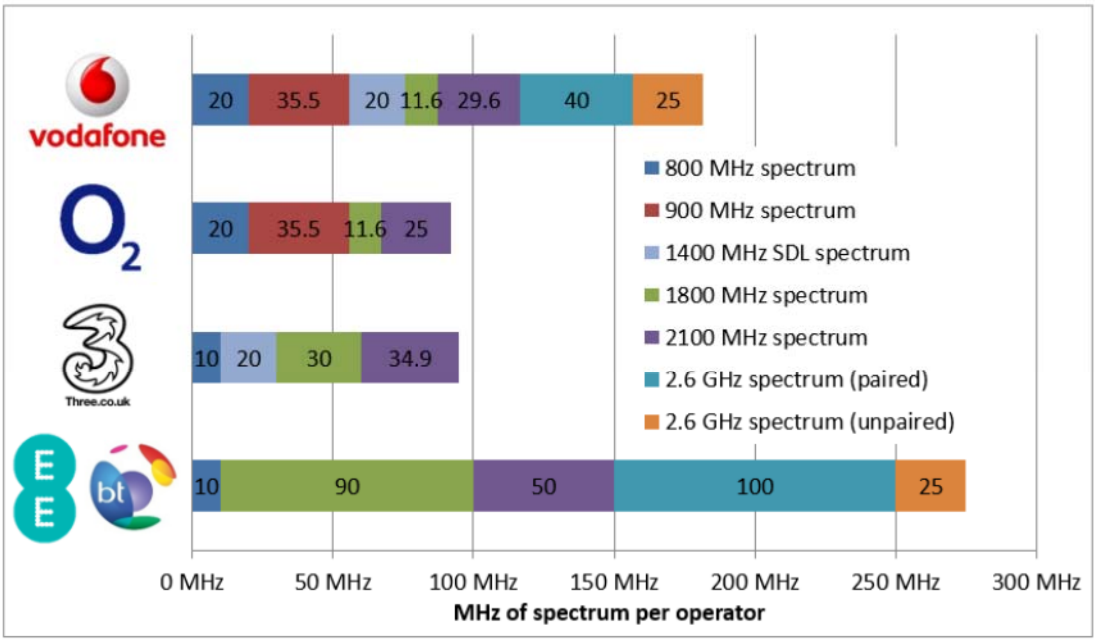


Figure 16: Licenced UK MNO spectrum amount and allocation (Source: Real Wireless)

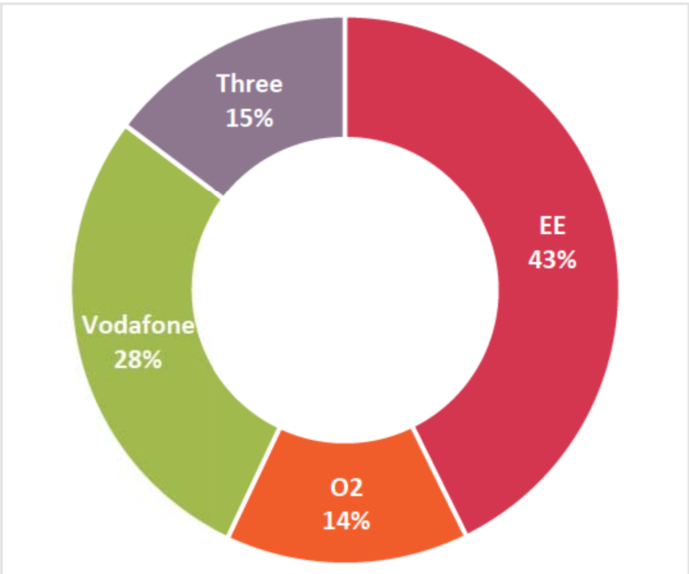


Figure 17: Licenced MNO spectrum distribution in the UK (Source: Real Wireless)

Figure 17 shows the overall spectrum ownership in the UK. The amount of spectrum relates to the total capacity that an operator could offer from each single cell site. It shows that EE holds the highest amount of spectrum, i.e.43% whereas Three and O2 have almost three times less spectrum compared to EE.

6.1.3 Network topology

The network topology describes the "shape of the network" or architecture. Key parameters in network topology are:

- **Antenna height**: Higher antenna height enables a larger coverage area.

- **Transmitted power**: Higher transmitted power makes signals travel over a greater distance, before the signal level falls below the minimum acceptable threshold to the receiver.
- **Site location**: Deploying the site at the right location i.e. where it is important to meet the coverage or capacity requirements.
- **Cell range**: cell range is determined by the transmitted power, antenna gain and height. In congested areas, cell coverage areas are designed to be smaller compared to non-congested areas to provide sufficient capacity within the area.
- **Number of cells**: The number of cells is determined by the area that needs to be covered and the cell range.
- **Type of cell**: Different types of cells exist in Mobile Broadband (MBB) to meet different requirements. For instance, macrocell sites cover a large outdoor area where as microcell sites cover a smaller area compared to macrocell sites. Picocell and femtocells usually cover indoor areas.

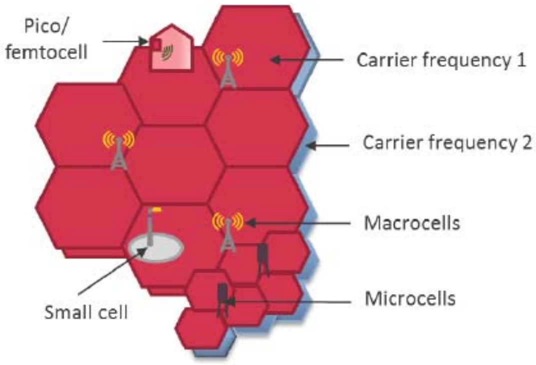
Transmitted power and cell radii for different cell types are shown in Table 6.

Cell type	Typical cell range			Power
	Dense urban	Suburban	Rural	
Macrocell (outdoor)	150-400 m	400 m-2 km	2 km – 5 km (or more)	20-40+ W
Microcell (outdoor)	150 m	200 m	250 m	1-10 W
Picocell (indoor)	150 m			0.25-1 W
Femtocell (indoor)	25-50 m			Up to 0.1 W

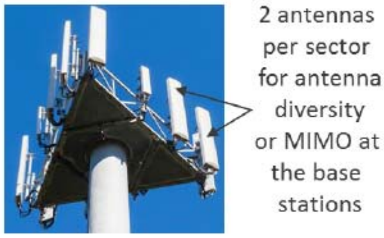
Table 6: Example cell radii and transmitted power of different cell types

Typical site configurations for mobile sites are shown in Figure 18. Operators have a choice of different site types to deploy to meet the capacity requirements. For instance, macrocell sites usually cover large areas compared to other cell sites such as microcell sites. A typical macrocell site is divided (known as" sectored") into 3 sectors i.e. 3 cells. Each sector usually has 2 antennas for diversity reception today, but the number of antennas is increasing to deliver MIMO operation with higher spectral efficiency.

The Capacity available from a single cell is limited and depends on the available spectrum. For this reason, cell ranges in high capacity areas are smaller compared to the areas with lower capacity demand. The deliberate covering of a smaller area and deploying multiple cell sites is known as **site densification**. This is the main topology change we consider during this study.



(a) Site configurations



(b) An example antenna placement for a macrocell site

Figure 18: Macrocell site configuration

Although, traffic offloading, i.e. offloading to Wi-Fi, is considered as a potential solution to address capacity congestion, offloading is not available for all types of traffic i.e. voice, at least now, and it is not available as a solution everywhere i.e. outside Wi-Fi access area. Further, there are additional challenges related to security and user perception with this solution. Due to these limitation, we exclude offloading to Wi-Fi as a capacity solution in this study.

7. Annex B: Details of the literature search for spectrum increase vs. site densification and practical aspects

Within this section we will consider the published documents to analyse the merits of spectrum versus site densification and whether operators with less spectrum can fundamentally 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.

Additionally, the practical aspects related to the ability, cost and timeliness of delivering network densification versus additional spectrum also plays a major factor. This is also considered in a later section of this report.

7.1.1 Peak Speeds

Larger spectrum allocations not only bring capacity benefits but they also enable higher average peak speeds to be achieved. This can provide significant marketing benefits to an operator as it allows high 'headline grabbing' speeds to be offered and quoted to retain and attract customers.

LTE Advanced introduces the concept of carrier aggregation to allow multiple spectrum bands to be aggregated together to offer higher speeds. The spectrum can either be in the same band, or in different bands, or a combination of the two. Carrier aggregation 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.

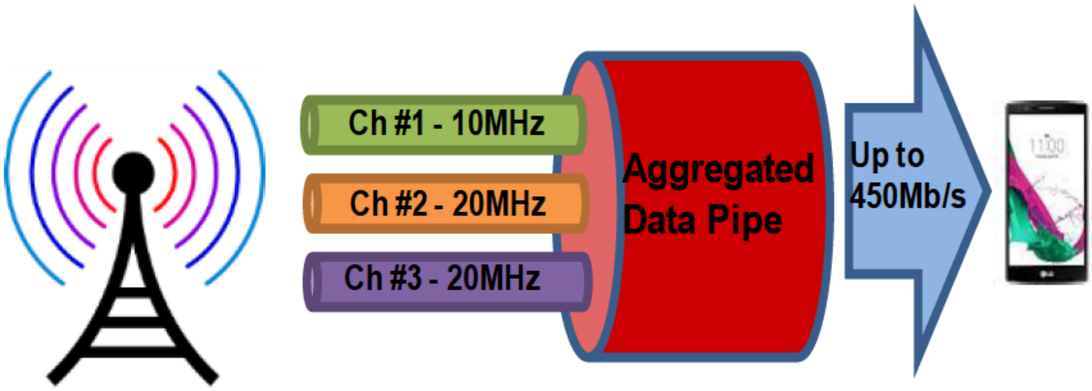


Figure 19: 3 Carrier Aggregation

With carrier aggregation the data rates scale depending on the volume of spectrum an operator has available. 3GPP Release 10 provides support for carrier aggregation with a maximum of 5 carriers, each up to 20MHz (100MHz in total), however, this level of aggregation is not yet commercially available, and very few operators in the world have this volume of spectrum at their disposal. Currently solutions supporting 2 or 3 carriers with data rates up to 450 Mbps have been demonstrated [21, 22, 23] and devices are becoming more readily available. To achieve full speed this requires a Cat 9 device, although Cat 6 (up to 300 Mbit/s) is currently more common.

The availability of high peak and average user speeds can bring significant marketing benefits to an operator. As shown in Figure 17, 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.

[redacted]

The table above only considers FDD spectrum. However, it is now also possible to aggregate time division duplex (TDD) and FDD carriers, hence with Ofcom's planned awards of spectrum at 2300MHz and 3500MHz this gives the potential opportunity for other operators (3 and O2 in particular) to be able to acquire spectrum and go some way to compete with EE/BT on peak speeds.

7.1.2 Capacity

An analysis of external papers and published works has been undertaken to further understand the spectrum vs site densification trade off as it relates to capacity.

FCC Staff Technical Paper – Mobile Broadband: The benefits of Additional Spectrum, October 2010 [24]

This historical paper produced by the FCC analysed the need for additional spectrum for mobile broadband to support the expected traffic growth. It recommended that the commission made available 300 MHz of additional spectrum for mobile use within 5 years. In reaching this conclusion the paper considered the ability and costs for operators to continue building new 'infill' cell sites as an alternative to making new spectrum available. The paper was able to compare the marginal cost of meeting mobile data demand by adding new cell sites relative to adding new spectrum. Doing so demonstrated that adding new spectrum would yield substantial economic value.

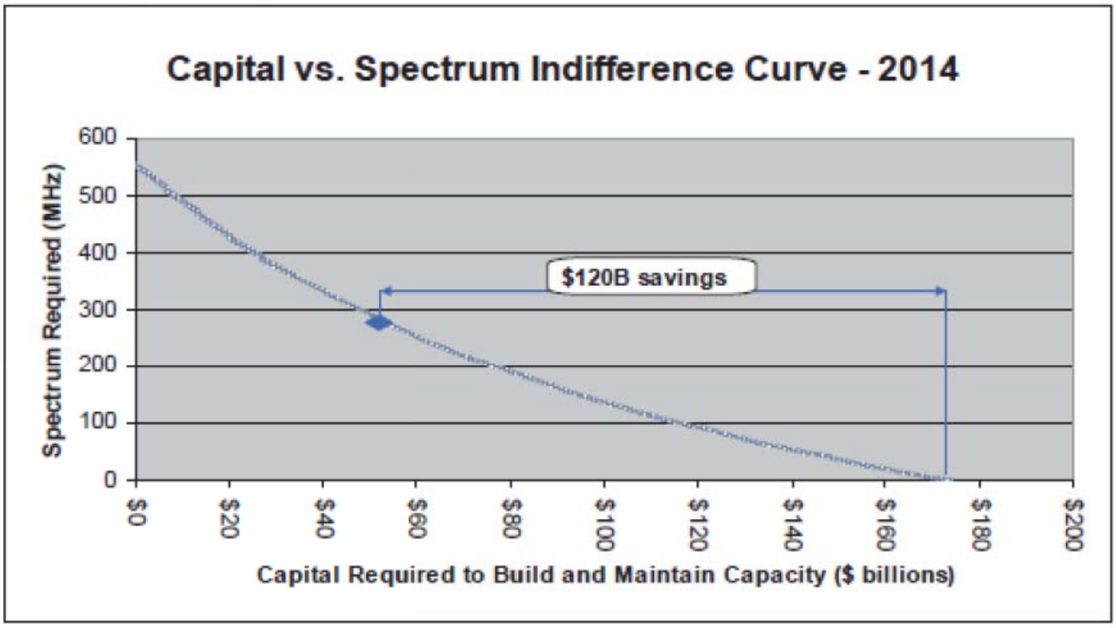


Figure 20: Capital vs Spectrum Indifference Curve from FCC study (Exhibit 22). *Source FCC*

Figure 20 above (Exhibit 22 in FCC study) shows the Capital vs. Spectrum Indifference Curve from the study. Based on the assumptions used and the top down forecast the curve illustrates that an additional 275 MHz of spectrum saves approximately $120 billion[4] in capital expenses that would have been needed to rollout additional 'infill' capacity sites to accommodate the mobile data demand.

Coleago Consulting report prepared for GSM Association (GSMA) "Revised spectrum forecasts using the new spectrum model - Spectrum required for various mobile communications markets in 2020", January 2013 [25]

This paper defines a model for spectrum estimation that was commissioned by the Global System for Mobile (GSM) Association to estimate future spectrum requirements for different countries, including the UK. The model takes as its starting point the existing number of sites within a given market and the scope for future site densification. A methodology is then developed for estimating the future spectrum that will be needed to support the forecast traffic.

[25] shows the results for the UK market in terms of sites per operator versus total spectrum requirement (for all operators).

[4] The blue diamond represents the point on the indifference curve corresponding to the site rollout that is assumed would have occurred anyway (7% CAGR site growth). This represents a capital investment by the mobile broadband industry of $54B in addition to 275 MHz of additional spectrum. The curve implies that if no additional spectrum is released, the cost to build enough capacity sites to handle the demand would be $174B. The difference between these costs represents the value created by additional spectrum in 2014, which is $120B.

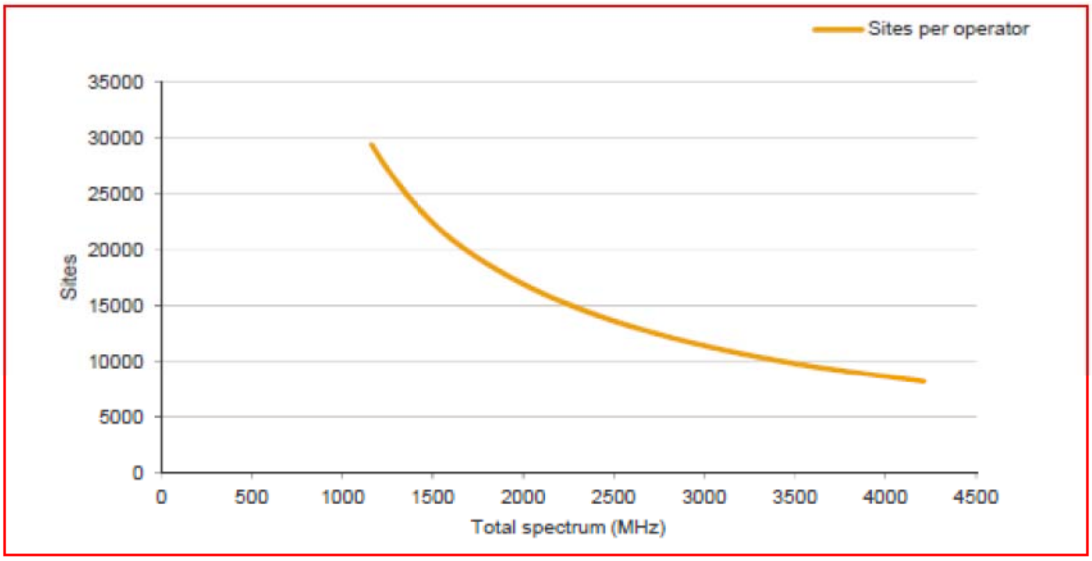


Figure 21: UK Sites per Operator versus Total Spectrum in 2020 (*Source Coleago Consulting for GSMA – Exhibit 3*).

The paper concludes that a total of 2074 MHz will be required in the UK in 2020, assuming the number of macrocell sites per operator is 16,370. Reading from the curve it can be seen that the number of sites needed per operator varies from 30,000 if only 1200 MHz of total spectrum is available to less than 10,000 sites per operator if greater than 4000 MHz of total spectrum is available. In the work no distinction is made between operators having different volumes of spectrum, however it can be inferred that if the spectrum is not evenly distributed and some operators have significantly more spectrum than others, then those operators with much less spectrum will need to build substantially more macrocell sites to be competitive and support similar levels of traffic.
[redacted] Clearly this is taking the analysis beyond its original purpose so needs to be treated with caution, but it gives a clear indication of the likely disparity.

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]

This paper analyses LTE-Advanced network expansion through the use of Heterogeneous Networks to support 1000 times capacity increase in a dense urban environment. The 1000 times increase is cited as a commonly anticipated level within the next 10-15 years. The study also includes a 10-fold increase in minimum user data rate requirements estimating that the minimum desirable user data rate will increase from approximately 1 Mbit/s today to at least 10 Mbit/s over the next decade. Rather than looking at peak data rates, the study focuses on the end-user experience defined as 90% coverage at a minimum user data rate.
The radio network capacity enhancement achieved with outdoor and indoor small cell densification and utilization of higher frequency bands is investigated. As the baseline, a full LTE-Advanced network deployment is assumed with an investigation area of

approximately 1.2 km2 which is covered by four existing three-sector macro sites with optimised antenna downtilt and average inter-site distance of approximately 300 m. In addition, 40 outdoor micro cells are deployed in the area to help offload the macro layer. Each of the 12 LTE-Advanced macro cell sectors is assumed to support 4 different FDD carriers at 800MHz, 900MHz, 1800MHz and 2100MHz and use ideal LTE Advanced carrier aggregation (CA) between the 800-900MHz bands and similar between 1800-2100MHz bands. As the basic configuration, the micro cell layer is assumed to operate in the FDD 2.6GHz band, where up to 2x20MHz is available. To further enhance the network capacity and indoor coverage, the paper considers large-scale deployment of femto cells, utilising several different spectrum allocation options at both 2.6GHz and 3.5GHz.

Various in-band (shared) and outband (dedicated) spectrum allocation strategies are considered, across the outdoor micro and indoor femto layers. The 3.5GHz spectrum is used in TDD mode where up to 200MHz of additional spectrum is considered for use on the outdoor microcell and indoor femto cell layers. A summary of the spectrum allocation and bandwidths considered is presented in Table 7 (Table I in the paper). It is noted that this volume of spectrum utilisation is only considered to be plausible beyond year 2020, and is certainly not achievable in the short term.

Scenario Name	Outdoor Micro cell	Indoor Femto cell
Reference	20 MHz @ 2.6GHz	None
2.6GHz Inband	20 MHz @ 2.6GHz	20 MHz @ 2.6 GHz
2.6GHz Outband	10 MHz @ 2.6GHz	10 MHz @ 2.6 GHz
3.5GHz Micro only	20 MHz @ 2.6 GHz 200 MHz @ 3.5 GHz	None
3.5GHz Femto only	20 MHz @ 2.6 GHz	200 MHz @3.5 GHz
3.5GHz Micro & Femto Outband	20 MHz @ 2.6 GHz 80 MHz @ 3.5 GHz	120 MHz @3.5 GHz
3.5GHz Micro & Femto Inband	20 MHz @ 2.6 GHz 200 MHz @ 3.5 GHz	20 MHz @ 2.6 GHz 200 MHz @ 3.5 GHz

Table 7: Multi-layer spectrum allocation assumptions. ***(Table I in reference [3]).***

The paper models the 1000 times traffic scenario in terms of increased number of simultaneous active users downloading data, with two options depending on the required minimum user data rate requirements, as follows:

1. 2800 simultaneously active downlink users with 1Mbit/s minimum user data rate requirement, or
2. 280 simultaneously active downlink users with 10Mbit/s minimum user data rate requirement.

The outage levels for the 'Reference' case, with only macro and outdoor micro cell deployment and not using any additional 3.5GHz spectrum are shown in Figure 22 for the two different user minimum user data rates of 1 Mbit/s and 10 Mbit/s.

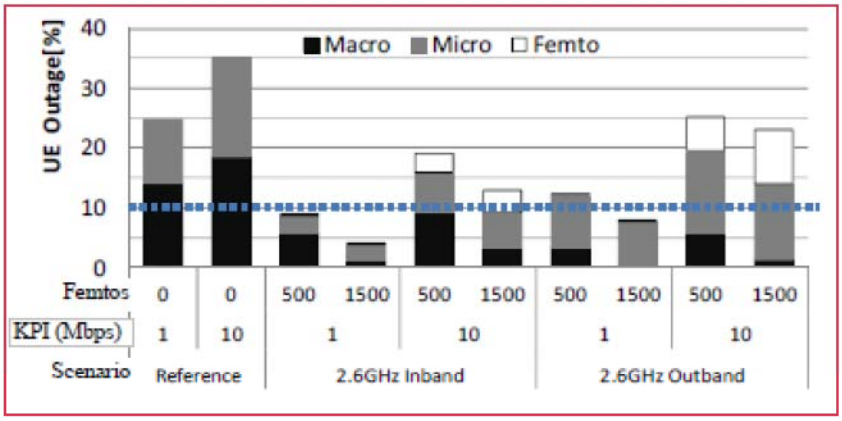


Figure 22: Multi-layer user outage – with no additional 3.5GHz spectrum (*Source: Fig 1 in reference paper [3]*).

As can be seen using this existing spectrum (no additional 3.5GHz), the user outage in the reference case is far above the desired 10% level, reaching values of 25% and 35% outage for the 1 Mbit/s and 10 Mbit/s KPI respectively. Adding indoor femto cells utilising the 2.6GHz band reduces the outage significantly. For 1 Mbit/s KPI the outage is in the range of 10%, whereas for 10 Mbit/s KPI the outage is still above the 10% target. The 2.6GHz 'Outband' case (dedicated spectrum) always leads to higher outage than the 2.6GHz 'Inband' case. This is because in the 'Outband' case some of the 2x20MHz allocation at 2.6GHz has had to be removed from the outdoor micro layer and allocated to the indoor femtos. In this case the performance bottleneck is the availability of the spectrum rather than any cross-layer interference.

Despite the significant improvement by the large-scale deployment of indoor femto cells in the 2.6GHz band, none of the cases are able to meet the 10 Mbit/s KPI. Thus, further capacity enhancement solutions using new 3.5GHz band are then considered, with the results shown in Figure 23 In this case several spectrum allocation schemes for the deployment of micro and femto cells in the 3.5 GHz band are considered for the same KPIs of 1 Mbit/s and 10 Mbit/s, as follows:

- In the '3.5GHz Micro only' case, the whole 200MHz TDD band is allocated to the outdoor micro cell layer without any indoor femto cell deployment and in this configuration it is shown to be impossible to reach the target KPI even for the 1 Mbit/s requirements.

- In the next '3.5GHz Femto only' case, the entire 200 MHz TDD band is allocated to the femto layer. By deployment of 1500 femto cells the overall network KPI of 10 Mbit/s can be achieved with less than 10% outage. In particular, the macro layer performance in terms of outage has benefited from indoor femto cells at 3.5GHz but the micro layer outage level remains almost the same (between the 500 & 1500 Femto cases). Therefore, enhancement of the micro cell layer is essential, since it limits the overall network performance.

- In the next '3.5GHz Micro & Femto Outband' case, 80 MHz of the 3.5GHz TDD spectrum band is allocated to outdoor micro cells (in addition to the 20MHz FDD band at 2.6GHz carrier) and the remaining 120 MHz allocated to indoor femto layer. The user outage in the micro layer is improved significantly, and a femto cell deployment density of 500 is now shown to be almost sufficient to reach the target 10 Mbit/s network KPI.

- In the last case, '3.5GHz Micro & Femto Inband', the full 200 MHz of 3.5GHz TDD spectrum is shared between the micro and femto layer. It is shown that the outage performance is just slightly worse for the 10 Mbit/s Key Performance Indicator (KPI) and slightly better for the 1 Mbit/s KPI compared with the previous case.

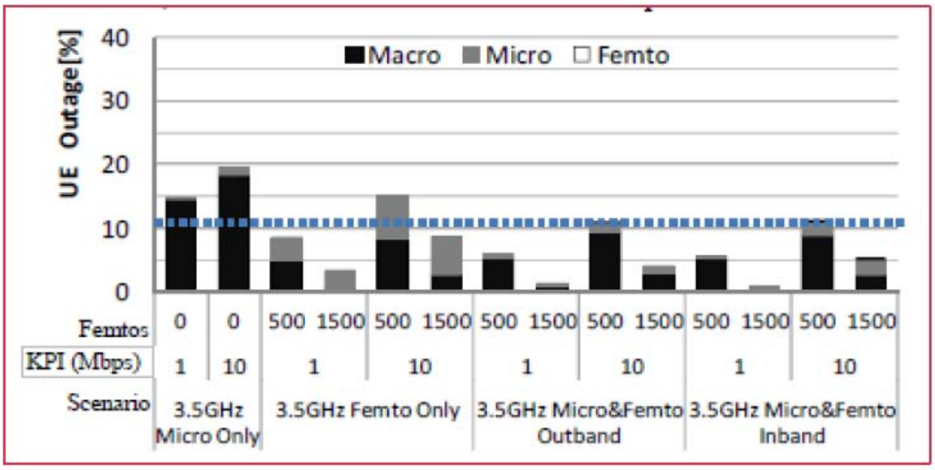


Figure 23: Multi-layer user outage for various 3.5GHz spectrum allocations (*Source: Fig 3 in reference paper [3]*).

The paper concludes that the 1000 times network capacity increase together with the 10 times increase of minimum user data rate can be reached by LTE-Advanced deployment with approximately 10 times more outdoor micro sites and 100 times more indoor femto cells with respect to the number of macro sites, provided that significant new spectrum is available.

It is concluded that new spectrum at 3.5 GHz is essential to reach the set target network capacity. Also based on the observations for a three-layer HetNet scenario with the relative densities of cells in the analysis then the paper recommends using dedicated spectrum with almost equal amount of spectrum for all the layers.

[redacted]

<u>Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030. Produced by Real Wireless on behalf of Ofcom, April 2012 [16]</u>

This study was conducted in order to determine the benefit that additional spectrum, notably a potential 700 MHz band, might play in meeting growing demand for wireless broadband capacity over the next 10 to 20 years. The role of additional spectrum is considered against the background of a wide range of other capacity enhancing techniques – including LTE-Advanced and small cells.

The analysis determined the extent to which the addition of spectrum (primarily 700MHz) would affect the cost of delivering wireless broadband in the UK. It considered:

- Existing mobile spectrum plus 800 MHz and 2600 MHz as a baseline in 2012

- Expected growth in the (spectrum and productive) efficiency of mobile technologies and topologies over the period
- A range of possible scenarios for the growth in quantity and nature of UK demand over the period.

The whole of the UK market and costs incurred by society as a whole were analysed rather than examining the view of any individual operator. Three study regions were used to represent urban, suburban and rural environments, between which the capacity/cost tradeoffs were significantly different, but which taken together comprise a significant portion (around 6%) of the overall UK demand.
Figure 24 shows one of the results comparing the percentage saving in costs for each of the three environments dependent on the timing of 700MHz spectrum introduction, relative to that spectrum never being available.

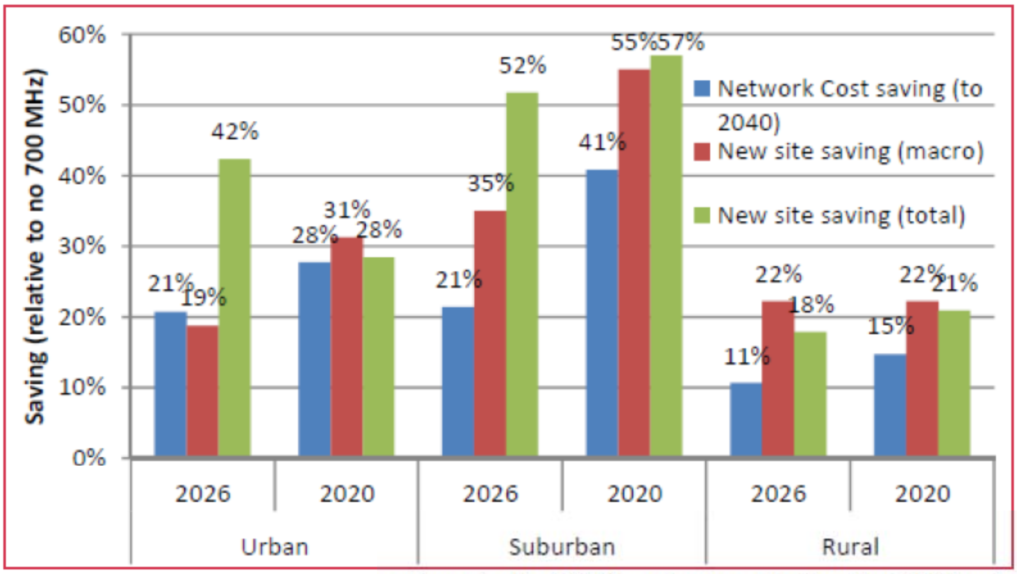


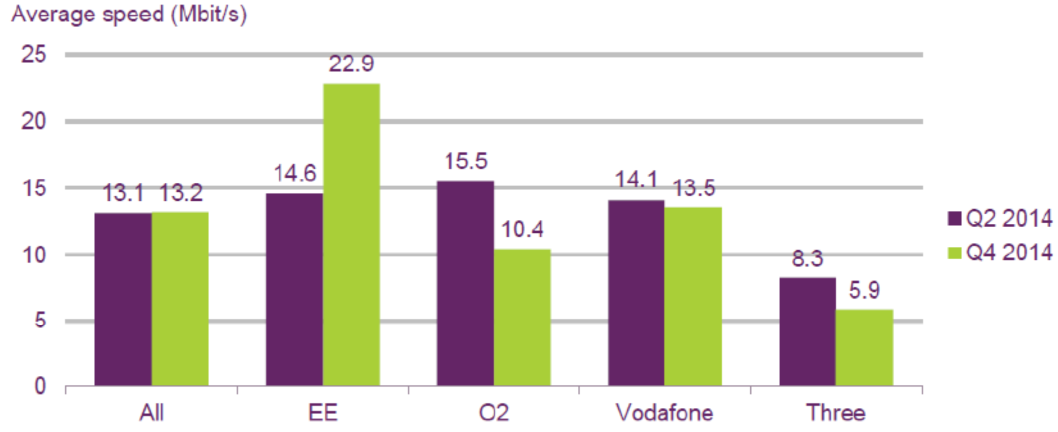
Figure 24: Relative savings in network costs (to 2040) and new cell sites (by 2030) arising from the availability of 700 MHz in 2020 or 2026 (mid demand and mid capacity scenarios) - (*Source: Figure 0-4 in reference paper [16]*).

Considering in particular the results for the urban and suburban area which are expected to be more capacity than coverage constrained, it is possible to infer from the analysis that [redacted]

[redacted]

7.1.3 Average User Throughput

This section considers whether there is a material difference in the user throughput that can be offered to customers by operators with less spectrum and if it is possible for any deficit to be compensated by additional site build. Essentially this is assessing the ability of a spectrum deficient operator to deliver an acceptable and competitive speed to its customers.
Clearly user throughput, network capacity and achievable peak speeds are all inter-related, but it is also important to make distinctions between them. After coverage, then arguably it is the 'minimum' or 'average' throughput that matters most to a MBB customer rather than network capacity or even headline peak speeds. Operators and regulators often consider the 'minimum throughput' or 'average throughout' offered to customers as one of the key mechanisms to define a customer's experience. Indeed, Ofcom have recognised this and include average download and upload speeds as one of the key metrics in its MBB performance reports.



Source: Ofcom mobile broadband measurement, fieldwork March to June 2014 and October to December 2014
Note: Average (mean) of all 4G tests, by operator. All differences are significant to a 95% confidence level.

Figure 25: Average 4G HTTP download speeds, by provider, in London
(Source: Ofcom MBB Performance Report [26])

Figure 25 shows the 4G download speed results from the April 2015 Ofcom MBB Performance report [26] for London. This highlights a significant difference in speeds between EE and the other operators particularly in Q4 2014 after EE has claimed to switch on its 'double speed' 4G and 4G+ network in London [27] which uses some of its additional 1800 and 2600 spectrum respectively. Of course other factors such as depth of coverage, traffic levels and volume of site rollout can also play a part in the differences.

To investigate this further an analysis of external papers and published works has been undertaken to further understand the spectrum vs site densification trade off as it relates to user throughput and speed.

Tradeoff Between Spectrum and Densification for Achieving Target User Throughput, Yanpeng Yang and Ki Won Sung, VTC Spring 2015 [28]
This paper investigates the trade off between base station density and volume of spectrum to achieve individual user throughput targets in wireless networks. The work takes into

account a load-dependent interference model and various traffic demands. It then determines the combinations of base station density and spectrum bandwidth which allow at least 95% of the users to achieve the target.

The simulation considers a square grid with uniformly distributed base stations and users, which is shown in Figure 26. The mobile users (represented by dots) are associated with base stations (circles) according to the highest Signal to Interference Ratio (SINR), as shown by the different colours. The densities of the Base Stations and Users are represented by λb and λu respectively.

REDACTED

Figure 26: Network Layout for Simulation *(Source: Reference paper [4])*

[redacted]

REDACTED

Figure 27: BTS Density vs. Spectrum Trade Off – Sparse area *(Source: Fig 5a in [44])*

[redacted]

REDACTED

Figure 28: BTS Density vs Spectrum Trade Off – Sparse area *(Source: Fig 5a in [4])*

[redacted]

In this study the dense area is defined as the point where the λb > λu, i.e. the density of base stations is greater than the density of users. Although this may be appropriate in the future, in current networks, the base station density exceeds the user density only in some parts of the network at certain times of day. Examining the curves for the sparse area as the Ratio (x axis) increases from -1 toward 0 indicates a similar trend that increasing the Base Site density gives a disproportionately lower benefit than increasing the volume of spectrum.

Case Study: Reduction of spectrum holdings and its impact on the number of 2G cell sites [29] – and Part 2 [30]. 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. A study was commissioned and undertaken by Red-M to understand the impact on the GSM network of removing different levels of GSM900 spectrum.

The analysis was a 'simulated' design exercise for three areas of the country in order to help Ofcom build a picture of the number of additional GSM900 macro cell sites that would be required as the amount of spectrum available was reduced. The work was broken into two reports. In the first [29]two areas were chosen by Ofcom:

- A 10km by 10km square of North London
- A 28km by 28km square centred around Burton-on-Trent in Staffordshire.

A third area was added in the 2nd report [30] which was chosen to be representative of the UK as a whole:

- A 25km by 25km square of the south-west of England including Bristol, Bath and rural areas.

The simulated design exercise was repeated five times for each scenario with reducing amounts of spectrum. Starting with a baseline, 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. These objectives did not vary as the amount of spectrum was reduced. The third area also had some sensitivity analysis conducted with changes to traffic density and power levels.

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

<u>Assessment of future mobile competition and awards of 800MHz and 2600MHz, Annexes 7 – 12, Ofcom, 24 July 2012 [31]</u>

This document presents the key results from Ofcom's technical analysis of the performance of LTE macrocell networks using paired spectrum which was conducted as part of the preparation for the 800 and 2600MHz spectrum awards that occurred in Q1 2013.

Comparison 2 in the analysis looks at the performance of two different spectrum portfolios as follows:

- 2x15 MHz @ 1800 MHz plus 2x20 MHz @ 2600 MHz;
- 2x15 MHz @ 1800 MHz plus 2x10 MHz @ 2600 MHz.

The results were derived for the 0-50% and 50-80% population simulation areas for both shallow and deep indoor locations, hence four sets of results, but only one is reproduced here in Figure 22 (the case for 0-50% population area for deep indoor coverage) as they all exhibit a similar trend.

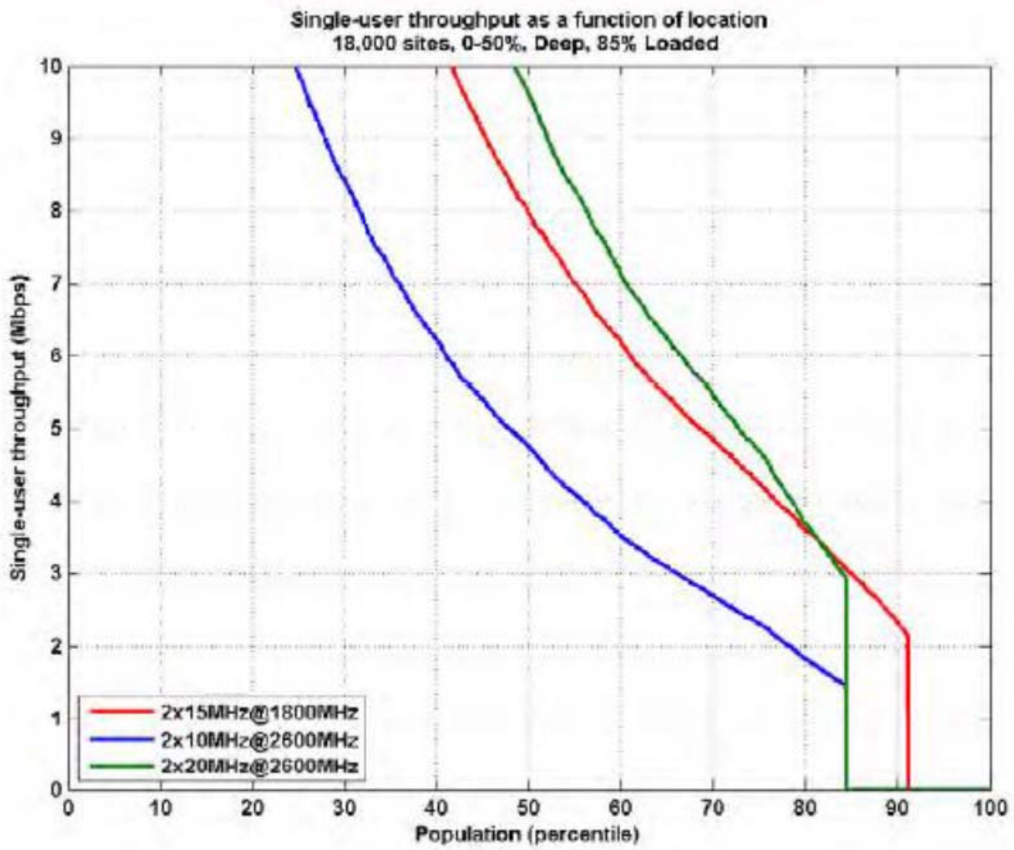


Figure 29: Single User Throughput results for different spectrum allocations, 0-50% population area, deep in-building penetration. ***(Source: Ofcom – Fig A7.49 in Ref [31]).***

At the 50% population percentile, it can be seen that the case with 2x20MHz@2600MHz spectrum provides double the user throughput compared with the case with 2x10MHz@2600MHz spectrum. All the curves give similar results highlighting, as would be expected, that doubling the spectrum allocation results in a doubling of the user throughput. Only a slight decline in this trend is noticed towards the edge of the cell, beyond ~80% population.

A similar trend is visible with Comparison 1 and 3 from the paper, which amongst others includes allocations of 2x10MHz@800 vs 2x15MHz@800 and 2x20MHz@2600 vs 2x40MHz @2600 respectively. Figure 30 shows some results from Comparison 1 for the shallow in building penetration case of 0-50% population zone. Looking at the 800MHz curves (red and green) a 50% increase in user throughput can be observed when the spectrum bandwidth increases by 50%.

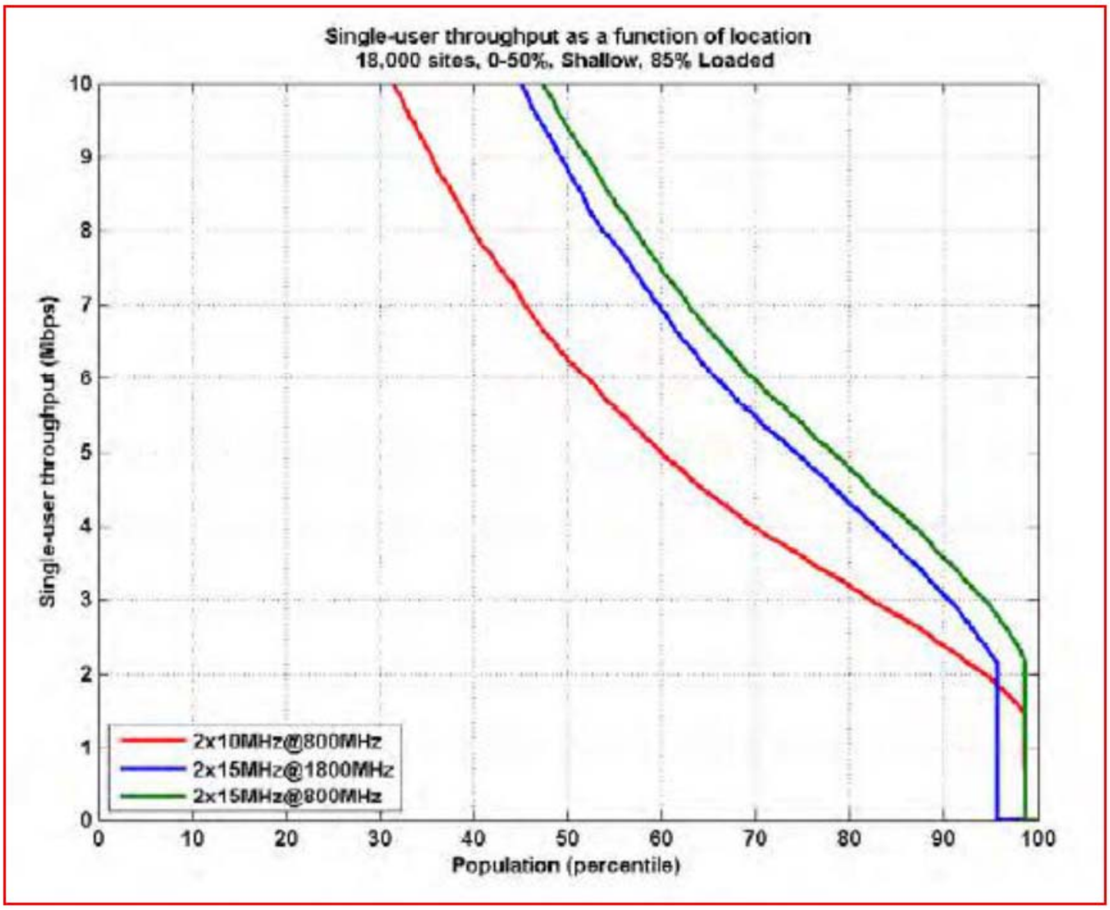


Figure 30: Single User Throughput results for different spectrum allocations, 0-50% population area, shallow in-building penetration. ***(Source: Ofcom – Fig A7.44 in Ref [31]).***

Elsewhere in the report results are provided for analysis with two different volumes of base sites, either 12,000 sites or 18,000 sites. Results for these two cases for the 0-50% zone, shallow indoor penetration and 85% load are shown in Figure 31 and Figure 32 respectively. Note that in the analysis each frequency band has the same volume of spectrum. Taking one of the bands as an example (say 2600MHz) and, say the 50% population percentile, it can be seen that the Single User Throughput only increases from around 4.5Mbit/s with 12,000 sites to 5.5Mbit/s with 18,000 sites.

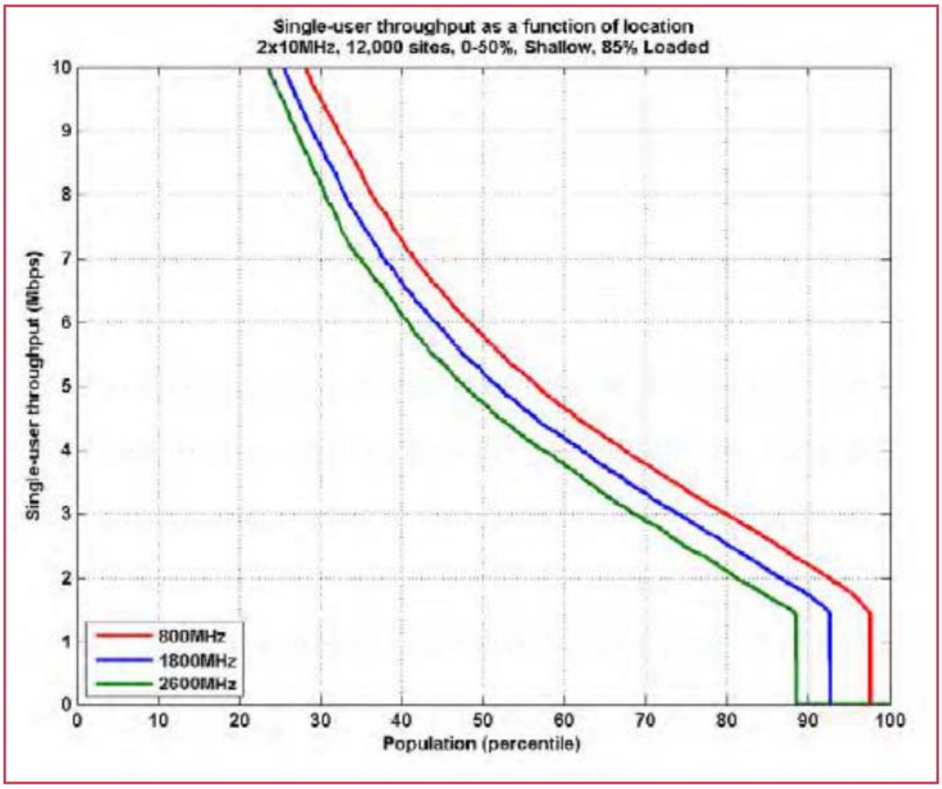


Figure 31: Single User Throughput results for 12000 sites, 0-50% population area, shallow in-building penetration. ***(Source: Ofcom – Fig A7.11 in Ref [31]).***

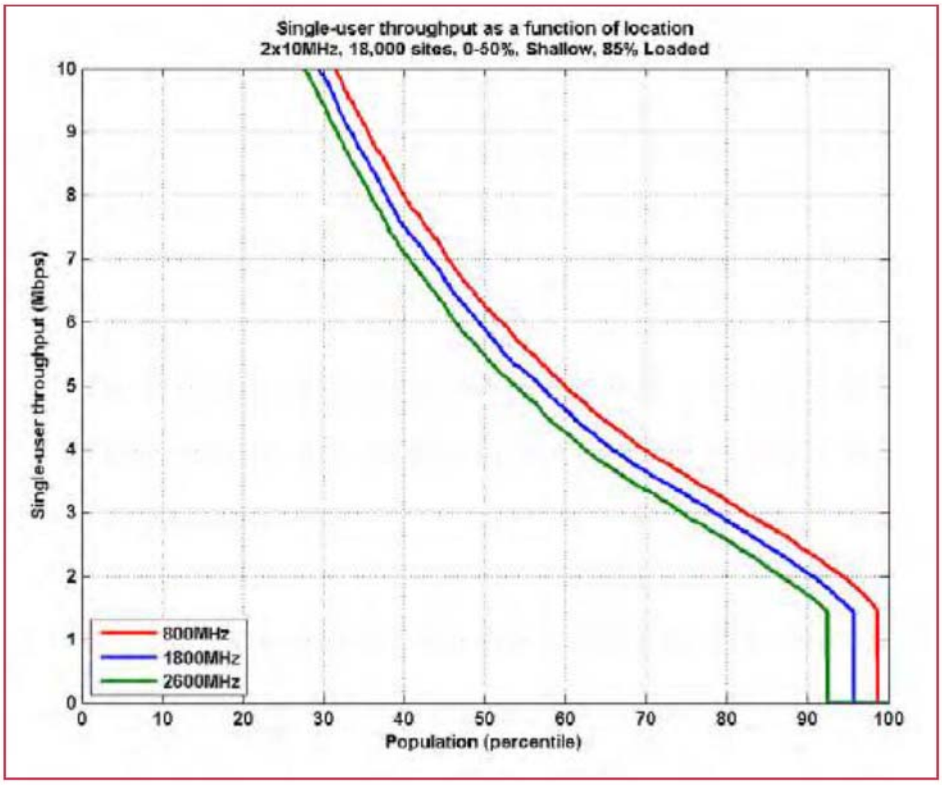


Figure 32: Single User Throughput results for 18000 sites, 0-50% population area, shallow in-building penetration. ***(Source: Ofcom – Fig A7.21 in Ref [31]).***

[redacted]

[redacted]

7.1.4 Practical Aspects

Previous sections have considered whether an operator with substantially less spectrum could 'in theory' match the user experience of an operator with a much larger spectrum holding by significant network densification. Although not really technical in nature, one critical aspect that must not be overlooked is an operator's ability to physical achieve this in practice. Broadly speaking it is relatively quick, easy and cheap to add further spectrum to an existing base station, however network densification typically requires new base station sites to be built and this can be very difficult, time consuming and expensive. In some city areas, especially London, it is extremely challenging indeed.
Subsequent sections will briefly review what is typically required to undertake each activity:

- Add Spectrum
- Network Densification

<u>Deploying Additional Spectrum</u>
In its most simple form adding additional spectrum to one or more existing base station sites, can be as easy as enabling through software parameter changes, which can be done remotely via the operator's OSS (Operation Support System). This would be the case for example where the frequency band was already supported on the site, with hardware already in place and simply the spectrum bandwidth was being increased. Examples might be extending from 2x10MHz to 2x20MHz at say LTE1800, or extending 2x20MHz at 2600 with a second 2x20MHz at LTE2600.
In these cases the antenna and Radio Frequency (RF) base site infrastructure would already be prepared for the additional spectrum, and it assumes that the RF power amplifiers and baseband processing had sufficient capacity available to support the extra bandwidth. If this was not the case then it may be necessary to add additional baseband processing modules and potentially add or upgrade the power amplifiers.
For more complex upgrades, in particular where a totally new frequency band was being added then it may be necessary to upgrade, change or add to the antenna systems as well as add additional base station hardware. In many cases base station antennas are now

wide band, with low band elements (covering 700MHz to 1 GHz) and high band elements (covering 1800MHz to 2600MHz) so existing installations may be future proofed to some extent to support new bands.

Depending on the traffic levels it may be necessary to upgrade the backhaul transmission solution as well to support the additional capacity.

In terms of cost, a guide can be obtained from reference [32] where Section 1.3.4 assumes a capital cost of £13,000 per site for this type of upgrade requiring RF/antenna changes.

Typically, the implementation time can vary from almost instant (overnight) for upgrades via parameter changes to potentially several months if antenna changes are needed. Clearly there can be extreme cases with planning and landlord issues, etc., but in general adding additional spectrum to existing sites should be a relatively quick and inexpensive process.

Network Densification

There are various techniques that can be used for Network Densification, the 3 most common being:

- Macrocell build
- Higher order sectorisation (e.g. 6 sectors)
- Small Cell deployment

Macrocell Build

Network densification via further macrocell build is the most common and straightforward option, arguably bringing the biggest benefit, but it can be expensive and very difficult to find and build new macrocell sites. This is especially true in cities, where traffic growth is the highest.

Site acquisition is one of the major challenges. This can take many years, proving very difficult and in some cases perhaps almost impossible to acquire suitable new macrocell sites in city centres. Typically, these types of deployments require very long term planning, with operators needing to forecast several years ahead when and where they will need to build new sites, so that the necessary projects can be established well in advance of the sites actually being needed. Planning for the vagaries of traffic growth and location can in itself be quite challenging. In addition to this, the pace and scale of new developments in cities such as London result in even more pressure on mobile networks where sites have to be removed from existing developments (Notice to Quit or NTQ's) whilst at the same time additional capacity is required to deliver services to users in the new office and residential space created.

An example of the challenge of site deployment can be seen with the Government's recent £150 million Mobile Infrastructure Project (MIP) [33, 34]. This started in 2013 and was due to deploy 600 new base stations to target 'not spots' in rural areas. At the end of November 2015, it had delivered just 15 sites, and was expected to build around 75 sites, a mere 12% of the target, by the time it closed in March 2016. Although the project was tasked with improving coverage in rural areas, not densification in high traffic (city) areas many of the challenges with site deployment are similar. In fact it can be argued that deployment in cities can actually be harder with the need to be much more precise with the site location.

Citi Research also comment about the difficulties of deploying mobile infrastructure in the UK in their 'Letter to Ofcom, dated July 2015 [35]. The article encourages Ofcom to "lend its support to addressing the numerous obstacles to improving the UK's substandard mobile infrastructure." The article states that:

"The UK has the most restrictive planning regime of any in Europe, the highest site costs and rents, and the most restricted access to sites than anywhere in Europe."

Citi Research argue that Government support may be needed more generally, to ensure that significant participants like the planning regime, local councils and Network Rail align their priorities to support the industry in deploying higher cell densities for effective 4G networks. By way of example it mentions that:

"Vodafone's Project Spring is less advanced in the UK than any other country in its extensive footprint. London's cell density (3G sites per sq km) is less than half of other major European cities, and mast heights are up to one third less. These shortcomings lead to poorer signal availability and depth and (ironically) having to operate the cells at higher power levels."

Although steps are now being taken to improve the planning regulations and permitted development rights [34], it is not so clear that these will make network densification in city areas significantly easier. Landlords and building owners are not obliged in any way to accommodate the infrastructure required and therefore the acquisition challenges will remain.

The cost of deploying macrocells is also high, and significantly more expensive than adding additional spectrum. Table 8 and Figure 33 provide the site cost and breakdown assumptions that were used for the study on 'Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030' [16]. Typically, macrocell site costs in cities tend to be higher than average, particularly for aspects such as site rental.

New Macrocells		Low	Medium	High
Capital expenditure	Greenfield	66,000	112,150	245,400
	Rooftop	53,850	82,950	141,250
	Street furniture	31,325	37,825	57,825
	Ofcom.*	*75,000*	*105,000*	*140,000*
Operating expenditure	Estimated average	18,850	18,850	18,850
	*Ofcom**	*7,500*	*10,500*	*14,000*

*Note- * Ofcom figures were for comparison and came from: "Application of spectrum liberalisation and trading to the mobile sector" http://stakeholders.ofcom.org.uk/consultations/spectrumlib/, February 2009.*

Table 8: Macrocell New Build Cost By Installation Type – *(Source: Reproduced from [32])*

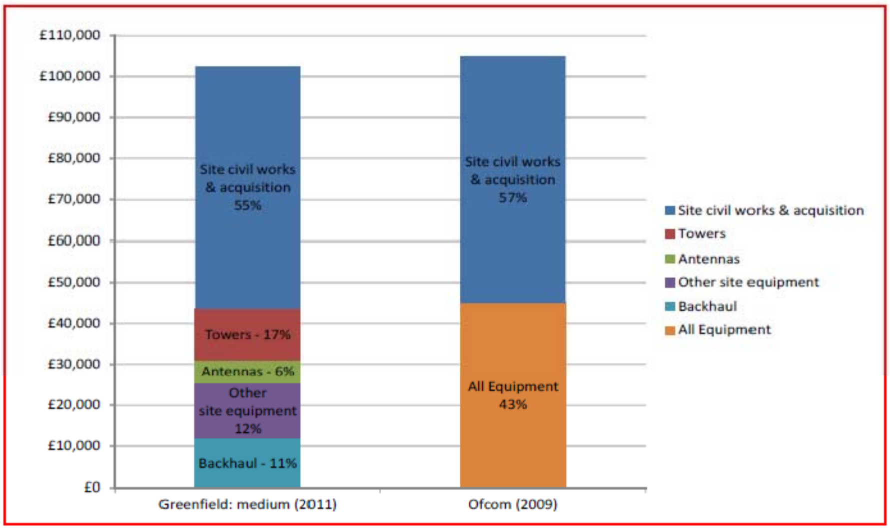


Figure 33: Breakdown of macrocell costs. ***(Source: Reproduced from [32]).***

Higher Order Sectorisation

Most macrocell sites are initially deployed with 3 sectors, but increasing the number of sectors on a base station is another form of network densification or cell splitting. This does not require the rollout of new base stations and is often known as higher order sectorisation, with 6 sectors being the most common implementation.

A 6 sectored site configuration should result in improved coverage and capacity compared with 3 sectors. The better coverage coming from the higher antenna gain and the extra capacity resulting from the use of more sectors. In theory increasing from 3 to 6 sectors should double the site capacity, but in practice this is not achievable due to various factors including the increase in inter-cell interference, distribution of users and traffic, increase in handovers, accuracy of site planning and antenna azimuth optimisation. Studies such as [36] show that capacity gains of around 70-80% are predicted with simulations, although this can vary with the local topology, location of traffic, and an average capacity gain of around 50% is probably a more realistic goal.

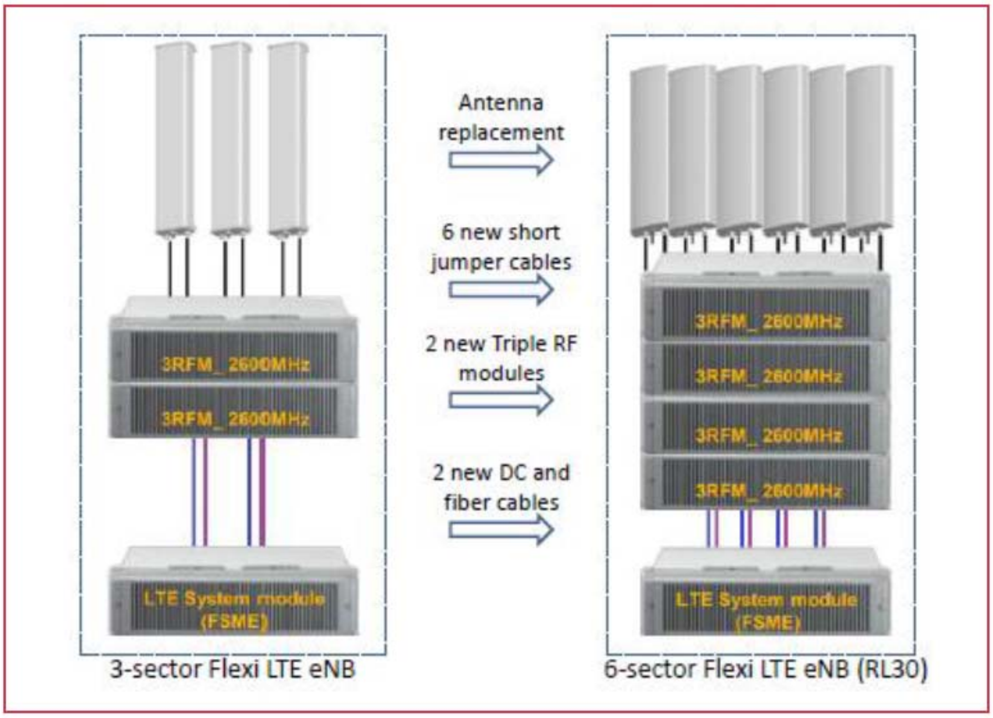


Figure 34: Example upgrade using Nokia Networks' 3 sector and 6 sector Flexi LTE eNode B and RL30 SW. *(Source: Reproduced from [36]).*

Typically, a six sector upgrade requires a significant amount of re-engineering work to the site and the need for additional base station equipment. This can be time consuming and typically will require landlord approval (with the inherent acquisition risks and associated timescales) and potentially further planning permission if the number of antennas is changing. It can also be challenging to deploy if not all the technologies or frequencies on the site are being upgraded to 6 sector operation, as the site then needs to be engineered for both 3 sector and 6 sector, typically with separate antennas for each configuration. Reference [36] provides the example in Figure 34 and initially comments that "there is an uncertainty on whether the capacity gain is high enough to justify the extra costs of the additional equipment and, more specifically, whether the 6-sector-site deployment is more economically attractive than a 3-sector-site deployment." However, it concludes that "with the parameters and the assumptions that were considered in the study, the adoption of 6-sector sites along with 3-sector sites in LTE macro-cell deployments allows service operator to reduce capital expenditures compared to only the adoption of 3-sector sites."

Overall the use of higher order sectorisation, in particular 6 sector sites, can provide a useful capacity benefit, but the re-engineering and landlord/local authority permissions required is non-trivial and it is not likely to be able to compete on cost or performance grounds with adding additional spectrum.

Small Cells

The use of small cells or 'microcells' is the other common form of network densification. Typically outdoor small cells are deployed when the use of cell splitting via macrocells has been exhausted. Small cells usually have antennas mounted down in the 'street canyon' well below average roof top height, and because interference is contained they allow a much denser network to be created.

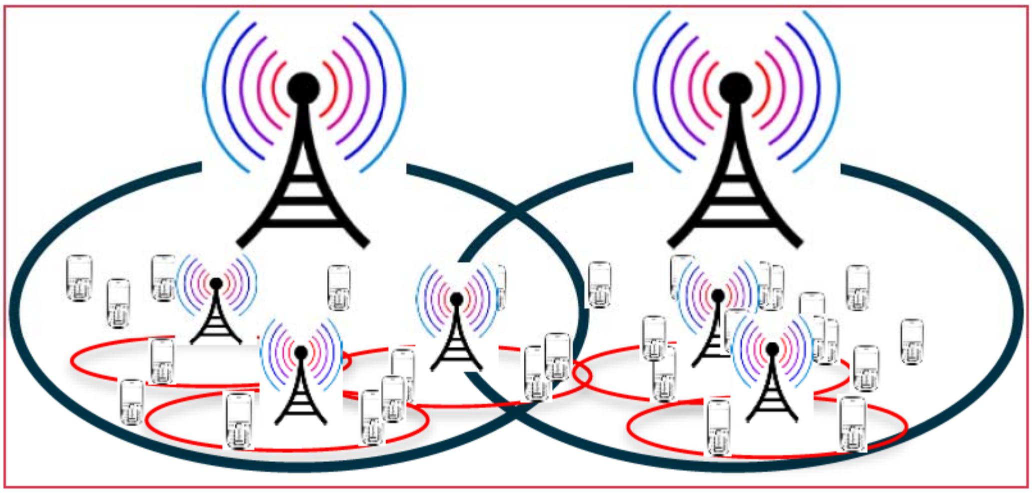


Figure 35: Schematic - HetNet with Macrocells and Outdoor Small Cells.

Whilst small cell deployments have been talked about for years, the actual volume of deployments is still quite modest, especially in street environments. This points to the fact that the business case for small cells remains weak, with such deployments still being very expensive and very time consuming to execute.

The main challenges with small cell deployment are described in [37, 38] and include:

- **Placement** - The radius of an outdoor microcell is typically only 50 metres or so, therefore it is very important to locate the small cell very close to the traffic source (or hot spot) to ensure it provides the expect benefit. Identifying the location of the traffic hot-spot can often be a challenge.
- **Site acquisition** – Once the traffic location has been identified then a suitable location has to be found and acquired to position the small cell. This could be a piece of street furniture such as a lamp-post or the side of a building. Street furniture seems like a good solution, but often 'real estate' companies have already negotiated large deals with local authorities and then demand high fees from operators which can make these solutions cost prohibitive. Deals involving individual property facades for small cells can take as much effort as for a macrocell, which can make the whole process expensive and very time consuming.
- **Backhaul** – This can be a major challenge, especially for street furniture installations which do not have ready access to fibre. Often fibre might only be a few tens of metres away, but it can be expensive and time consuming to get the necessary way-leaves and deploy to the exact location of the small cell. A range of wireless solutions are now becoming available which should ease the problem, but of course they add further capex.

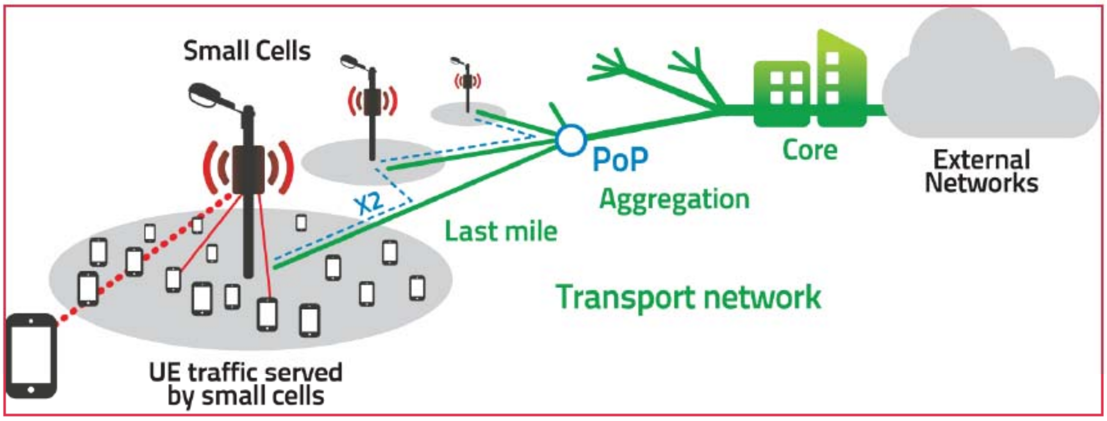


Figure 36: Example small cell architecture and backhaul topology *(Source: NGMN Alliance).*

- **BTS Hardware solutions** – Until recently the range of suitable small cell base station equipment was quite limited, especially from the major equipment manufacturers. Equipment mounted on street furniture or a building facade needs to be compact and light, typically less than 10 litres in volume and 10kg in weight. Outdoor solutions need to be relatively high power – typically 5+5 Watts to ensure sufficient cell range to give dominant coverage and traffic capture, especially if they are sharing spectrum with the macrocell layer and also need to provide in-building coverage.
- **Power** - As well as backhaul, often bringing power to microcell sites can also be a challenge. Whilst street furniture, such as lamp posts, often have power sometimes it is not possible to draw sufficient current, or it is controlled centrally, e.g. only live when the streetlights are illuminated. Therefore, power delivery can bring further complexity, cost and delays to small cell deployment.
- **Inter-operability** – small cell solutions need to be designed to interwork with the macrocells and any in-building solutions. This means the ability to handover, balance traffic between layers, potentially transfer high mobility customers to the macrocell layer and manage resources and interference between layers. Typically for best performance this requires a high degree of interaction between the cell layers.
- **Cost and Business Case** – Typically a small cell might provide 10% of the coverage of a macrocell and capture 10% of the traffic. By extension therefore it should also cost no more than 10% of a macrocell to be economic. Table 9 shows the small cell costs that were cited in the study in reference [16]. Comparing this with Table 8– in particular the 'rooftop' entry - shows that the 10% guideline is often exceeded.

Capital expenditure category	Cost per site
Site civil works & acquisition	£3,550
Other equipment	£3,300
Backhaul	£6,000
Total	£12,850

Table 9: Small Cell Cost Breakdown – *(Source: Reproduced from [16])*

In view of the challenges listed above most operators favour the use of macrocells, only turning to small cells as a last resort. An operator with a large allocation of spectrum which is readily deployable on the macrocell layer can avoid many of these challenges. Also it is more complex to manage a network with a larger number of sites and network layers versus a network with a simpler architecture and more spectrum.

<u>Summary of Practical Aspects</u>

Overall it can be seen that there are numerous practical challenges with network densification. These put an operator with significantly less spectrum at a major disadvantage as they will incur substantially more deployment cost and take significantly longer to rollout a dense network, compared with an operator who simply needs to add spectrum to existing sites.
The extra sites will all be needed in cities where it is very difficult to acquire new sites - and it takes a very long time (many years). Micro/Small cells could be used but again they are expensive, difficult to acquire and the backhaul is still a big challenge. Also it is more complex to manage a network with a larger number of sites vs a network with more spectrum.

7.2 Summary of findings

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:

- **Add spectrum** – either through additional spectrum acquisition or re-farming.
- **Enhance technology** - to improve spectrum efficiency, e.g. with higher order MIMO, interference mitigation, increased modulation schemes, etc.
- **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.

We then considered whether it would be possible for an operator with less spectrum to deliver an equivalent level of customer experience as one with a much larger spectrum holding through significant network densification. This aspect of the study was conducted primarily through a literature search and was broken down into several categories which all impact the user experience. These points and the key conclusions are as follows:

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

- **Capacity – effectiveness for dealing with traffic growth.** Four published papers were examined and taken together they demonstrate that [redacted]

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

[redacted]

8. Annex C: Comparison of different modelling approaches

In this section 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 for our analysis.

8.1 Comparison of different modelling approaches

We identified two different simulation methods that may be used to provide insights and establish an answer to the principal question we sought to address in this study:

1. "analytical microcell" modelling approach
2. "optimised macrocell" modelling approach

The following sections provide details about these two methodologies.

8.1.1 "analytical microcell" modelling approach

The first modelling method we evaluated was the "analytical microcell" modelling method which brings a level of insight into the tradeoff between spectrum and site densification. The analytical microcell modelling method requires the application of a system level simulator to evaluate a limited number of cell sites within a mobile network. A system level simulator is typically used to evaluate technologies that are implemented within a wireless communications network. It includes a simulation resolution appropriate to evaluate packet level scheduling to emulate how packets are scheduled on a per user basis for a specific and/or mixture of services. This modelling approach enables investigations of packet behaviour across the network including the impact of packet delay, quality of service and throughput. The modelling method also provides analytical expressions enabling the opportunity to analyse the problem with different parameter values such as base station use ratio etc. With such a capability the trade-off between spectrum and site densification may be evaluated Yang et al. [39]. An overview of the modelling approach is shown in Figure 37.

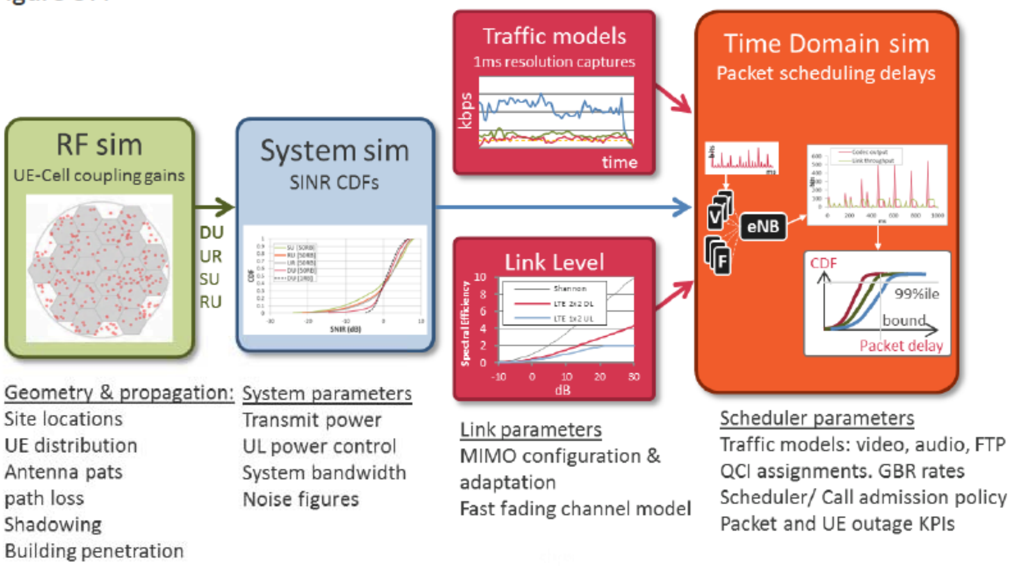


Figure 37: Overview of the modelling approach

Below we list the strengths and weaknesses of this modelling approach:

Strengths- 'Analytical microcell' modelling approach

- The modelling approach brings a level of insight into the trade-off between spectrum and site densification. The analytical expression provides the opportunity to analyse the problem with different parameter values such as base station usage ratios.
- Provides analytical expressions to establish different parameters such as the optimum physical resource block (PRB) utilisation for each cell. Analytical expressions provide an opportunity to evaluate the performance of different scenarios whilst optimising the length of simulations.

Weaknesses- 'Analytical microcell' modelling approach

- Although, it is possible to implement packet scheduling behaviour similar to that of a real network, detailed level implementation of user behaviours and simulation of multiple users with a packet scheduler requires a long simulation time. Practically it is not possible to simulate wider areas with thousands of base stations with this level of system abstraction. A small area with ~10 base stations whilst providing some insight will not provide sufficient variations to represent a national view of a mobile network.
- Approximations required for the analytical expressions will deviate from the real world implementations. Approximations used for the modelling of a low number of cells may diverge from a meta-view of a National Level network.

8.1.2 "optimised macrocell" modelling approach

The Optimised macrocell methodology provides a simulation platform that shows the average view of a capacity limited mobile network across a large area. This modelling approach does not look in to the details of how the packets flow through the network. It simply emulates the effect of a scheduler to give "fairness" to the multiple concurrent users at a high level. It provides the ability to perform a Monte-Carlo analysis of multi-user throughput on a capacity constrained network over a larger area. The larger area captures statistically relevant and sufficient variations across the Country so that it represents a national view of a mobile network.

Benefits- 'Optimised macrocell' modelling approach

- The Optimised macrocell methodology considers real world aspects, such as user distribution and actual site locations across a large area etc. this results in results that are constrained by and extended from a real mobile network.
- The exclusion of packet level implementations provides a faster simulation time, hence provides a mechanism to simulate a much wider geographical area with a larger site count compared to the analytical approach mentioned in the previous section.

In the past Ofcom has used a simplified version of this modelling approach for the comparison of indoor coverage from different spectrum bands [40]. This provides a useful touchpoint for applicability of the outcome of studies grounded in this method.

Weaknesses 'Optimised macrocell' modelling approach

- The area where 0-50% of the population lives represents the most densely populated areas in the UK. However, this does represent a large geographic area where there is a representative mixture of clutter and population density. There are likely to be less densely populated areas within the geographic area. Network characteristics may be different in these areas.

8.2 A Summary of the Comparison of Methods

Table 10 provides a summary of the comparison between two modelling methods.

Analytical microcell		Optimised macrocell	
Strengths	**Weaknesses**	**Strengths**	**Weaknesses**
Analytical expression provides opportunity to analyse the problem with different parameter values such as base station to use ratio etc. which can optimise simulation duration.	A realistic implementations of users and a packet scheduling requires long simulation times. Practically it is not possible to simulate a wider area with thousands of base stations with this level of abstraction. However, small geographic areas with ~10 base stations will not provide sufficient statistical variation to represent a national view of a mobile network	Exclusion of packet level implementations provides a faster simulation time, hence it provides a mechanism to simulate a much wider geographical area with a larger number of sites. The larger area captures sufficient variations across the country so that it represents a national view of a mobile network	averaging across 0-50% population areas
Analytical expressions provide an opportunity to evaluate the performance of different scenarios without lengthy simulations	Approximations required for the analytical expressions will deviate from the real world implementations.	Considers real world aspects, such as user distribution and actual site locations across a large area etc., resulting in more realistic results similar to a real mobile network.	
Provides analytics of system level behaviour in cells and cells in proximity utilising a realistic scheduler algorithm, similar to that of a real network		The methodology is recognised and has been applied by Ofcom.	

Table 10: Summary of comparison between two modelling methods

The analytical 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. Further, the simulation includes real network parameters such as site locations, which constrains the scenario under analysis to typical network deployments. This simulation method has the additional merits of not requiring lengthy simulation times providing evaluation of the effects under study within a reasonable simulation run-time. For these reasons, we adopted optimised macrocell modelling.

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