Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030

Annexes A1 - A6
Produced by Real Wireless on behalf of Ofcom

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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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A1. Site Costs

1.1. Introduction and overall approach

This annex sets out the approach, assumptions and sources of data we use in our cost model to estimate the costs that feed into our evaluation of the capacity enhancing techniques studied in this project. It covers both our approach to calculating the cost inputs used by the technical or study area models and the assumptions we use in our overall cost benefit assessment.

First we set out the overall framework for the cost modelling, explaining the type of costs we modelled. Then, we explain how we derived the costs for each of the capacity enhancing techniques.

1.2. Framework and general cost modelling assumptions

1.2.1. Outline of the costs estimated

We look at network costs only and do not cover retail costs. This is because retail costs are unlikely to vary significantly with the choices for increasing network capacity that are the main focus of this study.

The costs we estimate comprise:

- Annual operating costs
- Capital expenditure for new equipment
- Capital expenditure for replacement investment.

We estimate current costs\(^1\) and project forward in subsequent years by applying annual cost trends for broad equipment categories. We set out our assumptions below when we discuss the specific capacity enhancing techniques.

For replacement investment, we model a replacement cycle – for example, a unit of equipment deployed in year Y, will reach the end of its economic lifetime (and therefore is likely to need to be replaced) in each year Y + L, Y + 2L, ... until the end of the model period, where L is the economic lifetime of the equipment. Each replacement will incur a cost which will be the capital expenditure cost of a new unit of equipment in the year of replacement.

1.2.2. Modelling timeframe

Our modelling runs over the period 2012-2030. As a result, the model may not fully capture the cost impact of capacity enhancing techniques that are introduced towards the end of this period. This is because capital expenditure costs are incurred up front and the lifetime of some elements of expenditure may be long, e.g. 30 years for some civil works.

---

\(^1\) Most of the starting cost data are estimated for 2011 and then converted to 2012, the start of the model period, by applying a cost trend, some costs are estimated for 2012.
Therefore, in terms of the cost modelling, we “extend” the cost model for an additional 10 years to counter this bias against techniques introduced late in the model period. This means that we keep demand constant beyond 2030 so no completely new equipment is installed, and we measure the operating costs plus the costs of any replacement investment for existing equipment in that period.

1.2.3. Equipment costs are modelled explicitly, software upgrades implicitly

Many of the capacity enhancing techniques we study require changes in the network and hence additional equipment and potentially site related build works. Some techniques are explicitly modelled as operator choices, hence we explicitly estimate costs for the following:

- Macrocell densification
- Increased sectorisation (from 3 to 6 sectors per cell)
- Deployment of higher order MIMO (from 2 transmitters (Tx) to 4Tx and from 4Tx to 8Tx)
- Outdoor small cell deployment

We have assessed a number of other capacity enhancing techniques (listed below) which, unlike those mentioned above, largely require upgrades to software rather than additional equipment.

- LTE Advanced
- Carrier Aggregation
- Co-ordinated Multipoint (CoMP)
- A range of future, as yet unspecified, technologies as notionally standardised in 3GPP Releases 12 to 20, for which we model increases in spectral efficiency.

We model these techniques “implicitly” – i.e. we assume that they will be introduced automatically and do not model them as an operator choice in the technical model. So, we specify technology evolution scenarios which detail when these techniques are introduced and how spectral efficiency increases as a result. We assume that these technologies diffuse into the network as equipment is replaced and the costs are included within equipment costs as they evolve over time.

We specify three technology evolution scenarios with varying rates of new technology deployment, but we assume that costs trends are the same in each scenario. Hence in the faster innovation scenarios can be read as representing a scenario where operators (and consumers) get greater functionality for the same expenditure. There is a number of factors that may affect how technological progress impacts on the unit costs of equipment and it is uncertain what the overall effect might be. For example, higher research expenditure (and higher equipment costs) could lead to faster innovation, but not necessarily so.

1.2.4. Cost inputs for the technical model

The main capacity enhancing techniques that we explicitly model comprise a number of macrocell related costs, including upgrades to macrocell technology, the deployment of outdoor small cells and the deployment of additional spectrum bands.

For macrocells and outdoor small cells, the input for the technical model we estimate is the total cost per site. We identify the type and number of equipment components necessary
to implement that technique at each site. When we discuss the individual techniques below, we set out the breakdown of our total cost estimates.

The total cost per site feeds into the technical model, which calculates the number of new sites and/or upgrades to existing sites required to implement a particular technique. This enables the technical model to calculate the optimal technology to deploy in each modelling period, i.e. the lowest cost way of meeting capacity demand.

There are two exceptions to this:

- First, indoor smaller cells (femtocells, picocells, Wi-Fi access points) are modelled through their impact on demand – i.e. demand is off-loaded from the public mobile network and the demand needed to be met by macrocells and outdoor small cells is correspondingly reduced. However, there is still a cost to deploying indoor small cells, hence we calculate this separately from the cost of the public network.
- Second, spectrum related costs are treated differently. We input the cost of upgrading existing macrocell sites to carry new spectrum bands to the technical model, however we do not input the cost of acquiring new spectrum. Hence, we add back in the spectrum costs once we have run the technical model in order to assess whether adding a new spectrum band would be cost efficient.

We treat spectrum costs in this way because operators base their decisions to buy spectrum over a long time period, say 15 to 20 years. This does not fit well with the much shorter decision period, 12 months, which we use in the technical model.

1.2.5. We estimate the costs to society

Our default position is to assess costs to society. This means that we use a social rather than an operator discount rate when calculating the present value of costs (and benefits) in our scenarios. Further, we include any costs that consumers may incur from self-provision of equipment as well as those operators incur. This fits in with a regulatory perspective which is interested in the costs (and benefits) to society of decisions that could impact on wireless broadband capacity.

However, we also recognise that operator decisions on equipment and technology deployment do not take into account the wider costs to society. So, we carry out limited sensitivity checking by using a commercial rather than a social discount rate.

In theory, the treatment of indoor small cells and spectrum could be different. However, for femtocells, we assume that operators will take into account the cost of the femtocells or Wi-Fi access points in their decisions – we see today operators who supply femtocells to the user who pays for the femtocell directly, or indirectly through increased monthly charges. Further, we assume that the extent to which users will need to upgrade their fixed broadband connection as a result of deploying a femtocell, is likely to be limited. So, a difference does not arise between the operator view and the base assumptions for the societal view.

On spectrum costs, we have taken a relatively simple approach to estimating the cost of spectrum – benchmarking on relevant auction prices. We consider that this is a reasonable estimate for the value of the spectrum both to society and to an operator. We believe this
apparently simple approach is appropriate given that estimating the value of spectrum is not the main focus of this study.

1.3. Costs of capacity enhancing techniques

This section sets out our modelling of the costs of each capacity enhancing technique that we explicitly model, detailing our approach and sources, and summarising our estimates.

1.3.1. Techniques relating to macrocells

This section discusses macrocell densification, higher order MIMO and increased macrocell sectorisation. We have estimated the costs as far as possible on a common basis, since the type of equipment upgrades, if not the number of units required, will be similar.

In order to model the costs of these macrocell related techniques we need to estimate four types of new build costs and three types of upgrade cost as shown in Figure 1-1 below. We also estimate an upgrade cost for adding new spectrum bands to existing sites, also as shown in Figure 1-1.

Finally, there are those spectrum efficiency enhancing techniques which we assume largely require software upgrades and are implemented automatically as existing equipment is replaced – e.g. carrier aggregation.

Figure 1-1: Overview of cost calculations relating to macrocells
1.3.2.  **Macrocell densification**

We model rising unit macrocell costs with site density

The cost of deploying macrocells typically rises as the density of sites in an area increases – for example, it may be harder to find suitable new sites because more easily accessible (hence lower cost) sites may be acquired and built first. Also, getting planning approval may become more difficult over time, particularly in sensitive areas in both cities and the countryside.

We model a linear relationship between site cost and density (sites per km²). We estimate low and high unit costs for macrocells based on our practical experience in macrocell deployment and relate them to site density as shown in Figure 1-2 below. We assume that the low cost estimate relates to a site density of zero for simplicity and that the high cost estimate relates to a site density of 10 sites per km². We derived this site density from examining actual site densities in areas such as London where operators already face problems in deploying more macrocell sites to cope with current congestion on existing sites and we discussed this assumption with industry sources.

![Figure 1-2: Illustration of modelling of the relationship of site costs and density](image)

Figure 1-2 also shows a “hard limit” or maximum density of macrocells that can be effectively deployed before radio interference becomes a significant challenge. We assumed that this is effectively the same as the intercept on the x-axis for the high-density cost.
Costs vary by geotype

We used our practical experience of macrocell deployment and discussion with vendors & industry to derive representative cost estimates for three types of macrocell installation: greenfield, rooftop and street furniture\(^2\). The cost estimates relate to a tri-sector macrocell with a MIMO technology site configuration of 2 downlink transmit antennas (2Tx MIMO).

However, the cost efficient deployment model works at the level of study areas. Although these areas comprise several geotypes, they can each be linked to one principal geotype – urban, sub-urban or rural – for the purpose of cost modelling. We produce cost estimates per geotype by taking a weighted average of the greenfield, rooftop and street furniture costs according to the proportion of each site installation type by geotype. We estimate the distribution of site installation types across geotypes from our practical experience of macrocell network deployments, and the distribution is shown below in Table 1.

\[
\begin{array}{|c|c|c|c|}
\hline
 & Urban & Sub-urban & Rural \\
\hline
Greenfield & 0\% & 30\% & 80\% \\
Rooftop & 95\% & 60\% & 10\% \\
Street furniture & 5\% & 10\% & 10\% \\
\hline
\end{array}
\]

Table 1: Assumed distribution of site installation type by geotype

The cost data

Table 2 below presents a summarised view of our macrocell cost data on operating and capital expenditure.

For capital expenditure, we specified some 25 separate cost items such as towers, site electrical installations, backhaul and antenna rigging for our site installation types. The more site specific costs, such as site acquisition and design, varied by installation type whereas others, such as antenna costs, did not. Similarly, we broke operating expenses down into 5 constituent classes: rent; backhaul; rates; utilities costs and maintenance. Although operating costs do vary with each specific installation, we do not believe the variation by site installation type is consistent and significant enough that it would add value to model it.

---

\(^2\) This is a macrocell as opposed to a smaller cell and we have evidence that some operators have deployed these types of macrocell in urban locations.
Table 2: Macrocell new build cost by site installation types

<table>
<thead>
<tr>
<th>New Macrocells</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital expenditure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greenfield</td>
<td>66,000</td>
<td>112,150</td>
<td>245,400</td>
</tr>
<tr>
<td>Rooftop</td>
<td>53,850</td>
<td>82,950</td>
<td>141,250</td>
</tr>
<tr>
<td>Street furniture</td>
<td>31,325</td>
<td>37,825</td>
<td>57,825</td>
</tr>
<tr>
<td><strong>Operating expenditure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated average</td>
<td>18,850</td>
<td>18,850</td>
<td>18,850</td>
</tr>
<tr>
<td>Ofcom[1]</td>
<td>7,500</td>
<td>10,500</td>
<td>14,000</td>
</tr>
</tbody>
</table>

Note: we also calculated medium site cost estimates, although the technical model only requires the low and high cost estimates

Table 2: Macrocell new build cost by site installation types

We cross-checked our estimates against those used and published by Ofcom [1] in its 2009 Consultation on Mobile Spectrum [1], as shown in Table 2 above. In deriving our estimates, we also consulted Ofcom to make sure that our estimates were consistent with its analyses of macrocell site costs for mobile call termination and the 800MHz award.

Figure 1-3 below presents another view of our costs, aggregated up into categories that reflect the level of granularity at which we apply assumptions on cost trends and equipment lifetimes.
Figure 1-3: Breakdown of macrocell costs by broad equipment categories

We estimate current costs, i.e. for 2011, and project them forward for the period of the model run by applying a set of cost trends to the broad equipment categories shown above. We use the same assumptions used by Ofcom [1] in its Mobile Spectrum Liberalisation work. Backhaul was not specified separately, so we use our own industry sources to provide this assumption. Our assumptions on the evolution of costs are:

- Site civil works: +2.5% per annum
- Towers: +2.5% per annum
- Antennas: −7.5% per annum
- Other site equipment: −7.5% per annum
- Backhaul: −2% per annum.

1.3.3. Macrocell densification – modelling of the number of networks

The technical model assumes that there is one network across all study areas service all demand in order to manage modelling complexity. However, in reality there are several mobile networks. When we amalgamate our study area results to the UK as a whole, we want to measure the cost on a more realistic basis.

We assume that, over the course of the model, mobile broadband will be delivered over two shared networks with traffic equally split between them. There are currently two pairs of mobile network infrastructure providers each with network sharing agreements – MBNL (EE-H3G) and Cornerstone (O2-Vodafone) – although not all sites are shared and each mobile operator can elect to have a site built just to serve their needs. Further, there is a clear trend in many countries towards greater network sharing. Hence, we believe that it is reasonable to apply this assumption to the period we are modelling.
Figure 1-4 below illustrates how we have translated the output of the “one network” technical model to the “two network” case that we feel is more appropriate.

![Figure 1-4: Illustration of site deployment in two network case](image)

Based on our understanding of the current situation, we assume that one network will have around 12,000 3G macrocell sites and the other 18,000 at the beginning of our modelling period, 2012.

Further, we assume that the operator with 12,000 sites can expand to 18,000 by sharing the larger network’s sites (at a similar upgrade cost to adding new bands to an existing site) rather than building new sites\(^3\). We translate the single operator results to the two network case as follows. The first additional 6,000 macrocells required for the single operator in the technical model translate to an increase in capacity on the smaller network in the two network case. Since the smaller network can use the larger network’s sites, the first 6,000 additional macrocells should be treated as upgrades rather than new site builds.

Any further requirement for macrocell capacity beyond the initial 6,000 in the single operator case translates to a requirement for new build macrocells for either network in the two network case. Table 3 below provides a simple example to illustrate what this actually means for our calculations.

---

\(^3\) We recognise that this is a simplifying assumption as it may not be physically possible to share all sites & landlords may refuse permission.
As a result, we assume that the number of increases in demand tends toward the same number in either the one or two network case. It might seem that twice as many macrocells would be required in the two network case as in the single operator case. We assume (for this illustrative example only) that the capacity of a macrocell is 100 Busy Hour Mbit/s and that traffic is equally split in the two network case.

For any larger increase in capacity, the number of sites needed to meet incremental increases in demand tends toward the same number in either the one or two network case. The difference, as shown in Table 3, is in the phasing of the increase in capacity. As demand increases, more macrocells are needed at first in the two network case, but subsequently the number catches up in the one network case.

As a result, we assume that the number of additional macrocells required (in the form of new builds) once the initial threshold of 6,000 has been reached is the same in the two network case as in the single operator case.

<table>
<thead>
<tr>
<th>Demand</th>
<th>1 network</th>
<th>2 networks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sites</td>
<td>Capacity</td>
</tr>
<tr>
<td>&gt;100</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>101-200</td>
<td>2</td>
<td>200</td>
</tr>
<tr>
<td>201-300</td>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td>301-400</td>
<td>4</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 3: Comparison of the profile of capacity deployment in the one and two network cases
1.3.4. Deploying new spectrum bands

In addition to deploying more macrocells and improving their capabilities through higher order MIMO and higher sectorisation, capacity can also be improved by deploying more spectrum bands. In this section, we set out how we estimate the costs associated with this for macrocells\(^4\) which can be divided as follows:

- Additional base station equipment
- Spectrum costs.

**Additional base station equipment**

When an operator decides to use a new band, it impacts both new builds and upgrades of existing macrocells. For new builds, we make the simplifying assumption that if an operator decides to deploy new spectrum bands over time, this is implicitly included in the evolution of the capabilities and cost of new build macrocells as we are beginning to see with the deployment of multi frequency base stations today.

When a new band is added to an existing macrocell, we assume that operators will incur both a software upgrade cost and the costs of deploying a new antenna, which may well be a multi-frequency antenna. Our estimate of the capital cost for this type of upgrade in 2012 is about £13,000.

By adding a new band we mean either adding a band whose frequency is different to an existing band (i.e. using another part of an existing band does not require an upgrade) or a band with the same frequency but a different technology such as adding 2.1GHz TDD spectrum to a site already equipped for 2.1GHz FDD.

We also assume that operators have already planned for the upgrade of sites to 3G/LTE over the existing mobile spectrum bands of 900MHz, 1800MHz and 2100MHz (FDD) and 3.4GHz (UK Broadband’s assignment), therefore we do not model the cost of adding these bands to existing sites in our model.

**Spectrum**

As explained above, the spectrum costs associated with acquiring and using new bands are dealt with separately to the efficient cost deployment model.

We have estimated spectrum costs on the basis of the best current indicators of how much it would cost to acquire spectrum in a reasonably competitive market, which anchors our estimates in reality. However, we acknowledge that this does not take into account how spectrum prices might change either in relation to changes in the scarcity of mobile spectrum (with more harmonised spectrum becoming available over time scarcity may reduce, depending on demand, and spectrum costs fall) or changes in the cost of alternatives to deploying more spectrum (e.g. we might expect that use of spectral efficiency improving technologies would reduce the value of spectrum, everything else being equal). We did not attempt to estimate these effects, because we felt it would have

\(^4\) We describe how we model an increase in the spectrum bands supported by outdoor small cells separately below
been circular to model these effects as assumptions when they are to some extent outputs or conclusions that can be drawn from the whole modelling process.

As a result, our findings on spectrum costs should be viewed as indicative. They can also illustrate how current market-based spectrum costs compare with the network based alternatives to increasing capacity and give a high level indication of how the value of spectrum may change in the future.

We calculate one cost per MHz for spectrum below 1GHz and another for spectrum above 1GHz. This reflects the difference in outdoor and indoor propagation characteristics which has formed the basis of much of Ofcom’s analyses of mobile spectrum issues\(^5\). Differences are also apparent in recent auctions for mobile spectrum above and below this threshold.

We believe actual spectrum transactions are likely to provide the best source of information on the value of spectrum, if those transactions have taken place in reasonably competitive conditions. Hence, we use recent auction fees for 800MHz, 1800MHz and 2.6GHz spectrum as benchmarks for spectrum costs. Auction fees may reflect other factors in addition to the underlying economic value of the spectrum, such as the prevailing sentiment in financial markets and any specific restrictions placed on the use of spectrum. However, in our view, most recent mobile spectrum auctions have been sufficiently well designed and competitive that they do provide a good indication of the economic value of the spectrum.

We apply the UK exchange rate prevailing at the time of each auction and adjust for differences in population to derive a cost per MHz for above and below 1GHz spectrum. We take simple averages of the auction data we collected and this is shown in Table 4 below.

<table>
<thead>
<tr>
<th>Country</th>
<th>Date</th>
<th>£/MHz/Pop</th>
<th>Band (MHz)</th>
<th>UK £/MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>May 10</td>
<td>0.62</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>Jul 11</td>
<td>0.42</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>Sep 11</td>
<td>0.71</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td>Mar 11</td>
<td>0.35</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>n/a</strong></td>
<td><strong>0.52</strong></td>
<td><strong>Below 1 GHz</strong></td>
<td><strong>32,578,920</strong></td>
</tr>
</tbody>
</table>

Table 4: Mobile spectrum auction fees and our estimates of spectrum costs (2012)

**Upgrading from 3G to LTE**

We currently see in the market a trend to deploying multi-standard base stations\(^2\) ahead of the commercial provision of services over LTE. Hence we assume that, where necessary, operators will deploy or will have deployed LTE-ready multi-standard base stations.

\(^5\) e.g. Ofcom [1]
1.3.5. Increased sectorisation

We model the expansion of capacity by increasing sectorisation from 3 to 6 sectors. We model two types of cost: the cost of new build 6 sector (2Tx MIMO) macrocells and the cost of upgrading 3 sector (2Tx MIMO) macrocells to 6 sector (2Tx MIMO) macrocells.

We do not vary these costs with density as for 3 sector (2Tx MIMO) macrocells, because the variation of these costs with site density is more unpredictable, especially for upgrades. Hence we base the costs on our “medium” cost estimates for the various cost components.

For new build 6-sector sites, most of the component costs are the same as for a 3-sector site, except for antenna related costs which are nearly twice as much for a 6-sector macrocell.

For upgrades to 6-sector sites, costs are significantly lower than for new build sites because much less equipment and civil works costs are required. For example, existing towers are likely to be able to support the additional antennas. There are exceptions to this, particularly where the type of tower deployed has been selected to minimise the visual impact in a sensitive location, but we have assumed these sites are unlikely or unable to require large capacity upgrades. We also assume that no significant changes are necessary to equipment cabinets. As a result, the additional cost components that we estimate are as follows:

- Replacing existing 3 antennas with 6 new antennas
- Additional equipment e.g. rigging and cabling for the antennas
- Commissioning and testing costs
- Landlord costs for additional rights to deploy further antennas
- Other site civil works costs

Where the cost element is the same as for the 3 sector, 2Tx MIMO macrocell, such as the additional antennas, we use the same costs. However, for some cost elements we estimate lower costs – for example civil works and landlord related costs – because for the amount of work required for an upgrade will be lower than for a full new site build.

1.3.6. Higher order MIMO

- We model two types of higher order MIMO implementation:
  - 4 Tx MIMO (3 sector macrocell) – i.e. twice the current number of antennas would be deployed
  - 8 Tx order DL MIMO (3 sector macrocell) – i.e. 4 times the current number of antennas would be deployed

We do not model higher order MIMO together with 6 sector cells because we believe that operators are unlikely to pursue these combinations because of practical limitations, particularly with the number of separate antennas that would be required.

As for increased sectorisation, we model both the cost of new build higher order MIMO macrocells and the cost of upgrading 2Tx MIMO (3 sector) macrocells to both 4Tx MIMO (3 sector) and 8Tx MIMO (3 sector) macrocells.
Similar to 6 sector cells, we do not vary these site costs with density because the variation of these costs with site density is more unpredictable, especially for upgrades. So, we use our “medium” estimates for the cost components of our higher order MIMO deployments.

For new build 4Tx and 8Tx MIMO, most of the component costs are the same as for a 2Tx MIMO site, except for antenna related costs that are nearly twice or three times as much for a 2Tx MIMO macrocell because they reflect the greater number of antennas required.

For upgrades to higher order MIMO macrocells, costs are significantly lower because much less equipment and civil works costs are required. Again we make similar assumptions as for increased sectorisation and the additional cost components that we estimate are:

- Replacing existing 3 antennas with 6 (or 12) new antennas
- Additional equipment e.g. rigging and cabling for the antennas
- Commissioning and testing costs
- Landlord costs for additional rights to deploy further antennas
- Other site civil works costs

Where a cost element is the same as for a 3 sector, 2Tx MIMO site, e.g. additional antennas, we use the same costs per antenna. For other cost elements, we make adjustments based on the differences in the level of provisioning required for an upgrade compared to a new site build.

### 1.3.7. Outdoor small cells

We use this one term to cover microcells, picocells, and metrocells. We used our practical experience of metro and picocell deployments and cross-checked them with several manufacturers in order to derive our cost estimates.

We model outdoor small cell costs in a similar way to macrocell costs – i.e. we model operating expenditure, capital expenditure and a replacement investment cycle. However, we do not model variations in cost by geotype or site density. We consider that variations are likely to be lower than for macrocells and that it is a reasonable assumption on average to use just one central cost estimate for outdoor small cells.

We estimate operating expenditure as a proportion – 10% – of capital expenditure, based on our practical experience and discussions with vendors. We note that Ofcom has also used a figure of 10% to estimate operating costs for macrocells in cost analyses done in support of its Consultation on the Award of 800MHz spectrum.

We estimated capital expenditure similarly to macrocells, i.e. we identified 12 separate cost elements which we grouped into the following categories below and as shown in Table 5:

- Site acquisition and civil works
- Antennas
- Other base station equipment
- Backhaul
### Table 5: Composition of small cell costs, 2011

<table>
<thead>
<tr>
<th>Capital expenditure category</th>
<th>Cost per site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site civil works &amp; acquisition</td>
<td>£3,550</td>
</tr>
<tr>
<td>Other equipment</td>
<td>£3,300</td>
</tr>
<tr>
<td>Backhaul</td>
<td>£6,000</td>
</tr>
<tr>
<td>Total</td>
<td>£12,850</td>
</tr>
</tbody>
</table>

In the technical model, we assume that the number of spectrum bands supported by small cells increases from 1 in 2012 to 5 by 2025, and also that their capacity increases over time. To take account of these increases in small cell functionality, we model corresponding increases in unit costs between 2012 and 2025 and thereafter we apply the same cost trends as for macrocells.

We had to make an assumption to predict how much more expensive multiband small cells would be than single band. We looked at dual band vs. single band Wi-Fi access points as an initial indicator and found that the difference in price was currently 30%, but that this cost was narrowing quickly.

So we assumed that the equipment cost of a 5 band small cell in 2025 would be 50% higher than for a single band small cell in 2012 and then linearly interpolate to derive the costs between 2012 and 2025. This takes into account:

- The price differences that we see today for adding a band to Wi-Fi access points
- The fact that these prices differences narrow over time, and
- Our expectation that the relation between adding new bands to a cell and the incremental cost will not be linear – i.e. the increase in cost for adding N bands will be less than N x the cost increase for adding one band to a small cell.

For the replacement cycle we assume that the lifetime of all the cost components is 5 years. In the past, small cell upgrades were infrequent but, with the technology increases (spectrum bands and capacity) and significant increases in demand which we have modelled going forward, we consider that it is plausible that industry would be motivated to replace small cells every 5 years.

### 1.3.8. Indoor small cells

As stated above, we do not model indoor small cells as an explicit choice in the technical model. Rather we specify scenarios for traffic-offload and model the associated deployment of femtocells to carry that traffic, before calculating the costs related to indoor smaller cells separately from the cost efficient deployment model.

It is important to note that not all the indoor small cells we model represent new units of equipment since some offloaded traffic may be carried over existing indoor small cells, particularly Wi-Fi access points. Hence our cost estimates for indoor small cells include a potentially significant element of cost that may not be incremental to the current situation.
We produce separate estimates for enterprise and residential indoor smaller cells, however we first set out some common assumptions before detailing those specific to enterprise or residential femtocells.

We model the capital cost of the indoor smalls, but we assume operating expenses are bundled up into capital costs so we do not calculate them explicitly.

We assume that the extent to which users need to upgrade their fixed broadband connection is likely to be limited. In particular, mobile broadband use is likely to substitute for fixed broadband use and may even require less capacity, e.g. video will be scaled down for viewing on a smart phone screen as opposed to a laptop or PC screen. Hence, we decided not to attribute broadband costs to femtocell usage.

The final common assumption concerns the equipment lifetime. We assume this is 3 years on the basis that 3 years appears to be a reasonable average for Wi-Fi access points and mobile devices, experience of which is likely to condition consumers’ expectations in terms of the upgrade of femtocells. Further, Signals Research Group\(^4\) assume a lifetime of three years in their femtocell business case study of 2010.

### Residential

Currently only HSPA femtocells can be used in the UK, however from 2014, it is reasonable to assume that operators will want to make available dual mode HSPA/LTE femtocells. We put together a simple forecast of HSPA only and HSPA/LTE femtocells to examine the impact on prices.

- **HSPA only** – Over the past 3 years we have seen HSPA femtocell costs have fallen by a factor of 3 to below £100 in volume today\(^6\). After discussions with industry sources, we concluded that it was reasonable to assume that the cost could fall to around 150% of a Wi-Fi access point (today around £50) in another 3 years to 2014 and then at the same annual rate as our standard assumption for radio equipment. We think that femtocells will not reach quite the same level as Wi-Fi access points over the course of the model because they are unlikely to achieve the same production volumes and scale economies and because of additional IPR costs.

- **HSPA/LTE** – We reviewed a number of sources\(^7\) and concluded that £250 is a reasonable estimate of the current cost. However, after discussion with industry sources, we concluded that HSPA/LTE femtocells are not likely to have a significant impact on the average cost of residential femtocells. This assumes that production volumes will be low, hence the cost will remain significantly higher than for HSPA femtocells for some time. If our assumption is wrong and there is substantial take up dual mode femtocells in the residential market, then costs are likely to converge to the HSPA only level, hence using the HSPA only cost is still likely to be a reasonable proxy for the whole market.

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\(^6\) Signals Research Group [4]
\(^7\) e.g. Signals Research Group [4]
Enterprise smaller cells

There is a wide diversity of systems that could be deployed indoors. We distinguish between special cases such as airports and stadiums which have very particular requirements that vary greatly and buildings where capacity demand is much more homogenous and can be modelled more easily.

We assume that the special sites would be served by indoor cells regardless of the demand or technical scenario, so we model this as offloaded traffic from the public network.

For more standard deployments of enterprise smaller cells, we model a high level relationship between demand per building and the number of smaller cells needed to serve that traffic. This takes into account the likelihood that not all building tenants will deploy femtocells.

We based our estimate of the cost of an enterprise smaller cell on industry research. This indicated a figure of £420 in 2012 and we assume that the cost changes at the same rate as for macrocell equipment in subsequent years.

1.4. High level assessment of benefits and affordability

In order to place our cost results into some context, we want to give a high level indication of the benefits and the affordability of the networks that may result from our capacity scenarios.

We decided to assess the potential benefits on two levels, the overall benefit to UK wireless broadband consumers and the average revenue per consumer which could be used to check the affordability by comparing against the average cost per consumer. We would like to emphasise that this analysis should be regarded as indicative. We have taken a high level approach partly because the main focus of the study was the costs of meeting wireless broadband capacity demand and partly because of the inherent difficulties in measuring the future consumer benefits and revenues for wireless broadband services which are typically very difficult to predict over the long term that is the focus of this study.

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8 Signals Research Group [4]
1.4.1. Methodology for affordability

Figure 1-5 below gives an overview of the approach we take to examine the affordability of our scenarios.

Figure 1-5: Approach to assessing affordability

The key to devising the check on costs was to find a total cost per unit measure (over a relevant period) that could provide a useful comparison with current average revenues per residential subscriber for mobile services today. Similarly to the assessment of the scenario costs, we consider only those costs incremental to the existing network.

We decided to calculate the total cost per relevant user within each study area. We take the sum of the “mobile active” and “working” populations, as defined in our demand model because these are the users who generate the traffic to which network capacity is dimensioned.

We estimate the average cost per user over the full period of the model from 2012 to 2030 to produce an average monthly cost. Our costs in in present value terms, so the affordability comparator (average monthly revenue per user or willingness to pay) needs to be converted to the same basis, i.e. an average of the present value from 2012 to 2030.

Since access network costs are a fraction of total revenues (between 50-60%), the measure we use to judge affordability, e.g. the average monthly revenue per user is currently between £10-15 per month\(^5\) depending on how it is measured needs to be scaled by the same amount. The affordability threshold also needs to be adjusted by a factor to cover the discounting of the network costs. We discount costs using a social discount rate of 3.5%\(^6\). Over the course of 18 years, a fixed annual amount ‘X’ discounted at this rate and then averaged over this period would be 25% lower. Applying both these factors to the £10-15 monthly revenue gives a comparative range of about £4-6 which can be compared with the average monthly cost estimated from the model.
1.4.2. Benefits to consumers

Economists measure consumer benefits by consumer surplus, however it is usually not straightforward to estimate because it depends on data such as willingness to pay for wireless broadband services which are not easy to gather or to forecast future levels.

As a result, we have decided to produce a high level estimate the potential benefits to UK consumers in our analysis through an indirect assessment of consumer surplus for wireless broadband services.

Our approach is to use existing figures for mobile broadband consumer surplus per subscriber and apply that to the number of main handset subscriptions that we derive as explained above in the assessment of affordability. This allows us to estimate a total UK consumer surplus for wireless broadband use. We estimate this for each year in the model and calculate the present value of the total in 2012 terms.

Our source for mobile consumer surplus is the Europe Economics study for Ofcom. They estimated consumer surplus from cellular mobile usage at £18 billion for 2006. We divided this by the number of active mobile subscriptions in 2006 [Ofcom, 5] to get an estimate of £272 (£23/month) for consumer surplus per mobile subscription.

We assumed that consumer surplus would increase by 2% p.a. due the impact of increased functionality and falls in the price per unit of demand. Average spending on a basket of mobile services fell 2.2% p.a. from 2005 to 2010 [Ofcom, 5]. Hence, we conservatively assumed a similarly sized increase of 2% p.a. in the average consumer surplus per subscription. This gave a figure of £306 (£25.5/month) for 2012 which we continued to project forward at a 2% p.a.

We then applied this adjusted consumer surplus figure to the forecast number of main handset subscriptions and calculated the present value using a social discount rate of 3.5%, see HM Treasury [6], from 2012 to 2030 of consumer surplus at £340 billion.
A2. Technology Considerations and Spectral Efficiency

2.1. Overview of Technology Characterisation by Spectral Efficiency

In this annex we describe the techniques that can be used to increase the efficiency of mobile broadband delivery, and the method and assumptions used to combine the wide range of surveyed results into a numerical model for use in this study.

Spectral efficiency is a measure of how well mobile broadband infrastructure technology exploits each hertz of spectral resource to deliver bits per second of capacity. The units of our spectral efficiency metric are bits per second of capacity, per hertz of spectrum, per operator ‘site’. This differs from the more normally used capacity metric of cell spectral efficiency, since we incorporate the number of cells (or sectors) at the site.

2.2. Capacity Enhancing Techniques

In this section we describe the following capacity enhancing techniques to be included in the numerical model for spectral efficiency evolution

- Additional Antennas: Sectorisation and MIMO
- MIMO Algorithm Evolution
- Co-ordinated Multipoint
- Small Cells and Offload
- Relays

2.2.1. Additional Antennas: Sectorisation and MIMO

Along with sectorisation, MIMO is one of the main techniques for significantly increasing spectral efficiency. As a general rule network capacity is proportional to the number of transmitters. Multiple antennas can be used to create multiple cells or sectors, and they can also be used to create multiple ‘MIMO layers’. Whether sectors or MIMO layers, the idea is re-use the spectral resource multiple times from the same cell site. Provided these are orthogonal and do not interfere with each other, capacity will increase linearly. In practice, sector overlap and real world channel conditions and antenna designs do result in adjacent sector or cross layer interference, and the returns for increasing numbers of antennas are diminishing.

We explicitly model the operator’s decision for the number of downlink transmit antennas at the macrocell site, either 2, 4 or 8.

- More antennas gives higher spectral efficiency, but incurs higher site costs
- Doubling the number of antennas does not quite double the spectral efficiency, since the principle of diminishing returns applies.
- Higher order MIMO modes are not supported by the standards until later generations
- Number of cell site antennas is also taken into account for uplink range calculations
The number of UE antennas varies over time according to the device mix. We consider an evolving mix of 2, 4, and 8 antenna elements in the device. Whilst 8 antenna sites and devices results in the highest spectral efficiency, deployment will be constrained in practice by both cost and available space at the site or device.

2.2.2. MIMO Algorithm Evolution

LTE-Advanced (i.e. 3GPP Release 10 and beyond) and later generations introduce the following MIMO enhancements over LTE release 8:

**Downlink:**

- **Up to 8 layer transmission** enables the use of up to 8 antennas at the eNodeB, which can increase peak rates and/or spectral efficiency given suitable antennas and propagation conditions. Higher numbers of layers are aimed for use in array antennas, possibly with cross polar elements. E.g. a four beam per sector dual polar antenna would require 8 layers.

- **Multi User MIMO, with fixed or adaptive beams.** MU-MIMO enables transmission for multiple UEs in the same spectral resource at the same time. This is akin to SDMA (Space Division Multiple Access) where a sector is further divided into beams, in which the spectral resource can be reused for several users. MU-MIMO was possible in the Rel8-uplink, and is being added to the release 10 downlink. MU-MIMO can work with fixed or adaptive beams, where the latter requires UE specific reference signals that undergo the same precoding as the user traffic. UE specific Reference signals enables correct evaluation of channel state information at the UE. It is expected that adaptive beam MU MIMO will bring higher capacity.

- **Network MIMO: another name for CoMP.** CoMP and MIMO are closely related as both involve processing of transmissions and/or reception over multiple antennas. CoMP can be distinguished by the fact that the multiple antennas are located at different eNodeBs. MIMO implies multiple antennas at a single eNodeB, but potentially multiple UEs, as in the case of MU MIMO.

**Uplink:**

- Single User MIMO. Enables a UE to transmit on multiple layers. Release 8 only supported a single layer per UE on the uplink (but did support MU-MIMO). This increases the peak rate that can be achieved at high SINRs

- Up to 4 layers

- MU-MIMO Enhanced with CoMP. CoMP and MIMO are closely related as both involve

- Single User MIMO up to 4 layers (rel-8 only supported Multi-User MIMO on UL)

- Multi User MIMO enhanced by joint transmission (see CoMP)

Figure 2-1 illustrates the relative benefit of transmit and receive antennas in MIMO configurations. Doubling the number transmit antennas (1x2 vs. 2x2, or 2x4 vs 4x4) improves throughput at higher SINRs only, and so spectral efficiency will only occur in environments with a prevalence of higher SINR conditions, such as small cells. Increasing
the number of receive antennas (2x2 vs 2x4) improves throughput across the whole range of SINR, and should therefore provide capacity gains in any environment.

Figure 2-1: Single User MIMO Benefits. Source 3G Americas, Real Wireless graph

In addition to SINR, suitable combinations of multipath conditions and antennas are also required to ensure that the channel can be ‘decomposed’ into orthogonal propagation modes. This generally requires rich multipath scattering, although it should be noted that dual polar MIMO can provide orthogonal propagation modes without the need for scattering. MIMO channel and antenna combinations can be characterised by matrix parameters such as ‘rank’ which indicates the number of layers that can be supported and ‘condition number’, which indicates how reliably multilayer transmission can be achieved[9]. Figure 2-2 illustrates the prevalence of multilayer transmission (ranks higher than 1) in field trials of 2x2 and 4x4 MIMO with various cross polar antenna configurations. The impact on the user throughput distribution is also shown. The figure shows the importance of the UE antenna configuration, with the dual polar UE (labelled |-) achieving rank 2 significantly more than the single polar UE (||). Similar trends can be seen with the 4x4 configuration. Of note also is that the prevalence of rank 4 transmission is very low, occurring in only 1 or 2% of locations in the cell. This does not mean that 4x4 configurations are of no value, as significant throughput benefits can still be observed over 2x2. The 4x4 configurations have a higher prevalence of multi layer transmission (rank>1) than 2x2 configurations. Other trials results in an Ericsson paper[10] showed that 4x4 increased average user throughput by 50% compared to 2x2. This is indicative of the gains in cell spectral efficiency that could be achieved, and aligns well with simulation results shown later in Figure 2-4.
Figure 2-2: Prevalence of Multilayer Transmission in MIMO Propagation Trials. Copied from Ericsson Review11. Note that x indicates a cross polar eNodeB antenna, and | and – indicate vertical and horizontal UE antennas.

Figure 2-3: Benefit of LTE-Advanced DL MIMO Schemes over LTE Rel. 8 4x2. Source: 3GPP[12], Real Wireless analysis. Assumes eNodeB antenna configurations of | | | | and XXXX for 4 and 8 way tx, respectively.

Figure 2-3 summarises the benefits of the LTE-Advanced MIMO schemes over a baseline Release 8 SU-MIMO 4x2 scheme, in both Macrocell and Microcell environments. The 4x2 configurations show the benefit of the enhanced MIMO processing is around 30-50%. Doubling the number of transmit antennas to 8 brings further gains, especially in the macrocell environment. This is the reverse of the mechanism seen in Figure 2-1, where Tx antennas provided more gain in higher SINR environments. This may be because in this case, the number of Tx antennas (8) greatly exceeds the Rx (2).
Figure 2-4 illustrates the benefits of higher order MIMO configurations with Rel 8 SU MIMO, as well as LTE-Advanced MU-MIMO and CoMP schemes. As before, we see that LTE-Advanced schemes are able to extract more benefit from the higher order schemes, with 4x4 JP CoMP achieving almost 2x the spectral efficiency as the 2x2 equivalent. The same antenna upgrade with Rel8 MIMO would only have brought 1.5x benefit.

![Figure 2-4: Benefit of higher order MIMO schemes over 2x2, 3GPP Macrocells. Source 3GPP\textsuperscript{13}, Real Wireless analysis.](image)

Enhanced MIMO processing in LTE-Advanced can enhance the performance of a given MIMO configuration by 20-50%, with greater benefits for 4tx configurations than for 2tx. Increasing the number of antennas generally improves spectral efficiency. Both Trials and simulations of Rel 8 LTE indicate a 50% increase in cell spectrum efficiency is achieved with 4x4 compared to 2x2. With LTE Advanced schemes, up to 2x benefit could be achieved by doubling the number of antennas at both ends of the link. Upgrading the eNodeB to 8 antennas can bring further gains. 8x2 SU-MIMO gave over 2x the cell SE compared to the same scheme with 4x2 configurations.

Challenges

- It is difficult to design multiple diverse antennas on small form factor terminals, especially at low frequencies, see Varall 14
- MIMO cell site antennas may need to be larger, increasing site leasing costs
- MIMO requires high SINR and rich scattering. If this combination of conditions does not occur very often in the target environment, then benefits will be low.
Capacity Gains from MIMO

- Increasing the number of receive antennas in a MIMO configuration increases spectral efficiency.
- Increasing the number of transmit antennas increases peak rates at high SINR, but will only increase spectral efficiency if higher SINRs are prevalent in the environment. Small cell environments tend to have higher SINRs, hence greater MIMO benefits.
- MIMO Gains may be greater at higher carrier frequencies, where the smaller wavelength facilitates better antenna design for a given form factor.

Numerical Model for MIMO

Our site spectral efficiency figures represent an evolving mix of practical MIMO technology:

- HSPA+ provides MIMO, but the challenges of channel estimation for CDMA limit its efficacy.
- Release 8 LTE provides up to 4 layer single user MIMO on the downlink
- Release 10 increases to 8 layer, and support of Multi-User MIMO.
- MU-MIMO in release 10 combined with a closely spaced array antenna is akin to beamforming
- In practice, MIMO gains are limited by antenna correlation and presence of suitable scattering in the propagation environment.
- Our prediction for releases 12 and beyond considers further potential for algorithm enhancement depending on the technology scenario.

2.2.3. Co-ordinated Multi Point (CoMP)

In a cellular network, most UEs can hear (or be heard) by more than one cell. In a basic system, we consider the strongest signal to be the serving cell, and all others to be interferers. The premise of CoMP (Co-ordinated MultiPoint) is that cells share information to either reduce other cell interference or harness it to improve network capacity. Figure 2-5 illustrates the key concepts of CoMP. In LTE, the X2 is an optional interface between eNodeBs which can be used for co-ordination.

![Figure 2-5: Co-ordinated Multipoint Transmission Concepts](image-url)
We can imagine that the highest uplink theoretical capacity could be achieved by sending all the complex voltage waveforms received on each antenna element of all base stations to a massive central processing unit. This could extract and combine signals from each UE as well as cancelling known interference from other UEs. Similarly on the downlink, signals for all UEs could be optimally transmitted from all eNodes taking into account all complex channel responses of all UEs. In practice this approach would not be viable as the backhaul, synchronisation and processing requirements would be prohibitive. However, schemes have and are being specified for LTE and LTE-Advanced which can achieve some of the benefits with practical levels of information exchange and processing. These largely fall into two groups as follows:

1) **Joint Processing (JP):** A UE can have multiple serving cells, requiring user data to be transmitted (or received) in multiple locations. This requires sharing of both scheduling information and the users’ data between neighbour cells.

2) **Co-ordinated Scheduling (CS):** A UE only has one serving cell, so no sharing of user data is required. Scheduling information is shared between neighbour cells in order to avoid or reduce interference. Scheduling information could be power levels per resource block, load levels, beamforming weights, etc. CS schemes require less information sharing and processing than JP, but do not in general achieve such high potential capacity gains.

![Diagram of CoMP scenarios](image)

**Figure 2-6 Intra and Inter eNodeB CoMP**

The benefits of CoMP come at the expense of information sharing between cells. Such sharing is not always a problem as illustrated by the three scenarios in Figure 2-6.

1) UE1 sits near the edge of two cells around the same eNodeB so information exchange will be internal and thus can more easily be high bandwidth and synchronised.

2) CoMP for UE2 would be inter eNodeB, requiring the use of backhaul bandwidth on the X2 interface for information sharing. Latency on this interface impacts performance as described later.

3) UE 3 uses intra eNodeB CoMP between different Remote Radio heads. Since these are linked to their controlling eNodeB with the OBRI interface (a digitised baseband waveform), CoMP does not impact the bandwidth requirement.
Furthermore it should be noted that intra eNodeB CoMP can use proprietary algorithms, whereas inter-eNodeB needs to be standardised to work in a multi-vendor environment.

The following sections outline the downlink and uplink schemes being standardised for LTE.
2.2.3.1. Downlink CoMP

Inter-Cell Interference Co-ordination (ICIC)

ICIC is a simple CoMP scheme that was standardised in rel-8 LTE. This falls under the co-ordinated scheduling category, as each UE has one serving cell. Figure 2-7 illustrates a scenario where co-ordination improves capacity. The diagrams show two cells each serving one user. In a) both UEs are near to their cells, so the wanted signal is much stronger than the interfering signal. Maximum capacity is achieved by both cells transmitting maximum power. In scenario b), the UEs are near the cell edge, so the wanted and interfering signals are at similar levels. Working individually, each cell could maximise its UE throughput by transmitting more power. However the combined capacity will be higher if they co-ordinate so that only one of the cells transmits at a time (on a given frequency) and the other transmits nothing[15].

![Figure 2-7: Scenarios to illustrate benefit of inter cell Co-ordination](image)

In practice this can be achieved by categorising UEs as either cell-centre or cell-edge, and schedulers in adjacent cells co-ordinating to ensure no two adjacent cell edge UEs transmit on the same frequency resource as illustrated in Figure 2-8. In this example, cell centre UEs have N=1 reuse (all cells reuse the same frequency resource), whereas the cell edge is effectively N=3 reuse, where each cell edge region can only use a third of the spectrum. This is similar to the frequency reuse patterns used in early 2G networks (before frequency hopping), where the reuse factor allows a trade between cell capacity and cell edge performance.

The reader should be aware that in a real world propagation environment with terrain and clutter, the division between cell edge and centre would not be as neat as that shown in Figure 2-8. The criterion for deciding whether a UE is cell edge or centre would be based on signal strength/quality rather than its geographical location relative to the cell sites.
Static interference co-ordination requires cell planning to ensure no two neighbours share the same subset of the cell edge frequencies. This avoids any need for sharing of scheduling information over X2, but may have less benefit as it cannot adapt to time varying user distributions or variations in cell load. An example of this would be workers moving from offices areas to restaurant areas during their lunch break.

Semi-static interference co-ordination allows reconfiguration of the frequency subsets over a timescale of a few seconds. This achieved in LTE rel-8 by signalling a bitmap over X2 whether each RB has a high power or a lower power. Other information relating to load or cell size may also be shared.

Co-ordinated Scheduling (CS) & Co-ordinated Beam forming (CB)

LTE-Advanced extends the capability of ICIC with Co-ordinated scheduling and Co-ordinated beamforming. The former enables dynamic interference co-ordination that can react more quickly to changing conditions than the release 8 semi static variant. The latter adds the ability to co-ordinate beamforming over multiple cells. In theory, this brings a benefit by grouping UEs into sets which can more easily be orthogonalised in the spatial dimension.
Joint Processing Techniques

Joint Processing category requires the user’s data to be present at multiple cells in the ‘CoMP Cooperation Set’. There are two JP variants proposed for LTE-A: Dynamic Cell Selection and Joint Transmission.

i) **Dynamic Cell Selection** is akin to fast macro diversity: User data is present in all cells in the Coordination set, but is only transmitted from one cell at a time. The transmission cell can be rapidly changed on a per 1ms subframe basis, depending on channel conditions, cell load, etc. This is like a very fast handover

ii) **Joint Transmission** is where multiple cells simultaneously transmit data to the user. The multiple signals are co-ordinated such that they arrive at the UE to improve the strength of the wanted signal, or actively cancel interference from other UEs. Transmissions can be coherent or non-coherent. Coherent transmissions can improve the signal quality more, but require very tight synchronisation which is difficult to achieve for cells at different sites

Joint transmission is a type of network MIMO, where the multiple transmit antennas can be located at different cell sites, rather than an array antenna at a single cell site. The network uses the multiple cell sites to form ‘beams’ to particular UEs, whilst nulling out others. JT can also be used in conjunction with Multi-User MIMO, where the multiple receive antennas can be located on different UEs. This allows the network to reuse the same (frequency, time) resource to send different information to multiple users.

Further details of the CoMP schemes and the signalling to support them can be found in TR 36.813 [17]

2.2.3.2. Uplink CoMP

Both Joint Processing and Co-ordinated Scheduling schemes are possible on the uplink.

**Co-ordinated Scheduling and Beamforming**

Since the scheduler for both uplink and downlink resides in the eNodeB, co-ordination mechanisms are similar for both. In LTE rel-8, eNodeBs can share information on which resources they have scheduled high power uplink transmissions. They can also share reports of strong uplink interference which helps eNodeBs work out which UEs have strong signal paths to their neighbour cells, and thus need to be co-ordinated. LTE-Advanced extends the capabilities to include co-ordination over shorter timescales and over UE beamforming.

**Joint Reception**

The UE signal may be received at multiple cells and then recombined to reduce errors or packet loss. The degree of coherency depends on whether the cells are controlled by the same eNodeB, or whether user data must be sent over the backhaul between different eNodeBs.

Uplink CoMP is predominantly a function of the eNodeB scheduler and so little standardisation is needed as this can be left to vendor implementation. Specifications will however be needed for measurements and signalling needed to support UL CoMP.
2.1.1.1 Benefits of CoMP

Various different opinions exist on the extent of the benefits of CoMP.

Results of the 3GPP feasibility study show clear benefits to downlink cell spectrum efficiency. With 4 tx antennas at the eNodeB, gains of over 30% are achieved with for Co-ordinate Scheduleing and beamforming, and over 50% for Joint Processing CoMP, as shown in Figure 2-9. Figure 2-10 shows more simulation results with more modest gains in Cell SE for all but the most sophisticated of schemes. None of the Single User schemes achieve more than 11% benefit to SE compared to Rel8 LTE. Note that the antenna configuration has not been stated and a 2x2 configuration would result in lower gains, as shown by the 3GPP results in Figure 2-9.

Figure 2-9: Benefit of LTE-Adv DL CoMP Schemes over Rel8 LTE: Source 3GPP Feasibility Study18, Real Wireless Analysis

Figure 2-10: 3G Americas DL CoMP Simulation Results9 (Source: 3G Americas19)

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Figure 2-10 also shows benefits of CoMP for Cell edge User throughput of around 10-20% for the single user cases. It is these users with high interference levels that should get the most benefits of CoMP, and the result should be a fairer network able to guarantee a higher minimum throughput. Qualcomm results for CoMP shown in Figure 2-11 support this view, but show that the benefit to cell edge UEs comes at the cost of the 50% and 95%-ile with median and peak UE throughputs, respectively. These results suggest that CoMP can alter the shape of the UE Tput distribution, but do not bring a net improvement. The lack of benefit to the median (50%ile) UE Tput implies that cell spectral efficiency would not improve. The simulations assumed a 1x2 antenna configuration, which suggests that CoMP needs to be deployed in combination with MIMO to provide benefits. Figure 2-9 above showed that higher gains are achieved with the higher order antenna configurations.

Figure 2-11: Qualcomm Paper on Joint Transmission 20 in 1x2 configuration shows that whilst the proposed schemes improve 5%-ile UE Tputs, they actually degrade median and 95%ile throughput.
Figure 2-12: Co-ordinated Scheduling simulation results (Source: Alcatel-Lucent 21)

Figure 2-12 shows the benefits of CS Comp to cell edge UE Tput and Cell Spectral efficiency, and the impact of backhaul latency. With ideal 0 ms latency, CS Comp provides 6-8% benefit to Cell SE and 20-30% benefit to cell edge user Throughput. These gains are eroded slightly by 1ms latency, which is realistic for a well-engineered X2 backhaul link between neighbour eNodeBs. Higher latencies can result in losses for the UEs moving at 30km/h.

In summary, simulations suggest that CoMP can bring up to 60% benefit to cell spectrum efficiency. However, this requires sophisticated implementations and high order antenna configurations. In general, gains appear to be around 10-30%. CoMP improves ‘cell edge’ user throughput by around 10-30% in all but the most sophisticated implementations. Note that CoMP benefits to cell edge apply only to interference limited environments, and will not help in noise limited coverage scenarios to improve range.

2.2.3.3. Challenges

- Inter site CoMP uses backhaul bandwidth on the inter eNodeB X2 interface. Increased backhaul provisioning may increase costs for operators.
- Benefits of inter-site CoMP are sensitive to backhaul latency for the X2 peer-peer interface between eNodeBs, as shown in Figure 2-13. Low latencies less than 5ms are needed to realise useful gains. This could be a challenge for ‘untrusted’ backhaul networks, where X2 links must pass through centralised security gateways.
Figure 2-13: Impact of X2 latency on User Tput Distribution, with Joint Transmission
(Source: Brueck et al\textsuperscript{30} Real Wireless analysis)
2.2.4. Small cells

Two types of small cell are emerging: consumer and enterprise deployed femtocells, and operator deployed and managed small cells, also referred to as ‘metrocells’ or ‘picocells’.

In this study we refer to these different types of small cells as follows:

**Indoor small cells**

- Deployment and backhaul managed by consumer or enterprise customer.
- Treated as ‘offload’ by the capacity techniques study, by removing (or reducing) certain demand points representing indoor demand

**Outdoor small cells**

- Deployment and backhaul managed by operators.
- Explicitly modelled as a site type with shorter range and generally lower capacity than macrosites.

The concept behind femtocells is the ability to deploy/extend cellular coverage and capacity within a residential or small office environment. Femtocells enable consumers to effectively deploy mobile coverage within their home using the consumers’ broadband connectivity as the backhaul to the network. Femtocell technology is also being applied to public environments, overlapping with the traditional application areas of picocells, microcells and distributed antennas systems.

Coverage normally extends between 10 – 30m from the femtocell access point unit and typically supports 4–8 handsets when deployed in a residential environment and 10 -15 handsets within an enterprise environment.

There are some clear advantages and disadvantages for deploying femtocells that support enhancement for capacity in 4G networks and this is addressed in more detail in the sections below.

**Femtocells in the standards**

Femtocells have been added to 3GPP specifications from release 8 and 9 with use of the terms HNB (for UMTS/HSPA) and HeNB (for LTE). Standardising femtocell technology creates an enabler for the wide scale deployment and interoperability between global vendors and operators. For example, GSM, UMTS, HSPA and LTE cellular standards are all supported on femtocell networks.

The WiMAX Forum is also building femtocells into their standards (see WiMAX Forum website) and further supports interoperability between different cellular technologies.
Differences between home and enterprise femtocells

Initially femtocells started off being for coverage in the home but have evolved into enterprise femtocells to cover larger office areas.

Motivation for enterprise femtocells is to:

- Provide coverage more easily in indoor environments
- Offload capacity from the macro layer to small cell architectures
- Improve user experience by providing a better SINR so data rates are better
- Reduce the cost of delivering high quality service to subscribers – papers from Signals Research Group (SRG) and Small Cell Forum (formerly Femto Forum) indicate a 4-100 times cost reduction per GB with femtocells compared to macrocells, depending on the architecture, backhaul and traffic routing adopted in both the macrocell and femtocell layers [22].

A high level femtocell network architecture is shown in Figure 2-14 which highlights where the femtocell is situated in the wider (macro layer) network context. The capacity enhancement takes place due to the dedicated network resource provision with little or no contention to access the radio network, combined with a typically higher SINR across most of the cell.

![Figure 2-14 High level femtocell network structure Source: Femto Forum](image)

2.2.4.1. Benefits

- Enables order of magnitude increase in cell density at realistic costs
- Users self deploy capacity and coverage where they need it
- Reduces load on macro layer, improving service for outdoor high mobility users
Femtocells bring benefits to both users and operators.

The benefits to users include:

- Enhanced coverage indoors in areas where there may otherwise be poor cellular coverage
- Enhanced capacity to mobile broadband users, small lightly loaded cells offers higher data rates (this is dependent on the quality of the broadband connection)
- Attractive tariffs and bundles offered by operators when under femtocell coverage

The benefits to operators include:

- Offload traffic from macro layer to femtocells reduces the load thus freeing up capacity to the public network
- Reduced network roll out costs of network including capital and operational expenditure

The two main benefits of deploying femtocells in relation to capacity enhancements include:

- Femtocells provide enhancement to capacity
  a) Fundamentally femtocells enable spectrum to be reused at a higher density, delivering and increased capacity density which can be matched to hotspots of demand, provided interference between cells can be properly managed.
  b) The resulting capacity gains for the network as whole can be large, with for example a gain of around 100 times for a given user throughput indicated in [24] for 3G.
  c) Real-world deployments have now demonstrated femtocells working on the same carrier as macros without interference issues. For example, AT&T have indicated that they are successfully operating femtocells co-channel with both GSM and UMTS macrocells [24].

- Spectrum efficiency improvements
  a) Smaller cells give a better SINR distribution and result in improved spectral efficiency (see chapter 4)
  b) Higher channel rank should mean MIMO works better

2.2.4.2. Challenges

Many of the early challenges in femtocell deployment have been overcome. For example the interference issues that have been highlighted from early deployments have now been resolved by introducing interference mitigation techniques which enables co-channel operation between the femtocell and macrocell.[24]. Furthermore, the regulatory implications for unregulated use of spectrum by a consumer (that does not hold a licence) has been resolved in many territories, on the basis that the operator retains control of the femtocell transmission via the authenticated secure tunnel created between the femtocell and the operator’s core network.

Other challenges of deploying femtocells which can impact upon their use are mainly found in the use of consumer backhaul. There is a dependence on the consumer/user to have a
good quality broadband connection in their home or office to realise the key benefits of femtocells. Other challenges include:

- Ensuring self-deployment and optimisation work on a large scale
- Managing interference between femtocell and macrocell layers
- Ensuring sufficient QoS over DSL backhaul
- Ensuring femtocells are available cost-effectively so as to be attractive to sufficient numbers of consumers

2.2.4.3. Numerical Model

**Indoor small cells** are modelled as offload, utilising a network architecture of the form shown in Figure 2-15: Range is not modelled, rather an indoor small cell reduces or removes an amount of indoor demand at a single demand point (i.e. postal address). Small cell spectral efficiency is slightly higher than that of macrocells due to the improved isolation from neighbour cell interference. The number of bands and bandwidths per band supported is limited given the constraints of the small form factors required. Details and assumptions are described later.

**Outdoor small cells** are modelled explicitly in much the same way as macrocell sites, albeit with reduced range and site spectral efficiency. The number of bands supported is also limited, given form factor constraints.

![Network Architecture Diagram]

*Figure 2-15: Offload for the Access and Core Networks* (offload can occur at the access point or at the gateway depending on the configuration).

2.2.5. Relaying

Relays can be deployed in a number of scenarios to improve performance. They can be used to extend coverage and/or improve data rates in areas which would otherwise low signal quality. Other applications are temporary sites (at events, or in emergency scenarios), or on a moving vehicle such as train, to improve link stability and handle ‘group handover’. Relays might also be used during initial roll out to reduce costs of installing dedicate bandwidth to each eNodeB. A relay can be ‘upgraded’ to a eNodeB when justified by capacity demand.
A relay is like an eNodeB that uses the LTE air interface itself as a backhaul link, rather than another technology such as fibre or microwave. It provides a benefit because the signal paths from ‘donor’ eNodeB to Relay Node (RN) to UE are better than a direct eNodeB – UE connection. For example, a relay may be located above local clutter, providing both good coverage of the local area as well as a clear link back to the donor cell.

![Diagram of relay types](image)

**Figure 2-16: Types of Relay Considered for LTE-Advanced**

Figure 2-16 illustrates several types of relay under consideration for LTE-Advanced. A Type 1 relay looks like UEs like a separate cell. It has its own cell identity, and transmits synchronisation signals, reference signals etc. It appears to Release 8 UEs as a normal rel 8 eNodeB, whilst release 10 UEs will be able to differentiate a relay for potential performance enhancement. A type 1 relay operates ‘inband’ where the eNodeB-relay link (Un) shares the same carrier frequency as the relay – UE link (Uu). These links need to be time division multiplexed to avoid interference. A type 1a relay is the same as type 1, but operates ‘outband’ where the Un uses a different carrier frequency to the Uu.

Type 2 relays provide forwarding for the user plane traffic only, and do not appear to UEs as a new cell. This type of relay can enhance data rates to UEs already covered by the donor eNodeB. It does not have its own cell ID, or transmit control channel information.

**2.2.5.1. Benefits**

Relays are primarily a coverage enhancing technology rather than a capacity enhancer. Simulation results based on 3GPP assumptions show around 19% improvement to cell edge user throughput, and 10% gains to cell throughput or Cell spectral efficiency, as shown in Figure 2-17.
An in-band relay uses part of the spectrum for access, and part for self backhauling. This makes better use of the mobile broadband spectrum, but may displace other technologies like microwave backhaul, so may reduce the usage of other types of spectrum.

2.2.5.2. Challenges

Relays are not a new technology as such, and are already used in existing cellular networks. The main challenge of self interference can be overcome using time division multiplexing of signals to and from the relay node. Perhaps the main challenge is in the business model: Relays have all of the site costs of a normal cell site minus the backhaul, but provide only a fraction of the capacity and coverage enhancement of a normal eNodeB.
2.3. Overview of numerical model for spectral efficiency

<table>
<thead>
<tr>
<th>index</th>
<th>Site Name</th>
<th>Sectors</th>
<th>Base Tx antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Macro</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Macro</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Macro</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Macro</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Outdoor Small cell</td>
<td>1-2</td>
<td>2-4</td>
</tr>
</tbody>
</table>

Table 6 Site Configurations available for deployment in the model

For macrosites, site spectral efficiency increases with the number of sectors and number of antennas for MIMO. Different macrosite configurations are explicitly modelled as each will have different costs and thus the choice of which type to deploy (or upgrade to) will have to take into account the cost as well as the benefits.

We do not explicitly model such choices for the outdoor small cell, rather we consider operators will deploy the ‘technology of the day’, and that this will be replaced rather than upgraded. Once commonly available, it is likely there will be little difference in the overall cost of deploying more advanced small cell technologies, hence we do not explicitly model operator decisions between different types of small cell.

Assumptions

1. 3G → LTE → LTE-Advanced evolution is implicitly modelled as a changing mix of these technology generations over time
2. The number of antennas in the consumer devices is implicitly modelled as a changing mix of 1, 2, 4, and 8 antenna devices over time.
3. Six-sector macrosites are assumed to be limited to two transmit antennas per sector due to a lack of tower space.
4. Indoor small cells are implicitly modelled in demand offload
5. TDD and FDD will have the same spectral efficiency over the occupied spectral resource. The ‘net’ figures for MHz of spectrum in unpaired bands are weighted to represent the proportion of spectrum allocated to DL transmissions
6. Single site configuration for the small cell type - improvements will happen as part of the replacement cycle rather than a conscious upgrade by an operator
7. Outdoor small cell spectral efficiency implicitly incorporates an improvement due to an increasing mix of 4 transmit antennas and 2 sector sites.

Site spectral efficiency figures are provided to the model for the following combinations of variables:

- 5 Site configurations (macro with 3 or 6 sectors, 2, 4, or 8 antennas, and Outdoor small cell)
- 3 geotypes, (rural, urban, suburban)
- 2 consumer locations (indoor/outdoor)
- 18 evaluation periods (2012-2030)
- 3 scenarios for technology evolution (low, med, high)
The following sections provide detailed descriptions of the assumptions made to model how the above factors impact site spectral efficiency.

Indoor small cells (consumer deployed femtocells or Wi-Fi access points) are modelled as offload, by reducing or removing the demand at a single demand point. Assumptions for the spectral efficiency, bandwidth and resulting capacity are also given.

2.4. **Technology Evolution from 2012-2030**

We model an evolving spectral efficiency due to the following mechanisms:

- Development of technology generations
- Re-farming of spectrum to newer generations
- Increasing number of antennas in the device mix

The following sections provide detailed assumptions.

2.4.1. **Timing of Technology Generations: 3G-4G and beyond**

Over the period 2012 – 2030 technology will evolve from HSPA to LTE to LTE-Advanced and beyond. We do not explicitly model the operator decision to adopt or re-farm spectrum to newer generations, rather we assume that a site spectral efficiency will represent the ‘mix of the day’.

We consider the availability of 3GPP standards releases over the period 2010-2030. Freeze Dates for standards are available for up to release 12. Releases occur approximately every 18 months. In addition to GSM, HSPA, HSPA+, LTE rel 8 and LTE-Advanced rel 10, we model four future generations notionally representing releases 12, 14, 16 & 18. Figure 2-18 shows dates for specification freeze, commercialisation through to mass adoption for 3GPP releases. This provides a framework to model a continually evolving mix of deployed technology generations, each with improved spectral efficiency over its forebears. It is not important whether these are 3GPP releases or another specification group. What is important is the rate of improvement in spectral efficiency.

![Timing of Technology Generations](image)

Figure 2-18 Assumed timing of specification, commercialisation and mass adoption for 3GPP releases within the study period. Sources 3GPP\textsuperscript{27,28}, Informa\textsuperscript{29}, Real Wireless Extrapolation.
2.4.2. Spectrum Usage per Technology Generation and Re-farming

Based on the findings of lead times from standards freeze to commercial availability and mass adoption presented in our study of 4G Capacity Gains [30], we model each technology generation’s spectral occupancy building and falling over time as shown Figure 2-19. The lower plot is a cumulative version of the upper plot, presenting the same information in a different format. Generations beyond release 10 are assumed to follow similar trends to earlier releases. GSM is treated a special case, and is gradually replaced or re-farmed over time until 2020.

Spectral efficiency for a given year is computed as a sum of that of each generation, weighted according the proportion of spectrum deployed with that generation. We note that the total quantity of spectrum increases significantly during the study period, as described in the section on spectrum scenarios.

Figure 2-19 Assumed evolution of spectrum usage by different technology generations
2.4.3. Device Mix Evolution

Site spectral efficiency is impacted by the types of device being served. We consider how the changing mix of different devices impacts the split of traffic across UEs with 1, 2, 4 and 8 antennas. This is then used to weight spectral efficiency figures for different MIMO modes (2x2, 2x4, 4x2, etc.) to arrive at the spectral efficiency of the day.

We implicitly model the increasing numbers of laptops, tablets and smartphones in the device mix, a trend which leads to increasing numbers of antennas per device over time. The introduction of high volume low antenna device such as one supporting M2M may however start to reduce the average number of antennas per device. We therefore weight antennas per device by the amount of traffic served, which down weights the large number of basic devices which may only require a small amount of traffic. Figure 2-20 shows the evolving traffic split. This is combined with assumptions for the number of antennas on these devices over time to arrive at the traffic split by antenna count shown in Figure 2-21. The original data from the study in [30] has been extrapolated beyond 2020 as shown in the figure.

![Traffic Split Across Device Types](image)

Figure 2-20 Evolving Traffic Split over device Type. Source Real Wireless [30]
Figure 2-21 Evolving Traffic Split across devices with 1, 2, 4 and 8 antennas. Source Real Wireless [30]

2.5. **Impact of Traffic Mix and Network Utilisation**

Spectral efficiency figures are often quoted for ‘full buffer’ user traffic demand where all users continuously download data at the maximum rate they can achieve. This way, users in ‘good’ locations consume considerably more data than those at the cell edge. This provides an optimistic view of capacity compared to a ‘fixed file size’ assumption, where all users consumer the same volume of data regardless of their position in the cell. Serving the small packets associated with VoIP traffic also reduces efficiency as illustrated in Figure 2-22. We assume an adjustment factor of 65% applied to ‘full buffer’ simulation results to account a real world traffic mix, consistent with the 4G capacity gains study [30].

Most simulations also assume that all cells are 100% loaded for capacity evaluation. However in practical deployments networks work at less than 100% capacity utilisation in order to improve quality of service, ensure network stability and leave headroom for expansion of demand. A factor of 85% is assumed in [30] to account for utilisation.
2.6. **Technology Evolution Scenarios Low, Mid, High:**

In order to represent a range of possible evolution scenarios for standardised mobile broadband technology, we consider three possibilities (low, mid, high).

- Little further growth (low): This assumes that the current day mobile broadband technology is already approaching the limits of what is achievable in terms of site spectral efficiency. It assumes that no significant benefits will be achieved in practice with advanced techniques such as CoMP or enhanced MIMO due to limitations of backhaul quality or space for more MIMO antennas.

- Steady Growth (mid): The mid scenario represents a steady improvement in site spectral efficiency, as algorithms improve and new techniques are introduced to co-ordinate and reduce the interference which ultimately limits cell throughput. Furthermore, we can assume Self Optimising Network technology automatically adapts network configurations to optimally match the changing conditions in which they operate.

- Innovation dividend (high): This ‘high’ scenario represents continued strong growth in the spectral efficiency of mobile broadband technologies. Although we cannot specify exactly how this will come about, the actual efficiency figures will be based on a significant improvement over the ‘steady growth case’

The purpose of the scenarios is to model a spread of technology improvement which can help us understand the sensitivity of our findings to our assumptions in this area. This also enables us to ‘bound’ the plausible rates of technology improvement.

The scenarios impact the choice of spectral efficiency figures and growth beyond release 10 (LTE-Advanced) for which industry wide simulation results are available.
2.7. **Cell Spectral Efficiency Per Generation, Per Antenna Configuration**

2.7.1. **GSM and HSPA**

Assumptions for GSM and HSPA(+) technologies are based on the extensive analysis of 4G capacity gains which provides figures for low, mid and high end deployments, shown in Figure 2-23. The low, mid, high scenarios all start off the same in 2012, but diverge for later years.

GSM is assumed to have a spectral efficiency of 0.09 bps/Hz/cell for all antenna configurations, consistent with the 4G capacity gains report [30] and a previous PA Consulting study [31].

HSPA release 6 and 7 are based on [30], which gives figures for low-end, med and high-end device modems as shown in Figure 2-23. These device types are mapped onto this study’s technology evolution scenarios as follows:

- **HSPA Rel 6:**
  - Low scenario: low end, no evolution
  - Mid scenario: Low end evolving to mid
  - High scenario: low evolving to mid and high
- **HSPA Rel 7:**
  - Low scenario: mid, no evolution
  - Mid & High scenario: mid evolving to high end

‘Evolution’ is achieved by using the device antenna mix mechanism, where the device mix starts with predominantly 1 and 2 antenna devices with increasingly more 4 and 8 antenna devices. In the case of HSPA where 4 and 8 layer MIMO are not supported, these are replaced with mid and the high-end device types.
2.7.2. LTE Release 8 and LTE-Advanced Release 10

The source data for LTE and LTE-Advanced are the industry-wide evaluations performed by the 3GPP for their application of LTE-Advanced as an IMT-Advanced technology \cite{32, 33}. These sources provide a wide range of comparable results for LTE release 8 and 10 with different antenna configurations algorithms and CoMP schemes and in both ‘3GPP case 1’ macrocell conditions and ITU-R ‘Urban Macrocell’ environment with a 2GHz carrier frequency, described in detail in \cite{14}. In general the Urban Macrocell environment results are used, but where results are missing, relationships between comparable results from 3GPP case 1 are scaled to the ITU environment. These results are applicable to an urban macrocell with outdoor only demand at a mid carrier frequency. We show later how these results are scaled to other environments.

These 3GPP simulation results represent ‘full buffer’ traffic models and 100% network utilisation. They are scaled according to a ‘real world’ traffic mix and utilisation given earlier. This is broadly the approach used by the 4G capacity gains study \cite{30} and was found

![Cell Spectral Efficiency figures used for GSM and HSPA release 6 and 7, Source Real Wireless \cite{30}](image)

<table>
<thead>
<tr>
<th></th>
<th>WCDMA Rel-99</th>
<th>HSPA Rel-5</th>
<th>HSPA Rel-6</th>
<th>HSPA+ Rel-7/8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-end</strong></td>
<td>Rx diversity 1x2, 15 codes, 64QAM</td>
<td>Rx diversity 1x2, 15 codes, 64QAM</td>
<td>MIMO 2x2, 15 codes, 64QAM</td>
<td></td>
</tr>
<tr>
<td><strong>Typical expected rollout</strong></td>
<td>Rx diversity 1x2, 15 codes, 16QAM</td>
<td>Rx diversity 1x2, 15 codes, 16QAM</td>
<td>Rx diversity 1x2, 15 codes, 16QAM</td>
<td></td>
</tr>
<tr>
<td><strong>Low-end</strong></td>
<td>SISO 1x1, 5 codes, 16QAM</td>
<td>SISO 1x1, 5 codes, 16QAM</td>
<td>SISO 1x1, 5 codes, 16QAM</td>
<td></td>
</tr>
</tbody>
</table>
to provide good alignment with other industry studies, measurements and stakeholder inputs.

- **LTE Release 8**
  - Single User MIMO only, with 2 or 4 layers
  - Low and high evolution scenarios scaled from mid case simulation results in [32] by 90% and 110% respectively, representing small variations in the degree of success of SON assisted network optimisation and algorithm implementation
  - Based on ITU’s Urban Macro environment (UMa) [34]

- **Release 10 LTE Advanced**
  - Low: Multi User MIMO only, no CoMP
  - Mid: Equal mix of MU MIMO, Co-ordinated beamforming and scheduling and beamforming
  - High: Joint Processing CoMP
  - 8 site antennas supported by the standard.

### 2.7.3. Beyond LTE-Advanced: Release 12 and beyond

Assumptions for spectral efficiency improvement for later technology generations are based on improvement rates between the early LTE releases:

- **Mid case:**
  - Average improvement over all supported antenna configurations from rel 8 to rel 10 = 47% (8 transmit and receive antenna combinations are not supported in release 8, so these are omitted from the average)
  - The growth rate of the ‘mid’ case has been tuned to be consistent with that found in the ‘4G capacity gains’ study [30] – which is a 75% reduction in improvement for every two releases.

- **High Case:**
  - The same 47% improvements of LTE-Advanced rel 10 over LTE rel 8 achieved from release 10 to 12, and then reducing by 90% for every further ‘generation’: i.e. 38% for release 14 over release 12, and 34% for release 16 over release 14. This is seen to be an aggressive growth rate - maintaining a generation on generation improvement at similar levels from the initial improvements.

- **Low Case**
  - Similar to the mid and high cases, but with a per generation growth reduction factor of 40%, leading to a flattening off of SE improvements towards the end of the study period. This conservative view results in cell spectral efficiencies only slightly above what is expected for LTE-Advanced.
2.7.4. Cell Spectral Efficiency Evolution (Urban Macro 1800MHz, outdoor demand)

![Cell Spectral Efficiency Chart]

**Figure 2-24 Cell spectral efficiency evolution for macrocells with outdoor users**

Figure 2-24 shows the cell spectral efficiency for different macrocell configurations resulting from the evolving device mix and technology generation mix. Increasing cell spectral efficiency is due to increasing antennas in the device mix and algorithm improvements. This evolution is based on weighted and blended spectral efficiency figures from simulations of the urban macrocell environment with an 1800MHz carrier and outdoor only users. Spectral efficiency for other environments and frequencies are obtained through the ‘environmental scaling’ process described later.

In theory, if we assume modem performance limited by the Shannon bound [35], cell spectral efficiency is limited by the distribution of SINR that can be achieved for users of the network. Ever-increasing cell densities mean that noise limiting is likely be less of an issue, so interference will be the limiting factor for cell spectral efficiency. Once practical limits for the number of antennas per cell site and device have been reached, further enhancement can still be achieved through technologies which improve the SINR distribution through interference mitigation and cancellation, such as JP-CoMP.

In order to achieve high air interface capacity through high spectral efficiency, significant backhaul capacity will be needed to assist co-ordination and information sharing between cells. To some extent, the presence of suitable transmission technologies such as fibre may be a limiting factor in spectral efficiency improvements. Co-ordination is likely to emerge first in super-dense urban environments where site density is already very high driving a need for higher spectral efficiency, which a significant fibre penetration to enable co-ordination. Whilst the promise for co-ordination is significant, capacity gains shown for LTE-Advanced implementations are modest [30], suggesting potential for great improvements to come.
2.8. **Sectorisation Gains**

Cell spectral efficiencies are converted to site spectral efficiencies through multiplication by the sectorisation gain.

![Sectorisation Gain Graph]

**Figure 2-25 Sectorisation Gains for Different Sector Antenna Beamwidths, Source Jaiho et al\[^{36}\]**

Each sector antenna provides a ‘cell’ of coverage in which the spectral resource is re-used. More sectors means higher site spectral efficiency. There are diminishing returns for sectorisation gain where pattern roll-off causes adjacent sector interference. Larger apertures are needed for the tighter roll-off needed for higher order sectorisation. Softer handoff in 3G can exploit adjacent sector interference to increase site capacity. Although early HSPA and LTE only support hard handover, techniques like intra-site CoMP work in much the same way as soft(er) handoff. Scattering around the site can also increase adjacent sector interference- an issue for microcells in the clutter. The operators’ choice between 3 and 6 sector macro sites (combined with 2,4,8 Tx antennas) is explicitly modelled.

Source data for macro site cell spectral efficiency is based on trisector sites, so a straight forward multiple of 3x is needed here. For 6 sector sites, a sectorisation gain of 5.6x is used based on \[^{36}\] (see above graph, assuming the 33 degree antenna).

Initially outdoor small cell sites are assumed to have a single sector, with 2 sector small cell sites increasing in the mix towards 2030 (details are provided later).
2.9. **Adjustments for Outdoor Small Cells**

Operators are now looking to deploy small cell technology themselves to meet capacity needs in hot spot areas, where there is no remaining places for macrosites. It is anticipated that site acquisition can be simplified through single landlord deals such as on authority managed street furniture, or shop facades for chain stores. Benefits over femtocells are managed deployment and backhaul leading to improved QoS, including handover, latency and throughput.

Spectral efficiency for small cells is based on a blend of macrocell spectral efficiency for 2 and 4 tx antennas and 1 and two sectors, scaled to represent the increase from the environment.

Small cells have smaller form factors to enable them to be deployed in wider variety of locations than macro-sites, which typically require space for outdoor and indoor equipment. The smaller size does limit the RF power and hence range that small cells provide, so they needed to be deployed close to the users, down at street level. Deployment ‘down in the clutter’ results in a different propagation environment to rooftop macrocells, and it is believed the resulting isolation between cells reduces interference and results in higher spectral efficiency, as summarised in Table 7. The 3GPP and Deutsche Telekom sources are the most credible here, since they are based on an analysis of the small cell environment. The ITU-R is a requirement rather than the result of analysis, and so is indicative of an expectation that small cell spectral efficiency should be higher. Picochip and Huawei sources made no allowance for any difference between macro and small cell efficiency, and these are more likely to be the result of simplification rather than a considered analysis. We believe a scaling factor of 1.24 represents the most credible of these sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>Scaling factor: $\text{SE}<em>{\text{small cell}}: \text{SE}</em>{\text{macro}}$ (DL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP simulations$^{33}$</td>
<td>1.24x</td>
</tr>
<tr>
<td>Deutsche Telekom$^{37}$</td>
<td>1.25x (0.5-2x)</td>
</tr>
<tr>
<td>ITU-R (requirements)$^{38}$</td>
<td>1.18x</td>
</tr>
<tr>
<td>Picochip$^{39}$</td>
<td>~1x but inconclusive</td>
</tr>
<tr>
<td>Huawei (2 sources)$^{40,41}$</td>
<td>1x assumed</td>
</tr>
<tr>
<td>Proposed scaling factor:</td>
<td>1.24x</td>
</tr>
</tbody>
</table>

| Table 7 Scaling macrocell spectral efficiencies to small cells due to the different propagation environment |

Unlike macrosites, where sectorisation and number of transmit antennas will be explicitly modelled as an upgrade option, it is assumed that small cells will be replaced rather than...
upgraded, and that the site spectral efficiency will represent the ‘mix of the day’. We expect to see an evolution of small cell technology from single sector only towards two sectors (which may for example point in opposite directions down a street) and from 2 antennas to 4 antennas, enabling the higher order MIMO modes. Figure 2-26 shows the assumed mix over the study period. By 2024 we expect all outdoor small cells to support 4 transmit antenna MIMO. At the device end, we assume the same mix of 2,4 and 8 antenna devices as used for macrocells.

![Evolving Transmit Antenna Mix](image1)

**Figure 2-26 Assumption for evolving mix of 2 and 4 transmit antenna outdoor small cells**

Initially outdoor small cells are all single sector devices; however, we anticipate that 2 sector devices will be introduced, for example with different sectors in opposite directions up and down a street. Figure 2-27 shows the assumed mix of 1 and 2 sector small cell sites. By 2030 50% of small cell sites are assumed to support two cells per site.

![Evolving Cells per site mix](image2)

**Figure 2-27 Assumption for the evolving mix of small cells sites with 1 and 2 cells per site**
2.10. **Site Spectral Efficiency**

![Site Spectral Efficiency Evolution for Various Configurations](image)

**Figure 2-28 Site spectral Efficiency Evolution for Mid Case Macro and Outdoor small cells with outdoor consumers**

Figure 2-28 shows site spectral efficiency resulting from the combination of cell spectral efficiency with sectorisation gain, and in the case of outdoor small cells, the sectorisation and transmit antenna mix. This represents spectral efficiency with outdoor only consumers in an urban environment with an 1800MHz carrier frequency. Scaling factors applied to represent other environments are described later. The slight undulations in the curves are the result of moving between the technology generations, which is largely averaged out by the overlap between generations shown earlier.

Figure 2-29 compares the low, mid and high technology evolution scenarios for an example site configuration. Other configurations have broadly the same relationship. Spectral efficiency for all scenarios is similar at the beginning of the study period, where we have a confident view of what is achieved in practice today. The lines diverge in the latter part of the study period as predictions are increasingly speculative. Relative to the mid case in 2030, the low and high cases are 54% lower and 64% higher respectively. The low to high represents a range of 3.0x.
Figure 2-29 Comparison of Low, Mid and High case technology evolution scenarios for an example configuration
2.11. Environmental Scaling for Geotypes, Carrier Frequency and Indoor Users

Site spectral efficiencies for outdoor only consumers are adjusted by a range of scaling factors to represent indoor only users for different clutter types and carrier frequencies. The model itself then combines the outdoor only and indoor only figures to represent the actual mix.

Scaling factors are obtained from an analysis of SINR distributions generated by a model designed for coverage and capacity analysis by Ofcom\cite{42}. This uses site and demand point data as defined under study areas, which are based on site counts equivalent to 13k sites UK wide. SINR CDFs are obtained for outdoor-only UEs and indoor-only UEs (10m depth “Depth1+”). Indoor penetration losses vary with frequency consistent with the link budgets used in this study for site range calculations. Figure 2-30 shows SINR distributions for the rural Lincolnshire study area. Similar results were obtained for the other study areas.

Note that this SINR analysis is based on an 800MHz spot frequency, whereas our site ranges assume 700MHz. In both cases we are applying the findings to represent all bands in the <1GHz group, so it not critical that they are the same. We expect that any differences in the performance at these spot frequencies can be assumed to be negligible.

Figure 2-30 Example SINR distributions from a coverage analysis, used to determine ratio of spectral efficiency between outdoor and indoor

The resulting SINR distributions are combined with link level performance for 2x2, 4x2 and 4x4 configurations from a 3G Americas report \cite{43} to yield cell spectral efficiencies. Differences in SE for 2x2, 2x4 and 4x4 MIMO antenna configurations were all less than 0.5%, so environmental scaling is considered to be independent of antenna configuration.
The cell spectral efficiencies are normalised to the outdoor urban 1800MHz case, as this closely represents the environment assumed for the source spectral efficiency data from 3GPP. Figure 2-31 shows the resulting scaling factors for other environments. In general, spectral efficiency is lower for indoor only demand than for outdoor only demand, and lower carrier frequencies result in higher spectral efficiency for a given environment. Outdoor spectral efficiencies are lower in the suburban environment and higher in rural. More variation is seen between indoor and outdoor at higher carrier frequencies and in the rural environment.

Figure 2-31 Environmental Scaling factors relative to Outdoor Urban 1800MHz

Figure 2-32 Ratio between Spectral Efficiency for indoor and outdoor consumers
Figure 2-32 shows the indoor:outdoor ratio of cell spectral efficiencies at different carrier frequencies for each study area. This reveals one of the key benefits of sub 1GHz spectrum – that it can serve indoor users with high spectral efficiency even in rural environments. Using higher carrier frequencies for indoor coverage results in moderate reductions of cell spectral efficiency (almost 30% for 2600MHz in the Rural Lincolnshire study area).

Note that this may appear to contradict some views that lower frequencies are poor for capacity and are better suited for coverage applications. These views arise from two sources:

1. The quantity of spectrum available in lower frequency bands is usually more limited;
2. That the lower propagation losses at lower frequencies may cause excessive interference between sites in high capacity density areas.

Our modelling explicitly incorporates the available spectrum quantities at each band, addressing (1) above. Regarding (2), while indeed frequency reuse requires greater care in order to contain interference at lower frequencies, this can be achieved via a variety of techniques including antenna tilts, beamforming, power control and smart scheduling. Once these are included, the improved propagation is an advantage for spectrum efficiency, as demonstrated in the modelling results above.
2.12. **Indoor Small cells (Femtocells)**

Indoor small cells are modelled as implicit data offload, where some of the demand points are reduced (or removed entirely) by the capacity of the small cell. We assume the following to derive the capacity:

- Cell spectral efficiency as for outdoor small cells (i.e. slightly higher than for macrocells)
  - Includes evolution in site antennas from 2-4, and device antennas from 2-4-8
  - Includes low, mid and high cases
- Single band per femtocell
- Single channel bandwidth increasing from 5MHz in 2010 to 40MHz in 2030, as shown in Table 8
- Low, med high scenarios following spectral efficiency growth

Figure 2-33 shows the resulting capacity for indoor small cells, increasing from 1Mbps in 2010 to over 200Mbps by 2030, in the mid case. We assume that backhaul capacity is not a limiting factor due to the expected roll-out of superfast broadband.

<table>
<thead>
<tr>
<th>Year</th>
<th>Assumed technology</th>
<th>Bandwidth MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012-2013</td>
<td>SC-HSPA</td>
<td>5</td>
</tr>
<tr>
<td>2014-2019</td>
<td>DC-HSPA / 10MHz LTE</td>
<td>10</td>
</tr>
<tr>
<td>2020-2025</td>
<td>20MHz LTE</td>
<td>20</td>
</tr>
<tr>
<td>2026-2030</td>
<td>20MHz LTE + 2 way Carrier Aggregation</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 8 Assumed Bandwidth Evolution for Indoor Small cells
Figure 2-33 Indoor Small Cell Capacity Evolution over the Study Period
A3. Spectrum scenarios

3.1. Introduction

This annex explains the sources of the spectrum scenarios used in our modelling, which have been developed in close discussion with Ofcom.

We considered individual mobile spectrum bands that could become available for use in the UK based on a set of selection criteria. The criteria helped to identify those spectrum bands that are available today or could become available in the future for mobile use. The criteria used to select the spectrum bands are given below:

- Will the spectrum be allocated for mobile / harmonised use?
- Will the band be cleared/available for use in the UK?
- Will the band be used at scale (standardised) internationally?
- Will the band be attractive (i.e. given factors like adjacent use interference etc.)?

If a band is selected, then the relevant quantity is determined by considering the following:

- How much spectrum is there in the band?
- Are there adjustments to make to the amount that is actually available (e.g. guard bands etc.)?
- Is there sufficient to be attractive for deployment in practice?

The format for modelling the spectrum input required the net spectrum bandwidth for the downlink portion only since the study was interested in delivering capacity to users, as this is limiting factor within current mobile broadband networks. It is accepted that the symmetry of networks may shift over time but we assume the majority of traffic provision and associated limits on capacity will be predominantly in the downlink (Note however that in some cases the uplink may limit range and we have incorporated this in our site range calculations). Furthermore, the spectrum was to be available across the UK in the time frame between 2012 and 2030.

Paired and unpaired spectrum were both under consideration and we factored in the proportion of time that TDD systems allocate to the downlink.

The gross spectrum quantities were identified to give the total spectrum for each band. However, in order to determine the precise amount of net spectrum available for use in the model we had to take into account various factors such as future availability, re-farming etc. Other specific considerations for deriving net spectrum also included the use of guard bands, duplex spacing etc.

The assumptions we made to determine the quantity and timing of introducing each of the frequency bands were based on the best available information and confirmatory discussions with Ofcom. The current status of spectrum bands in the UK was derived according to the Frequency Allocations Table[44] and the UK Interface Requirements (See Table 12, Table 13 and Table 15 for specific reference), or from public sector spectrum announcements for the release of MOD spectrum or other public sector spectrum under the spectrum release programme[45].

We identified 17 (2 in the high case only) distinct frequency bands that will be made available for capacity purposes over the whole timeframe. The quantity and timing of each
of the spectrum bands varies according to the different scenarios proposed. The 700 MHz band was a special variable input that we set to be introduced at different times within the 18 year period, these were in year 2020 or 2026.

Table 9 below shows the full list of spectrum bands for consideration.

<table>
<thead>
<tr>
<th>Paired spectrum</th>
<th>Unpaired spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 MHz</td>
<td>1452-1492 MHz (SDL)</td>
</tr>
<tr>
<td>800 MHz</td>
<td>2100 MHz 1900-1920 MHz</td>
</tr>
<tr>
<td>900 MHz</td>
<td>2100 MHz 2010-2025 MHz</td>
</tr>
<tr>
<td>1800 MHz</td>
<td>2300 MHz</td>
</tr>
<tr>
<td>1980 MHz (High case only)</td>
<td>2600 MHz</td>
</tr>
<tr>
<td>2100 MHz</td>
<td>2700-3100 MHz (High case only)</td>
</tr>
<tr>
<td>2600 MHz</td>
<td>3600-3800 MHz</td>
</tr>
<tr>
<td>3400 – 3600 MHz</td>
<td>3600 – 3800 MHz</td>
</tr>
<tr>
<td>3400 – 3600 MHz</td>
<td></td>
</tr>
</tbody>
</table>

Table 9 Paired and unpaired frequency bands under consideration

3.2. **Spectrum as a source of supply for mobile capacity**

Efficient use of spectrum is fundamental for the delivery of services within mobile networks and the properties of spectrum at different frequency bands can have a beneficial impact depending on the type of deployment and environment.

This study has considered spectrum within the practical capabilities of mobile use with the most practical and effective operation taking place below 4GHz. Although, more bandwidth is available at higher frequency bands the practical range rapidly declines (See annex A4 on site ranges). Therefore, the limit of frequency bands suitable for the purposes of this study was considered up to 3.8 GHz.

3.3. **Quantity and timing assumptions for frequency bands**

The following section describes the assumptions made for the quantity and timing of each of the individual frequency bands for consideration and a justification is given against each one.
3.3.1. Quantity and timing of introducing paired frequency bands

700 MHz spectrum band (695 MHz – 735 MHz paired with 746 MHz – 786 MHz)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross quantity available is 90 MHz based broadly on likely available spectrum from the boundary 700 – 790 MHz according to the quantity given in FCC band plan[^46] since there is no agreed quantity identified yet for Europe</td>
<td>Timing of introducing this spectrum is based on expiry of existing licensees taking place in 2026</td>
</tr>
<tr>
<td>Net quantity incorporates the potential use of:</td>
<td>Scenarios for modelling take into account the introduction of this band earlier to 2020 to determine if there will be any benefit in doing so</td>
</tr>
<tr>
<td>1 MHz guard band from 694 – 695 MHz</td>
<td></td>
</tr>
<tr>
<td>40 MHz UL portion</td>
<td></td>
</tr>
<tr>
<td>11 MHz duplex gap</td>
<td></td>
</tr>
<tr>
<td>40 MHz DL portion</td>
<td></td>
</tr>
<tr>
<td>5 MHz guard band from 786 MHz to 791 MHz</td>
<td></td>
</tr>
<tr>
<td>This results in 2 x 40 MHz of total usable spectrum and therefore 40 MHz of Downlink spectrum</td>
<td></td>
</tr>
</tbody>
</table>

Table 10 Quantity and timing of 700 MHz band

800 MHz spectrum band (791 – 831 MHz paired with 842 – 862 MHz)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross quantity available is 72 MHz based Commission Decision 2010/267/EU[^47]</td>
<td>Timing of introducing this spectrum is based on the expected of award of this spectrum in the UK in Q4 2012 as announced by Ofcom in its recent statement (Oct ’11)[^48]</td>
</tr>
<tr>
<td>Net quantity incorporates the use of:</td>
<td>Scenarios for modelling take account introducing the total quantity of this band in 2013</td>
</tr>
<tr>
<td>11 MHz duplex gap</td>
<td></td>
</tr>
<tr>
<td>1 MHz guard band at 790 MHz</td>
<td></td>
</tr>
<tr>
<td>This results in 2 x 30 MHz of total usable spectrum and therefore 30 MHz of Downlink spectrum</td>
<td></td>
</tr>
</tbody>
</table>

Table 11 Quantity and timing of 800 MHz band
### 900 MHz frequency band (880 MHz – 915 MHz paired with 925 MHz – 960 MHz)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
</table>
| • Gross quantity available is 70 MHz based on Ofcom Interface Requirement IR 2014 Public Wireless Networks (Aug 2005)  
• Net quantity is equal to gross quantity with all duplex gaps and guard bands already taken into account with 2 x 35 MHz available in total  
• This results in 35 MHz of Downlink spectrum | • This band is already available for HSPA with at least one 5 MHz carrier used in London by O2  
• We assume HSPA is being used today (2011) 5 MHz carrier used for London for mobile broadband and increases to 10 MHz in 2013 through to 2016, then increases linearly to 35 MHz to 2021. This is based on the majority of the spectrum still being used for GSM across the period  
• After this point (2021) the band is assumed to be fully refarmed  
• This assumption is supported by the increasing availability of HSPA devices at 900 MHz according to the Global Mobile Suppliers Association[^52] |

Table 12 Quantity and timing of 900 MHz band

### 1800 MHz frequency band (1710 MHz – 1785 MHz paired with 1805 MHz – 1880 MHz)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
</table>
| • Gross quantity available is 150 MHz based Interface Requirement IR2014[^49] Public Wireless Networks (Aug 2005)  
• Net quantity will be 144 MHz including the 2 x 15 MHz released to the market. All duplex gaps and guard bands already taken into account with 2 x 72 MHz available in total  
• This results in 72 MHz of Downlink spectrum | • This band is currently (2011) used for GSM.  
• The 1800 MHz band is liberalised for HSPA (2013). We have assumed therefore only 22 MHz available (DL) for HSPA/LTE over a 3 year period to 2016. This is based on the majority of the spectrum still being used for GSM  
• After this point (2016) the quantity linearly increases over a five year period until it fully refarmed by 2020.  
• This assumption is supported by the increasing availability of devices at 1800 MHz predominantly for LTE according to the GSA[^54] |

Table 13 Quantity and timing of 1800 MHz band
1980 MHz (High case only) frequency band (Frequency separation not yet defined for terrestrial mobile use)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Gross quantity available is 60 MHz based on globally harmonised allocation[44] for Mobile satellite. The band is adjacent to the IMT bands</td>
<td>• This band is currently used for Mobile satellite use and is only considered in the high spectrum case scenario. MSS is likely to remain until re-allocation takes place no earlier than 2020</td>
</tr>
<tr>
<td>• Net quantity assumes the use of similar guard bands and duplex gaps currently in place resulting in 2 x 30 MHz available in total</td>
<td>• We assume full availability of the band from 2020 onwards for mobile broadband services</td>
</tr>
<tr>
<td>• This results in 30 MHz of Downlink spectrum</td>
<td></td>
</tr>
</tbody>
</table>

Table 14 Quantity and timing of 1980 MHz band

2100 MHz frequency band (1920 MHz – 1980 MHz paired with 2110 MHz – 2170 MHz)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Gross quantity available is 120 MHz based on IR 2019 Third Generation Mobile[52]</td>
<td>• This band is currently used for HSPA and likely to continue to be used predominantly for evolutions of HSPA up to 2020</td>
</tr>
<tr>
<td>• Net quantity incorporates the use of guard bands and duplex gaps resulting in 2 x 60 MHz available in total</td>
<td>• We assume full use of the band from 2010 onwards for mobile broadband services</td>
</tr>
<tr>
<td>• This results in 60 MHz of Downlink spectrum</td>
<td></td>
</tr>
</tbody>
</table>

Table 15 Quantity and timing of 2100 MHz band
2600 MHz frequency band (2500 MHz – 2570 MHz paired with 2620 MHz – 2690 MHz)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Gross quantity available is 140 MHz based on ECC Decision (05)05[33]</td>
<td></td>
</tr>
<tr>
<td>• Net quantity includes a total of 2 x 70 MHz of usable spectrum which takes into account duplex gap and guard bands</td>
<td></td>
</tr>
<tr>
<td>• This results in 70 MHz of Downlink spectrum</td>
<td></td>
</tr>
<tr>
<td>• Timing of introducing this spectrum is based on the expected of award of this spectrum in the UK in Q4 2012 as announced by Ofcom in its recent statement[38] (Oct ’11)</td>
<td></td>
</tr>
<tr>
<td>• Scenarios for modelling take account introducing this band in 2013</td>
<td></td>
</tr>
</tbody>
</table>

Table 16 Quantity and timing of 2600 MHz band
### 3500 MHz frequency band (3480 – 3500 MHz paired with 3580 – 3600 MHz UK Broadband spectrum and 3410 MHz – 3480 MHz paired with 3510 MHz – 3580 MHz)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 3480 – 3500 MHz paired with 3580 – 3600 MHz Gross quantity available is 40 MHz based on Interface Requirement IR2015[44] (2011) noting amendment of licence to mobile</td>
<td>• This band is currently used by UK Broadband for mobile Wireless Broadband services</td>
</tr>
<tr>
<td>• Net quantity will be 20 MHz based on 3GPP 36.101[45] Release 10 September 2011 resulting in 2 x 10 MHz and therefore 10 MHz of Downlink spectrum</td>
<td>• We assume this band will be used for a future LTE network which is likely to be available as early as 2012 as announced by UK Broadband[46]</td>
</tr>
<tr>
<td>• 3410 MHz – 3480 MHz paired with 3510 MHz – 3580 MHz</td>
<td>• This band is currently used for defence purposes but is a high priority for release by the MOD under its release programme</td>
</tr>
<tr>
<td>• Gross quantity available is 140 MHz (excl UKB spectrum) as stated in DCMS Enabling UK growth – Releasing public spectrum Making 500 MHz of spectrum available by 2020[45]</td>
<td>• The DCMS reports that the release of this spectrum is likely to be within current Government spending round i.e. March 2015</td>
</tr>
<tr>
<td>• Net quantity will be 140 MHz (2 x 70 MHz) based on 3GPP 36.101 Release 10 September 2011[55] which identifies 2 x 80 MHz in this whole spectrum band. This also assumes partial release to market and the need for the MOD to retain spectrum for defence purposes</td>
<td>• We have assumed some approximate quantities to be made available over the time frame:</td>
</tr>
<tr>
<td>• This results in 70 MHz of Downlink spectrum</td>
<td>• Less than 1/3 of this spectrum to be made available in the low quantity scenario over the whole time frame</td>
</tr>
</tbody>
</table>

**Table 17 Quantity and timing of 3500 MHz band**
3.3.2. Quantity and timing of introducing unpaired frequency bands

The downlink portion for TDD systems differs to that of FDD due to sharing of spectrum resources between the uplink and downlink. Therefore, we have assumed a proportion of traffic generated by the downlink based on a set of TD-LTE frame configurations developed by 3GPP[57]. The chart in Figure 3-1 shows the ranges of percentage of DL for TD-LTE and we have assumed 89% in the downlink based on the majority of time spent in the downlink to support growing demands for mobile traffic. All downlink spectrum in the following tables have been adjusted by 89% from the total net quantity.

<table>
<thead>
<tr>
<th>Uplink-downlink configuration</th>
<th>Subframe number</th>
<th>totals</th>
<th>%DL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>D</td>
<td>S</td>
<td>U</td>
</tr>
<tr>
<td>1</td>
<td>D</td>
<td>S</td>
<td>U</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
<td>S</td>
<td>U</td>
</tr>
<tr>
<td>3</td>
<td>D</td>
<td>S</td>
<td>U</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>S</td>
<td>U</td>
</tr>
<tr>
<td>5</td>
<td>D</td>
<td>S</td>
<td>U</td>
</tr>
<tr>
<td>6</td>
<td>D</td>
<td>S</td>
<td>U</td>
</tr>
</tbody>
</table>

Figure 3-1 TD-LTE frame configurations and % resource allocated to DL. Source: 3GPP[57]

1452 -1492 MHz frequency band

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Gross quantity available is 40 MHz based on ECC DEC 03(02)[58]</td>
<td>• Timing of introducing this spectrum is based on Plum’s report which takes into account conclusion of ECC decision end of 2012, inclusion of the band by 3GPP and availability of devices</td>
</tr>
<tr>
<td>• Net quantity incorporates all 40 MHz use for TDD operation as a supplemental downlink. Plum conducted a study[59] which investigated the economic benefits from use of 1452-1492 MHz for a supplemental mobile downlink for enhanced multimedia and broadband services</td>
<td>• We assume the availability of all 40 MHz will be from 2014 to create a supplemental downlink band for mobile broadband use</td>
</tr>
</tbody>
</table>

Table 18 Quantity and timing of 1452 - 1492 MHz band
### 2100 MHz Unpaired frequency band

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
</table>
| • 2 GHz 1900 – 1920 MHz  
  Gross quantity available is 20 MHz based on Interface Requirement IR2019[^52]  
  Net quantity is equal to the gross quantity as it already accounts for any guard bands or constraints. | • This spectrum is available and currently unused but we have assumed this spectrum will be used for HSPA around 2013 |
| • 2 GHz 2010-2025 MHz  
  Gross quantity available is 15 MHz based on Ofcom consultation[^60]  
  Net quantity is equal to gross quantity with all duplex gaps and guard bands already taken into account with 15 MHz available in total | • This band is likely to be released independently of 2.6 GHz and therefore could be available as early as Q1 2012. However, we have assumed full availability of the band by 2013 based on timing for operators to deploy the frequency. |

[^52]: Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030

Table 19 Quantity and timing of 2100 MHz unpaired band
### 2300 MHz frequency band

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
</table>
| • Gross quantity available is 80 MHz as stated in DCMS Enabling UK growth – Releasing public spectrum Making 500 MHz of spectrum available by 2020[45]  
• Net quantity initially is 71.2 MHz based on the likely partial release to market by the MOD and accounting for proportion of TDD downlink | • This band is currently used for defence purposes but is a high priority for release by the MOD under its release programme  
• The DCMS reports that the release of this spectrum is likely to be within current Government spending round i.e. March 2015  
• We have assumed:  
  • 26.7 MHz MHz to be released in 2015 for the low quantity scenario available up to 2030  
  • 35.6 MHz to be release in 2015 available up to 2019. From 2020 all spectrum is available  
  • All 71.2 MHz to be released in 2015 for the high quantity scenario should the MOD identify all spectrum can be released to the market  
  • Devices already available for use in this band due to the deployment of networks in Asian markets such as China and India according to consultants at Heavy Reading[61] |

Table 20 Quantity and timing of 2300 MHz band

### 2600 MHz frequency band

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
</table>
| • Gross quantity available is 50 MHz based on ECC Decision (05)05[53]  
• Net quantity includes 45 MHz which takes into account a 5 MHz restricted block | • Timing of introducing this spectrum is based on the expected of award of this spectrum in the UK in Q4 2012 as announced by Ofcom in its recent statement (Oct ’11)[48]  
• Scenarios for modelling take account introducing this band in 2013 |

Table 21 Quantity and timing of 2600 MHz band
2700 -3100 MHz frequency band (High case only)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Gross quantity available is 400 MHz based on globally harmonised allocation for radionavigation services for both civil military. The band is adjacent to the top of the 2.6 GHz IMT band&lt;br&gt;• Net quantity assumes the use of 50 MHz of spectrum out of the total for mobile spectrum bands</td>
<td>• This band is currently used for primary radar both aeronautical and maritime. Radio navigation is likely to remain in place for at least 15 years, therefore reallocation will take place no earlier than 2025&lt;br&gt;• We assume partial availability of the band from 2025 onwards for mobile broadband services based on reallocation and re-planning of radionavigation services in the bottom portion of the band thus creating a 50 MHz dividend</td>
</tr>
</tbody>
</table>

Table 22 Quantity and timing of 2700 MHz band
### 3600-3800 MHz frequency band

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Gross quantity available is 82 MHz based on current allocation of Fixed Wireless Service to UK Broadband[^54]</td>
<td>• This band is currently used by UK Broadband for fixed Wireless Broadband services</td>
</tr>
<tr>
<td>• Net quantity is equal to the gross amount spectrum as guard bands have been taken into account</td>
<td>• We assume this band will be used for a mobile wireless broadband services which is likely to be available as early as 2013 in the baseline case</td>
</tr>
<tr>
<td>• 3600-3800 MHz</td>
<td>• There are deployment constraints due to the numerous satellite earth stations deployed across the UK in the adjacent bands which may limit its full availability</td>
</tr>
<tr>
<td>• Gross quantity available is 200 MHz based on IR 2015[^54]</td>
<td>• This spectrum is not available at all in the low case scenario</td>
</tr>
<tr>
<td>• Net quantity equates to 60 MHz based on the likely partial release of spectrum with the remaining spectrum to be retained for other civil purposes</td>
<td>• 35.6 MHz of spectrum is available from 2013 to 2030 in the baseline case</td>
</tr>
<tr>
<td></td>
<td>• 71.2 MHz of spectrum is available from 2013 to 2030 in the high case</td>
</tr>
<tr>
<td></td>
<td>• 0 MHz of this spectrum to be made available in the low quantity scenario</td>
</tr>
<tr>
<td></td>
<td>• 53.4 MHz of spectrum be made available in the baseline and high case from 2025 to 2030</td>
</tr>
<tr>
<td></td>
<td>• These timings are based on the numerous satellite earth station still in use across the UK and shifting these frequencies can take many years of international allocation, harmonisation and coordination</td>
</tr>
</tbody>
</table>

[^54]: https://example.com/references

**Table 23 Quantity and timing of 3600-3800 MHz band**
3.4. **Spectrum scenarios**

The spectrum scenarios were derived so that a distinct spread of different quantities and timings could be analysed to determine the impact of introducing new bands and specifically the timing of introducing 700 MHz.

We proposed three scenarios which were based on the following factors:

- **‘Less’ Spectrum scenario**: Representing existing incumbent mobile spectrum with the quantity and timing as outlined in Table 12, Table 13 and Table 15 in the section above. However, other more speculative spectrum bands such as 1452 MHz to 1492 MHz, 2.3 GHz, 3400 – 3600 MHz and 3600-3800 MHz each having reduced spectrum quantities or no spectrum at all across the time frame.

- **Baseline case scenario**: Representing existing incumbent mobile spectrum with the quantity and timing as outlined in Table 12, Table 13 and Table 15 in the section above. However, other more speculative spectrum bands such as 1452 MHz to 1492 MHz, 2.3 GHz, 3400 – 3600 MHz and 3600-3800 MHz each having half or a third of the total spectrum quantities available across the time frame to represent a more plausible representation of available spectrum.

- **‘More’ Spectrum scenario**: Representing existing incumbent mobile spectrum with the quantity and timing as outlined in Table 12, Table 13 and Table 15 in the section above. However, other more speculative spectrum bands such as 1452 MHz to 1492 MHz, 2.3 GHz, 3400 – 3600 MHz and 3600-3800 MHz each having total spectrum quantities available from the point of release and available across the time frame to represent a more plausible yet more aggressive approach to spectrum availability.

- **‘Late public sector (PS)’ scenario**: Representing existing incumbent mobile spectrum where the 3.4 GHz and the 2.3 GHz bands are delayed relative to the ‘low’ case by a further 7 years and where the 2010-2025 MHz band is not available. The proportion of spectrum which comes from public spectrum sources varies amongst these scenarios from 11% (‘low PS’) via 22% (medium) to 24% (high).

A summary chart of the spectrum scenarios can be seen in Figure 3-2 which shows the spectrum quantities in each case evolving over time based on our assumptions. The total quantity at the end of the period varies by as much as 340 MHz between the high case and the low case. There is a smaller variation between the baseline (mid) case and the high case due to increased proportion of spectrum becoming available in the middle and the end of the time frame.
Figure 3-2 Summary of harmonised downlink spectrum scenarios showing timing of 700 MHz availability

We divided the total quantities into frequency ranges for ease of modelling and to analyse how the quantity utilised in each range compares in our model outcomes. The ranges are defined as:

- <1 GHz bands
- 1 – 2.1 GHz bands
- >2.1 GHz bands

Figure 3-3 shows the proportion of spectrum and quantities within each frequency range. It shows that from the starting point 1-2.1 GHz bands and >2.1 GHz are similar in quantity within the total up to 2015. Beyond 2015 frequency bands above 2.1 GHz start to increase until the majority of the bandwidth is from the > 2.1 GHz range from 2020 onwards. Spectrum below 1 GHz remains the smallest proportion of spectrum across the whole time frame even following the introduction of 700 MHz.
Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030

Figure 3-3 Total quantity of spectrum over time divided by frequency grouping - Baseline scenario

Figure 3-4 shows the total quantity of spectrum over time with the frequency bands grouped into paired and unpaired bands. The quantity of paired bands is greater across the whole time frame compared to the unpaired bands. This suggests that in our baseline scenario paired spectrum will continue to play a key role in delivery of mobile broadband services with growing support from unpaired spectrum over time.

Figure 3-4 Total quantity of spectrum over time divided by paired and unpaired grouping – Baseline scenario
The following set of tables outline the specific detail of the quantities and timing of each of the frequency bands identified for use in the model. Each table shows the frequency band, its respective frequency range (<1 GHz, 1-2.1 GHz, >2GHz), quantity or downlink, uplink and total spectrum and the available bandwidth for each year.

It is noted that in 2012 2 x 5 MHz of the 900 MHz spectrum is available in London only and not in the other study areas. This is based on the recent deployment of a UMTS900 network by O2[^2] in London and we therefore assume data traffic will be deployed in one carrier in this band initially.
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Table 24: Low case scenario spectrum quantity and timing per frequency band (Note: This scenario is for Central London as it includes 5 MHz of 900 MHz spectrum in 2012)
This scenario is for Central London as it includes 5 MHz of 900 MHz spectrum in 2012.

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<td>2200 MHz - 2244 MHz (UK4)</td>
<td>High</td>
<td>2200</td>
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<td>2695</td>
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<td>2700/2740 MHz</td>
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<td>2700</td>
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<tr>
<td>3600 MHz - 3800 MHz (UK4)</td>
<td>High</td>
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<td>0</td>
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</table>

Table 25 Baseline case scenario spectrum quantity and timing per frequency band (Note: This scenario is for Central London as it includes 5 MHz of 900 MHz spectrum in 2012)
Table 26: High case scenario spectrum quantity and timing per frequency band (Note: This scenario is for Central London as it includes 5 MHz of 900 MHz spectrum in 2012)

<table>
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<tr>
<td>Paired, Harmonised</td>
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<td>800 MHz</td>
<td>Low</td>
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<tr>
<td>1800 MHz</td>
<td>Med</td>
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<tr>
<td>1900 MHz (1980-2010 MHz)</td>
<td>Med</td>
<td>1900</td>
<td>0</td>
<td>0</td>
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</tr>
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<td>2000 MHz</td>
<td>Med</td>
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<tr>
<td>3600 MHz</td>
<td>High</td>
<td>2655</td>
<td>0</td>
<td>0</td>
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<tr>
<td>3400 MHz - 3600 MHz (UK3)</td>
<td>High</td>
<td>3510</td>
<td>0</td>
<td>0</td>
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<td>2000 MHz TDD (2900-1920 MHz)</td>
<td>Med</td>
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<tr>
<td>2000 MHz TDD (2020-2025 MHz)</td>
<td>Med</td>
<td>2010</td>
<td>0</td>
<td>0</td>
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<tr>
<td>2300 MHz (2310 - 2390 MHz)</td>
<td>High</td>
<td>2300</td>
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<td>0</td>
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</tr>
<tr>
<td>3600 MHz (unpaired)</td>
<td>High</td>
<td>2555</td>
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<td>40</td>
<td>40</td>
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<tr>
<td>2700 - 3000 MHz</td>
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<td>2900</td>
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<tr>
<td>3600 MHz - 3800 MHz (UKB)</td>
<td>High</td>
<td>3700</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>3600 MHz - 3800 MHz</td>
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</table>
3.5. **Modelling spectrum bands as a choice for supply**

This section notes some assumptions made when considering the use of certain spectrum bands in the model. The software model takes the spectrum as an input by way of total quantity available in each year and by the end of the study period 17 frequency bands \((\text{max})\) are available for use.

We have assumed a mix of devices that can support a sub set of the available frequency bands in any one year thus making full use of the available bandwidth amongst the population of mobiles. This does not require that individual mobiles can support all of the bands, only that there is ultimately a reasonable match between capacity requirements and frequency bands supported. We also assume the same mix of device types is used across all bands.

Spectrum is made available as total bandwidth per year, however, the order of the choice of spectrum bands is ranked based on the frequency band with highest maximum total available bandwidth deployed first.
A4. Site Ranges

This annex explains the calculation of maximum site ranges for different combinations of site types, technologies, clutter types and frequencies.

![Diagram showing site ranges for different types of cells](image)

**Figure 4-1: Illustration of site ranges for 1800 MHz**

Figure 4-1 illustrates key concepts for site ranges: each site type has a different maximum range for indoor and outdoor consumers. Macro sites have larger maximum ranges than small cells. Other aspects such as the geotype of the study area and the carrier frequency also impact the ranges as detailed in later sections. It can also be seen from the figure how the site range reduces when serving indoor demand. This is mainly due to the building penetration loss and location variability of user devices in the indoor environments. Outdoor small cells with lower power transceivers have less site ranges compared with that of macro cells as shown in Figure 4-1. In addition to site types, the maximum range of a site is also dependent on other factors such as the bandwidth available to user devices and minimum required cell edge throughput. Note however that the actual range of a site will also be influenced by its capacity and by the interference scenario, so the calculations in this section relate only to the *maximum* range of each site.
4.1 **Requirements**

Given the large number of sites and their types coupled with different propagation environments, user requirements there is a large combination of site ranges that needs to be calculated. This work requires calculation of site ranges for all combinations of the parameters shown in Table 27.

<table>
<thead>
<tr>
<th>Combinations of site range calculations</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td></td>
</tr>
<tr>
<td>Clutter type: Rural, Urban, Suburban</td>
<td>3</td>
</tr>
<tr>
<td>b</td>
<td></td>
</tr>
<tr>
<td>Demand type: Indoor and Outdoor demand</td>
<td>2</td>
</tr>
<tr>
<td>c</td>
<td></td>
</tr>
<tr>
<td>Frequencies: Sub 1GHz, 1-2.1 GHz and 2.1GHz</td>
<td>3</td>
</tr>
<tr>
<td>d</td>
<td></td>
</tr>
<tr>
<td>Link direction: Uplink and Downlink</td>
<td>2</td>
</tr>
<tr>
<td>e</td>
<td></td>
</tr>
<tr>
<td>Site types: 1) Macro cells 3 sectors 2 antennas , 2) Macro cells 3 sectors 4 antennas, 3) Macro cells 3 sectors 8 antennas, 4) Macro cells 6 sectors 2 antennas, and 5) Small cells 1-2 sectors 2-4 antennas</td>
<td>5</td>
</tr>
<tr>
<td>f</td>
<td></td>
</tr>
<tr>
<td>Year: Time evolving ranges for min user data rate on UL and DL 2012-2030</td>
<td>19</td>
</tr>
<tr>
<td>Total site ranges (a \times b \times c \times d \times e \times f)</td>
<td>3420</td>
</tr>
<tr>
<td>Final ranges= min(downlink ranges, uplink ranges)</td>
<td>1710</td>
</tr>
</tbody>
</table>

4.2 **Modelling methodology**

The site range calculation work first involves calculation of maximum allowable path loss (MAPL) by means of link budget formulas. In the next step, the MAPL value is used with an appropriate propagation model for the site and clutter type to determine the range. The site range calculation for all combinations has been implemented in a Matlab model, due to the possibility of automating the calculations for the large number of combinations and generating the entire site ranges outputs within very short time period.
The whole site range calculations work can also be summarised in the steps as follows:

1. Select a year from the range 2012-2030
2. For the selected year:
   2.1. Obtain the cell edge throughput requirements in Mbps, minimum user device bandwidth, SINR cut off values
   2.2. Select a combination of parameters
   2.3. Calculate maximum allowable path loss (MAPL) for the selected combination
   2.4. Using the MAPL and selected combination calculate maximum range as minimum of the associated uplink and downlink ranges
   2.5. Repeat for all parameter combinations
3. While year<2031, run steps 1 and 2

The above steps give a total of 3420 site ranges as shown in Table 27 where 1710 ranges are for the downlink transmissions and the other 1710 ranges are for the uplink transmissions. The final site ranges are obtained from the minimum of the downlink and uplink site ranges.

4.2.1 Flow charts

Flow charts of steps involved in the calculation are shown in Figure 4-2 and Figure 4-3 for the MAPL and site range calculations, respectively.

4.2.1.1 Link Budget

Figure 4-2 shows the flow diagram of link budget calculation algorithm that runs the steps to give MAPL value for each combination shown in Table 28 at each run. For example, when site type is macro cells of 3 sectors 2 antennas, frequency is 1-2.1GHz, demand is indoor and link direction is downlink, the algorithm uses these inputs to selection list of parameters and assumptions in the link budget formulas to give the MAPL value for that scenario.
4.2.1.2 Range calculation

The MAPL value corresponding to the given scenario that has been output from the algorithm in the previous section is then used as an input in this stage to calculate the final site range for macro and small cells. At this stage, additional inputs from the Table 30 on the urban, suburban and rural clutter type are used to assign antenna heights from sites and user devices along with appropriate propagation models so that the MAPL value is converted to a maximum site range. A detailed description of parameters and assumptions used for this calculation is provided in Section 4.2.2.

---

**Figure 4-2 Flow diagram of link budget calculations**

**Figure 4-3 Flow diagram of range calculation methods**
4.2.2 Link budget parameters and assumptions

In this section, the parameters and assumptions used in the calculations of site ranges for macro and small cells are described. Table 28 lists parameters and assumptions used for the calculation of MAPL values for different site types and technology considerations. An example of maximum allowable path loss calculation for the case of LTE downlink transmission in urban areas at the frequency of 700 MHz for the indoor demand is shown in Table 28.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>MHz</td>
<td>700, 1800 and 2600</td>
<td>Project inputs. The frequencies represent the cases for low mid and high frequency scenarios</td>
</tr>
<tr>
<td>Number of sectors</td>
<td></td>
<td>Macro sites: 3,6</td>
<td>Typical macro cell sites with 3 sectors assumed and increasing to 6 sectors as demand increases in later years</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small cells: 1-2</td>
<td>Although we model an increasing mix of 2 sector small cells sites, we assume the ranges are always based on single sector performance as a worst case.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Macro sites: 2,4,8</td>
<td>Mainly used to provide higher throughput or diversity for in cell users.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small cells 2-4</td>
<td>For small cells we consider an evolution from 2-4tx antennas. The overall EIRP remains constant, so the range does not change.</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>MHz</td>
<td>5, 10,20,30,40</td>
<td>Minimum capability device bandwidths available for deployment in the time period considered. For more information please see section 2.7</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>kHz</td>
<td>15</td>
<td>Standard specification for 3GPP LTE technologies.</td>
</tr>
<tr>
<td>Equivalent Isotropic radiated power (EIRP)</td>
<td>dBm</td>
<td>64.0</td>
<td>64 dBm /10MHz for the downlink (over all antennas) [43]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33 dBm for small cells [44]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>23 dBm for the uplink mobile devices</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Value</td>
<td>Notes</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>------</td>
<td>-------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Transmit antenna gain</td>
<td>dBi</td>
<td>15 for 700 MHz, 18 for 1800 MHz, 19.1 for 2600 MHz</td>
<td>Assumption, Kathrein 742 265 65 antenna specifications [65]. For 700, 2600 MHz extrapolated from Kathrein 742 265 65 antenna specifications 6 dB for small cells [66] In the reverse link the transmit gain also corresponds to receive antenna gains.</td>
</tr>
<tr>
<td>Transmit cable, combiner and connector losses</td>
<td>dB</td>
<td>0.0</td>
<td>Assumption, no loss due to cables, combiners and connector consistent with [66] This losses also correspond to receive cable, combiner and connector losses for the uplink</td>
</tr>
<tr>
<td>Receiver antenna gain</td>
<td>dB</td>
<td>0</td>
<td>Assumption, no receive antenna gain for user devices [67] This also corresponds to transmit antenna gain for the user devices in the uplink</td>
</tr>
<tr>
<td>Body loss (relative to free space)</td>
<td>dB</td>
<td>0</td>
<td>Assumption, typical data connection for laptops, tablets</td>
</tr>
<tr>
<td>Noise figure (NF)</td>
<td>dB</td>
<td>NF of user devices 10 for 700 MHz, 9 for 1800 MHz, 9 for 2600 MHz NF of cell sites 5</td>
<td>Noise of receivers affected by frequency, allocated bandwidth, duplex gap. Consistent with Ofcom study in [68]</td>
</tr>
<tr>
<td>Thermal noise density</td>
<td>dBm/Hz</td>
<td>-174</td>
<td>Constant</td>
</tr>
<tr>
<td>Thermal noise</td>
<td>dBm</td>
<td>-132</td>
<td>Noise power over the bandwidth of a subcarrier</td>
</tr>
<tr>
<td>Background RSSI</td>
<td>dBm</td>
<td>-122</td>
<td>Thermal noise power added with noise figure of the receiver</td>
</tr>
<tr>
<td>Interference degradation margin</td>
<td>dB</td>
<td>4</td>
<td>Accounts for inter cell interference with frequency reuse ratio of 1. 4.0 dB for the downlink [69] 1 dB for the uplink [70]</td>
</tr>
<tr>
<td>Cell edge throughput requirement</td>
<td>Mbps</td>
<td>2</td>
<td>Cell edge throughput expected. 2Mbps the downlink and 64 kbps in year 2012 [71] and the requirement increasing at 10% CAGR each year. See Section 4.4.3</td>
</tr>
<tr>
<td>Cell loading factor</td>
<td>%</td>
<td>85%</td>
<td>Assumption, The loading is defined here as the percentage of available resources (frequency and time) used to deliver download service to users as in [67,68]</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Value</td>
<td>Comment</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>--------</td>
<td>-------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Frequency selective scheduling gain</td>
<td>%</td>
<td>0%</td>
<td>Assumption, Single user active on the network at the cell edge and hence no scheduling gain</td>
</tr>
<tr>
<td>Overhead for control and reference channels</td>
<td>%</td>
<td>20%</td>
<td>This is to account for the loss of data rate, due to the need for transmission of control, reference signals on top of actual data information. Consistent with [67].</td>
</tr>
<tr>
<td>Number of RB's available for data</td>
<td>RBs</td>
<td></td>
<td>Actual number if resource block used for transmission of data after accounting for overhead and scheduling gain</td>
</tr>
<tr>
<td>Required throughput per data RB</td>
<td>Mbps</td>
<td></td>
<td>Throughput to be carried by each resource block</td>
</tr>
<tr>
<td>Required spectral efficiency in data RB</td>
<td>bps/Hz</td>
<td></td>
<td>User throughput requirement is distributed over the available resource blocks to calculate spectral efficiency per resource block. See Section 4.1</td>
</tr>
<tr>
<td>Required signal to noise ratio (SNR)</td>
<td>dB</td>
<td></td>
<td>SINR required to achieve the cell edge throughput This is calculated from the required spectral efficiency using the mapping function described in Section 4.1</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>dBm</td>
<td>0.78</td>
<td>Assumption, corresponds to approx. 90% cell-area coverage-confidence [67]</td>
</tr>
<tr>
<td>Cell-edge coverage-confidence</td>
<td>%</td>
<td>0.78</td>
<td>Assumption, corresponds to approx. 90% cell-area coverage-confidence [67]</td>
</tr>
<tr>
<td>Confidence factor</td>
<td></td>
<td>0.77</td>
<td>Inverse of the normal cumulative distribution (mean: 0, standard deviation: 1)</td>
</tr>
<tr>
<td>Location variability</td>
<td>dB</td>
<td>6.8 for 700 MHz, 7.6 dB for 1800 MHz and 8 dB for 2600 MHz</td>
<td>Effects of building obstructions, shadowing [72]</td>
</tr>
<tr>
<td>Building penetration loss (BPL)</td>
<td>dB</td>
<td>8.5 for 700 MHz, 11.3 dB for 1800 MHz and 13 dB for 2600 MHz</td>
<td>Assumption depth 1+ BPL, corresponds to indoor depth of 10 m [67]</td>
</tr>
<tr>
<td>Standard deviation of BPL</td>
<td>dB</td>
<td>6 for 700 MHz, 8 dB for 1800 MHz and 9 dB for 2600 MHz</td>
<td>Assumption depth 1+ BPL [67]</td>
</tr>
</tbody>
</table>

To show how these parameters and assumption are used to calculate MAPL, Table 29 is used. In this table all the link budget parameters and assumptions are used to calculate MAPL value for a macro cell with 3 sectors and 2 antennas operating at 700 MHz serving indoor demands in urban areas.
Table 29: Link budget calculation example for a macro cell site with 3 sectors 2 transmit antennas on the downlink of 700MHz serving indoor demands in urban areas

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td></td>
<td>MHz</td>
<td>700</td>
</tr>
<tr>
<td>Receiver type</td>
<td></td>
<td></td>
<td>Laptop/Dongle</td>
</tr>
<tr>
<td>Number of antennas per sector</td>
<td>AntCnt</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>BW</td>
<td>MHz</td>
<td>20</td>
</tr>
<tr>
<td>Subcarrier Spacing, Receiver filter BW</td>
<td>subBW</td>
<td>kHz</td>
<td>15</td>
</tr>
<tr>
<td>EIRP/10MHz (over all antennas)</td>
<td>EIRP10</td>
<td>dBm</td>
<td>64.0</td>
</tr>
<tr>
<td>Tx antenna gain</td>
<td>TxGain</td>
<td>dBi</td>
<td>15.0</td>
</tr>
<tr>
<td>Transmit Cable, Combiner and Connector Losses</td>
<td>TxCCL</td>
<td>dB</td>
<td>0.0</td>
</tr>
<tr>
<td>No of occupied Subcarriers</td>
<td>subCnt</td>
<td>subcarriers</td>
<td>subCnt = (BW/5) x 300</td>
</tr>
<tr>
<td>No of occupied Resource Blocks</td>
<td>RBcnt</td>
<td>RBs</td>
<td>RBcnt = subCnt/12</td>
</tr>
<tr>
<td>EIRP in channel</td>
<td>EIRPch</td>
<td>dBm/15 kHz/ant (DL)</td>
<td>EIRPch = EIRP - 10log10(subCnt)</td>
</tr>
<tr>
<td>Receiver Antenna Gain</td>
<td>RxGain</td>
<td>dB</td>
<td>0</td>
</tr>
<tr>
<td>Receive Cable, Combiner and Connector Losses</td>
<td>RxCCL</td>
<td>dB</td>
<td>0.0</td>
</tr>
<tr>
<td>Body Loss (relative to free space)</td>
<td>BL</td>
<td>dB</td>
<td>0.0</td>
</tr>
<tr>
<td>Noise figure</td>
<td>NF</td>
<td>dB</td>
<td>10.0</td>
</tr>
<tr>
<td>Thermal Noise Density</td>
<td>thNsDns</td>
<td>dBm/Hz</td>
<td>-174</td>
</tr>
<tr>
<td>Thermal Noise</td>
<td>thNs</td>
<td>dBm</td>
<td>thNs = thNsDns + 10log10(BW x 1000)</td>
</tr>
<tr>
<td>Background RSSI</td>
<td>RSSI</td>
<td>dBm</td>
<td>RSSI = NF + thNs</td>
</tr>
<tr>
<td>Interference Degradation Margin</td>
<td>IM</td>
<td>dB</td>
<td>4.0</td>
</tr>
<tr>
<td>Coverage obligation</td>
<td>covObl</td>
<td>Mbps</td>
<td>2.0</td>
</tr>
<tr>
<td>Network loading</td>
<td>Loading</td>
<td>%</td>
<td>85%</td>
</tr>
<tr>
<td>Frequency selective scheduling gain</td>
<td>schGain</td>
<td>%</td>
<td>0%</td>
</tr>
<tr>
<td>Overhead</td>
<td>OHpc</td>
<td>%</td>
<td>20%</td>
</tr>
<tr>
<td>Number of RB's available for data</td>
<td>RBcntData</td>
<td>RBs</td>
<td>RBcntData = floor(RBCnt x Loading x (1 - OHpc))</td>
</tr>
<tr>
<td>Required throughput per data RB</td>
<td>reqThPerDatRB</td>
<td>Mbps</td>
<td>reqThPerDatRB = covObl/RBcntData</td>
</tr>
<tr>
<td>SINR cutoff</td>
<td>SINRct</td>
<td>dB</td>
<td>-5</td>
</tr>
<tr>
<td>Required spectral efficiency in data RB</td>
<td>reqSE</td>
<td>bps/Hz</td>
<td>reqSE = reqThPerDatRB x 1000 / (subBW x )</td>
</tr>
</tbody>
</table>
In Figure 4-5 and Figure 4-6 MAPL values for all the sites types for the case of downlink and uplink, respectively for year 2012 are plotted. It can be seen from the figures that the MAPL values for macrocell sites are higher than that of small cells. This is due mainly due to higher EIRP and antenna gains of the macro cells sites. Comparing the MAPL values in Figure 4-5 and Figure 4-6, it can be observed that MAPL does not increase for the downlink of macro cells for additional antennas. Although techniques such as transmit diversity, beamforming etc. can be used to improve the downlink performances, the gain in practice from such techniques are still limited due to difficulties in accurate channel and direction of arrival estimation and hence has not been considered in the link budget. In the uplink of macro cell sites with more sectors e.g. from 3 to 6, improvement in the link is achieved due to reduced impact of interference from other cells. Similarly having more antennas i.e. from N = 2 to 4 and 8, improve the SNR gain of uplink transmission by 10 log 10 (N) dB even without antenna diversity gain as signal energies from different can be coherently combined [3].

Figure 4-7 shows the evolution of minimum MAPL values from the both downlink and uplink of cell sites.

Note that MAPL values generally reduce with time as the minimum throughput expectation at the cell edge increases as discussed in Section 2.10. The periodic rise in MAPL values corresponds to the years when the minimum bandwidth for user devices increases from 5 MHz in 2012 to 40 MHz in 2030 as discussed in Section 2.7. This leads to improved spectral efficiency so that lower SINR is required to achieve the same throughput requirement. This, in turn leads to increase in MAPL values as can also be seen from the calculations shown in Table 29.
Figure 4-5 Maximum allowable path losses for downlink transmissions for different site types in year 2012
Figure 4-6: Maximum allowable path losses for uplink transmissions for different site types in year 2012
Figure 4-7 Evolution of MAPL for macro and small cell sites in years 2012-2030 (Rural areas, 700 MHz, outdoor demand)
4.2.3 Propagation models and maximum range calculations

4.2.3.1 Macro cells

The steps involved in site range calculation using the MAPL values consists of determining the antenna heights for the base station sites and user devices and then applying these values in an appropriate propagation model for different clutter types. For the case of macro cells used in urban and suburban areas (clutter types in Table 31, SE21 Hata model [74] has been used. The antenna heights used are shown in Table 30. The path loss expressions used in this work using the SE21 Hata propagation model are shown in Table 31.

**Table 30: Antenna heights for macro cell sites (Urban and suburban clutter types)**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Values</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base station height</td>
<td>Hb</td>
<td>m</td>
<td>30 for urban, 15.75 for suburban</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Median site heights calculated from MNO data</td>
</tr>
<tr>
<td>Height of user device</td>
<td>Hm</td>
<td>m</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Standard assumption consistent with [70]</td>
</tr>
</tbody>
</table>

**Table 31: SE21 Hata propagation model [74]**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤1500MHz</td>
<td>$L = 49.2 + 26.2 \log f + 35.2 (\log d)^2 - a(h_m) - b(h_b)$</td>
</tr>
<tr>
<td>1500 &lt; f ≤2000MHz</td>
<td>$L = 25.9 + 33.9 \log f + 35.2 (\log d)^2 - a(h_m) - b(h_b)$</td>
</tr>
<tr>
<td>&gt;2000MHz</td>
<td>$L = 25.9 + 33.9 \log f + 10 \log(f(2000)) + 35.2 (\log d)^2 - a(h_m) - b(h_b)$</td>
</tr>
</tbody>
</table>

where

- $a(h_m) = 0.09 \log f - 0.25$
- $b(h_b) = \min[0, 20 \log(h_b/30)]$
- $\alpha = \begin{cases} 1 & d \leq 20km \\ 1 + (0.14 + 0.87 \times 10^{-4} f + 1.07 \times 10^{-3} h_b)(\log d/20)^{0.8} & .20 < d < 100km \end{cases}$
For the case of macro cells used in rural areas (clutter types in Table 31), the extended Hata model for open areas as given in [74] has been used. The antenna heights used are shown in Table 32.

Table 32: Antenna heights for macro cell sites (Rural clutter types)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Values</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base station height</td>
<td>Hb</td>
<td>m</td>
<td>16.5 Median site heights calculated from MNO data</td>
</tr>
<tr>
<td>Height of user device</td>
<td>Hm</td>
<td>m</td>
<td>1.5 Standard assumption consistent with [70]</td>
</tr>
</tbody>
</table>

4.2.3.2 Small cells

The site range calculation methodology for small cells is as follows. The antenna heights for both cell sites and user devices are obtained as shown in Table 33. Next, using the MAPL values the small cell sites, two sets of ranges corresponding to the scenarios of line of sight (LOS) and non line of sight (NLOS) are calculated using the models in [75].

Table 33: ITU 1411 outdoor LOS or NLOS model based on WINNER model for LOS probability

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Values</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base station height</td>
<td>Hb</td>
<td>M</td>
<td>5 for urban, 5 for suburban, 4 for rural Median site heights calculated from MNO data</td>
</tr>
<tr>
<td>Height of user device</td>
<td>Hm</td>
<td>M</td>
<td>1.5 Standard assumption consistent with [71]</td>
</tr>
</tbody>
</table>

To account for both LOS and NLOS propagation conditions in the final range calculation, the models of LOS probabilities for different site types are given in the WINNER project [76]. The following expressions from the models are used to calculate the LOS probabilities.
Table 34 Site configuration against WINNER model and LOS probabilities

<table>
<thead>
<tr>
<th>Site configuration</th>
<th>WINNER model</th>
<th>LOS probabilities, P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cells in urban areas</td>
<td>B1-Hotspot</td>
<td>P=1 if range&lt;15 m,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P=1-(1-(1.56-0.48log10(range)))</td>
</tr>
<tr>
<td>Small cells in suburban areas</td>
<td>C1- suburban macro cell</td>
<td>P=exp(-range(m)/500),</td>
</tr>
<tr>
<td>Small cells in rural areas</td>
<td>D1- rural macro cell</td>
<td>P=exp(-range(m)/1000)</td>
</tr>
</tbody>
</table>

To calculate the final range, weighting of ranges calculated for LOS and NLOS conditions is carried out using their respective probabilities of occurrences. A weighted range, $R_w$, is calculated from the LOS range $R_{LOS}$ with a probability of LOS $P_{LOS}$, and from the NLOS range $R_{NLOS}$, and its probability of NLOS, $(1 - P_{LOS})$, as follows:

$$R_w = \frac{P_{LOS}R_{LOS} + (1 - P_{LOS})R_{NLOS}}{P_{LOS} + (1 - P_{LOS})}$$
4.3 **Site Ranges**

The final site ranges for the different site types for the year 2012 is plotted in Figure 4-8. These results are obtained from the MAPL values as calculated in Table 29 and then applying the propagation models according to the clutter types. It can be seen from the figure that the macro cell sites offer significantly higher site ranges compared with small cell sites. The low frequency sites provide higher ranges compared with higher frequency sites for all cases. It is also clear from the figure that site ranges are significantly reduced when serving the indoor demands. This is mainly due the building penetration loss as discussed in Section 4.2.1.1.
Figure 4-8 Site ranges for minimum of uplink/downlink transmissions for different site types in year 2012
Figure 4-9 shows the final site ranges for different site types operating in 700 MHz in rural areas serving outdoor demands. Site ranges for other frequencies and propagation scenarios also follow similar trends and hence are not shown here. The final site ranges are obtained from both the downlink and uplink by selecting the one with minimum range for each year. In has been discussed earlier that in the downlink, minimum bandwidth of user devices increases over time from 5 MHz in 2012 to 40 MHz in 2030 (See Section 2.7). This increase of bandwidth in different years leads to improvement in downlink site ranges. It can be seen from Figure 4-9 that in 2012, site ranges for all macrocells are equal. In this year, the limiting case from the downlink and uplink ranges has been the downlink ranges since only 5 MHz of bandwidth is available for user devices. Hence, even if the uplink ranges for macro cells 3 sectors and 8 antennas are much higher, the downlink ranges are selected as final ranges. In year 2014, the device bandwidth increases to 10 MHz; this leads to increase in ranges for all macro cell sites.

For macro cell sites with 3 sectors and 2 antennas, from 2014 the uplink ranges become limiting cases and hence the ranges decrease each year till 2030. For macro cells with 3 sectors and 4 antennas and 6 sectors and 2 antennas have almost the same ranges. The macro cell sites with 3 sectors and 8 antennas have the highest ranges, this is mainly due to combination of the two factors: a) minimum user device bandwidth increasing in different year till 2030 and hence increasing the downlink ranges, b) use of 8 antennas for the uplink also leads to significant gain in the link budget and hence the high site ranges. Ultimately, the uplink ranges become the limiting cases and the site ranges drop from year 2020 onwards.

![Figure 4-9: Evolution of maximum site ranges for macro and small cell sites (Rural areas, 700 MHz, outdoor demands) in years 2012-2030](image-url)
The effects of varying site ranges over time can potentially introduce randomness into the deployment of sites. For example if one particular site does not get upgraded early in the timeframe and another one does, then the upgraded site has an advantage in terms of range from that point in time and can create an imbalance later in the timeframe. Therefore, in order to minimise potentially misleading effects in the results we decided to set all site ranges across types to the same level. Figure 4-10 shows the site ranges across all the environments that remain static over time from 2012 through to 2030.

![Figure 4-10 Site range variation between environments (Demand, geotype and frequency group)](image-url)
4.4 Technology Considerations

4.4.1 SINR to SE mapping

The required spectral efficiency (SE) per resource block based on the cell edge throughput requirement for the calculation of the MAPL for the case of downlink and uplink transmission are obtained from ([7]) where alpha scaling factors used for the downlink is 0.6 and for the uplink is 0.4 as shown in Figure 4-11 and Figure 4-12. The SE value is then used to calculate the required SINR at the cell edge to add the required SNR margin. The higher the required SE, the higher the SINR required and hence the lower the site range and vice versa. The SINR cut-off of -5 dB is assumed for the site range calculation for year 2012 and gradually improves to -10 dB in the year 2030.

![Figure 4-11: SINR to SE mapping for the LTE downlink](image)

Figure 4-11: SINR to SE mapping for the LTE downlink
Mapping For 1x2 Uplink
(alpha = 0.4, -5dB cutoff same as DL, max SE 2bps/s/Hz from 36.942 annex A)

Figure 4-12: SINR to SE mapping for the LTE uplink
4.4.2 Minimum bandwidth of user devices

It is expected that due to availability of larger amount of bandwidth in the coming year, the minimum bandwidth for user devices also increases. Table 35 shows Real Wireless’ estimates for the bandwidth available for user devices in year 2010-2030 assuming that total available spectrum is shared by two operators with their separate radio access networks.

Table 35: Minimum bandwidth available for user devices in different years

<table>
<thead>
<tr>
<th>Year</th>
<th>Initial estimate</th>
<th>Low end device assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>5 SC-HSPA</td>
<td>DL &amp; UL, MHz</td>
</tr>
<tr>
<td>2011</td>
<td>5 SC-HSPA</td>
<td>10 DC-HSPA / 10MHz LTE</td>
</tr>
<tr>
<td>2012</td>
<td>5 SC-HSPA</td>
<td>10 DC-HSPA / 10MHz LTE</td>
</tr>
<tr>
<td>2013</td>
<td>5 SC-HSPA</td>
<td>10 DC-HSPA / 10MHz LTE</td>
</tr>
<tr>
<td>2014</td>
<td>10 DC-HSPA / 10MHz LTE</td>
<td>10 DC-HSPA / 10MHz LTE</td>
</tr>
<tr>
<td>2015</td>
<td>10 DC-HSPA / 10MHz LTE</td>
<td>10 DC-HSPA / 10MHz LTE</td>
</tr>
<tr>
<td>2016</td>
<td>10 DC-HSPA / 10MHz LTE</td>
<td>10 DC-HSPA / 10MHz LTE</td>
</tr>
<tr>
<td>2017</td>
<td>10 DC-HSPA / 10MHz LTE</td>
<td>10 DC-HSPA / 10MHz LTE</td>
</tr>
<tr>
<td>2018</td>
<td>10 DC-HSPA / 10MHz LTE</td>
<td>10 DC-HSPA / 10MHz LTE</td>
</tr>
<tr>
<td>2019</td>
<td>10 DC-HSPA / 10MHz LTE</td>
<td>10 DC-HSPA / 10MHz LTE</td>
</tr>
<tr>
<td>2020</td>
<td>20 20MHz LTE</td>
<td>20 20MHz LTE</td>
</tr>
<tr>
<td>2021</td>
<td>20 20MHz LTE</td>
<td>20 20MHz LTE</td>
</tr>
<tr>
<td>2022</td>
<td>20 20MHz LTE</td>
<td>20 20MHz LTE</td>
</tr>
<tr>
<td>2023</td>
<td>20 20MHz LTE</td>
<td>20 20MHz LTE</td>
</tr>
<tr>
<td>2024</td>
<td>20 20MHz LTE</td>
<td>20 20MHz LTE</td>
</tr>
<tr>
<td>2025</td>
<td>20 20MHz LTE</td>
<td>20 20MHz LTE + 2 way Carrier Aggregation</td>
</tr>
<tr>
<td>2026</td>
<td>20 20MHz LTE + 2 way Carrier Aggregation</td>
<td>40 20MHz LTE + 2 way Carrier Aggregation</td>
</tr>
<tr>
<td>2027</td>
<td>20 20MHz LTE + 2 way Carrier Aggregation</td>
<td>40 20MHz LTE + 2 way Carrier Aggregation</td>
</tr>
<tr>
<td>2028</td>
<td>20 20MHz LTE + 2 way Carrier Aggregation</td>
<td>40 20MHz LTE + 2 way Carrier Aggregation</td>
</tr>
<tr>
<td>2029</td>
<td>20 20MHz LTE + 2 way Carrier Aggregation</td>
<td>40 20MHz LTE + 2 way Carrier Aggregation</td>
</tr>
<tr>
<td>2030</td>
<td>40 20MHz LTE + 2 way Carrier Aggregation</td>
<td>40 20MHz LTE + 2 way Carrier Aggregation</td>
</tr>
</tbody>
</table>

4.4.3 Cell edge throughput evolution

The anticipated minimum throughput for user devices at the cell edge is also expected to increase each year. This is due to increase in variety of mobile applications that will require higher throughput than the applications available today. Figure 4.11 shows a graph of expected increase in required throughput at the cell edge over time assuming 10% compound annual growth rate (CAGR) is a reasonable growth rate. This can be justified since [24] also states that there is an increase of about 40-70% increase in cell edge throughput from the evolution of 3GPP LTE Rel. 8 to LTE-Advanced. The cell edge throughput values in Figure 4.11 are obtained from year 2012 [24] and then extrapolated to other years using the CAGR value. This assumption is used in all the site ranges calculated in this work.
Figure 4-13: Cell edge minimum throughput evolution over time per user device
A5. Demand assessment

5.1 Introduction

The demand assessment has drawn upon a wide range of published data and forecasts to build up a model of demand growth extended over the 18 year study timeframe that could be mapped on to regional study areas. Population, postcode and route (road and rail) data inputs were used for the demand points to produce representative spatial forecasts in each case. Figure 5-1 presents an example demand map for rural Lincolnshire which was produced using the software model that incorporates the demand distribution data mapped across a set of geographical demand points.

![Demand map for rural Lincolnshire](image)

Figure 5-1 Demand map in 2012 for rural Lincolnshire across population, postcodes and road/rail

As explained in section 3.4 the input data and approach used to determine the demand was built up from a set of required distributions using independent analyst, vendor and operator demand forecasts. This data was gathered according to each distribution and analysed to produce a set of plausible growth assumptions for the demand inputs.
The following set of distributions were individually analysed to build up the demand data into a growth chart for the low, mid and high cases:

- Volume of traffic generated by device types
- Penetration of devices amongst the general population
- Distribution of traffic amongst individual users
- Location of traffic generated such indoors at home or on the move
- Variation of traffic generated at particular times of day

The blend of each of the above attributes forms the input data used to generate the demand spread across each of the geographical locations.

This annex outlines the general approach, methodology and assumptions used to derive a set of demand growth scenarios which in turn provide the demand challenges for the mobile network deployment (supply) modelling and capacity dimensioning. Ultimately it is the magnitude of demand that dictates the capacity that is required to satisfy it, therefore it was essential to ensure credible and plausible demand scenarios were produced for modelling.

In this study we have used the updated forecasts such as the widely quoted forecasts by Cisco[75] and the recent (Nov 2011) published forecast by Ericsson[80] which now includes data on the impact of tablet devices such as the iPad and embedded modules which are now becoming a feature of more recent analyses.

5.2 General approach

Our general approach is outlined in Figure 5-2, showing the high level flowchart and inputs required to build up the demand distribution. The inputs in the blue boxes represent the geographical data which includes the delivery addresses of both residential locations and businesses according to postcode, road and rail routes, special locations such as airports, shopping centres and stadia and geotype (Urban, Suburban and Rural).

The inputs in the orange boxes represent the various distributions that make up the attributes of demand as listed in section 5.1. Combining these attributes provides a total volume of traffic that can be defined by the population of the study areas and quantified based on three separate busy hours which we determine in our analysis (described in more detail in section 5.3).

The processing stage is where we combine the distributions and the geographical data to produce a set of aggregated demand values that can be mapped on to the study area demand points by weighting the proportion of traffic according to the time of day across the different locations.
Figure 5-2 General approach for deriving demand over regional study areas

The evolution of the mobile network roll out is dependent on how we assume demand will increase over time. The following factors were derived as a set of broad expectations of how the trend in demand will grow:

- There will be growth in the mobile traffic consumed by current and future applications
- Enhancement of mobile devices, such as smartphone screens, tablets offer the ability to consume more data per session
- Increased uptake in mobile data services due to enhanced user experience and wider choice of applications
- Increase in customer expectation for minimum data rate to constitute viable mobile broadband
- Increase in UK population from 62 million in 2011 to 70 million in 2029 thus increasing general uptake in mobile broadband services

These aspects are implicitly modelled in our demand methodology.

Our demand growth assumptions, as shown in Table 36, were predicated on a set of three broad scenarios that represented different states of uptake in mobile broadband services, devices and consumption of mobile data traffic.
<table>
<thead>
<tr>
<th>LOW CASE</th>
<th>MID CASE</th>
<th>HIGH CASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EARLY GROWTH IN DEMAND (2012-2015) FOR MOBILE DATA THAT FLATTENS OUT DUE TO REACHING THE CAPACITY PEAK OF NETWORKS AND THUS POOR QOS DELIVERY FROM OPERATORS RESULTING IN SLOWER RATE OF INCREASED TRAFFIC</td>
<td>DEMAND INCREASE BASED ON CURRENT TRENDS FROM VENDOR AND ANALYST FORECASTS. TRAFFIC STEADILY RISES UP TO 2020 AND STARTS TO SLOW DOWN FROM 2020 ONWARDS AS DEVICES REACH PENETRATION AND TRAFFIC CONSUMPTION REACHES PEAK LEVELS</td>
<td>RAPID UPTAKE IN HIGH RESOLUTION MOBILE VIDEO FROM HIGH DEFINITION THROUGH TO 3D IN 2020. THIS IS DRIVEN BY DEMAND IN MOBILE 3D EXPERIENCE + HIGH RESOLUTION VIDEOGAMING ETC</td>
</tr>
<tr>
<td>Over time development in devices stagnates with innovations focusing on mobile payment systems as a new method of revenue generation rather than screen enhancements, resulting in slower uptake of enhanced devices</td>
<td>Growth tracks current trends and forecasts, as summarised from the sources for the next 5 years. This is based on continued growth in smartphones and tablets dominating the market and new media rich services emerging such as HD video gaming and other HD video applications</td>
<td>In this scenario we expect a vast and quick ramp up in the use of mobile broadband consumption based on Cisco’s expected use of high quality video on all smartphone, tablet and laptop devices to meet the demand for very high video resolution devices</td>
</tr>
<tr>
<td>Traffic consumption growth is slower than expected This is based on constraints within networks hitting the capacity limit in high demand areas forcing trends in upward growth to slow down</td>
<td>Traffic consumption growth is based on current trends which has seen consumers increasingly utilise their mobile devices for uploading and downloading media rich content such as video and online gaming</td>
<td>Smartphone (HTC HD7), tablet (Samsung and Netbook screens are becoming HD ready and soon there will be 3D screens on these devices, in each case requiring more data and throughput for seamless connectivity. Rapid uptake of these devices and of more advanced devices also results in increased mobile data consumption</td>
</tr>
<tr>
<td>Approximately 13% growth in population from 62 million in 2011 to 70 million in 2027</td>
<td>Approximately 13% growth in population from 62 million in 2011 to 70 million in 2027</td>
<td>Approximately 13%81 growth in population from 62 million in 2011 to 70 million in 20279</td>
</tr>
</tbody>
</table>

Table 36 Demand growth assumptions for low, mid and high cases

Modelling demand is broadly divided into two key parts:

- The quantity of demand
- The location of the demand and how the demand varies with time of day
The amount of demand generated depends on a number of independent elements:

- Penetration of different devices types within the population such as: Smartphones, Tablets, Dongles etc.
- Multiple devices per user will result in >>100% penetration overall
- Traffic generated per device type (MB/month)
- E.g. laptops generate more traffic than smartphones per session

In this study we consider demand is generated by the following device types:

- **Smartphones** - These devices are considered to be high end handsets that utilise both touchscreen and non-touchscreen interface and used for mobile data such as video, audio, email etc. amongst other applications such as voice calls. Types of Operating System found in these devices include Android, iOS, Symbian and Windows etc. The volume of traffic generated by these devices is expected to be a third of that generated by tablets.
- **Tablets** – These are considered mobile PC’s with large high resolution touchscreens with the ability to surf the web, stream video, audio, basic editing of documents, email etc. The volume of traffic generated by these devices is expected to be a quarter that of embedded laptops.
- **Embedded laptops** – Laptop PC’s with embedded cellular modules to connect via 3G (4G in future) to the internet. These devices are expected to generate the largest amount of traffic out of all the devices.
- **USB modems** – USB modems are very basic devices that are plugged into Laptops or tablets whenever necessary to connect to the 3G(4G in future) network. The volume of traffic generated by these devices is expected to be a less than half of that generated by laptops.
- **3G phones** – These handsets have some data capabilities such as send email, browse the internet but not good for high resolution video, predominantly used for voice. The volume of traffic generated by these devices is expected to be a more than a twentieth of that generated by smartphones.
- **M2M10 (machine to machine)** – These devices are basic modules embedded in another machine or device that consumes very little data at frequent intervals. (Early devices consume 10’s of kbps)

Our study investigates how the location of demand varies according to certain times of day. We have chosen three key times to investigate based on source data (described later in section 5.3):

- Work time 9-10: When users are mostly indoors at business addresses
- Rush hour 5-6pm: When users are mostly outdoors on the move along road and rail routes
- Evening 8-9pm: When users are mostly indoors at residential addresses

Figure 5-3 outlines the processes involved in profiling demand in this way.

---

10 M2M was considered a special case for demand and did not feature as part of the core modelled devices
Figure 5-3 High level demand profiling

Section 3.3 discussed the choice of study areas to be modelled to determine the quantity of capacity required in each area based on the demand for that area. Figure 5-4 illustrates, at a high level, how the demand points are mapped on to the study areas, in this case Central London (Urban). Each demand point is represented by either a residential delivery address, a business delivery address or a road/rail point in kilometres. The data is based on postcode database which provides the total number of delivery addresses for the study area and the Ordnance Survey provides the length of road and rail data for the study area.

Figure 5-4 Demand points mapped on to the Central London study area
5.3 **Demand methodology and detailed assumptions**

The following methodology presents a step by step process of how mobile traffic demand has been derived according to the source data and implemented into the model based on our assumptions.

The methodology used was a bottom-up approach using the required set of distributions to calculate the average demand generated by devices according to the level of penetration of each device within the UK population. The process set out below illustrates the logical sequence of calculations undertaken to derive the average demand in Megabits per second (Mbps) for each of the demand points in the study area. Table 37 below provides the demand points by type according to each of the study areas and their locations, and what each location represents.
<table>
<thead>
<tr>
<th>Demand type</th>
<th>Study area</th>
<th>Indoor</th>
<th>Outdoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>per residential delivery address</td>
<td>Urban London</td>
<td>Home</td>
<td>Outside home e.g. Garden, balcony, street</td>
</tr>
<tr>
<td></td>
<td>Suburban London</td>
<td>Home</td>
<td>Outside home e.g. Garden, balcony, street</td>
</tr>
<tr>
<td></td>
<td>Lincolnshire and Berkshire</td>
<td>Home</td>
<td>Outside home e.g. Garden, balcony, street</td>
</tr>
<tr>
<td>per business delivery address</td>
<td>Urban London</td>
<td>Offices, shops etc.</td>
<td>Outside business e.g. Street, car park, site</td>
</tr>
<tr>
<td></td>
<td>Suburban London</td>
<td>Offices, shops etc.</td>
<td>Outside business e.g. Street, car park, site</td>
</tr>
<tr>
<td></td>
<td>Lincolnshire and Berkshire</td>
<td>Industry, small shops/offices</td>
<td>Outside business e.g. Street, car park, site</td>
</tr>
<tr>
<td>per km of road/rail</td>
<td>Motorway</td>
<td>Cars/buses</td>
<td>Pedestrians (Set to 0 as no pedestrians along motorway)</td>
</tr>
<tr>
<td></td>
<td>A road</td>
<td>Cars/buses</td>
<td>Pedestrians (Set to 0 as pedestrians located outdoors business and residential)</td>
</tr>
<tr>
<td></td>
<td>B road</td>
<td>Cars/buses</td>
<td>Pedestrians (Set to 0 as pedestrians located outdoors business and residential)</td>
</tr>
<tr>
<td></td>
<td>Railway</td>
<td>Trains</td>
<td>Pedestrians (Set to 0 as no pedestrians along rail track)</td>
</tr>
</tbody>
</table>

Table 37 Types of demand and the locations where it is generated within the study area
5.3.1 Process for deriving demand per study area

We adopted the following process to determine the average demand per demand type (residential/business delivery address and road/rail route):

1. Evaluate penetration of each device type (devices per pop) from 2012-2030.
2. Calculate number of each device type in the study area = penetration (step 1) x population in the study area, for each study area.
3. Evaluate average demand (Bytes/month) per device type from 2012-2030.
4. Calculate total traffic (Bytes/month) in study area by device type = number of devices of each type (step 2) x traffic per device (step 3).
   a) Validate total traffic in the study area (summed across all device types) against UK wide forecast (e.g., PA) scaled to population of study area.
5. Calculate traffic rate (bits/second) for the three different times of day, by device type = Total Traffic (step 4) / proportion monthly traffic during the hour.
   a) Convert Bytes/month into Bytes/day.
   b) Scale by proportion of daily traffic in the hour for: rush hour, work time, evening (Mbps).
6. Split the total traffic (by device) across different locations for the three times of day = total traffic in the hour for that device (step 5) x proportion of traffic across locations (for each device type).
   a) Traffic will move from business addresses, to on the roads/rail, to at home. Resulting in a work time, rush hour and evening time, respectively.
   b) This step inherently gives you the traffic split by device type at each location.
7. Sum traffic across device types for each location and time of day (step 6).
8. Evaluate traffic per address or km of road/rail = total traffic by location (step 7) / number of addresses or km per study area.
9. Traffic split by clutter type = Traffic per address or km x percent of rural, suburban or urban clutter type.
10. Split traffic by location according to indoor and outdoor components = proportion of indoor/outdoor traffic per location x total traffic per location (step 9).
11. Distribution of data amongst individuals = Plot distribution of users (%) against distribution traffic (%) for each year to 2030.

In each step we present the data used to derive the growth assumptions and traffic values which in some cases used various analyst and vendor forecasts or reports. In other steps, basic calculations were conducted in order to divide or multiply the traffic according to that step in the process. The example output plots have used the Central London study area under the mid case scenario.
5.3.2 Practical implementation of demand points (Peak-to-mean ratio)

The average demand is represented as Mbps across three busy hours which means the user experience is spread evenly across a whole hour for access to the network. In practice demand is not spread evenly over the period, so we introduced a peak to mean ratio for each of the demand points to represent a more practical level of service for each user.

The peak to mean ratio was calculated as 1:20 by using the Urban London study area as a calibration area (since it has the highest demand density) and ensuring that the model results lead to networks which were close in scale to today’s mobile operator networks.
Step 1 - Evaluate penetration of each device type (devices per pop) from 2012-2030

This first step evaluated the penetration of device types within the population. This metric establishes the proportion of devices of each type across the study area population. The available source data provided a mix of population groups with some of the sources using penetration as proportion of the country population, or proportion of the mobile user population and the proportion of the mobile broadband population and so on.

Table 38 outlines how the different population groups impact the level of penetration per device type.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Smartphone</td>
<td>32.4 [&quot;]</td>
<td>62 [&quot;]</td>
<td>38 [&quot;]</td>
<td>106.28</td>
<td>81.1 [&quot;]</td>
<td>52%</td>
<td>85%</td>
<td>30%</td>
</tr>
<tr>
<td>Tablet</td>
<td>3.62 [&quot;]</td>
<td>62</td>
<td>38</td>
<td>106.28</td>
<td>81.1</td>
<td>6%</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>Laptop</td>
<td>3.9 [&quot;]</td>
<td>62</td>
<td>38</td>
<td>106.28</td>
<td>81.1</td>
<td>6%</td>
<td>10%</td>
<td>4%</td>
</tr>
<tr>
<td>USB modem</td>
<td>5 [&quot;]</td>
<td>62</td>
<td>38</td>
<td>106.28</td>
<td>81.1</td>
<td>8%</td>
<td>13%</td>
<td>5%</td>
</tr>
<tr>
<td>3G phone</td>
<td>61.36 [83]</td>
<td>62</td>
<td>38</td>
<td>106.28</td>
<td>81.1</td>
<td>99%</td>
<td>161%</td>
<td>58%</td>
</tr>
<tr>
<td>Total</td>
<td>106.28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>171%</td>
<td>280%</td>
</tr>
</tbody>
</table>

Table 38 Penetration levels of different population groups by device type

It can be seen from the table that the different population groups result in different levels of penetration which depend on the size of the population considered. It was our view that the most appropriate population group to use was the population of the UK. This meant consistent penetration levels could be produced from a known set of authoritative statistics for the population growth over time. In addition, taking penetration of devices against the UK population also meant a more robust metric in determining the average quantity of traffic generated per person as individuals can have more than one connection or device.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Smartphone</td>
<td>55</td>
<td>75</td>
<td>N/A</td>
<td>Confidential GIGAOM, IDATE, Analysys, Mason, Rysavy, Kantar</td>
<td>42% in 2012 This value is based on the penetration of smartphones across the population. This value is derived from middle of the range of penetration of smartphone devices in the UK population in 2011. The average is 37.5% from the sources but we have uplifted to represent the situation in 2012 based on current trends. Growth rates range from 11% - 46% CAGR. We assume growth of smartphones over the time frame rises rapidly in the first eight years and then is likely to slow down in the final nine years once saturation has been reached. <strong>Growth assumptions:</strong> Low: 2012 – 2020 12% CAGR 2021-2030, 3% CAGR Mid: 2012 – 2020 14% CAGR 2021-2030, 3% CAGR High: 2012 – 2020 15% CAGR 2021-2030, 3% CAGR</td>
</tr>
<tr>
<td>Tablet</td>
<td>7.5</td>
<td>N/A</td>
<td>N/A</td>
<td>Guardian, Mobile marketing, Morgan Stanley</td>
<td>6% in 2012 This value is set between the two lowest numbers of all the sources as these are most aligned with actual data. This value is based on current global penetration levels of tablets which we assume will match that of UK penetration. Growth rates are assumed to be greater than smartphones - as tablets are still quite new in the market with lots of growth potential - and rise rapidly in the first eight years and then growth is likely to slow down in the final nine years as device penetration starts to saturate. <strong>Growth assumptions:</strong> Low: 2012 – 2020 12% CAGR 2021-2030, 2% CAGR Mid: 2012 – 2020 33% CAGR 2021-2030, 2% CAGR High: 2012 – 2020 37% CAGR 2021-2030, 3% CAGR</td>
</tr>
<tr>
<td>Laptop</td>
<td>2 (laptops)</td>
<td>N/A</td>
<td>N/A</td>
<td>Disruptive, IDC, Cisco (derived)</td>
<td>6% in 2012 This value has been derived based on the number of connected units in the UK as of 2012 and current global penetration levels of connected laptops. These devices have started to emerge on the market in the last year or two which means there is lots of growth to come in this market. Growth rates are assumed to be similar to tablets as they are still quite new in the market with lots of growth potential and rise rapidly in the first eight years and then growth is likely to slow down in the final nine years as device penetration starts to saturate. <strong>Growth assumptions:</strong> Low: 2012 – 2020 34% CAGR 2021-2030, 2% CAGR Mid: 2012 – 2020 35% CAGR 2021-2030, 2% CAGR High: 2012 – 2020 37% CAGR 2021-2030, 3% CAGR</td>
</tr>
<tr>
<td>USB modem</td>
<td>51</td>
<td>N/A</td>
<td>N/A</td>
<td>YouGov, Green Packet, ISPreview</td>
<td>8% in 2012 This value is based on number of units connected in the UK as of 2011. Other penetration numbers are of total mobile broadband devices which is not a representative proportion of devices across the population. These devices tend to be used by business users, students and some recreational users but sources suggest penetration amongst the total population is around 6% which we have uplifted to 8% for 2012. Penetration of these devices will start to decline as embedded laptops grow in popularity thus removing the necessity of USB modems. However, we do take into account the impact of technology evolution and the use of these devices by operators to enable rapid access to new mobile data networks.</td>
</tr>
</tbody>
</table>
Table 39 Penetration of devices across the across various populations

|----------|---------------------------------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| 77% (2010)| 99%itus 
| 64%     | N/A                                                               | N/A                                             | N/A                                           |

This value is based on the number of expected early 3G type phones across the population in 2012. Sources suggest there is almost 1 3G phone per pop. These devices are likely to be replaced by smartphones as new devices come on to the market. In addition, vendors are now focusing produces on smartphone technology and new sales of 3G phones likely to decline.

Growth assumptions: Low: 2012 – 2020 -49% CAGR 2021-2030, -100% CAGR
Mid: 2012 – 2020 -49% CAGR 2021-2030, -100% CAGR
High: 2012 – 2020 -49% CAGR 2021-2030, -100% CAGR

Figure 5-5 Penetration of smartphones across mix of sources and Real Wireless proposal

Figure 5-5 compares the main sources for smartphones, since there were more sources for this device compared to the other devices, against the Real Wireless proposal which is within the middle of the range compared to the sources. The Real Wireless proposal sits between the Analysys Mason forecast and the GIGAOM forecast which suggests a mid-range between the relevant population forecasts.
The following growth assumptions have been made for device penetration:

- Growth assumptions have been based on the sources for each of the device types as closely aligned with public market data for 2011 and used for the starting point in 2012
- Extending growth over a longer period but keeping the rate the same depending on the high medium and low scenario
- The growth rates for smartphones are based on sources up to 2015
- The growth for tablets has been assumed to be slightly lower than smartphones based on the higher tier consumer growth market for tablets
- The growth rates for laptops and USB dongles is based on sources which suggest there will be parity between devices by 2015
- Growth in traffic for early 3G phones is based on source data with a steady declining rate to 0% by 2025

The plots in Figure 5-6, Figure 5-7 and Figure 5-8 show the different rates of penetration per device across the study time frame. The trend in each scenario is consistent in that:

- Smartphone penetration takes the highest proportion out of all devices
- Tablet and laptop penetration are the next two devices with the highest penetration after smartphones
- USB modem (i.e. dongle) penetration does not grow but remains consistent over much of the timeframe up to 2025 when the penetration begins to decrease
- 3G phones are already in decline from 2012 and continue to decline in penetration until 2020 when they are no longer available
Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030

Low case:
- Decline in total penetration owing to 3G phone decline with slow growth of smartphones, tablets and laptops

Mid case:
- Gradual growth with devices reaching 250% of the population across the device mix

High case:
- Fast growth with devices reaching 380% of the population across the device mix

Figure 5-6 Device penetration for the low case scenario

Figure 5-7 Device penetration for the mid case scenario

Figure 5-8 Device penetration high case scenario
Step 2 - Calculate number of each device type in the study area

In this step we calculate the number of each device type in the study area based on its population statistics. We take the penetration of device types from step 1 and multiply by both the working population and mobile active population in the study area, for each of the study areas.

<table>
<thead>
<tr>
<th>Study area</th>
<th>Residential population</th>
<th>Working population</th>
<th>Mobile active population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban – Central London</td>
<td>434000[95]</td>
<td>1570300[98]</td>
<td>86800 (20% of Residential pop)</td>
</tr>
<tr>
<td>Rural Lincolnshire</td>
<td>692800[95]</td>
<td>333000[96]</td>
<td>359800 (Residential pop – working pop)</td>
</tr>
<tr>
<td>Rural Berkshire</td>
<td>152767[95]</td>
<td>82891[96]</td>
<td>69876 (Residential pop – working pop)</td>
</tr>
</tbody>
</table>

Table 40 Residential population, mobile active population and working population statistics for each of the study areas

Table 40 shows the statistics of the working population and the derived mobile active population. The working population are those that work within the study area assuming a net balance of 0 of those leaving the area to work and those coming into the area to work, apart from Central London which is a special case. In Central London the population increases over three times due to the large incoming working population.

The mobile active population, are those people that are not travelling to work during rush hour or located at business addresses during work time. This population is estimated based on the residential population by subtracting the working population from the residential population, resulting in the mobile active population. This method is applied to all but the Central London study area since there is a disproportionate number of working population coming into London each day. Therefore, we assume 20% of residential population is mobile active in this study area and take into account the residential population level in the 8-9pm busy hour (discussed later in step 5).

We take the percentage of penetration of each device from step 1 and multiply by the population of each study area. This results in the number of each device across the study area population. It can be seen that we assume 3G enabled devices will be in decline across the time frame with no devices in the mix by 2020. We assume these handsets will be replaced by smartphones as our sources suggest from step 1. The growth in the number of tablets and laptops will also increase at faster rate than smartphones.
Figure 5-9 shows an example of the growing number of device types that exist in the Central London study area for the mid case scenario. It can be seen that almost half the number of devices in 2030 are smartphones with tablets and laptops making up the other 50%, the smallest proportion of devices are USB dongles.

![Graph showing total number of device types in the study area - Mid scenario](image)

Figure 5-9 Total number of device types in the study area – Mid case scenario
Step 3- Evaluate average demand (Bytes/month) per device type from 2012-2030

At the beginning of this step we know the total number of devices within the study area as calculated in step 2. In this step we calculate the average volume of traffic generated by each of the devices within the study area to produce the total demand generated within the study area by all devices. Shown in Table 41 are the values for volume of traffic in MB/month from the different sources for smartphones and tablets.

<table>
<thead>
<tr>
<th>Device</th>
<th>2012 (MB/month)</th>
<th>2015 (MB/month)</th>
<th>2020 MB/man</th>
<th>Source</th>
<th>Date of source</th>
<th>Real view</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smartphone</td>
<td>85 200 375 500 max 400-500 1000 max 146 600 (max) 300 (2011)</td>
<td>776 1300 1500 N/A 4000 450 N/A 800 N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td>7000</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Majorlity of this data is based on video and social network media applications available to smartphones. Variations are wide in 2012 with IDATE data taken from actual operators experiences. Growth forecasts are very uncertain with minimum below 1 GB/month. Research has shown industry generally perceives high growth (around 50-80% -YoY) over the next three years</td>
</tr>
<tr>
<td>Tablet</td>
<td>405 (2010) 1000 (2010) 800 800</td>
<td>2311 N/A N/A N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Trends suggest tablets consume more traffic than smartphones, by around 25%. Range of around 800MB -1GB/month in 2012 seems reasonable when compared to smartphones as sessions last longer for tablets and more data can Wireless be consumed due to increased form factor and screen size. Latest Ericsson data shows average tablet traffic at 250-800 MB/month, however the 800 value is similar to the other sources</td>
</tr>
</tbody>
</table>

Table 41 Smartphone and tablet volumes of traffic from different sources
Figure 5-10 Comparison between sources for smartphone and tablet traffic

Figure 5-10 shows the range of different values from the reference sources for both smartphones and tablets against the Real Wireless value used for demand in 2012. Much of the smartphone volumes were considered high based on their peak volumes and the value used in the model is based on the average of the non-peak values. The traffic volume data for tablets was consistent amongst the sources between 400 MB/month and 1000 MB/month and the value used in the model for 2012 was in the middle of the range at 750 MB/month.
<table>
<thead>
<tr>
<th>Device</th>
<th>2012 (MB/month)</th>
<th>2015 (MB/month)</th>
<th>2020 MB/month</th>
<th>Source</th>
<th>Date of source</th>
<th>Real Wireless view</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laptop</td>
<td>2500</td>
<td>6522</td>
<td>N/A</td>
<td>Cisco VNI 2011[97]</td>
<td>Feb 2011</td>
<td>Laptops consume the largest volume of traffic out of all devices - this is due to longer sessions, larger and more advanced screens compared to smartphones and tablets. Reasonable traffic consumption between 2500 – 3000 MB/month for 2012. Expected to be at least double the traffic of tablets based on above rationale and sources such as Cisco suggesting laptop traffic is more than three times that of tablets.</td>
</tr>
<tr>
<td></td>
<td>5000 max</td>
<td>N/A</td>
<td>N/A</td>
<td>Rysavy[101]</td>
<td>May 2011</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3500</td>
<td>11200</td>
<td>N/A</td>
<td>Ericsson[95]</td>
<td>Feb 2010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1900</td>
<td>6500</td>
<td>N/A</td>
<td></td>
<td>Nov 2011</td>
<td></td>
</tr>
<tr>
<td>USB modem</td>
<td>2000</td>
<td>N/A</td>
<td>N/A</td>
<td>Cisco VNI 2011[97]</td>
<td>Feb 2011</td>
<td>Similar to laptops in terms of session times and larger screen use. However, length of sessions may be shorter compared to embedded modules this is based on fixed line replacement and more ‘on the move’ type of usage. Reasonable consumption between 1500-2000 MB/month based on average consumption above 1000 MB/month</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>8000</td>
<td>N/A</td>
<td>IDATE[98]</td>
<td>May 2011</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>1969</td>
<td>N/A</td>
<td>Analysys Mason[102]</td>
<td>July 2010</td>
<td></td>
</tr>
<tr>
<td>3G phone</td>
<td>3.3</td>
<td>54</td>
<td>N/A</td>
<td>Cisco VNI 2011[97]</td>
<td>Feb 2011</td>
<td>These devices are unlikely to consume large quantities of data more than 50MB/month, this is due to the small screens, and amount of useful applications that can be used on these handsets. Traffic growth not likely to exceed 100 MB/month</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>N/A</td>
<td>N/A</td>
<td>IDATE[98]</td>
<td>May 2011</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>500</td>
<td>N/A</td>
<td>Ericsson[95]</td>
<td>May 2011</td>
<td></td>
</tr>
</tbody>
</table>

Table 42 Traffic volumes MB/month for Laptops, USB modems and 3G phones against different sources
Figure 5.11 Comparison between sources for smartphone and tablet traffic

Figure 5.11 shows the range of different values from the reference sources for both laptops and USB modems against the Real Wireless value used for demand in 2012. Laptop traffic varied quite widely amongst the sources and we took the average of the non-peak traffic data as the level in 2012. The Real Wireless value for USB modems was based on the average of all the source numbers, as data available for mobile broadband traffic across modems is aligned with traffic volumes measured in practice around 1100 MB/month on average.

Traffic demand of devices

- The multiple sources as shown in Table 41 and Table 42 provide a wide range of traffic values per device. We used the average excluding the maximum of those numbers as the value in 2012.

Growth assumptions:

- Growth assumptions have been broadly based on the sources for each of the device types aligned with public market data for 2011 and the average used for the starting point in 2012 for each device (except 3G phones).
- We have assumed extended growth trends over a longer period (8-10 years) keeping the rate the same depending on the high medium and low scenarios.
- We assumed the rate of growth in the latter part of the time frame would fall based on the maturity of the market and that consumption of applications will reach a certain limit based on patterns of mobile use over time [104].
- The growth rates for tablets and laptops are considered to be similar owing to similar trends in data consumption across those devices. This includes, video streaming, audio streaming, email and download of high resolution content.
- The growth rates for USB dongles begin to decline in the latter years of the timeframe due to the uptake of embedded laptops. We expect laptops to start taking the share of the dongle traffic as more embedded laptops become available on the market.
- Growth in traffic for 3G phones is based on the IDATE source which provides data up to 2020. This shows that in 2020 there will still be 3G enabled handsets in 2020. Our assumption suggests these handsets will be superseded by smartphones and future generations of smartphones, although we assume the traffic will grow on the 3G handsets until they are phased out.

<table>
<thead>
<tr>
<th>Device</th>
<th>Traffic in 2012</th>
<th>Year</th>
<th>Low CAGR</th>
<th>Mid CAGR</th>
<th>High CAGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smartphone</td>
<td>270 MB/month</td>
<td>2012-2020</td>
<td>4%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2021-2030</td>
<td>4%</td>
<td>8%</td>
<td>12%</td>
</tr>
<tr>
<td>Tablet</td>
<td>751 MB/month</td>
<td>2012-2020</td>
<td>6%</td>
<td>15%</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2021-2030</td>
<td>6%</td>
<td>13%</td>
<td>17%</td>
</tr>
<tr>
<td>Laptop</td>
<td>2633 MB/month</td>
<td>2012-2020</td>
<td>6%</td>
<td>15%</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2021-2030</td>
<td>6%</td>
<td>12%</td>
<td>17%</td>
</tr>
<tr>
<td>USB</td>
<td>1125 MB/month</td>
<td>2012-2020</td>
<td>5%</td>
<td>13%</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2021-2030</td>
<td>1%</td>
<td>4%</td>
<td>8%</td>
</tr>
<tr>
<td>3G phone</td>
<td>10 MB/month</td>
<td>2012-2020</td>
<td>5%</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2021-2030</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 43 Mobile traffic growth assumptions

Table 43 shows the traffic growth rates we have assumed across each of the devices for the low, mid and high scenarios. The figures suggest the highest rate of growth will come from tablets and laptops which aligns with sources such as Cisco[100] and Ericsson[101]. However, smartphone traffic will also continue to rapidly grow over the next five years which is considered under our mid/high scenarios whose range is closest to Analysys Mason[102] of
48% CAGR rather than higher estimates from Cisco[79] 119% CAGR Rysavy Research[101] and Ericsson[102] 60% CAGR.

USB modem traffic is still likely to grow over the study timeframe as mobile broadband evolves into new technologies and dongles offer a ‘quick to market’ solution for operators to switch users on to new networks. However, growth will likely be lower than tablet and laptop traffic and more than smartphone traffic based on the ‘shorter session’ use of USB modems compared to tablets and embedded laptops.

Figure 5-12 shows the growth of traffic in GB/month per device over time according to the mid-scenario. Laptop traffic is clearly the device which is likely to consume the most traffic in future, followed by tablets, then USB modems and then smartphones.

The output suggests that laptop traffic will generate almost traffic, almost 25 GB/month by 2030 with tablets the next highest traffic consuming device at 8 GB/month on average and UB dongles on 5 GB/month. We estimate smartphones, in this case, will generate around 1.3 GB/month on average by 2030.

**Figure 5-12 Mobile traffic growth across devices – Mid scenario**

**Step 4 - Calculate total traffic (Bytes/month) in study area by device type**

In this step we calculate total traffic in the study area by device type. This means the ‘total quantity’ of traffic for the study area, which has been based on the population (working and
mobile active) of the study area and penetration of devices, can be distributed across the study area locations and times of day to calculate the average demand per demand point.

In this step we take the number of devices of each type from step 2 and multiply the traffic per device from step 3.

Figure 5-13 shows an example of the total mobile traffic generated in the Central London study area for the mid scenario across device types. The largest proportion of traffic generated is from laptops taking over 60% of the total traffic followed by tablets and then smartphones. USB dongles and 3G phones become a very low proportion of the total traffic in this case.

![Total traffic in the study area by device type - Mid scenario](image)

Figure 5-13 Total mobile traffic in the Central London urban study area by device type – Mid scenario

We expect the Central London study area to generate the highest amount of traffic across all the study areas due to having the largest population and we can compare the total mobile traffic in 2030 in Figure 5-13 against the total mobile traffic in Figure 5-14 which is the Lincolnshire rural study area which shows a factor of 6 difference between the two study areas.
It is at this point, we compare the total amount of traffic for the study area against other sources as a validation step. In the figures below we show results from the model against results from the PA Consulting [105] research report on “Predicting areas of spectrum shortage” which forecast demand out to 2025.
The total traffic in the top plot shows the low, mid and high growth for the Central London study area based on the average traffic per device. The total traffic shown at the bottom is extrapolated from the PA Consulting UK demand growth number assuming the same proportion of population and busy hours traffic.

It can be seen that the plots show relatively good degrees of alignment across the years noting PA figures are slightly greater than the real Wireless figures due to subtle differences between the models.

Figure 5-15 Mobile traffic validation against PA Consulting [105] values extrapolated for London
Figure 5-16 shows another comparison chart between Real Wireless growth estimates against PA Consulting forecasts for demand growth for the whole UK. The Real Wireless figures used the latest UK population estimates for 2011\(^{[3]}\) and the penetration values and traffic volume per device estimates to produce the Real Wireless curves in the plot above. It can be seen that the starting point in 2012 is just below the PA mid curve for 2012 which suggests good correlation between the data. The growth curves differ in that our estimates, based on average traffic volume per device, show a rapid increase in the early years in all scenarios which means our low case scenario closely follows the PA-mid case, however the rate of growth shows good correlation.

All our scenario cases lie between PA mid and high cases with our high case starting to increase above the PA high around 2015. This suggests that our estimates are within plausible ranges of independent forecasts.
Step 5 - Calculate traffic rate (bits/second) for the three different times of day, by device type

At step 5 we calculate the traffic rate and convert from GB/month to megabits per second (Mbps) for the three different times of day across each device type.

The quantity of traffic varies across the time of day as users go about their everyday business. The example distribution given in Figure 5-17 shows a distinctive spread in the volume of traffic generated at different times of the day. It can be seen that the low volumes of traffic are in the early hours of the morning which is not zero but sees a 75% reduction in consumption in that period, whereas mid to late evening is when the most traffic is generated. The times in between can represent certain locations the general population will be and activities the general population will be doing. This includes, travelling to work, working in an office, lunchtime etc. The plot also shows the different applications that are being used with video and internet browsing the largest proportions of the total traffic.

![Downlink Data Over 24 Hours](image)

**Figure 5-17 Distribution of mobile broadband traffic across a 24 hour period, Source: Global Metrics report[30]**

In this study we decided to choose three times of day that would distinctly weight the traffic to certain locations the population would be generating traffic within the study area. This means the network would need to be dimensioned to the peak traffic loading in each of the locations providing a more realistic approach to distributing demand.
Figure 5-18 relative traffic volume according to locations across a 24 hour period, Source: Nokia Siemens[107]

Figure 5-18 shows the relative traffic for the various locations across a 24 hour period which we based our assumptions for dividing traffic across the three times of day. The plot in the figure shows the mix of City, suburban and residential area traffic, varying according to the time of day. Traffic progressively grows in the suburbs throughout the day, however this is exceeded by traffic in the City location as the population arrives at work. The residential traffic matches the suburbs from around 6pm onwards to 12am and City traffic is in decline from 3pm onwards.

Similar to the plot in Figure 5-17 the period of lowest consumption occurs in the late evening and early morning hours across all locations types.

The charts show how traffic varies over the time of day and according to location. This maps on to our traffic split across our three representative times of the day.

Proportional split* of total traffic by time:
- Peak @8-9pm/Total daily traffic = approx 6%
- Peak @5-6pm/Total daily traffic = approx 6%
- Peak @9-10am/Total daily traffic = approx 3%

*Numbers derived from chart (left) by taking mid-point of each hour and summed for total traffic over the whole day. Traffic for each hour of interest was then divided by total traffic for the day.

Proportion of traffic in hour of interest = Traffic in hour of interest/Total daily traffic

Figure 5-19 Real Wireless proposal for traffic across three different times of day, Source: Elisa[108] and Nokia-Siemens[107]
Our proposal for the three different busy hours per day is as follows:

a) 9-10am: At this hour of day we assume the majority of the traffic in each study area will be generated from business locations

b) 5-6pm: At this hour of day we assume the majority of the traffic in each study area will be generated by commuters either on the road (in-vehicle) or on trains along rail lines

c) 8-9pm: At this hour of the day we assume the majority of the traffic in each study area will be generated at residential locations

Figure 5-19 describes how we derived the proportion of traffic in each busy hour across the total traffic in a 24 hour period from the distribution in the Elisa chart. This chart provides the total quantity of traffic in each hour with details of the particular application. It also broadly supports the trend found from the other distributions of how much traffic is consumed at specific times of day.

![Mobile traffic divided into three times of day across devices](image)

**Figure 5-20 Total mobile traffic across devices for three busy times of day**

Figure 5-20 shows the output from the demand model of the total mobile traffic across each of the three busy hours in the Central London study area.
Step 6 - Split the total traffic (by device) across different locations for the three times of day

In this step we split the total traffic by device type for the three times of day calculated from step 5 across the different locations within the study area. It is at this point we determine the proportion of traffic across locations for each time of day and assume:

- Traffic will move from business addresses, to on the roads to at home. Resulting in a work time, rush hour and evening time, respectively
- This step inherently gives you the traffic split by device type at each location

Figure 5-21 shows how the mobile active population and the working population are distributed across locations for the different times of day. We have assumed that the largest proportion of traffic should be distributed according to where largest proportion of the population will be located. For example, the majority of the working population will be at business locations between 9-10am; we assumed this to be 78% of the working population and hence traffic. The other 22% of the traffic is ranked and distributed amongst the other locations according to the next likely highest location which in this case is rail (7%), residential (5%), Motorway (4%), A-road (4%), B-road (2%). The equivalent process is done for the mobile active population, however, this population are more likely to be at residential locations or road and rail locations and not business locations.

![Figure 5-21 Traffic split by population both for mobile active and working populations](image-url)
The following sets of figures provide extracts from the demand model of how the traffic is split by device type for each of the locations for each time of day. The example shown in the figures is for the Central London urban study area mid case scenario. Note the values of mobile traffic at each of the locations for the different times which will impact the level of capacity required.

**Figure 5-22** Traffic at residential locations by device type for each of three busy hours

**Figure 5-23** Traffic at business locations by device type for each of three busy hours
Figure 5-24 Traffic at A-road locations by device type for each of three busy hours

Figure 5-25 Traffic at B-road locations by device type for each of three busy hours

Figure 5-26 Traffic at rail locations by device type for each of three busy hours
Step 7 - Sum traffic across device types for each location and time of day

This step simply adds together the total traffic by device type within each busy hour to give a total volume of traffic for each location. This step is necessary so that the traffic can then be divided into volumes of traffic per residential or business address or kilometre of road or rail in step 8.

The following figures provide examples outputs from the demand model of the total traffic for all devices across each location for the three busy hours in the urban study area, mid case scenario.

![Total traffic for all devices by location](image)

**Figure 5-27 Total traffic for all devices across each location – Work time (9-10am)**

In the 9-10am work time busy hour the largest proportion of traffic is expected to be at business locations as confirmed in Figure 5-27.
In the 5-6pm rush hour busy time the largest proportion of traffic is expected to be at the road and rail locations as confirmed in Figure 5-28.

In the 8-9pm rush hour busy time the largest proportion of traffic is expected to be at residential locations as confirmed in Figure 5-29.
Step 8 - Evaluate traffic per address or km of road/rail

This step takes the statistics for each of the study areas to calculate the average traffic in Mbps per address of kilometre of road or rail. This step is necessary so that the traffic can then be split according to its indoor or outdoor locations in the next step.

The statistics for each study can be seen in the tables below. The delivery address data has been sourced from the UK postcode database and the road and rail data has been sourced from the Ordnance Survey database.

<table>
<thead>
<tr>
<th>Total delivery addresses Study area</th>
<th>Urban</th>
<th>Suburban</th>
<th>Rural</th>
<th>Urban</th>
<th>Suburban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RESIDENTIAL</td>
<td>BUSINESS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Central London</td>
<td>273,723</td>
<td>21,085</td>
<td>8,356</td>
<td>31,794</td>
<td>4,420</td>
<td>1,204</td>
</tr>
<tr>
<td>Total</td>
<td>303,164</td>
<td>Total</td>
<td>37,418</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suburban West London</td>
<td>40,090</td>
<td>395,298</td>
<td>38,877</td>
<td>3,212</td>
<td>18,600</td>
<td>2,104</td>
</tr>
<tr>
<td>Total</td>
<td>474,265</td>
<td>Total</td>
<td>23,916</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural Lincolnshire</td>
<td>22,484</td>
<td>192,163</td>
<td>114,964</td>
<td>806</td>
<td>9,097</td>
<td>6,196</td>
</tr>
<tr>
<td>Total</td>
<td>329,611</td>
<td>Total</td>
<td>16,099</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural Berkshire</td>
<td>643</td>
<td>46,585</td>
<td>23,704</td>
<td>15</td>
<td>2,654</td>
<td>1,259</td>
</tr>
<tr>
<td>Total</td>
<td>70,932</td>
<td>Total</td>
<td>3,928</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 44 Absolute number of residential and business delivery addresses for each study area

<table>
<thead>
<tr>
<th>Study area</th>
<th>Road/Rail (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Motorway</td>
</tr>
<tr>
<td>Urban Central London</td>
<td>-</td>
</tr>
<tr>
<td>Suburban West London</td>
<td>22</td>
</tr>
<tr>
<td>Rural Lincolnshire</td>
<td>-</td>
</tr>
<tr>
<td>Rural Berkshire</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 45 Absolute number of road and rail kilometres for each study area

The total number of delivery addresses for residential and business in each study area is used to calculate total traffic per address for the study area. Similarly, the sum total of kilometres for Motorway, A-road, B-road and rail in each study area is used to calculate total traffic per address for the study area. Note there is 0 km of motorway in the urban Central London and rural Lincolnshire study areas.
The following figures give examples of the quantity of demand for each busy hour at each location within the Central London study area. The charts show the proportion of traffic per delivery address, or per kilometre of road/rail according to the busy hour. It can be seen that the mobile traffic generated on the road and rail is significant due to the smaller quantities of kilometres compared to the much larger quantities of delivery addresses. This means there is more traffic per kilometre for road/rail than for per residential or business delivery addresses.

![Figure 5-30 Total traffic per address or km by location in the 9-10am busy hour for Central London](image)

![Figure 5-31 Total traffic per address or km by location in the 5-6pm busy hour for Central London](image)
Figure 5-32 Total traffic per address or km by location in the 8-9pm busy hour for Central London
Step 9 – Traffic split by clutter type

In this step we split the traffic in the study area by clutter type. This has the impact of distributing the traffic to the areas in which our demand points are located. The set of assumptions made for this step are based on the location of devices expected in certain clutter types taking into consideration our interpretation of clutter type.

An example definition of clutter types is given below extracted from “Antennas and Propagation for Wireless communications Systems” [109, pp 167]:

- **Open area**: Open space, no tall trees or buildings in path, plot of land cleared for 300–400 m ahead, e.g. farmland, rice fields, open fields.
- **Suburban area**: Village or highway scattered with trees and houses, some obstacles near the mobile but not very congested.
- **Urban area**: Built up city or large town with large buildings and houses with two or more storeys, or larger villages with close houses and tall, thickly grown trees.

**Assumptions:**

We assume the average traffic per address and per km are equal for urban and suburban clutter types, this is based on:

- We assume the total traffic generated by individuals within residential and business locations for urban and suburban clutter types to be equal due to similar proportions of devices within homes and offices and usage of devices is unlikely to change.

We assume the average traffic per address and per km for rural clutter type will be reduced compared to urban and suburban clutter types, this is based on:

- We expect in rural clutter such as parks and open spaces the traffic will be greatly reduced by a factor of almost 100 compared to urban and suburban clutter types
- We note these values will vary according to the study areas

**Values:**

- Urban and Suburban - 99% of total devices located in urban and suburban clutter types
- Rural - 1% of devices located in urban and suburban clutter types

The above values are based on Ericsson’s traffic forecast[80] for traffic generation reducing across different clutter types which shows a declining proportion of traffic for rural areas >30% in 2011 reducing to 16% in 2016. The value has then been adjusted according to the expected quantity of devices found in rural clutter types such as open spaces, farm land etc, which is assumed to be nearer 1% of devices in the study areas.
Calculation:

- Total traffic for residential/business address urban/suburban clutter type = 0.99 x Total traffic per residential/business address (Mbps) (Step 8)
- Total traffic for residential/business address rural clutter type = 0.01 x Total traffic per residential/business address (Mbps) (Step 8)
Step 10 - Split traffic by location according to indoor and outdoor components

It is in this step that traffic generated per address or kilometre is split according to the indoor and outdoor components. This is an important step when dimensioning for traffic since a lot of mobile traffic is offloaded when indoors and therefore the proportion of traffic generated indoors can have an overall impact on the demand of cellular networks.

We gathered source data from independent analysts, vendors and operators on the proportional split in traffic between indoors (home or office) and outdoors/on the move. We researched usage of device types by environment to understand usage behaviour amongst individual devices. However, all the sources consistently state that the majority (of which the quantity varies) of traffic is generated indoors regardless of the device. Below we summarise the findings from a selection of the sources which suggest more than 70% of traffic is generated indoors.

- Analysys Mason[120] forecast 84% of traffic generated indoors (2010) growing to 87.9% of total traffic (voice and data) from cellular devices generated indoors by 2015.
- Jaime Lluch Ladron of Telefonica[111] expects that 95% of data traffic will come from indoor locations in a few years’ time.
- Upwards of 70 percent of 3G data traffic originates indoors, IDC[112]
- 42% of US mobile data is consumed at home according to Gordon Mansfield of AT&T[113]
- 60% of mobile data traffic will be generated in the home by 2013 according to Informa Telecoms and Media[114]
- 75% of mobile traffic will be generated indoors by 2015, and 95% of that traffic will be data suggested by Analysys Mason[115]

The following chart from Informa Telecoms and Media shows there will be growth in the consumption of traffic indoors over the next few years as traffic generated outdoors and on the move declines.
Figure 5-33 Growth in mobile data traffic indoors at home and in the office, Source: Informa Telecoms and Media[114]

We assume that the number of indoor users will steadily increase over time as more traffic is generated from indoor locations and will peak at around 90 - 95%. The remaining balance (5-10%) if traffic is generated from outdoor locations as there is likely to be a small proportion of usage outdoors.
<table>
<thead>
<tr>
<th>Source</th>
<th>% indoor (home)</th>
<th>% indoor (office)</th>
<th>% indoor not location specific</th>
<th>% outdoor</th>
<th>% on the move</th>
<th>Real Wireless summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysys Mason</td>
<td></td>
<td></td>
<td>84% (2010) to 87.9% (2015)</td>
<td></td>
<td></td>
<td>Growth forecast based on convenience of smartphones and tablets utilised heavily indoors. Mid level compared to other source data</td>
</tr>
<tr>
<td><a href="http://www.mobilecommercedaily.com">www.mobilecommercedaily.com</a></td>
<td></td>
<td></td>
<td>93%</td>
<td></td>
<td></td>
<td>This data is based on indoor usage within a shopping centre so although indoors it could be considered part of on the move</td>
</tr>
<tr>
<td>Cisco</td>
<td></td>
<td></td>
<td>95% (laptops)</td>
<td></td>
<td></td>
<td>This data is based on laptop usage indoors and not representative of all mobile devices</td>
</tr>
<tr>
<td>Telefonica</td>
<td></td>
<td></td>
<td>95%</td>
<td></td>
<td></td>
<td>This data is from an operator’s expectations on the growth of mobile traffic being consumed indoors. Highest proportion out of all sources</td>
</tr>
<tr>
<td>ADC</td>
<td></td>
<td></td>
<td>70%</td>
<td></td>
<td></td>
<td>White paper on in-building wireless providing a statistic for indoor 3G data traffic as a dominant location</td>
</tr>
<tr>
<td>Guardian</td>
<td>90% of tablet owners</td>
<td></td>
<td>41% of tablet owners</td>
<td></td>
<td></td>
<td>This is more to do with offloading but suggests where tablet owners are typically located when using their devices</td>
</tr>
<tr>
<td>Informa</td>
<td>54%</td>
<td>28%</td>
<td>13%</td>
<td>5%</td>
<td></td>
<td>Helpful split of traffic share across locations based on current trends of usage of mobile data devices predominantly driven by smartphones</td>
</tr>
<tr>
<td>Ofcom report, Aug 08</td>
<td>75% (dongles)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slightly out of date source but helpful comparison against current sources and specific for home</td>
</tr>
<tr>
<td>Gordon Mansfield, AT&amp;T, Jun 08</td>
<td>42%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mobile video consumption at home based on operator experiences slightly out of date and lowest level compared to others</td>
</tr>
<tr>
<td>Market Tools, May 08</td>
<td>46% mobile TV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Survey data of 18-34 year olds. Helpful source but uncertain of what device types, but useful metric for in home use</td>
</tr>
<tr>
<td>Gordon Mansfield, AT&amp;T, Jun 08</td>
<td>50% mobile TV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mobile video consumption at home based on operator experienced for watching mobile TV. An addition metric to compare with the other home based use</td>
</tr>
<tr>
<td>Informa Telecoms &amp; Media., Aug 08</td>
<td>60%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Growth forecast of mobile traffic generated indoors by 2013. Useful for comparison against current sources for home based use</td>
</tr>
<tr>
<td>Mobile marketing magazine Feb 11</td>
<td></td>
<td></td>
<td>20%</td>
<td></td>
<td></td>
<td>Article highlighting the growing use of smartphones at work, based on the added functionality and reliance of smartphones to get work done</td>
</tr>
<tr>
<td>Statica 2011</td>
<td>82%</td>
<td>8%</td>
<td>10%</td>
<td></td>
<td></td>
<td>This source is based on tablet usage of a survey of users in the US</td>
</tr>
</tbody>
</table>

Table 46 Sources of information for traffic generated indoors and outdoors
Based on the majority of source data our starting point for indoor percentage of traffic was 80% in 2012 which is a relatively conservative estimate compared to the majority of the source data. The split between the amount of indoor traffic at home and office is biased to the home environment with more than 50% of indoor traffic generated at home. This means the remaining 20%-30% of indoor traffic is generated at office/business locations and therefore the balance of traffic is generated outdoors or on the move (20%)

The sources that present growth assumptions (Informa[114], AM[115]) suggest there will be continued growth in the near term for indoor traffic for both home and office locations. This is compared to traffic generated outdoors/on the move which is in decline across the same time frame.

Our assumption beyond 2015 is based on continued growth with indoor home and office reaching a peak of 95% by 2024 and continues at this level until 2030 for all devices. This is based on continued growing trends of traffic generated indoors. In turn there is a proportion of traffic consumed outdoors or on the move resulting in a balance of 5% in 2030.

<table>
<thead>
<tr>
<th>Location</th>
<th>% of traffic in 2012:Assumptions 2012-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic consumed Indoor (residential)</td>
<td>60% Gradual increase to 72% by 2030</td>
</tr>
<tr>
<td>Traffic consumed Indoor (business)</td>
<td>20% Gradual increase to 23% by 2030</td>
</tr>
<tr>
<td>Traffic consumed Indoor (A-road)</td>
<td>100% No change</td>
</tr>
<tr>
<td>Traffic consumed Indoor (B-Road)</td>
<td>100% No change</td>
</tr>
<tr>
<td>Traffic consumed Indoor (HS)</td>
<td>100% No change</td>
</tr>
<tr>
<td>Traffic consumed Indoor (Rail)</td>
<td>100% No change</td>
</tr>
<tr>
<td>Traffic consumed Outdoor (residential)</td>
<td>10% Gradual decrease to 2.5% by 2030</td>
</tr>
<tr>
<td>Traffic consumed Outdoor (business)</td>
<td>10% Gradual decrease to 2.5% by 2030</td>
</tr>
<tr>
<td>Traffic consumed Outdoor (A-road)</td>
<td>0% No change</td>
</tr>
<tr>
<td>Traffic consumed Outdoor (B-Road)</td>
<td>0% No change</td>
</tr>
<tr>
<td>Traffic consumed Outdoor (HS)</td>
<td>0% No change</td>
</tr>
<tr>
<td>Traffic consumed Outdoor (Rail)</td>
<td>0% No change</td>
</tr>
</tbody>
</table>

![Traffic consumed at indoor locations](image)

**Figure 5-34 Real Wireless indoor traffic component against study area locations residential and business**

We assume that all traffic is consumed indoors along road and rail routes since the traffic will either be ‘in-vehicle’ or ‘on-train’ at these locations. The traffic generated at outdoor locations along road and rail routes is covered by outdoor residential and business locations.
Step 11 - Distribution of usage amongst individuals

This final step is applied once average demand per address or km has been calculated for each study area. Operator[11] and vendor[79] reports suggest that distribution of mobile data traffic is currently asymmetric across mobile operators’ networks with a small proportion of users generating the majority of the traffic.

The impact of the distribution of traffic amongst users can cause bottlenecks in some networks and capacity provision biased towards areas where the most aggressive users are located. Therefore, we have taken into account this distribution factor to represent how network dimensioning is affected.

The following set of sources suggest how a significant proportion of mobile traffic is generated by such a small proportion of users:

<table>
<thead>
<tr>
<th>Device</th>
<th>% of device base</th>
<th>% of total traffic</th>
<th>Source</th>
<th>Real Wireless summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smartphone</td>
<td>6    13  9 78   38</td>
<td>50 78</td>
<td>Tgdaily 2010[16][17] Cisco VNI2011[79] Softpaedia[11]</td>
<td>Mix of data for smartphones depending on the metric being used either percentage of total device (6%) or percentage of handsets (13%). Percentage of total traffic ranges from 38%-78%. Cisco and Tgdaily numbers are based on reports from operators providing credible figures. Softpaedia is a snapshot of an application used (video) rather than general use.</td>
</tr>
<tr>
<td>Tablet</td>
<td></td>
<td>46.8</td>
<td></td>
<td>No data found for the % of devices but the % of total traffic found based on split between iPhone and iPad. This does not provide useful source of data without the % of devices</td>
</tr>
<tr>
<td>Laptop</td>
<td></td>
<td>85</td>
<td></td>
<td>Source data based on operator’s feedback on the heaviest device mobile traffic consumption. This does not provide useful source of data without the % of devices</td>
</tr>
<tr>
<td>USB dongle</td>
<td></td>
<td>85</td>
<td></td>
<td>As above</td>
</tr>
<tr>
<td>Early 3G phone</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td>Early 3G phones generate a fraction as much traffic as all the other devices and therefore does not offer any source data for the small proportion of users generating a large proportion of traffic</td>
</tr>
<tr>
<td>All devices</td>
<td>5 6 10 5-10 10 10</td>
<td>68 54 60 80 90 83</td>
<td>Mobile Europe[11] Mobile Europe[11] Cisco VNI 2011[79] Analysys Mason[11] Bytemobile 2011[11] 4G Americas[11]</td>
<td>This data takes into account all users on a network and that includes the mix of devices. The heavy users are typically using smartphones, tablets, laptops and dongles. The numbers are spread from 60-90% of total traffic from around 5-10 % of the users. The numbers seem consistent although widely spread but offer an indication of the likely distribution amongst users. The sources do not tend to give forecasts of this metric and therefore some estimates can be made on the likelihood of change over time</td>
</tr>
</tbody>
</table>

Table 47 Distribution of mobile traffic amongst users sources of data
Table 47 shows the data of distribution of traffic amongst users from the various sources which include a mix of independent analysts, industry websites and equipment vendors. There was little specific data across the different devices, apart from smartphones where three particular sources provided an inconsistent mix of data. The data that was most consistent in terms of similar distribution values was that for all mobile traffic irrespective of device. Therefore, it was this data that was used to determine the distribution of mobile traffic amongst users.

- Starting point in 2012 is 10% of users consume 80% of the traffic
- In terms of variation of this metric over time Cisco VNI 2011\(^7\) found that distribution of traffic amongst users is becoming more uniform over time. The table extracted below shows the top 1% of users generating 29% of traffic in month 1 and declining over time to 22% of traffic by month 9.

<table>
<thead>
<tr>
<th>Table 47. Percentage of Traffic by User Tier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Users</td>
</tr>
<tr>
<td>% of traffic due to top 1%</td>
</tr>
<tr>
<td>% of traffic due to top 3%</td>
</tr>
<tr>
<td>% of traffic due to top 10%</td>
</tr>
<tr>
<td>% of traffic due to top 25%</td>
</tr>
<tr>
<td>% of traffic due to the bottom 60%</td>
</tr>
</tbody>
</table>

Source: Cisco, 2011

Therefore, we propose to base our variation over time assumptions on a similar decline in non-uniform distribution of mobile traffic amongst users. We expect the rate of change to start at similar rate to that of the Cisco numbers for the first five years and then to slow down to a constant rate from 2017 to 2030 as traffic becomes more uniform.

<table>
<thead>
<tr>
<th>Device</th>
<th>% of user base (2012)</th>
<th>% of total traffic (2012)</th>
<th>Growth assumptions</th>
</tr>
</thead>
</table>
| Across all devices | 10 | 80 | 10% of users use 80 traffic in 2012
- This is based on sources shown in Table 47
10% of users use 45% traffic by 2017
- This is based on growth rate similar to that of the Cisco VNI findings for increased uniformity of traffic
10% of users use 38% traffic by 2020
- This is based on a slight slow down in growing uniformity as a wider proportion of users are already generating a higher proportion of the traffic
10% of device base 28% traffic by 2030
- The trend from 2020 to 2030 slows pace as traffic saturates in some hot spot areas |

Table 48 Real Wireless proposal for growth of distribution of traffic amongst individuals
Figure 5-35 Evolution of distribution of traffic amongst individuals over time
A6. Technical model description

6.1 Introduction

This section describes the modelling framework that was set up in order to estimate the cost of upgrading a mobile network in the period of interest 2020 to 2030. The inputs to this model are listed and explained. Several algorithms are discussed and the form of output is presented. The model combines together several pieces of previous modelling work by Real Wireless into a comprehensive overall framework for network capacity evolution, sensitive to both technical characteristics and financial metrics of benefit.

6.2 Brief description

The model accepts several inputs, such as the spectrum scenarios or the expected spectral efficiency, performs a series of decisions to upgrade the 2012’s network to 2030 based on cost effectiveness, and outputs the cost of performing these decisions. Three study areas were identified to run the model, each with distinct propagation characteristics.

6.2.1 Prior to first modelled year

In each run, the model reads the following inputs which are varied across scenario runs

- Spectral efficiency
- Available spectrum quantities from all modelled bands (17 bands in total)
- Average demand (Mbps/demand point) in three hours of a busy day
- Offloaded demand

The model begins by plotting a map of the study area and populating this map with demand points, which are locations where traffic demand is requested. A buffer area is added externally around the study area to mitigate edge effects. Results are reported for the study area.

The demand locations are real geographical locations of postcodes and locations along real roads and railways that run through the study area. Each demand point corresponds to a number of domestic and business delivery addresses, if the demand point is a postcode, or to a transport type, see Table 49. Although the demand points do not have clutter information assigned to them, a clutter database is used to determine the geotype where the demand point lies on. Three geotypes are considered in this model, namely urban, suburban and rural.
Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030

Table 49 Demand point location within the study area

In order to serve the requested-demand in the demand-points, the modelled operator commissions sites and upgrades existing sites. Two different site types are considered in this model: a macro site and an outdoor small cell. A macro site can have different configurations, see Table 50.

<table>
<thead>
<tr>
<th>Site type</th>
<th>Site configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrocell</td>
<td>Macro, 3 sector, 2 antennas</td>
</tr>
<tr>
<td>Macrocell</td>
<td>Macro, 3 sector, 4 antennas</td>
</tr>
<tr>
<td>Macrocell</td>
<td>Macro, 3 sector, 8 antennas</td>
</tr>
<tr>
<td>Macrocell</td>
<td>Macro, 6 sectors, 2 antennas</td>
</tr>
<tr>
<td>Outdoor small cell</td>
<td>Outdoor small cell, 1-2 sectors, 2-4 antennas</td>
</tr>
</tbody>
</table>

Table 50 Site types and configuration

Note that the model considers the total demand in the study area, assuming that the operator holds 100% of the market share and has access to the total of the available spectrum.
6.3 **Overview of the model between 2012 and 2030**

At the beginning of each year the model starts by querying the available quantities of spectrum for that year. If this is not the first modelled year, then the operator already has license for several of the bands and has equipped the macro sites and small cells accordingly.

The available bands for each year are ordered with primary preference the high to low-frequency, and secondary preference the more to less-bandwidth. The primary order is to simplify the distribution of the demand in the different frequency bands. The closest demand points to a site are given priority of service, and are tried to be accommodated by the high frequency bands. The secondary order has an economic rationale. In this model, all band acquisitions have the same cost; therefore it is more cost effective to serve the demand in the band with the greatest bandwidth. More about the cost of band acquisitions can be found in the relevant chapter.

The model then continues with populating the demand points with the requested demand for that year. As a result, each demand point acquires 6 requested-demand values, expressed in Mbps. This is a result of combinations from the 3 modelled hours of the day (5pm to 6pm, 8pm to 9pm, and 9am to 10am), and 2 positions of the demand (indoor, outdoor).

At this point the model allocates the requested demand to the existing sites. The capacity of the sites is different in each year, prior to any spectrum of site configuration upgrades, because of two reasons: a) the spectral efficiency of the site improves, and b) more carriers may become available as the band is re-farmed. If the existing sites suffice to serve the demand, then the algorithm advances a year and the process that is described in this subsection is repeated.

In the case that existing network is not adequate to satisfy the demand, then the algorithm proceeds with upgrading existing sites and/or commissioning new sites. The modelled area is divided into rectangular partitions of approximately same size as a site. Since two site types are modelled, two partition sizes are tried. The demand that falls within each partition is summed, and the partition with the greatest demand is identified. As a consequence the area with the denser un-served demand is identified. The merit of commissioning a site to serve these demand points is calculated for each site type and configuration. The merit of upgrading neighbouring sites is also calculated. The algorithm then chooses the solution that has the greatest merit, and the new site is built or the site is upgraded accordingly. The demand is allocated to the newly acquired network capacity. Then, the un-served demand is re-calculated, and the process that is described in this paragraph is repeated.

Once all demand points are satisfied, the algorithm advances a year and the algorithmic process that is described in this subsection is repeated.
6.4 Flowchart

6.4.1 Flowchart overview
The model that calculates the cost of upgrading a mobile network in the period of interest 2020 to 2030 comprises of a sequence of algorithmic steps. These can be captured in a flowchart. In this subsection a series of flowcharts is presented.

The model’s algorithm starts with the main flowchart of Figure 6-1. The model starts with a pre-processing step. In this step the necessary variable are constructed so as to prepare the inputs to the code. Then, these inputs are inserted in the next algorithmic block, where the network is built from 0 macro and 0 small cells to several macros and small cells. The site commissioning represents the mobile network in year 2012, which is the starting year in this model.
Figure 6-1 Main algorithm flowchart

Then the model compares the requested mobile traffic demanded against the network’s capacity in the starting year, 2012. More about this step is described further in this section. If the model is capable of satisfying the demand in the year 2012, then the algorithm proceeds with advancing a year and performing the necessary network upgrades to meet the demand in the next year, 2013. A loop is then created, where the year is increased by the step 1 year and the network is upgraded so as to meet the traffic demand.

In each year the requested demand and the network’s capabilities are refreshed. The demand is increased because of the mobile network users becoming more in number as well as using more devices and/or data demanding devices.
The network’s capabilities also change each year. For example the user’s expectations dictate the site ranges, so that the network’s coverage area shrinks. The spectral efficiency increases as a result of improved network interfaces and hardware implementations. More bandwidth also may become available in bands that the operator has already license for. More information on the technical capabilities of the network and the increase of the demand is provided in the chapter 3 of the main report.

6.5 **Model calibration in year 2012**

The requested demand is a model’s input. In the year 2012, we have a more informative insight about the traffic demand and the network’s capabilities to serve it, compared to future years. We know for example the number of 3G carriers that will be switched on in several parts of the UK. Thus we are able to perform a model’s calibration with respect to our expectations in 2012. The number of sites that are built by the model for the year 2012 was calibrated so that in the Central London study area it is roughly the same as existing operator networks.

The model’s calibration was conducted against the Central London study area, and thus other study areas’ network’s size is expected to deviate from real mobile network deployments. Since modelling the coverage of hotspots is not within the scopes of this study, in all study areas we consider that coverage is provided in all demand locations, regardless of today’s networks coverage maps. Therefore, after having calibrated the network’s size, macros and outdoor small cells, in the Central London study area, the network’s size in other study areas is expected to be higher than what the operators have deployed. This is because we expect the operator’s coverage extent to be less than that of the Central London study area.

6.6 **Pre-processing of data**

The model performs site building and upgrading based on the demand in the study area, the network’s capabilities and the cost of new sites or site upgrades. In order to perform the above actions, the model uses data from several files, e.g. demand, spectral efficiency, offload, etc. The model also loads up several decision making constants that affect the model’s performance. In this subsection the input files that are loaded for the model to work are listed out and discussed.

In each run, the model reads the following inputs which are required for the scenario runs:

- Grouping of the bands into three broad frequency categories (sub-1GHz, 1 to 2.1 GHz, and above-2.1 GHz)
- Spot frequency of each modelled band
- Distribution of the demand amongst stationary users (domestic and business)
- Split of the traffic between indoor and outdoor
- Cost of new sites (macro sites and outdoor small cells) and cost of upgrades of macro sites. Outdoor small cells are assumed to be upgraded on their 5th birthday, and this cost is included in their commissioning PV.
- Site ranges
- Capacity of offload devices, e.g. femtocells and Wi-Fi
Table 51 below provides a list of the model’s constants. Figure 6-2 shows a schematic of the algorithmic steps in the pre-processing step of the model.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random seed</td>
<td>A random seed is used for distributing the demand amongst users, in domestic and business addresses</td>
<td>Random seed for the distribution</td>
</tr>
<tr>
<td>Buffer zone about the focus area</td>
<td>A buffer zone is included in each study area to build sites that could serve demand in the focus area. Site in the focus area can also serve demand in the buffer area. For time saving purposes, we assumed that the demand does not grow in the buffer zone as time advances.</td>
<td>14km rural 2.5km suburban 1.5km urban</td>
</tr>
<tr>
<td>Minimum inter site distance</td>
<td>A minimum separation distance between macro sites, and a minimum distance between small cells is applied to avoid the algorithm placing sites too close together. This is based on technical challenges of increased interference when sites are positioned very close.</td>
<td>340m macro, corresponding to 10 sites/km² 18m outdoor small cell, corresponding to similar LOS probability as 340m for macros</td>
</tr>
<tr>
<td>Macro site commissioning cost, as a function of the local average site density</td>
<td>The commissioning of a new macro site is a function of the local average macro site density. For each new site, the neighbouring macro sites are identified and the local site density is calculated.</td>
<td>0sites/km² for the low cost site 10sites/km² for the high cost site</td>
</tr>
<tr>
<td>Weighting function for the determination of the neighbouring sites</td>
<td></td>
<td>0.2*α leads to approximately 8 neighbouring sites</td>
</tr>
<tr>
<td>Replacement cycle of outdoor small cells</td>
<td>Outdoor small cells area replaced on their 5th birthday</td>
<td>5 years</td>
</tr>
<tr>
<td>Maximum number of neighbours for upgrade trial</td>
<td>Having identified the area where the demand is not satisfied, the algorithm examines the merit of upgrading a number of sites in the area. The closest sites to the centroid of the local under-served demand are listed. This list is chopped at the 6 closest sites, however it is provisioned that 1 macro is always provisioned.</td>
<td>6 sites</td>
</tr>
<tr>
<td>Technique</td>
<td>Description</td>
<td>Reference</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Demand peak to mean ratio</td>
<td>The demand is calculated initially as an average value in three modelled hours of a busy day. In order to capture the effect of the demand fluctuation within the busy hour, the demand is multiplied with a peak to mean ratio. This was selected 1:20, so that the user expectation is 20 times larger than the hourly average, e.g. a user is expected to download a 6 MB email in 3 sec instead of 1 min, if the hourly speed is 0.8 Mbps and the peak speed is 20 times the hourly speed. This peak to mean ratio was calibrated in the Central London study area so that the requested demand populates the network sites and carriers with roughly the same network size as that expected by 2012 existing operators.</td>
<td>1:20</td>
</tr>
<tr>
<td>Road and rail database</td>
<td>The Meridian 2 DXF data base is loaded. The demand points in the model include locations along the length of this database’s transport lines. The transport lines were converted into a matrix of equidistant demand locations, with a different separation distance in each study area, so that the resulting number of demand points is manageable. As a result of this conversion, the traffic junctions have a higher demand than the length of the transport lines. Several simplifications were required in this conversion, so as to treat transport lines that either run parallel to boundary lines, penetrate transport lines multiple times, or have a small length.</td>
<td>Motorway, A road, B road, Railway</td>
</tr>
<tr>
<td>Focus area boundary lines database</td>
<td>The Ordnance Survey’s Boundary Line is loaded</td>
<td></td>
</tr>
<tr>
<td>Addresses database</td>
<td>The Geopoint database was loaded. The demand points in the model include locations of domestic and business addresses from this database. PO boxes were not included in the demand locations.</td>
<td></td>
</tr>
<tr>
<td>Clutter database</td>
<td>The InfoTerra UK Sea data base is loaded. This database determines 10 types in a 50x50m grid. For the purpose of this exercise these types were reduced to 3 broader clutter types, namely urban, suburban and</td>
<td></td>
</tr>
</tbody>
</table>
rural/open. These should not be confused with the naming of the study areas. For example the Rural Lincolnshire study area includes urban, suburban and rural clutter pixels.

Each demand point acquires the clutter type of the 50x50m pixel where it lies. This affects its ‘visibility’ by the network sites. For example, an indoor urban address that is 1km from a site is not ‘visible’ from the site if the urban site range < 1km, whereas an indoor suburban address that is 1km from a site is ‘visible’ if the suburban address > 1km.

| Optimisation reduction factor | The merit maximisation algorithm reduces the size of the search area (i.e. the rectangle with the greatest demand density) by this factor, with the aim to find the most cost effective site location. | Golden ratio |

Table 51 Model constants list
Figure 6-2 Pre-process flowchart of algorithmic steps
### 6.7 New sites and site upgrades

This subsection provides information about the algorithmic processes that take place when the model pursues to match the requested demand by building new sites or upgrading existing sites. The algorithmic steps are similar, regardless of whether the network is built for the first modelled year, 2012, or for future years. The exception is that in the starting year, 2012, the network is built up from 0 macro sites and 0 small cells, towards satisfying all the demand in the focus of the study area, without any upgrade options.

At the start of each modelled year the model updates the indices to the input entries. Table 52 summarises the input entries that are loaded from the input files.

<table>
<thead>
<tr>
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<td>Cost of macro site commissioning (high density)</td>
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<td>Range of macros and small cells</td>
<td>Clutter type and frequency group</td>
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<td>Distribution of traffic amongst stationary users</td>
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<td>Offload device capacity</td>
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**Table 52 Input entries for the model**

After preparing the input data, the model sorts the available bands on the modelled year with a preference order for serving the demand. The order is from high to low frequency-group, and from high to low bandwidth. The model continues with creating a map of the demand points in the modelled area, and calculating the rectangle dimensions where the demand density is found. More details about these algorithmic processes are provided in the previous section.
For each site configuration and site type, the site-location search algorithm identifies the position of the site that leads to the greatest merit. During this part of the location search, the merit is calculated using the maximum captured demand within the site’s range, ignoring any capacity limitations. This is done because the operator would choose the best locations for serving the demand, knowing in advance that several technical advances and spectrum acquisitions will eventually increase the served demand that can be satisfied by a capacity-constrained site. At the end of this algorithmic process, the site location and site type & configuration that lead to the greatest merit have been calculated.

The algorithm then calculates the merit of upgrading sites. With respect to the identified site location with the greatest merit, the model calculates the distance to all existing sites. The merit of the site commissioning, for the identified location and site configuration, is calculated, this time by taking into account the site’s capacity. For each of the closest neighbours, the merit of an upgrade is also calculated. Outdoor small cells that have a life duration of more than 5 years are replaced with new cells, without inducing a spectrum upgrade cost, since the replacement cost has been included in the installation cost. If there are no small cells within the neighbours, which can be upgraded for zero cost, spectrum and configuration upgrade options are tried for macro sites within the neighbour list.

In all tried spectrum and configuration upgrade options, the merit is calculated for comparison amongst the different options to provide coverage to the un-served demand. The merit is defined as the amount of captured un-served demand, expressed in Mbps, over the cost of the upgrade or commissioning.

The upgrade, or the commissioning, that has the greatest merit is identified and takes place. The un-served demand is allocated to the newly acquired capacity, and the demand map is refreshed to take into account the network upgrade.

The following flowchart presents the algorithmic steps for building the network for year 2012.
Figure 6-3 Flowchart for algorithmic steps for building the network for year 2012 (starts on previous page)
6.8 Modelling of spectrum

The available quantity of spectrum in each year is an input to the model. The model reads the available spectrum quantities and converts it to network capacity. This section discusses how the spectrum is used by the model in order to satisfy the requested demand in each year.

The spectrum input consists of a table of values, one row for each modelled band and one column for each modelled year. See Table 53. The values of this table are expressed in MHz. In each year the model reads the available bandwidth for each band. If the bandwidth is 0, then the band is assumed not be available. For example, there is 0MHz in 900MHz in 2012 in the rural Lincolnshire study area, whereas there is 5MHz in the same band and year in the Central London study area.
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It is noted that, the band availability in a year does not force the operator to use the available band, i.e. the modelled operator can choose from the available bands. If the model finds that is cost effective for the operator to upgrade the technology of a macro site to support a band that the macro did not previously support, then this incurs a spectrum upgrade cost. All new commissioning of macro sites are assumed to support all bands that the operator has licence for, i.e. the union of supported bands across all macro sites in the commissioning year.

It is assumed in this model that all macro spectrum upgrades have the same cost. This is because the cost is closer related to the upgrade requirement, rather than the amount of additional bands that need to be supported. It is assumed that it is more cost effective for the modelled operator to acquire the band with the largest bandwidth first, so as to maximise the increase of the site’s capacity. In order to refrain the operator from upgrading to support all the available bands at once, the model assumes that the modelled operator will upgrade to that many additional bands so that the demand is satisfied. This means that the operator can upgrade a macro site to support e.g. 9 additional bands, see Table 53, if the demand is large enough, however it will upgrade to support a smaller number of bands, if the demand is lower.

Small cells can only be upgraded on their fifth birthday, or later. Depending on the year a different number of bands is supported.

Based on the above, the order of preference in filling-in the bands with demand is from bands of larger- to smaller-bandwidth. This is the secondary order of preference, whereas the primary order is from bands with a higher- to lower-frequency. For the primary order of preference the frequency group is used, rather than the spot frequency, see Table 53. The primary order is required because the demand points are accommodated in the bands starting from the closest- to the furthest-point. Thus the closest points will be sought to be accommodated by the high frequency bands, whereas further points by the low frequency.

The primary and secondary order of preference are also discussed below in an example. Figure 6-4 plots the band utilisation output from Scenario 18, Rural Lincolnshire, introduction of the 700MHz band in 2026, low demand, high offload of demand, high spectrum availability. This scenario corresponds to the spectrum input of Table 53. The utilisation of each band is plotted for each year and band. The utilisation is defined as the ratio of the demand that is accommodated in a band over the total demand (capacity) that the band can accommodate. Each site has a different utilisation of its spectrum resources. The plotted curves correspond to the average across all macro sites.

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In 2012, only the 2100MHz is available, and this band about 50% utilised. This means that there are several sites that are fully utilising this band; however there are a large number of sites that provide coverage. The reader is advised to compare this figure against a similar one for the Central London study area, where the band utilisation is close to 100%. In 2013, a large number of bands become available to the modelled operator. Out of the 9 new bands, the operator chooses the low frequency band that offers the greatest capacity, i.e. the 800MHz band. This is because the un-served demand-points in 2013 are at the outskirts of several sites, and a low frequency band is able to reach and serve them. The demand also increases closer to the sites, thus the 2100 MHz band utilisation increases.

In 2014, one or more macro sites run out of capacity, and they are upgraded to support two new bands, namely the TDD 1452 -1492 MHz and the TDD 3600 MHz -3800 MHz. The former band is used as an alternative to the fully utilised – in that site –2100 MHz, since it boasts the greatest bandwidth amongst the medium frequency bands. The latter band is used for even more capacity close to the site, since it boasts the greatest bandwidth amongst the high frequency bands. However, since most sites have not run out of capacity and therefore have not been upgraded to support these two bands, the band utilisation of these bands is quite low. In the same year, several sites are upgraded to support the 800MHz band to provide coverage to demand-points that were left outside the shrinking site ranges. Further, the 2100 MHz band utilisation continues to rise, because of the increasing demand in all sites.

In 2015, more sites require spectrum upgrade as a consequence of the increased demand filling-up their capacity. The bands that are best candidates to accommodate the demand are: the 800MHz for far points, the TDD 1452 -1492 MHz for medium distance points, and
the TDD 2300 MHz (2310 - 2390 MHz) for close points. The latter offers the same capacity as the favourite high-frequency band of the previous year, TDD 3600 MHz -3800 MHz, but is further up in the rows of the spectrum table.

The demand continues to be accommodated in each band, in each site independently, according to the needs for each site and the available spectrum in each year. There is an interesting shift in the order of preference between years 2018 and 2019 in the medium-frequency bands. In 2019, the 1800MHz band becomes more attractive than the 2100MHz. This is reflected by the decline of the 2100 MHz band utilisation, and the sharp rise of the 1800 MHz band. Note that although the 2100 MHz utilisation declining trend is continuing in the next years, the 1800 MHz band utilisation-curve does not rise as fast. This is because the 1800 MHz bandwidth continues to increase in 2020. A similar shift in preference is noticeable between the low frequency curves of 700 and 800 MHz.

As the total available bandwidth across all bands increases, through re-farming, without need of further spectrum upgrades, the bandwidth utilisation curves are dragged downwards, i.e. the bands are less utilised because of the total increase in spectrum.
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