Annex 14

LTE Technical Modelling Revised Methodology

Executive Summary

A14.1 This Annex describes how we have modelled the downlink performance of LTE macrocell networks using paired spectrum for the purposes of our competition analysis. The main results from this model are presented in Annex 7. In addition to this executive summary, the annex comprises the following sections:

- *Modelling approach*, which describes the technical model we have used for generating the results reported in this consultation document;
- *Modelling the capacity of multi-frequency networks*, which describes in particular how we have assessed the relative capacity of multi-frequency networks;
- *Presentation of results,* which sets out how we present results;
- *Variability in our modelling,* which provides details of the various sources of variability and uncertainty we have considered in our modelling and how we have chosen to include these in our results;
- *Parameters and assumptions*, which tabulates our parameter choices and assumptions;

A14.2 The technical model has been developed using the MATLAB numerical computing language. It is an evolution of the model developed for the March 2011 consultation. For the most part the changes to the underlying model are relatively small. However, following a detailed review of responses to the March 2011 consultation and further internal analysis, a number of the parameters and assumptions have been changed. One significant change to the modelling since March 2011 is the way we approach the analysis of multi-frequency networks.

A14.3 In order to allow respondents to this consultation to understand in detail the algorithms underlying our model, as well as the detailed description below, we intend to publish the MATLAB[1] source code of our model on 26th January 2011.

A14.4 The heart of the model is the generation of signal to interference plus noise ratio (SINR) and single-user throughput distributions for one or more simulation areas. A high level description of the model is as follows:

i) A synthetic base station network of a particular size (number of sites) is established covering the chosen simulation area plus a buffer zone 20 km deep surrounding the simulation area. The base station network is constructed, as far as is possible, to have similar characteristics (in terms of site density vs. population density, antenna heights, etc.) as current or potential future mobile macrocell networks.

[1] The version of MATLAB we used was the latest available to us (2011b), we cannot guarantee that the source code will work with any other version

ii) An SINR distribution is calculated for a hypothetical test terminal (which we refer to as a UE, or user equipment, after 3GPP) positioned at the geographic location of a randomly selected sample[2] of postcode units[3] within the simulation area. SINR is calculated taking into account signals from sites within the base station network within a certain distance (20 km) of the each sample postcode unit location up to a maximum of the 20 closest sites.

iii) Using the SINR distribution generated in step ii) above together with an appropriate SINR to throughput mapping function, and taking into account system overheads, the average downlink single-user throughput distribution for the sample of postcode unit locations is established.

iv) Steps i), ii) and iii) above are repeated to establish SINR and single-user throughput distributions for a range of base station network sizes, network loadings, carrier bandwidths and building penetration depths for the frequencies under consideration (e.g. 800MHz, 1800MHz and 2600MHz).

v) From the single-user throughput distribution statistics within the chosen simulation area, three metrics of performance are calculated:

- *Coverage* – the proportion of domestic delivery points[4] within the simulation area to which it is technically possible to deliver a service with a particular *downlin*k speed (if 85% of the resource blocks of the serving cell, including system overheads, were dedicated to a single customer[5]), as a function of the number of network sites and the loading on the wider network.

- *Speed* – for a given number of sites and network loading, the downlink single-user throughput (if 85% of the resource blocks of the serving cell, including system overheads, were dedicated to a single user) attained or exceeded by a particular proportion of domestic delivery points within the simulation area.

- *Capacity* – for a particular wider network loading, the capacity to simultaneously serve a particular proportion of domestic delivery points within the simulation area with a given downlink speed and number of sites (assuming 85% of the resource blocks of the serving cell, including system overheads, are dedicated to serving users).

A14.5 As with all technical modelling, decisions have to be made about the details of the methodology adopted and the value of every technical parameter used. In this consultation we have formed our best judgement with respect to all aspects of the model and parameters. We accept that there will be considerable uncertainty around many of the parameter values and assumptions.

A14.6 To reflect the major areas of uncertainty we have chosen to model a range of values for certain key parameters. To illustrate this range we have chosen to group the key parameter values into two cases: those that tend, in most circumstances, to minimise the relative performance variation between frequencies (‘Min var’) and

[2] We have used 10,000 sample points in our analysis

[3] A postcode unit is a sub-area of a postcode sector as extracted from Code-Point® data.

[4] Each postcode unit has associated with it a number of domestic delivery points: each delivery point will generally correspond to one residential address.

[5] 85% is considered, for the purposes of this analysis, to be a practical upper bound to loading on average

those that tend, in most circumstances, to maximise the relative performance variation ('Max var'). The model is then run twice to produce results for these two cases. In the **Modelling approach section** (paragraphs A14.7 to A14.116 below) we indicate the parameters for which a range is modelled and in the **Variability in our modelling section** (paragraphs A14.148 to A14.182) we discuss the major areas of uncertainty and variability in our model and give details of the parameter values we have chosen for our 'Min var' and 'Max var' cases as well as providing a series of graphs illustrating how our model's results are influenced by these choices.

Modelling Approach

A14.7 This section describes the modelling approach we have adopted to analyse and compare the downlink performance of LTE macrocell networks operating in the 800 MHz, 1800 MHz and 2600 MHz bands.

A14.8 In the text below the following definitions apply:

- base station network: a network of base stations being simulated, each base station being characterised by its location and the height of its antenna array above ground level;
- site: a base station site consisting of three antenna sectors with each sector pointing in directions 0, 120 and -120 degrees;
- serving site: the site, one of whose sectors is assumed to be providing a data service to the UE during a simulation snapshot;
- sector: one of the three antenna sectors of any site in the base station array (sectors are often referred to as cells). Any reference to a cell in the text below can be assumed to have the same meaning as a reference to a sector;
- serving sector: the sector (or cell) of the serving site that is assumed to be providing a data service to the UE during a simulation snapshot;
- non-serving sector: a sector of any site in the base station network that is not the serving sector.
- network loading: the fraction of the total number of resource blocks utilised for both data and overheads. The serving cell may have a different loading to cells of the wider network. Note that, throughout this consultation document, network loading (or loading) is always with reference to the wider network unless explicitly stated otherwise.

A14.9 The main parameters and assumptions used to generate the key results in this consultation document are as follows:

- base station network distributions (locations and antenna heights) representative of existing mobile operators' macro networks
- base stations are assumed to be 3-sectored macro sites deployed in a 2 x 2 MIMO configuration

- base station antenna patterns are based on theoretical equations from 3GPP TR 36.814[6] with each of the horizontal and vertical 3dB beam-widths the same for all frequencies.

- loading of serving cell

- loading of cells of wider network

- clutter type for each UK postcode unit location (i.e. UE location) extracted from the Infoterra 50 m x 50 m clutter database

- building penetration depth – e.g. outdoors, 1 metre, 5 metres, 10 metres and 15 metres

Simulation Areas

A14.10 Underlying all the results presented in this consultation are SINR distributions generated across a two specific simulation areas.

A14.11 The majority of results are for the same 100 km x 100 km area we used in the March 2011 consultation (referred to as the West London area), see Figure 1.

A14.12 This area was chosen as we believe it is reasonably representative of the more populous areas of the country where competition between national wholesale players will be predominantly focused. A full set of coverage, speed and capacity results are presented in Annex 7 for this area.

Figure 1: West London simulation area

A14.13 In addition we have also looked at another area, a 100 km x 100 km area around Cambridge, see Figure 2.

A14.14 This area was chosen to contrast the first. It is much less populous but is likely to be an area where reasonably contiguous coverage could be provided (as is the case

---

[6] 3GPP TR 36.814, "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects", http://www.3gpp.org/ftp/specs/html-INFO/36814.htm

for 2G coverage in this area today). A number of the coverage results are presented in Annex 7 for this area.

Figure 2: Cambridge simulation area

A14.15 Table 1 gives the breakdown of the simulation areas in terms of population per clutter type and compares this with the corresponding breakdown for each of the nations (England, Wales, Scotland and Northern Ireland) and to the UK as a whole.

Table 1: Population by clutter type

	Dense urban	Urban	Suburban	Rural
West London	51,409	716,184	6,696,509	980,684
Cambridge	307	11,302	1,378,355	460,904
England	149,325	1,960,701	39,308,727	7,723,377
Scotland	59,291	450,868	3,662,664	889,117
Wales	763	108,997	2,080,898	711,705
Northern Ireland	1,248	18,969	1,015,181	649,965
UK	210,627	2,539,535	46,067,470	9,974,164

A14.16 Table 2 gives a similar breakdown but this time the population in each clutter type is given as a percentage of the total population within the relevant area.

Table 2 : Population percentage per clutter type

	Dense urban	Urban	Suburban	Rural
West London	0.61%	8.48%	79.30%	11.61%
Cambridge	0.02%	0.61%	74.47%	24.90%
England	0.30%	3.99%	79.99%	15.72%
Scotland	1.17%	8.91%	72.36%	17.56%

Wales	0.03%	3.76%	71.70%	24.52%
Northern Ireland	0.07%	1.13%	60.24%	38.57%
UK	0.36%	4.32%	78.36%	16.97%

A14.17 It is clear that neither of the simulation areas are an exact match to the UK as a whole in terms of the proportion of the population within each of the four clutter types we are using in the model. The West London area has a greater proportion of the population in Dense Urban and Urban areas, a similar proportion in Suburban areas and less in Rural areas. Cambridge has less in Dense Urban and Urban areas, a similar proportion in Suburban areas and a greater proportion in Rural areas.

Synthetic Networks

A14.18 A number of synthetic networks were generated in each simulation area and its surrounding 20 km buffer zone. These networks were generated from a seed macro-cell network. This seed network had an equivalent national (UK) site count of approximately 9,000 sites. The synthetic networks generated have been scaled to represent national networks with equivalent national site counts of 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10000, 11000, 12000, 13000, 14000, 15000, 16000, 17000, 18000, 19000 and 20000. A detailed description of the process used to create these synthetic networks follows:

i) Sites from a seed network (having similar characteristics in terms of site density, antenna heights etc as current mobile networks) were selected within the selected simulation area and buffer zone.

ii) The seed network was scaled up to create a synthetic network in the simulation area and buffer zone representing the equivalent of a 20,000 site national network. The scaling up process was as follows:

a) All the sites in the simulation area and buffer zone were connected to their nearest neighbours using a Delaunay triangulation such that a closed polygon consisting of unique triangles was formed.

b) The triangle containing the highest number of delivery addresses (associated with postcode unit locations in Code-Point® data) was selected and, a new artificial site was placed at its geometric centroid. The new site was given an antenna height (for each of its three sectors) which was the mean of the antenna heights of the three sites forming the triangle.

c) Step b) was repeated, each time picking the triangle containing the next highest number of delivery points until sufficient sites were added to form a synthetic network representing the equivalent of a 20,000 site national network.

iii) To generate the remaining synthetic networks in the selected simulation area plus buffer zone, the 20,000 site network was sub-sampled by removing sites one by one (at random) until the target number of sites (representing equivalent national site counts of 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10000, 11000, 12000, 13000, 14000, 15000, 16000, 17000, 18000 and 19000 sites) in the simulation area plus buffer zone was reached.

iv) The target number of sites required in the selected simulation area plus buffer zone for each case was calculated as the number of sites in the equivalent national network multiplied by the ratio of the number of sites the seed network has in the selected simulation area plus buffer zone to the number of sites the seed network has nationally. For instance, if the seed network has 3,000 sites in the selected simulation area plus buffer zone and it represents the equivalent of a national network with 9,000 sites, then the synthetic network with the equivalent of 12,000 sites nationally has a target of 12,000 x 3,000 / 9,000 = 4,000 sites in the sample area plus buffer zone.

v) The sub-sampling was progressive such that, in turn, each of the 21 different synthetic networks was created each being a strict sub-set of all larger networks.

A14.19 For each simulation area, the synthetic networks were created only once and were used for every modelling run at all frequencies.

SINR Distribution Model

A14.20 We use a Monte Carlo method to generate a set of SINR distributions for each combination of frequency, in-building depth, network size, network loading, 'Min var'/'Max var' case and simulation area considered. The 'Min var'/'Max var' cases are given in Table 14.

A14.21 An overview of the steps involved in each simulation run to generate an SINR distribution is as follows:

- Establish a set of 10,000 sample locations within the sample area. These are taken from a random sample of Code-Point® postcode unit locations within the simulation area, with clutter for each postcode unit location taken from the Infoterra clutter database with 50 metre resolution[7].

- Using simple geometry, calculate the median outdoor path loss at each sample location from each of the three sectors of the 20 closest surrounding base stations (including base stations from the buffer zone) using the Extended Hata[8] propagation model accounting for horizontal and vertical base station antenna patterns, antenna heights and the clutter at the sample location.

- Calculate the median building penetration loss (BPL) for the particular in-building depth under consideration (the median BPL at the sample location is assumed to be the same for transmissions from all surrounding base stations).

- For each sample location, generate a set of shadow fading values for each of the 20 closest surrounding base stations (assuming 50% shadow fading

[7] The same set of random locations are used for each and every SINR distribution generated in the same sample area.

[8] ERC Report 68 and http://tractool.seamcat.org/raw-attachment/wiki/Manual/PropagationModels/ExtendedHata/Hata-and-Hata-SRD-implementation_v2.pdf

correlation). Shadow fading is assumed to have a log normal distribution with a zero mean and characteristic standard deviation σ_s.

- For each sample location, generate a set BPL variability values for each of the 20 closest surrounding base stations (assuming 50% correlation). BPL variability is assumed to have a log normal distribution with a zero mean and characteristic standard deviation σ_{bpl}.

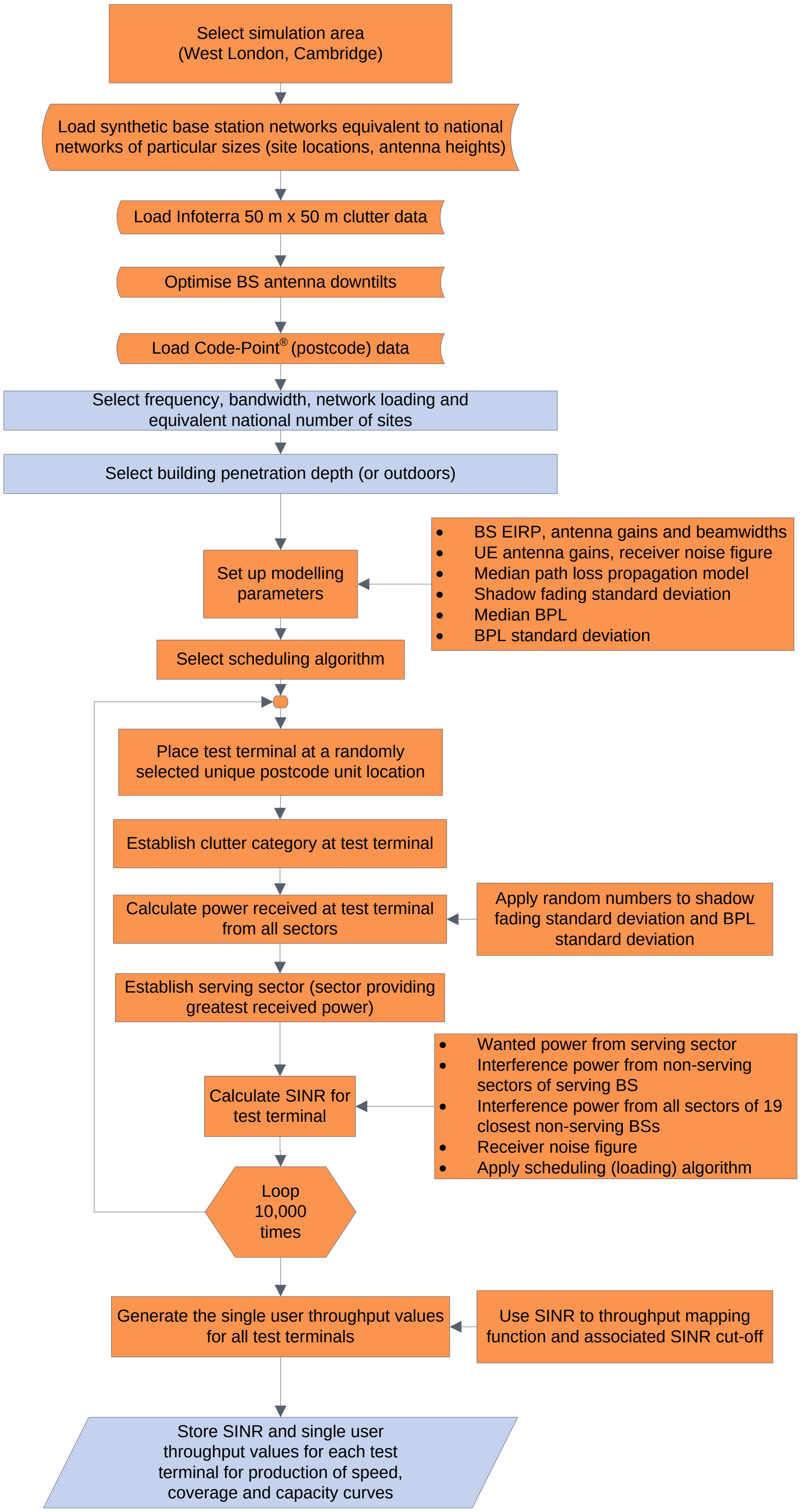
- Combine the median BPL and median outdoor path loss figures together with the shadow fading and BPL variability figures to derive an overall path loss to each sample location from each of the three sectors of the 20 closest surrounding base stations.

- From the above, find the sector that provides the greatest received power at the sample location and designate this as the serving sector.

- The signal to interference plus noise ratio at the sample location for a single resource block is calculated from the wanted power of the serving sector, the interference power from every other sector of the 20 closest surrounding base stations and the UE receiver noise. This calculation assumes that the resource blocks from the serving sector transmit at 47 dBm EIRP per resource block (i.e. the maximum allowed by our proposed technical licence conditions). Interference power from non-serving sectors is taken into account by weighting the calculated interference power by the probability that the interference is received during the same time period and at the same frequency as the wanted power from the serving sector. The probability is dependent upon the network loading and scheduling algorithm used for the allocation of resource blocks.

A14.22 This is illustrated in the flow chart below (Figure 3).

Figure 3: Model flow chart



A14.23 A detailed description of individual steps in the generation of the SINR distributions is given below:

Sample locations

A14.24 For each sample location (Code-Point® postcode unit location) within the simulation area:

- its clutter category (Dense Urban, Urban, Suburban or Rural) is established from the Infoterra clutter database with 50 metre resolution;
- a set of 21 random variables is generated. These values are drawn from the normal distribution with a zero mean and standard deviation σ_S. The first value in the set represents the local shadow fading component for the sample location and the next 20 represent the shadow fading component for the 20 base station sites closest to that location; and
- a further set of 21 random variables is also generated. These values are similarly drawn from the normal distribution with a zero mean and standard deviation σ_{bpl}. The first value in the set represents the local building penetration loss variability component for the sample location and the next 20 represent the building penetration loss variability component for the 20 base station sites closest to that location.

Shadow fading

A14.25 The shadow fading standard deviation σ_S (in decibels) is derived from equation 32 in Annex 5 of Recommendation ITU-R P.1546-4[9]:

$$\sigma_S = K + 1.3 \cdot \log_{10}(f) \tag{1}$$

where we have adopted a value of K = 4.2 dB for Dense Urban and Urban clutter and K = 3.5 dB otherwise. Frequency, f, is in MHz.

Building penetration loss

A14.26 Our modelling of mobile service provision within buildings is detailed below. This adopts an approach that is consistent with our work for previous consultations. This is because:

- The February 2009 consultation, Application of spectrum liberalisation and trading to the mobile sector[10], provided a detailed description of the issues around propagation into buildings, consideration of the literature and available evidence, and justification for the values used (see Annex 13, paragraphs A13.220 to A13.261[11]). It also included a consideration of information requested from mobile operators on their own approach to planning for indoor customers. It summarised the conclusions on appropriate modelling and parameters and consulted on that issue.

[9] Recommendation ITU-R P.1546-4: Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz
[10] http://stakeholders.ofcom.org.uk/consultations/spectrumlib/
[11] http://stakeholders.ofcom.org.uk/binaries/consultations/spectrumlib/annexes/annex13.pdf

- For the March 2011 consultation, Assessment of future mobile competition and proposals for the award of 800 MHz and 2.6 GHz spectrum and related issues[12], we adopted the same basic modelling approach and parameter values consistent with the February 2009 consultation.

- For this consultation we conducted a further review of the literature on building penetration loss and relevant responses to the earlier consultations and concluded that there is no strong evidence to justify switching to a different overall approach.

A14.27 The majority of our earlier analysis was focused primarily on reception at relatively hard to serve locations (proxied by locations deep indoors). In the analysis presented here we have extended this to encompass analysis of easier to serve locations (proxied by shallower depths within buildings and outdoors).

A14.28 As per the February 2009 consultation the simulation models signals propagating indoors as being attenuated by two components; firstly a loss at the external wall and secondly by an increasing loss as the signal propagates further and further indoors. This is discussed in detail below. Though presented as an actual physical distance from the external wall, we exercise caution in interpreting this literally. For instance, whilst our results for a depth of 1 metre may represent someone very close to the external wall where the major influence is the external wall loss, our results for a depth of 15 metres could be taken to represent a user physically very deep within a relatively low loss building but could also represent a user who is at a shallower physical depth but subject to greater propagation losses e.g. behind several internal walls or in a building with a very thick external wall etc. So our interpretation of the analysis is one of ability to serve a distribution of easier and harder to reach locations, rather than one of serving users at absolute depths in a building.

A14.29 Our subsequent analysis of the overall characteristics of networks with different spectrum portfolios necessarily has to make an assumption about the distribution of demand over locations which are easier and harder to serve. For the purpose of this analysis we have chosen to assume an equal number of users at each of the ‘depths’ we have modelled.

A14.30 We acknowledge this further analysis has not been subject to the same degree of consultation as our previous analysis of harder to serve locations. We therefore particularly welcome stakeholder views on our modelling and analysis of serving users in a range of locations, both easier and harder to serve.

Median building penetration loss

A14.31 The median BPL depends on the clutter type at the sample location and the specific scenario under investigation. The values used in the modelling for the March 2011 consultation were derived from those used in previous Ofcom publications[13,14] for which the relevant frequencies were 900 MHz, 1800 MHz and 2100 MHz.

[12] http://stakeholders.ofcom.org.uk/consultations/combined-award/

[13] Application of spectrum liberalisation and trading to the mobile sector – A further consultation, Annex 13, Ofcom, 13 February 2009

[14] Advice to Government on the consumer and competition issues relating to liberalisation of 900 MHz spectrum for UMTS, Annex 5, Ofcom, 25th October 2010.

A14.32 The February 2009 consultation, Application of spectrum liberalisation and trading to the mobile sector[15], provided a detailed description of the issues around propagation into buildings and justification for the values used (see Annex 13, paragraphs A13.220 to A13.261[16]).

A14.33 For the March 2011 consultation, Assessment of future mobile competition and proposals for the award of 800 MHz and 2.6 GHz spectrum and related issues[17], Ofcom adopted the same basic modelling approach to median BPL values as in the February 2009 consultation.

A14.34 For the purposes of this consultation we conducted a further brief review of the literature on building penetration loss (see for example [[18,19]]) and have concluded that there is no strong evidence to justify switching to a different overall approach.

A14.35 In this approach the total loss is split into two components[20]:

- The loss in passing through the external wall of the building (L_{We});
- An additional loss encountered as signals penetrate deeper into the building (L_{i}), due propagation through and around internal walls, furniture and fixings inside the building.

A14.36 These components are then summed to give the total building penetration loss (L_{BP}) as follows:

$$L_{\mathrm{BP}} = L_{\mathrm{We}} + L_{\mathrm{i}} \quad (2)$$

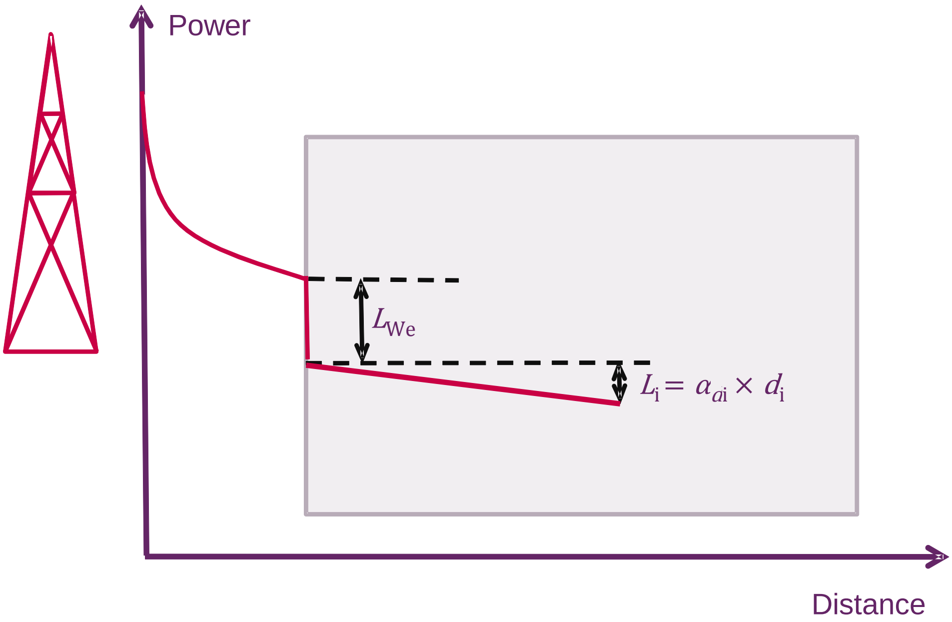
A14.37 The internal loss L_{i} (in dB) is modelled as depending on the distance signals have to penetrate into the building d_{i} (in metres) and a specific attenuation rate α_{di} (in dB/metre) as follows:

$$L_{\mathrm{i}} = \alpha_{\mathrm{di}} \times d_{\mathrm{i}} \quad (3)$$

A14.38 Figure 4 below provides an illustration of this.

[15] http://stakeholders.ofcom.org.uk/consultations/spectrumlib/
[16] http://stakeholders.ofcom.org.uk/binaries/consultations/spectrumlib/annexes/annex13.pdf
[17] http://stakeholders.ofcom.org.uk/consultations/combined-award/
[18] Okamoto H., Kitao K. and Ichitsubo S., "Outdoor-to-Indoor Propagation Loss Prediction in 800-MHz to 8-GHz Band for an Urban Area", *IEEE Transactions on Vehicular Technology,* vol. 58, no. 3, Mar. 2009, pp. 1059 – 1067
[19] Ferreira L., Kuipers M., Rodrigues C. and Correia L.M., "Characterisation of Signal Penetration into Buildings for GSM and UMTS", *3rd International Symposium on Wireless Communication Systems,* Sept. 2006, pp. 63 – 67
[20] It should be noted that the two component model we have adopted is an abstraction of a much more complicated physical situation. It is similar to other approaches to modelling outdoor to indoor propagation interface such as that suggested in COST231. These approaches are attempts to fit parameters to statistical measurement data (which is often very sparse). They should not be interpreted as a real physical representation of propagation mechanisms and for the purposes of this consultation we do not interpret the 'depth' parameter as a literal distance from external wall of a building but more as an indication of easier or harder to serve locations within and between buildings.

Figure 4: Building penetration loss modelling



A14.39 Both the initial loss due to propagation through the external wall (L_{We}) and the internal loss (L_i) are uncertain and will depend in a complex way on a number of factors including:

- The nature of the building materials used;
- The placement of apertures such as walls doors, etc;
- The angle of incidence of the signal;
- The multipath environment between the base station and the building;
- The internal structure of the building,
- Placement of furniture and fixture and fittings inside the building;
- etc

A14.40 It is likely that these factors will all impart some form of frequency dependency but that dependency may well be very complex. It is likely that certain of these factors will lead to a frequency dependency that is not monotonic. However, it is anticipated that there will be a general trend of increasing building penetration loss with frequency.

A14.41 For the purposes of our current modelling, we have assumed that both L_{We} and α_{di} vary linearly with $\log_{10}$(frequency). This means that L_{BP} will also vary linearly with $\log_{10}$(frequency).

A14.42 In previous consultations we have described our BPL assumptions by referring to certain BPL depths. Depth 0 represented a user notionally 1 metre inside a building, Depth 1 was notionally 10 metres and Depth 2 was notionally 15 metres. All users were modelled at exactly the same notional depth indoors and on the ground floor. In the March 2011 consultation the majority of results were for what we called Depth

2+ (i.e. notionally 15 metres inside a building), with the '+' representing a frequency dependency approximately mid-way between the February 2009 consultation's "base case" and "rising at a higher rate" case.

A14.43 For our current model we have used an upper and lower bound for the frequency dependency of both L_{We} and α_{di} encompassing no frequency dependency at all (corresponding to a lower bound used in our 'Min var' cases) to one where there is a significant dependency (corresponding to an upper bound used for in 'Max var' cases).

A14.44 For L_{We}, we have additionally assumed it is also dependent on the clutter environment with lower values of external loss associated with Suburban and Rural clutter environments and higher ones for Urban and Dense Urban environments.

A14.45 We have ensured that the median BPL values we are using are consistent with those of earlier consultations, with values for 800 MHz and 2600 MHz (Depth 1 and Depth 2) being extrapolated from the 900 MHz and 2.1 GHz figures of the February 2009 consultation. Ensuring that L_{BP} varies linearly with $\log_{10}$(frequency) means that the median BPL values for 1800 MHz we are using are slightly higher than those used in the March 2011 and February 2009 consultation (but not significantly higher).

A14.46 Table 3 gives details of the external wall loss (L_{We}) and attenuation rate with distance from the external wall (α_{di}) values that we have used in our modelling for the specific frequencies and clutter environments considered.

Table 3: Values for L_{We} and α_{di} – Upper and Lower bound

	800 MHz	900 MHz	1800 MHz	2100 MHz	2600 MHz
	All clutter environments				
α_{di} – Lower bound	0.32	0.32	0.32	0.32	0.32
α_{di} – Upper bound	0.65	0.72	1.14	1.23	1.36
	Suburban/Rural				
L_{We} – Lower bound	1.53	1.53	1.53	1.53	1.53
L_{We} – Upper bound	3.06	3.27	4.49	4.77	5.14
	Urban				
L_{We} – Lower bound	2.87	2.87	2.87	2.87	2.87
L_{We} – Upper bound	5.72	5.93	7.15	7.43	7.81
	Dense urban				
L_{We} – Lower bound	4.20	4.20	4.20	4.20	4.20
L_{We} – Upper bound	8.39	8.60	9.82	10.10	10.47

A14.47 As discussed in the February 2009 consultation, COST 231[21] indicates a value for α_{di} of 0.6 dB/m. This value is broadly constant with another source quoted, Ofcom-SES-07[22]. As can be seen in Table 3 above, for our lower bound we are using a value approximately half of this. For our upper bound we use a value that is

[21] COST Action 231, "Digital mobile radio towards future generation systems, final report.", tech.rep., European Communities, EUR 18957, 1999
[22] Ofcom project SES-2005-08, "Predicting coverage and interference involving the indoor-outdoor interface.", Final Report, 26 January 2007

approximately the same for 800 MHz but which rises to approximately twice this for 2600 MHz.

A14.48 COST 231 suggests values for L_{We} in the range 4 to 10 dB (for the frequency range 900 MHz to 1800 MHz), whilst Ofcom-SES-07 suggests 2.5 to 3.5 dB for 1 and 2 GHz respectively. In this consultation we are using values for our lower bound that are more or less consistent with Ofcom-SES-07. COST231 does not distinguish between genotypes and suggests typical values of L_{We} for wood of 4 dB and concrete of 7 dB. A significant difference between our model and COST231 is that COST231 also applies a floor height gain whereas our model does not.

A14.49 Applying the L_{We} and α_{di} values in Table 4 to equations (2) and (3) give the median BPL values we have used to generate the results reported in the consultation as given in Table 4 to Table 9 below.

Table 4: Median BPL values – Suburban/Rural – Lower bound

Depth (metres)	800 MHz (dB)	900 MHz (dB)	1800 MHz (dB)	2100 MHz (dB)	2600 MHz (dB)
1	1.85	1.85	1.85	1.85	1.85
5	3.15	3.15	3.15	3.15	3.15
10	4.77	4.77	4.77	4.77	4.77
15	6.39	6.39	6.39	6.39	6.39

Table 5: Median BPL values – Suburban/Rural – Upper bound

Depth (metres)	800 MHz (dB)	900 MHz (dB)	1800 MHz (dB)	2100 MHz (dB)	2600 MHz (dB)
1	3.71	3.99	5.63	6.00	6.50
5	6.29	6.86	10.17	10.90	11.92
10	9.55	10.46	15.86	17.06	18.72
15	12.79	14.06	21.54	23.20	25.50

Table 6: Median BPL values – Urban – Lower bound

Depth (metres)	800 MHz (dB)	900 MHz (dB)	1800 MHz (dB)	2100 MHz (dB)	2600 MHz (dB)
1	3.19	3.19	3.19	3.19	3.19
5	4.48	4.48	4.48	4.48	4.48
10	6.10	6.10	6.10	6.10	6.10
15	7.73	7.73	7.73	7.73	7.73

Table 7: Median BPL values – Urban – Upper bound

Depth (metres)	800 MHz (dB)	900 MHz (dB)	1800 MHz (dB)	2100 MHz (dB)	2600 MHz (dB)
1	6.37	6.65	8.29	8.66	9.17
5	8.96	9.53	12.84	13.58	14.60
10	12.21	13.12	18.52	19.72	21.38
15	15.45	16.72	24.20	25.86	28.17

Table 8: Median BPL values – Dense urban – Lower bound

Depth (metres)	800 MHz (dB)	900 MHz (dB)	1800 MHz (dB)	2100 MHz (dB)	2600 MHz (dB)
1	4.52	4.52	4.52	4.52	4.52

Depth (metres)	800 MHz (dB)	900 MHz (dB)	1800 MHz (dB)	2100 MHz (dB)	2600 MHz (dB)
5	5.82	5.82	5.82	5.82	5.82
10	7.44	7.44	7.44	7.44	7.44
15	9.06	9.06	9.06	9.06	9.06

Table 9: Median BPL values – Dense urban – Upper bound

Depth (metres)	800 MHz (dB)	900 MHz (dB)	1800 MHz (dB)	2100 MHz (dB)	2600 MHz (dB)
1	9.04	9.32	10.96	11.33	11.83
5	11.63	12.19	15.51	16.24	17.26
10	14.87	15.79	21.19	22.39	24.05
15	18.12	19.39	26.87	28.53	30.83

A14.50 As indicated in paragraph A14.28 above, though ‘depth’ is modelled and presented as an actual physical distance from the external wall, we exercise caution in interpreting this literally. Our interpretation of the ‘depth’ is one of ability to serve a distribution of easier and harder to reach locations, rather than one of serving users at absolute depths in a building.

A14.51 The adoption of lower bound and upper bound values for the median BPL is a change to our modelling for the March 2011 consultation where we did not explicitly take into account the uncertainties in the modelling.

Building penetration loss variability

A14.52 The other important factor in modelling BPL is the statistical distribution assumed. BPL is usually modelled as a log normal distribution[23, 24], with a characteristic standard deviation.

A14.53 For the February 2009 and March 2011 consultations we assumed that the BPL standard deviation was independent of depth but, to some extent, dependent on frequency. We used the same standard deviation values for 1800 MHz and 2600 MHz but for 800 MHz the standard deviation was somewhat lower. We also assumed that the standard deviation was dependent on the rate at which the median BPL varied with frequency.

A14.54 Our model is sensitive to the choice of BPL standard deviation, and in order to quantitatively explore this sensitivity in our ‘Min var’ and ‘Max var’ cases we have decided to model a range for BPL standard deviation. However, there is limited evidence upon which to base a range. The values of BPL standard deviation adopted in the modelling are given in Table 10.

[23] COST 231 Final Report, Chapter 4: Propagation Prediction Models
[24] The following paper indicates that log normal is a good fit: Ferreira L., Kuipers M., Rodrigues C. and Correia L.M., “Characterisation of Signal Penetration into Buildings for GSM and UMTS”, *3rd International Symposium on Wireless Communication Systems,* Sept. 2006, pp. 63 – 67.

Table 10: BPL standard deviation values (for use with 'Min var' and 'Max var' cases)

Frequency (MHz)	BPL standard deviation (dB)	
	Min var	Max var
800	4.0	8.0
1800	5.4	10.8
2600	6.0	12.0

A14.55 The values at 800 MHz and 2600 MHz are derived from those used for the March 2011 consultation document. However as we have now decided to model a range, for our 'Min var' case we use 2/3 times the March 2011 values and for our 'Max var' we use 4/3 times them. The values at 1800 MHz are calculated using a $\log_{10}$(frequency) interpolation from the relevant 800 MHz and 2600 MHz values.

A14.56 These values are used for all penetration depths.

Geometry and antenna patterns

A14.57 For each simulation snapshot a UE is placed at a sample location (Code-Point® postcode unit location) within the simulation area.

A14.58 Simple geometry is used to calculate the distances and angles between each transmitter of each sector of the closest 20 base station sites and the UE location.

A14.59 Using the angle information, the relative gain of every antenna in the direction of the UE location is calculated by combining the azimuth and elevation radiation patterns of each antenna. The theoretical radiation patterns (in decibels) are obtained from equations (4) and (5) below which are taken from 3GPP TR 36.814[25]:

Azimuth pattern: $$A_{\mathrm{H}}(\varphi) = -\min\left[12\left(\frac{\varphi}{\varphi_{3\mathrm{dB}}}\right)^2, \mathrm{A_m}\right] \quad (4)$$

Elevation pattern: $$A_{\mathrm{V}}(\theta) = -\min\left[12\left(\frac{\theta-\theta_{\mathrm{tilt}}}{\theta_{3\mathrm{dB}}}\right)^2, \mathrm{SLA_v}\right] \quad (5)$$

A14.60 The values of $\varphi_{3\mathrm{dB}}$ and $\theta_{3\mathrm{dB}}$ are 65˚ and 7.5˚, respectively for all frequencies; θ_{tilt} is the down-tilt; $\mathrm{A_m}$ = 25 dB; and $\mathrm{SLA_v}$ = 20 dB.

A14.61 Down-tilt is optimised in response to variation of two parameters, u and v, used in calculations of down-tilt:

$$\theta_{\mathrm{tilt}} = \tan^{-1}(h_{\mathrm{BS}}/(\mathrm{u} * ISD_{\mathrm{m}}) + (\mathrm{v} * \theta_{3\mathrm{dB}})) \quad (6)$$

A14.62 Where h_{BS} is the antenna height of the particular base station and ISD_{m} is the mean distance between the base station under consideration and the next six closest base stations. The value of v was established to by trial and error with a value of 2.5 being reasonably optimal for all sites of all synthetic networks considered. The best value of u for all sites of each synthetic network is found by iterating over a small number of trial values (with u ranging from 0.2 to 2). From these trials the best value of u is considered to be the one that maximises the average of the throughputs for the three frequencies 800 MHz, 1800 MHz and 2600 MHz for the particular synthetic network being considered.

[25] 3GPP TR 36.814, "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects", http://www.3gpp.org/ftp/specs/html-INFO/36814.htm

A14.63 In the modelling we undertook for the March 2011 consultation document, we used the same equation for down-tilt but had fixed values for both the u and v down-tilt parameters. It should be noted that the simulation results are relatively insensitive to down-tilt, and though not perfectly optimal for all combinations of network size and frequency band under consideration, equation (6) has been found to provide a reasonable compromise for the calculation of down-tilts across the simulation areas. This is partly a due to the fact that we now use a common value for vertical antenna beam-width for base stations rather than different vertical beam-widths at different frequencies as was the case for March 2011.

Determination of serving sector

A14.64 Shadow fading and building penetration loss values for each base station site at the UE location are calculated using relevant random variables generated for the postcode unit location (as described in paragraph A14.24), assuming shadow fading and building penetration cross correlation coefficients of 0.5 used according to the method in section 3.2.4 of IEEE 802.16m-08/004r5[26].

A14.65 The coupling loss to the UE location from each sector of the closest 20 base station sites is calculated accounting for path-loss using the Extended Hata model[27] (the Dense Urban path-loss being set to the Urban path-loss + 3 dB), relative antenna gain in the direction of the UE, shadow fading and building penetration loss. Note that for the calculation of the Rural path loss we use the open Extended Hata loss.

A14.66 The sector that provides the greatest receive power at the UE location is designated as the 'serving' sector and its site is designated as the 'serving' site.

Serving cell power at UE locations

A14.67 The wanted power (P_{wanted}) at the UE location is calculated from the power received (radiated power multiplied by coupling loss) from the 'serving' sector. In calculating P_{wanted}, shadow fading and building penetration losses are accounted for as in paragraph A14.24

Calculation of other cell interference power

A14.68 The other-cell interference power (P_{other}) at the UE location is calculated from the sum of the interference power received (radiated power multiplied by coupling loss) from each sector of the closest 20 base station sites (including from non-serving sectors of the 'serving' site but excluding the 'serving' sector). In calculating other-cell interference, shadow fading and building penetration losses from sites other than the 'serving' site are assumed to be cross-correlated with a coefficient of 0.5 (A14.24). Shadow fading and building penetration losses for different sectors of the 'serving' site are assumed to be fully correlated. This follows the method described in section 3.2.4 of IEEE 802.16m-08/004r5[28].

A14.69 Network or system loading is accounted for, when calculating P_{other}, by multiplying the interference power from each sector by an interference probability. In response to concerns over our March 2011 assumptions on loading, the interference

[26] IEEE 802.16m-08/004r5, "Evaluation Methodology Document (EMD)"
[27] ERC Report 68 and http://tractool.seamcat.org/raw-attachment/wiki/Manual/PropagationModels/ExtendedHata/Hata-and-Hata-SRD-implementation_v2.pdf
[28] IEEE 802.16m-08/004r5, "Evaluation Methodology Document (EMD)"

probability is now calculated in accordance with two different algorithms covering the two extremes in terms of impact of interference: 1) random allocation in which it assumed that the resource blocks in each cell are allocated on a purely random basis (used for our 'Min var' case); and 2) intelligent allocation where each the resource blocks in each cell are allocated on a basis that accounts for the scheduling of the corresponding resource blocks on other sectors of the serving cell in order to minimise inter cell interference (used for our 'Max var' case).

A14.70 A transmitter will only cause interference to a receiver if it is operating on the same resource blocks as the wanted signals. Resource blocks occupy discrete frequencies. A frequency re-use pattern of 1x1 is assumed and each resource block may be used only once in any given sector (cell) at a particular time. It is therefore assumed that, in a given cell, users will be on *orthogonal* channels and there will be no intra-cell interference.

Scheduling algorithms

A14.71 As we do not have knowledge of the scheduling algorithms that operators will use, we have therefore modelled two scheduling algorithms: intelligent and random as described in paragraph A14.69. In both cases, we calculate the probability that the interference power from a non-serving sector is on the same resource block as the wanted signal. We refer to this as the "interference probability" and multiply the interference power from non-serving sectors by this factor when calculating the SINR.

Random scheduling algorithm

A14.72 In the calculation of other cell interference we assume that resource blocks are allocated in a random manner across the whole bandwidth. The interference probability, I, applied to interference from other sectors is therefore given by:

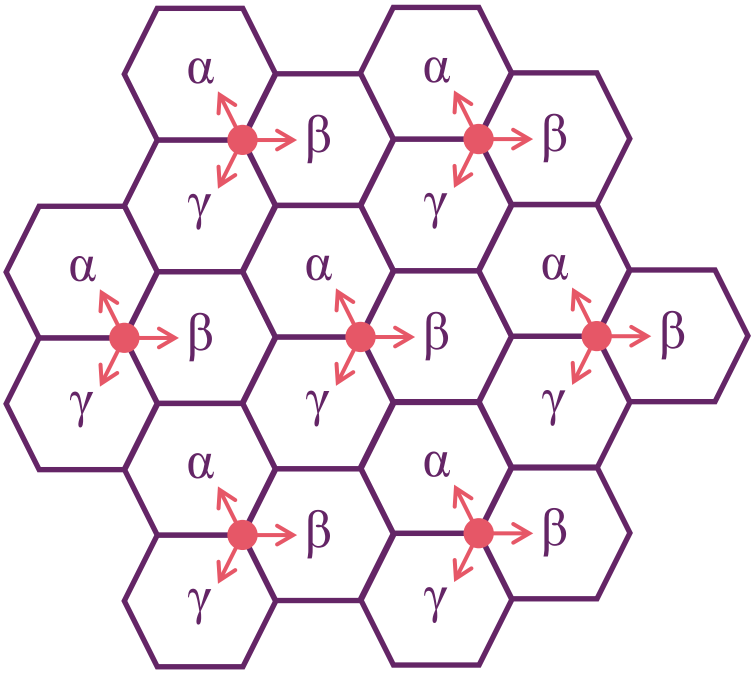
$$I = Loading_{other} \tag{7}$$

A14.73 Where $Loading_{other}$ is the loading on the wider network (i.e. sectors other than the serving cell).

Intelligent scheduling algorithm

A14.74 The intelligent scheduling algorithm assumes that resource blocks are allocated in an *intelligent* way. By intelligent loading we mean that the radio resource algorithm is assumed to allocate resource blocks in a manner that minimises interference between sectors of the same site (i.e. where possible the site seeks to avoid allocating the same resource block in more than one sector). Between sites it is assumed that there is no explicit coordination, and it is assumed that sites allocate their resource blocks in the same fashion as each other (i.e. all sectors with the same azimuth orientation schedule resource blocks in exactly the same way). This is achieved by the placing the sectors into three sets (referred to here as types α, β and γ), with each sector type preferentially using a primary sub-group of resource blocks. Figure 5 illustrates this arrangement.

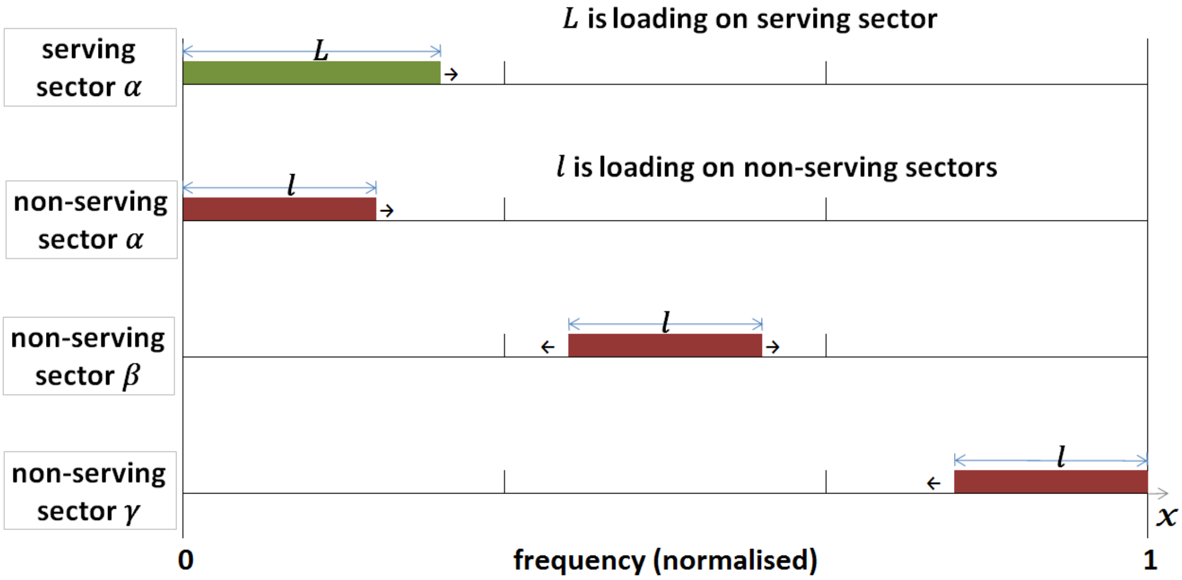
Figure 5: Illustration of sector arrangement in intelligent loading



A14.75 As loading increases, corresponding sectors allocate resource blocks from the same primary *sub-group* first before moving on to allocate resource blocks from the other sectors' primary sub-groups. This means that, if each sector is loaded to no more than 1/3 (i.e. uses no more than 1/3 of the total available resource blocks), interference between sectors of the same site, to a first approximation, is eliminated. It also means that, if each sector is loaded to no more than 1/3, the serving sector will only experience interference from 1/3 of the sectors from the rest of the network (those assigned the same primary sub-group of resource blocks).

A14.76 The intelligent algorithm adopted here is not intended to represent any particular algorithm that might be implemented in real LTE networks. Rather it is an abstraction designed to illustrate the impact that such algorithms can have on network performance. It is designed to minimise interference from those sectors that are not in the same set as the serving sector. Accordingly, sectors with the same azimuth preferentially use resource blocks from the same primary sub-group and each sector is loaded in the manner shown in Figure 6, where we illustrate the case in which the serving sector is a sector of set α and the other non-serving sectors are in sets α, β and γ.

Figure 6: Intelligent scheduling of sectors



A14.77 For the purposes of this illustration (Figure 6) the bandwidth is normalised to unity, meaning that the frequency (denoted x) lies between 0 and 1, and the sectors α, β and γ are arranged relative to frequency as shown in the diagram.

A14.78 In our modelling we have assumed that the serving sector is in set α and the other (non-serving) sectors are in sets α, β and γ, the occupancy of spectrum in the band is as illustrated in the diagram. We use the following notation in this description;

- $L = Loading_{own}$ (i.e. loading on serving sector);
- $l = Loading_{other}$ (i.e. loading on non-serving sector); and
- $H()$ is the Heaviside (or unit step) function[29]:

A14.79 It can be shown that:

i) Probability that a serving sector resource block in set α is interfered with by a non-serving resource block in set α is:

$$P(\alpha_l|\alpha_L) = [l - (l - L)H(l - L)]/L \quad (8)$$

$$= \min(l, L)/L \quad (9)$$

ii) Probability that a serving sector resource block in set α is interfered with by a non-serving resource block in set β is:

$$P(\beta_l|\alpha_L) = \left[\frac{1}{2}\{(2L - 1 + l)H(2L - 1 + l) - (2L - 1 - l)H(2L - 1 - l)\}\right]/L \quad (10)$$

$$= \min(\max(L - 0.5 + \frac{l}{2}, 0), l)/L \quad (11)$$

iii) Probability that a serving sector resource block in set α is interfered with by a non- serving resource block in set γ is:

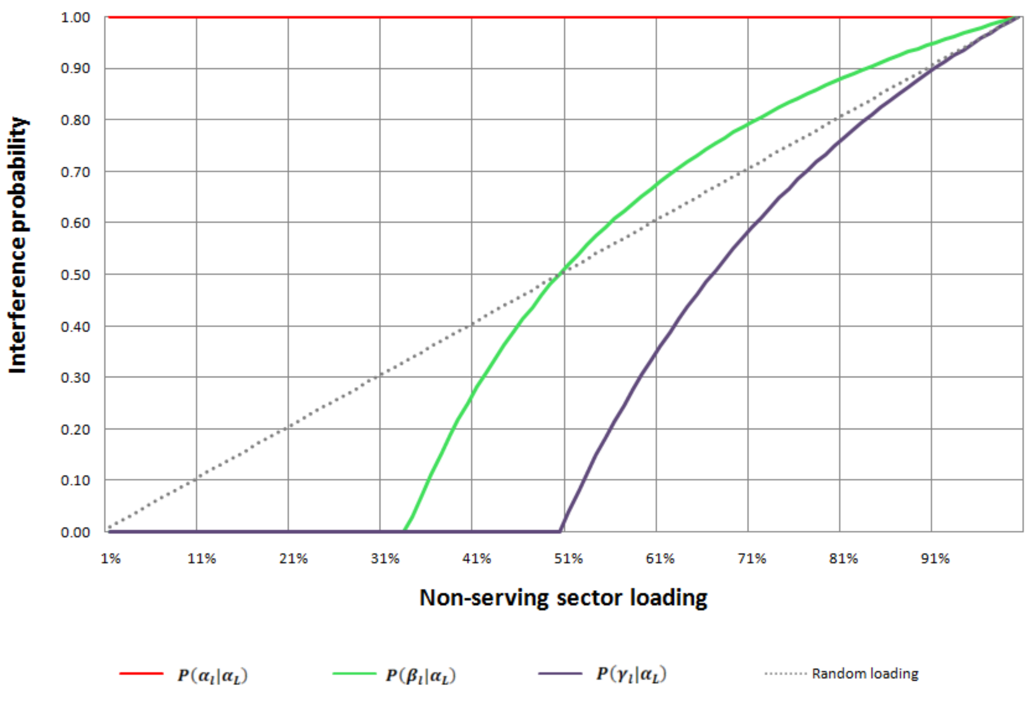
[29] For this approximation we have not taken account of individual resource blocks.

$$P(\gamma_l|\alpha_L) = [(L + l - 1)H(L + l - 1)]/L \quad (12)$$

$$= \max(L + l - 1, 0)\ /L) \quad (13)$$

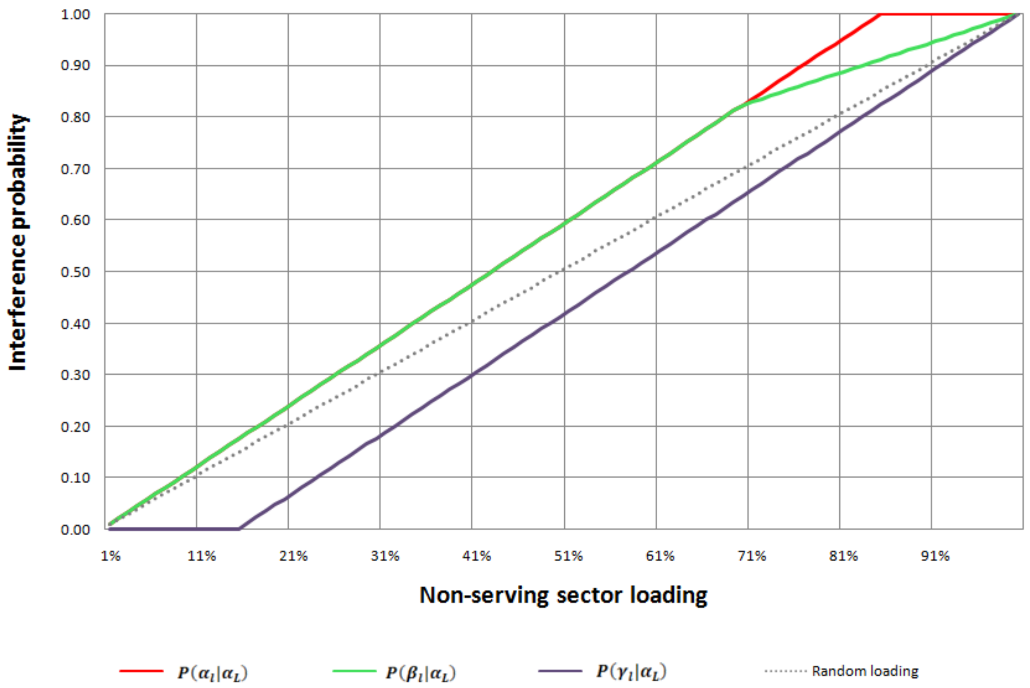
A14.80 Figure 7 below illustrates the case where the non-serving sector and the serving sector have equal loading. As we would expect the interference probability between sectors of the same set is 100%. We also see that, for light loading, random loading provides a higher probability of interference than intelligent loading for interference into sector α from the other two sectors. However, we see that for higher loading the situation is not so clear cut. At high loading, the probabilty of interference from a sector β into α is higher if intelligent loading is used compared with if random loading is used, although the interference probability is less for inteference from γ into α.

Figure 7: Interference probability vs non-serving sector loading – serving sector loading equals non-serving sector loading



A14.81 Figure 8 below illustrates the case where the serving-sector loading is fixed at 85%. For such heavy loading we see that the interference probability does not have a great dependence on the loading algorithm chosen. However we see again that, at loadings above 50%, intelligent loading does not provide on average a lower interference probability than random loading.

Figure 8: Interference Probability vs non-serving sector loading – server sector loading is 85%



A14.82 In our implementation we have assumed that all serving sectors are in set α. This is a simplification, but we believe this to be a reasonable approximation.

Generation of SINR distributions

A14.83 The SINR at the UE location is calculated according to the following equation

$$SINR = \frac{P_{\text{wanted}}}{P_{\text{other}} + P_{\text{noise}}} \quad (14)$$

A14.84 Where:

- The wanted power, P_{wanted} , at the UE location is the calculated power received per resource block from the serving sector
- The other power, P_{other} , is the total other cell interference power received during the same time period and at the same frequency as P_{wanted} .
- The noise power, P_{noise} , is the noise power at the UE given by *k*TB multiplied by the noise figure where *k* is Boltzmann's constant, T is the temperature (290 K) and B the bandwidth (i.e 180 kHz for one resource block)

A14.85 The steps in paragraph A14.21 are repeated for each test UE location within the simulation area (10,000 sample locations) to build up an SINR distribution which is unique to the particular combination of frequency, base station network size, network loading and building penetration depth chosen for that run of the model.

A14.86 A series of different SINR distributions are generated covering each particular combination of frequency, base station network size, network loading and building penetration depth required.

Throughput calculations

A14.87 The selection of an SINR to throughput mapping function has been given careful consideration. Various different SINR to throughput mapping functions are available in the literature[30, 31, 32] . These functions scale differently for different channel models, but the general shapes of these functions are similar to each other.

A14.88 For the purposes of our present analysis we have explored the use of two alternative mapping functions. The first, which we have called ‘realistic’, is based on an mapping function which has been used in many studies and is used by the SEAMCAT tool[33]. It is an attenuated and truncated form of the Shannon bound taken from Annex A Section A.1 of 3GPP TR 36.942[34] and is normally applicable to a 1x2 (SIMO) antenna configuration. The second, which we have called ‘theoretical’ is also derived from the same function from 3GPP TR 36.942 but this time we have modified the equations to make it applicable to a 2x2 (MIMO) antenna configuration.

A14.89 As discussed in paragraph A14.94 below, the ‘realistic’ mapping function is fairly close to that seen in current implementations of LTE. By contrast, in comparison with our ‘realistic’ function and real world results our ‘theoretical’ function is likely to give optimistic performance results relative to near term LTE networks. As we believe that our ‘realistic’ mapping function is likely to give results closer to actual LTE networks in the real world (at least for the short to medium term) and given that we have no evidence to understand if, how and when performance may move toward the ‘theoretical’ function in future networks, illustrative results using the ‘Min var’ and ‘Max var’ parameter sets have used the ‘realistic’ case.

‘Realistic’ mapping function

A14.90 Our ‘realistic’ mapping function is expressed (in bps/Hz) as follows:

$$Thr_{real} = \begin{cases} 0, & \text{for } SINR < \mathrm{SINR_{min}} \\ \alpha.\,\mathrm{S}(SINR), & \text{for } \mathrm{SINR_{min}} < SINR < \mathrm{SINR_{max}} \\ \mathrm{Thr_{max}}, & \text{for } SINR > \mathrm{SINR_{max}} \end{cases} \quad (15)$$

A14.91 Where $\mathrm{S}(SINR)$ is the Shannon bound (in bps/Hz) given by:

$$\mathrm{S}(SINR) = \log_2(1 + 10^{SINR/10}) \quad (16)$$

A14.92 Where:

α	Attenuation factor, representing implementation losses
$\mathrm{SINR_{min}}$	Minimum SINR of the codeset, dB
$\mathrm{Thr_{max}}$	Maximum throughput of the codeset, bps/Hz
$\mathrm{SINR_{max}}$	SINR at which max throughput is reached, dB

[30] LTE Capacity compared to the Shannon Bound, Mogensen P et al, Proceedings of the IEEE 65th Vehicular Technology Conference (VTC 2007-Spring), IEEE, 22 – 25 April 2007.
[31] 3GPP TR 36.942, “Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios”, http://www.3gpp.org/ftp/Specs/html-info/36942.htm
[32] “LTE for UMTS: Evolution to LTE-Advanced”, Holma H and Toskala A, John Wiley and Sons
[33] http://www.seamcat.org/
[34] 3GPP TR 36.942, “Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios”, http://www.3gpp.org/ftp/Specs/html-info/36942.htm

A14.93 The values of these parameters for a 1 x 2 LTE downlink, in a typical urban fast fading channel at 10 kmph, from 3GPP TR 36.942, are given in Table 11 below:

Table 11: Parameters from the attenuated and truncated form of the Shannon bound (Annex A Section A.1 of TR36.942)

Parameter	Value	Unit	Notes
A	0.6	-	Represents implementation losses
$SINR_{min}$	-10[35]	dB	Based on QPSK, 1/8 rate
Thr_{max}	4.4	bps/Hz	Based on 64QAM 4/5 rate

A14.94 We have benchmarked the performance given by this 'realistic' mapping function against a number of real world results. See, for example, Rysavy Research and 3G Americas paper[36] which highlights some work by Ericsson[37]. These indicate that the performance given by this function is fairly close to that seen in current implementations of LTE with a 2x2 antenna configuration (even though it is modelled as a 1x2 implementation).

A14.95 We consider that our 'realistic' mapping function is lower bound to likely LTE performance. Early LTE deployments are likely to have similar performance and it may be some time before performance significantly improves upon that given by this function.

A14.96 Though we explore an alternative mapping function below. The main results presented in the Annexes 6 and 7 and (unless otherwise stated) in this annex are based on our 'realistic' function.

'Theoretical' mapping function

A14.97 For our 'theoretical' mapping function, equation (15) above is replaced by the following:

$$Thr_{theoretic} = \begin{cases} 0, & \text{for } SINR < \mathrm{SINR_{min}} \\ 2.\alpha.S(SINR - 3dB), & \text{for } \mathrm{SINR_{min}} < SINR < \mathrm{SINR_{max}} \\ \mathrm{Thr_{max}}, & \text{for } SINR > \mathrm{SINR_{max}} \end{cases} \quad (17)$$

A14.98 The factor 2 in the above expression accounts for the fact that this is a 2x2 MIMO implementation and therefore there are two spatial streams of data. Adjusting the SINR value by -3 dB accounts for the fact that the transmit power is shared between the two transmit antennas.

A14.99 In poor channel conditions, it might be expected that an open loop transmit diversity scheme would apply rather than spatial multiplexing. However, we examined other idealised mapping functions, particularly with reference to Mogensen et al[38] and concluded that the *theoretical* mapping function is representative of a 2 x 2 LTE

[35] Note, as indicated below, for our modelling we have used a range for the $SINR_{min}$ value
[36] Transition to 4G, 3GPP Broadband Evolution to IMT-Advanced (4G), Rysavy Research & 3G Americas, September 2010, p. 49, Figure 17.
http://www.rysavy.com/Articles/2010_09_HSPA_LTE_Advanced.pdf
[37] Initial field performance measurements of LTE, Jonas Karlsson and Mathias Riback, Ericcson Review No. 3, 2008, pp. 22 – 28.
http://www.ericsson.com/ericsson/corpinfo/publications/review/2008_03/files/LTE.pdf
[38] LTE Capacity compared to the Shannon Bound, Mogensen P et al, Proceedings of the IEEE 65th Vehicular Technology Conference (VTC 2007-Spring), IEEE, 22 – 25 April 2007.

downlink, with idealised channel conditions, which automatically selects the optimum SIMO/MIMO mode for the given channel conditions.

A14.100 Our 'theoretical' mapping function represents performance in idealised channel conditions. Comparison with our 'realistic' function and real world results suggest that the estimated throughput per resource block based on our 'theoretical' function may be optimistic.

A14.101 We consider that our 'theoretical' mapping function is an upper bound to likely LTE performance. As LTE networks mature and become better optimised with experience it is possible that the 'real world' performance of these networks will approach more closely to that provided by our 'theoretical' function.

SINR cut-off

A14.102 Table 11 above quotes a value of $SINR_{min}$ of -10dB. This SINR cut-off point is based on the mapping function of 3GPP TR 36.942. However, the work of 3GPP TR 36.942 pre-dated later 3GPP work on control channel design, and so was an early approximation. Later work [[39]] has concluded that system coverage is limited by the PDCCH, and that the 36 bit payload format (needed to carry DL grants) requires -5.3 dB Es/No, a similar figure to that given by Laselva et al[40].

A14.103 The coverage analysis in [[41]] does also go on to describe how control channel coverage can be extended by power boosting or puncturing, suggesting a 3dB power boost is feasible. Such a boost would mean the PDCCH could have an SINR of -5.3dB whilst wideband SINR could be 3dB lower at -8.3dB, which is the same as that needed to support the most robust channel the P-BCH. Other suggested wideband SINR cut off figures from coverage analysis are -8.3dB[42] and -9dB[43].

A14.104 Since it is not yet known whether power boosting and puncturing techniques can and will be used in practice, and as there is particular sensitivity of the coverage results to the choice of SINR cut-off, we have made a decision to adopt a two values of SINR cut-off: -10 dB and -5 dB. These values are reflected in our 'Min var' and 'Max var' cases.

System overheads

A14.105 Our 'theoretical' and 'realistic' mapping function do not take account of system overhead. We therefore account for the following overheads when calculating throughput:

- Reference Signals
- Physical Downlink Control Channel (PDCCH)
- Primary and Secondary Synchronisation Channels (PSCH/SSCH)
- Physical Broadcast Channels (PBCH)

---

[39]'E-UTRA Coverage', 3GPP document R1-073371, August 2007
[40] On the Impact of Realistic Control Channel Constraints on QoS Provisioning in UTRAN LTE, Laselva et al, Vehicular Technology Conference (VTC- Fall), 20 - 23 Sept. 2009.
[41] E-UTRA Coverage', 3GPP document R1-073371, August 2007.
[42]S.Sesia et al, "LTE the UMTS Long Term Evolution", Wiley 2009, p416
[43]"LTE for UMTS, Evolution to LTE-Advanced", H. Holma, A.Toskala, 2nd Ed, Wiley 2011, p269

A14.106 The size of these overheads on a per-channel basis is illustrated in Table 12.

Table 12: Calculation of overheads

	Overheads (%)				
	Number of MIMO streams (s = 2)	Number of resource blocks (n)			
		25	50	75	100
Reference signals	4s/84	9.52	9.52	9.52	9.52
Physical Downlink Control Channels (PDCCH)	(2 x 12 - 4s) / (2 x 84)	9.52	9.52	9.52	9.52
Primary and Secondary Synchronisation Channels (PSCH/SSCH)	(6 x 2 x 1 x 12) / (10 x 84n)	0.69	0.34	0.23	0.17
Physical Broadcast Channels (PBCH)	(6 x 4 x 12) – 4s) / (40 x 84n)	0.33	0.17	0.11	0.08
Total		20.07	19.56	19.39	19.30

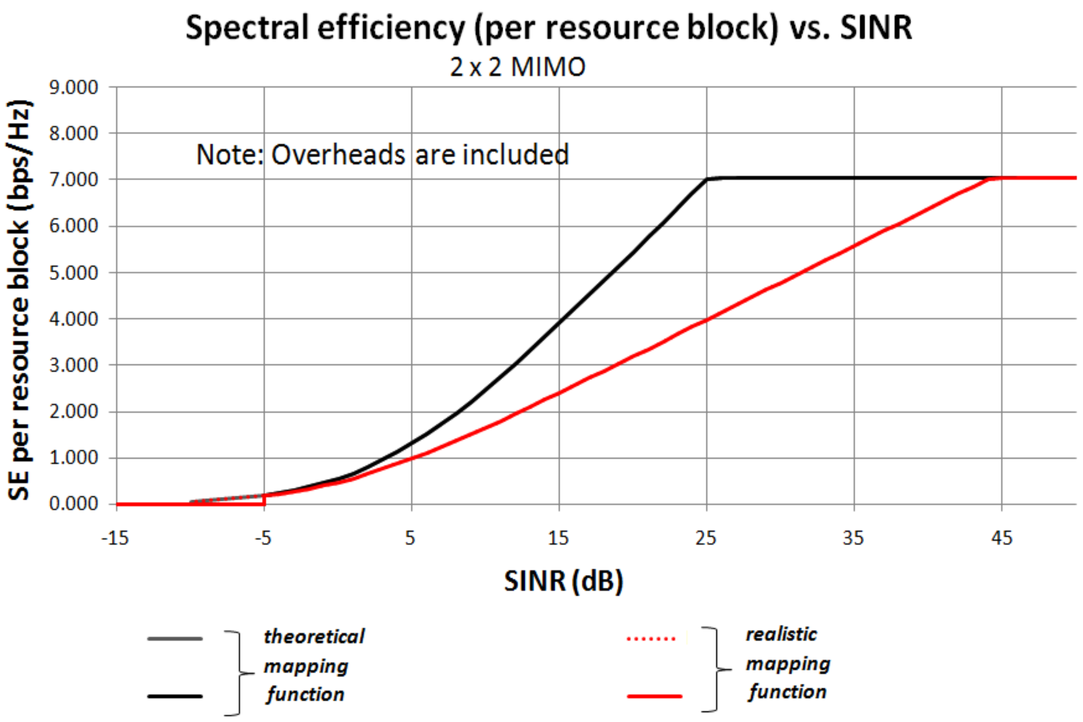
A14.107 The number of resource blocks in Table 12 (25, 50, 75, 100) corresponds to the various bandwidths in the modelling (5, 10, 15, 20 MHz respectively). It is apparent that the proportion of overheads varies with bandwidth, so that the peak throughput for a 10 MHz channel is not exactly half that of a 20 MHz channel. However, the difference is only slight and we have adopted of a single figure of 20% to account for the overall effect of overheads.

Throughput per resource block

A14.108 The use the appropriate mapping function, combined with a reduction of 20% to account for overheads, gives us a net spectral efficiency (bps/Hz) vs SINR for the user data in a resource block.

A14.109 The resulting spectral efficiencies are plotted Figure 9 below, where curves with SINR cut-offs of both -10 dB and -5 dB are plotted.

Figure 9: Spectral efficiencies used in the modelling



A14.110 For the generation of the (speed) single user throughput curves, the available user bit rate per resource block is calculated by multiplying the spectral efficiency by 180 kHz (the occupied bandwidth of an LTE resource block).

A14.111 For the generation of the capacity results, the data-rate available per resource block is enhanced by including an approximation for the effect of frequency domain packet scheduling, as detailed in paragraphs A14.112 to A14.115.

Frequency domain packet scheduling

A14.112 Frequency domain packet scheduling (FDPS) exploits the fact that an LTE carrier is split into multiple sub-carriers and that these sub-carriers are grouped together in frequency and split by time to form individual physical resource blocks (a 5 MHz carrier has 25 resource blocks whilst a 20 MHz carrier has 100). At any instant in time different users can be allocated a different number of physical resource blocks depending on their instantaneous demand and their signal quality. If the channel quality is significantly different for different physical resource blocks (which is typically the case for macro cellular networks with bandwidths equal or greater than about 5 MHz) then LTE can exploit this by optimally scheduling users on physical resource blocks with the best channel quality at their location. This can lead to a FDPS gain which for pedestrian users can be of the order of 40% for a 10 MHz system bandwidth. To achieve this level of gain however there needs to be multiple users all demanding a service that requires a relatively small proportion of the resources available in the cell at any instant of time. If there are just a few users requiring a large proportion of resources then the gain is reduced.

A14.113 We have included the effect of FDPS in our capacity results (for all other results presented in this consultation FDPS gain is not applied).

A14.114 A FSPS gain is applied to the calculated single-user throughput results to account for improved performance from scheduling users on groups of resource blocks whose SINR is highest for that user.

A14.115 The calculation is in three steps as follows:

a) Calculate a factor between 1 and 1.4 using the following equation[44]:

$$\gamma = 1.4 - 0.729 \times e^{-0.599U} \quad (18)$$

Where U is the number of simultaneous users (for a given guaranteed data-rate service) who could be supported at a particular location if the single-user throughput was shared equally between them.

b) Multiply the factor (γ) calculated in step a) by an additional bandwidth dependent factor (δ)[45]. The value of (δ) for each carrier bandwidth is given in Table 13 below:

Table 13: FDPS gain bandwidth factors

Bandwidth	5 MHz	10 MHz	15 MHz	20 MHz
(δ)	0.9643	1.000	1.0179	1.357

c) The single-user throughput per resource block (in the absence of FDPS) is multiplied by the product of γ and δ.

Downlink performance

A14.116 The results presented are for downlink performance only. In order to explore the possibility of results being invalidated by deficiencies in the ability of the UE to communicate with the base station using the uplink we have conducted a link budget analysis. For the uplink we assumed that the maximum power (23dBm) is transmitted over one resource block to give maximum range, and assume that this gives a high enough data rate for the required control and acknowledgement data. We concluded that for the vast majority of cases presented in this consultation the performance is not impaired by uplink limitations, with uplink and downlink at worst being very finely balanced.

Modelling the capacity of multi-frequency networks

A14.117 A number of the capacity results presented in Annexes 6 and 7 are for networks with spectrum in more than one frequency band. For these cases the aim of the analysis is to understand the overall capacity of a multi-frequency (or multi-carrier) network where traffic is managed between the available carriers in such a way as to ensure that users, regardless of which actual carrier they are served by, can receive the same (or similar) quality of service (i.e. can get the same specified data-rate with the same likelihood of success, irrespective of their location). This is a significant change to our modelling compare to the approach we took for the March 2011 consultation.

[44] This equation above is an approximate curve fit to the curves shown in Holma & Toskala, HSDPA/HSUPA for UMTS, Figure 7.13.

[45] The value of δ is derived from Holma & Toskala, LTE for UMTS, 2nd Edition, Table 10.18; having been normalised to the 10 MHz bandwidth

A14.118 Our analysis is limited to modelling carriers in two different frequency bands or to two carriers in the same band. We have assumed that the traffic from harder to serve locations is preferentially served on the lower of the available frequency bands and that traffic from easier to serve locations is served on the higher of the available frequency bands. Obviously, if we model two carriers in the same band the approach is adapted accordingly but we still assume that one of the carriers is dedicated to the traffic from the harder to serve locations and the other to the traffic from the easier to serve locations.

A14.119 A description of the multi-frequency analysis is provided below.

A14.120 For each BPL depth, each network size and each frequency, generate an SINR distribution for a range of network loadings between the minimum and maximum loadings considered (e.g. 15% to 85% in 2% steps).

A14.121 The SINR distributions for each notional depth (e.g. outdoor, 1 metre, 5 metres, 10 metres, and 15 metres) corresponding to a specific network size, frequency and loading are combined into a single (composite) set of distributions weighting each notional depth equally.

A14.122 The composite SINR distributions are ordered high (easiest to serve locations) to low (hardest to serve locations) to form a composite distribution.

A14.123 Each multi-frequency spectrum portfolio is defined in terms of the frequency and bandwidth of the carrier in the lowest frequency band and the frequency and bandwidth of the carrier in the highest frequency band. The analysis can also be applied to portfolios with two carriers (with the same or different bandwidths) in the same frequency band.

A14.124 For each target level of coverage (between 60% and 100% in 1% steps) the maximum loading that is needed for the carrier in the lowest frequency band to just provide service at the specified data-rate (e.g. 5 Mbps) to that level of coverage is established from the relevant SINR distribution using the SINR to throughput mapping function and accounting for FDPS gain.

A14.125 We assume that easier to serve locations are preferentially served by the carrier in the higher frequency band and the harder to serve locations are served by the carrier in the lower frequency band.

A14.126 For each target level of coverage (between 60% and 100% in 1% steps), by a process of iteration we find the optimum split between users on each of the frequency bands considered and the loading on the higher frequency band such that:

- The target coverage can be achieved (if possible); and
- The total proportion of demand (across both frequency layers) that can be supported by the network at each target level of coverage is maximised conditional on the proportion of demand that can be served by each frequency layer being the equal (so that the users on each layer experience the same likelihood of being able to receive service).

A14.127 For the purposes of our analysis, the proportion of demand that can be supported by each frequency layer is assessed as the total resources available to the network at that frequency (i.e. number of resource blocks (a function of carrier bandwidth) multiplied by the total number of sectors in the simulation area multiplied by the fraction of locations assigned to that frequency layer) divided by the resources that would be needed to serve the total population in the sample area at a specified data-rate (e.g. 5 Mbps) assuming they are distributed evenly across every delivery address in the sample area. This is equivalent to estimating the proportion of the population that could simultaneously be served at the specified data-rate.

A14.128 The demand on a particular frequency layer D is calculated by:

$$D = \frac{RA}{RR} \tag{19}$$

A14.129 Where RA is the resources available to that layer and is given by:

$$RA = 0.85 \times N_{RB} \times 3N_{Sites} \tag{20}$$

A14.130 Where the factor 0.85 is the maximum loading we assume for any serving cell, N_{RB} is the number of resource blocks available to a carrier at the particular frequency (e.g. for a 10 MHz carrier $N_{RB} = 10$), and N_{Sites} is the number of sites in the simulation area.

A14.131 And where RR is the resources necessary to serve every user in the sample area with the specified guaranteed data-rate

$$RR = \frac{Pop_{SA}}{N_{SP}} \times \sum_{n_{min}}^{n_{max}} RR_n \tag{21}$$

A14.132 Where Pop_{SA} is the population in sample area (from census data), N_{SP} is the number of sample points, RR_n is the resources needed to serve a single user with the specified data-rate at sample point n (obtained from the throughput distribution with FDPS applied), n_{min} is the easiest to serve location allocated to the frequency layer in question and n_{max} is the hardest to serve location allocated to the frequency layer in question.

A14.133 We are not suggesting that this is exactly how an operator would, in practice, manage traffic on their network. However it is likely that an operator will want to manage traffic, to the extent possible, in a way that maximises the overall performance of their network as a whole. The extent to which they can do this will be dependent on a number of factors, including for example whether there are a significant number of terminals on the network that are not able to work at all network frequencies. There are also practical issues in optimally managing traffic across multiple carriers (e.g. avoiding ‘ping ponging’ between layers when a user’s channel quality is close to a handover threshold, unavoidable inaccuracies in estimating channel quality, etc.) that mean that our approach is almost certainly a simplification. As a consequence of these practical issues, our results may over-estimate the contribution of lower frequencies to the performance of a multi-frequency network because in a real network a proportion of traffic will inevitably be carried on the less optimal frequency layer. Despite these limitations, we believe that the results are useful in illustrating the difference in relative potential performance of different multi-frequency spectrum portfolios.

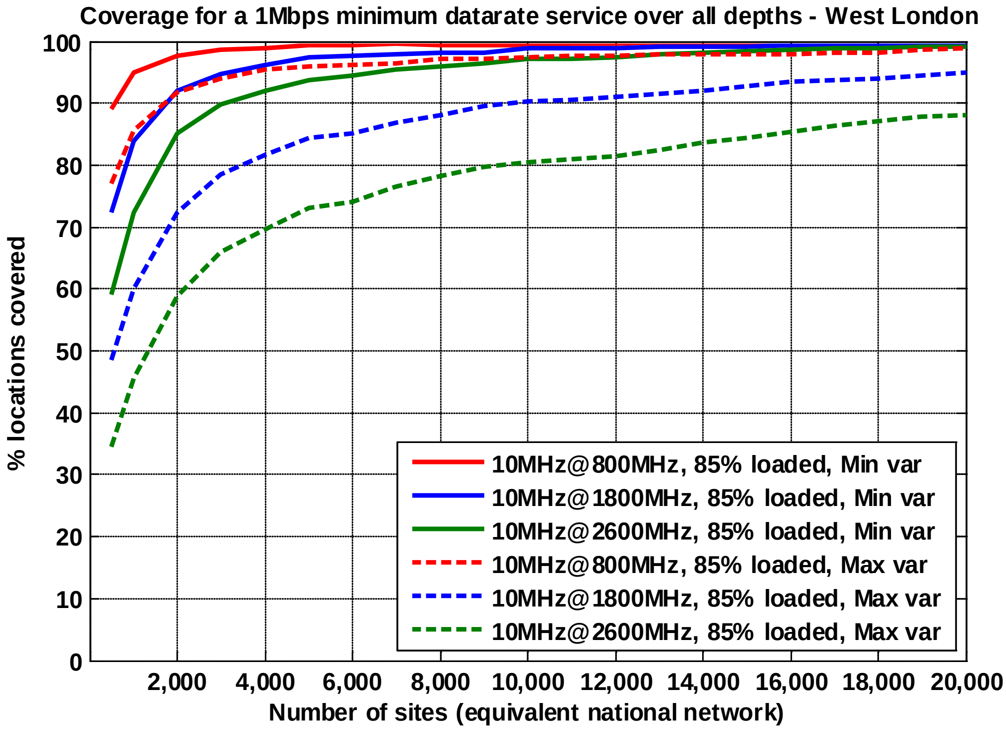
Presentation of results

Coverage

A14.134 For each postcode unit location the number of domestic delivery points is known. The population coverage for a particular guaranteed minimum downlink data-rate associated with a particular combination of frequency, channel bandwidth, base station network size, network loading and building penetration depth is estimated by summing the number of delivery points associated with each UE location (post code unit location) whose calculated data-rate (single-user throughput) is equal to or greater than the guaranteed minimum downlink data-rate. This estimation is based upon assuming an equal number of users at each domestic delivery point.

A14.135 Figure 10 below illustrates the coverage results for a 1 Mbps minimum guaranteed data-rate for the full range of sites simulated for a 10 MHz carrier at 85% loading in the West London simulation area. This figure is for coverage at 'all' depths, i.e. where the five notional 'depths' modelled (outdoors, 1m, 5m, 10m and 15m) are given equal weight[46].

Figure 10: Coverage as a function of number of sites for a 1Mbps service, 10 MHz, 85% loading, various frequencies – West London



A14.136 Figure 10 should be interpreted as follows: the x-axis represents the size of the networks modelled in terms of the number of sites an equivalent national network covering the UK would have (the actual number of sites within the simulation area being a only a fraction of these). Therefore, 2,000 in Figure 10 represents a national network with 2,000 sites. The y-axis shows the percentage of delivery points able to

[46] Noting our interpretation of depth as outlined in paragraph A14.28 above is less literal, being about 'easier' and 'harder' to serve locations

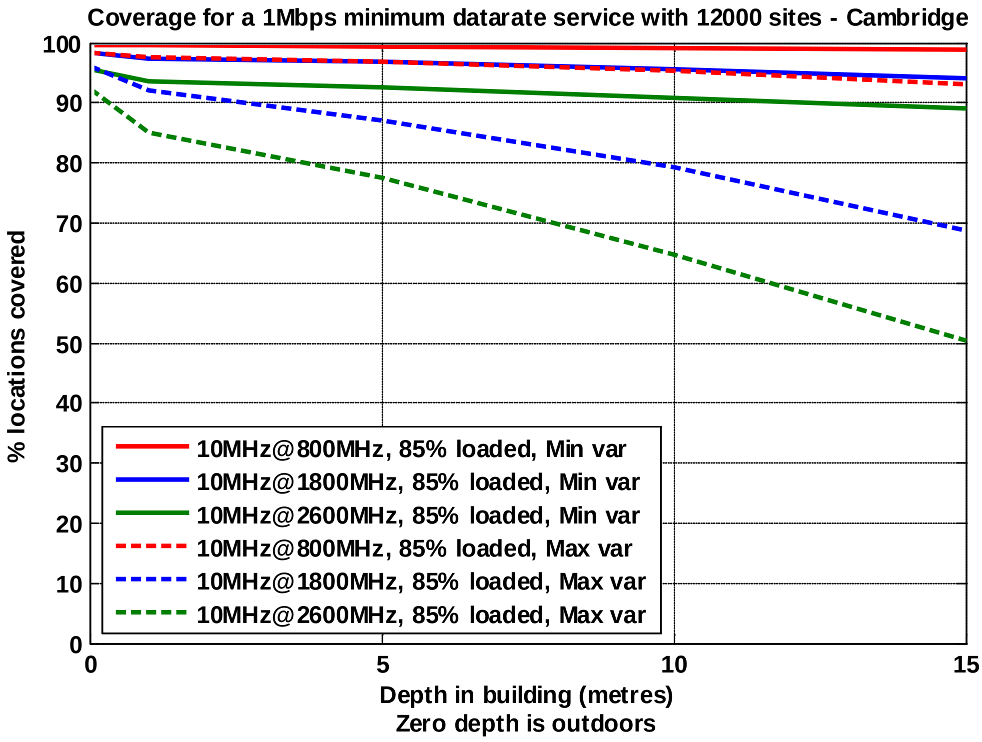
receive a minimum downlink speed of at least the guaranteed minimum data-rate (in this case 1.0 Mbps).

A14.137 It should be noted that users in the hardest to serve locations will require the entire resources of a cell in order to be able to receive the minimum guaranteed data-rate, leaving no resources for other users in that cell. Therefore, the coverage results, by themselves, only indicate the extent of coverage the network would achieve when a there is a single active user per 'serving' cell.

A14.138 It should be stressed that coverage results are not a prediction of the nationwide coverage. Rather they indicate the coverage achievable within the particular simulation area.

A14.139 Figure 11 below illustrates the coverage results for a 1 Mbps minimum guaranteed data-rate for users at each of the 5 notional 'depths' we have modelled. Where, the notional depths at the left hand side of the graph (e.g. 0[47] to 5 metres) represent users in the easiest to serve locations whilst the notional depths at the right hand side of the graph (e.g. 10 to 15 metres) represent users in the hardest to serve locations.

Figure 11: Variation of coverage with 'depth' in building for a 1Mbps service, 10 MHz, 85% loading, 12,000 sites, various frequencies - Cambridge



Speed

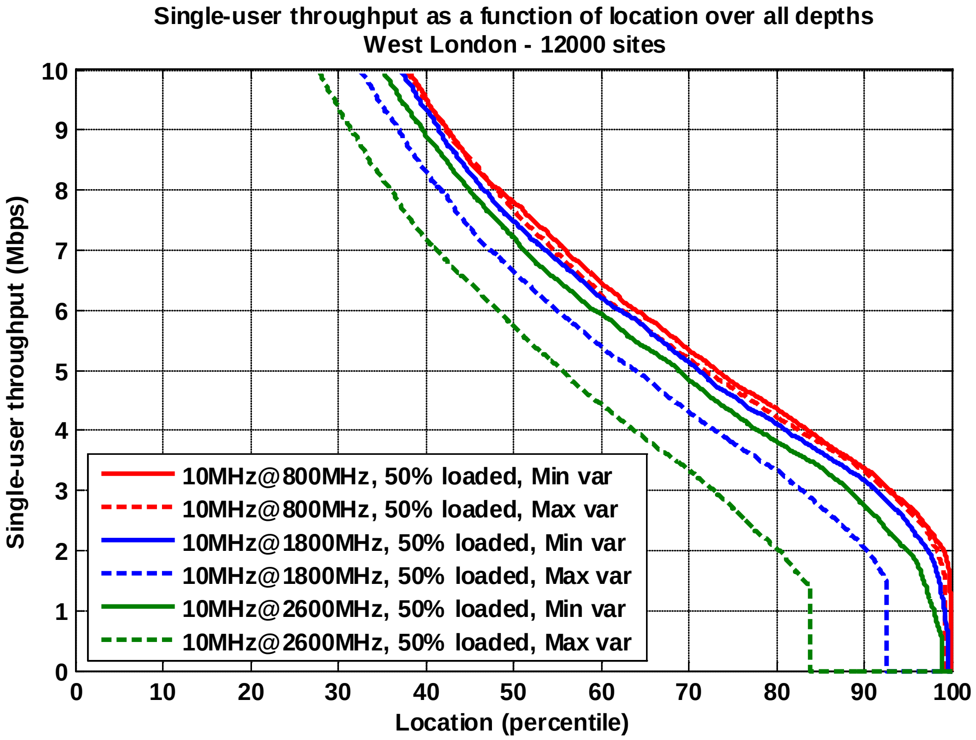
A14.140 The speed of a network, for a particular combination of frequency, channel bandwidth, base station network size and network loading is obtained directly from the single-user throughput distribution for the particular channel bandwidth. This distribution is sorted in descending order. Each throughput value from the distribution is then plotted against the location (cumulative number of delivery

47 Note; zero in these graphs represents outdoors.

points) expressed as a percentage of the total number of locations that can receive at least that throughput.

A14.141 Figure 12 below illustrates the speed results for outdoor users for a network with the equivalent of 12,000 sites nationally for a 10 MHz carrier at 50% loading in the West London simulation area.

Figure 12: Single-user throughput as a function of location, 10 MHz carrier, 50% loading, various frequencies – West London



A14.142 Figure 12 should be interpreted as follows: the x-axis indicates the percentage of delivery points within the simulation area ordered such that those having the best signal conditions are to the left, and those with the worst to the right. So “50%” in Figure 12 represents the 50% of delivery points which are in locations with the best signal conditions and hence highest throughput for each of the 800 MHz, 1800 MHz and 2600 MHz networks (these are not necessarily the same 50% of locations). The y-axis shows the single-user throughput attained or exceeded at each of these locations when a single user consumes the full capacity of the serving cell.

Capacity

A14.143 In general terms, the capacity of a network is a measure of how much offered traffic it is able to serve whilst maintaining key quality of service metrics. Such metrics might include the number of connection request failures, the number of dropped connections, the ability to maintain a minimum throughput to users, the number of lost data packets, latency, etc. Different users demanding different services from the network will need a different combination of these metrics. For instance, for a streaming video user maintaining an acceptable minimum guaranteed data-rate is important to avoid interrupts; for an online gamer latency might be the most important feature; for someone surfing the web both latency and data-rate may be key. A network will try and balance all of the competing demands of its users. Moreover, if the traffic profile of the users of one network is different from the traffic profile of another network, even if they have the same number of customers and the same network and spectrum resources they might, in practice, perform very differently with one network struggling to meet demand whilst the other does not.

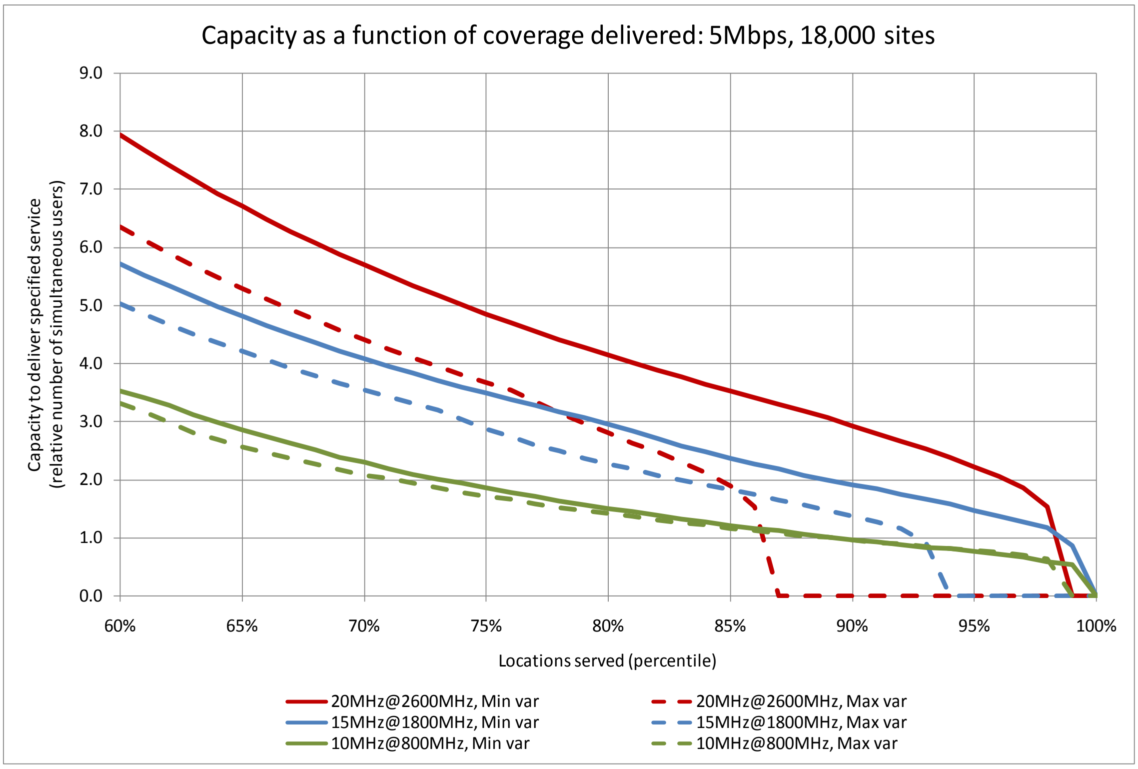
A14.144 As a consequence of the above, it is very difficult to derive a single capacity metric that adequately addresses all of the important network quality features that an operator is likely to feel are important. However, as many of these network quality features are likely to be independent of the frequency band they have not all been addressed in this analysis.

A14.145 For the purposes of our analysis we have assumed all users are to be provided with the same service – a guaranteed data-rate service of a specified speed – and that users are uniformly distributed over all modelled locations (including over all depths at each modelled address). We then calculate the relative number of such users that could simultaneously be served by the network, taking account of the resources available to the network and the resources required to serve each user with the specified service. This is a simple scenario, but allows an illustration of relative capacity without having to make a lot of detailed assumptions about the specifics of the services that will be demanded by different users.

Networks with a single carrier operating in a single frequency band

A14.146 Figure 13 below illustrates the capacity results for single frequency networks for different carrier bandwidths at different frequencies for a 5.0 Mbps guaranteed data-rate.

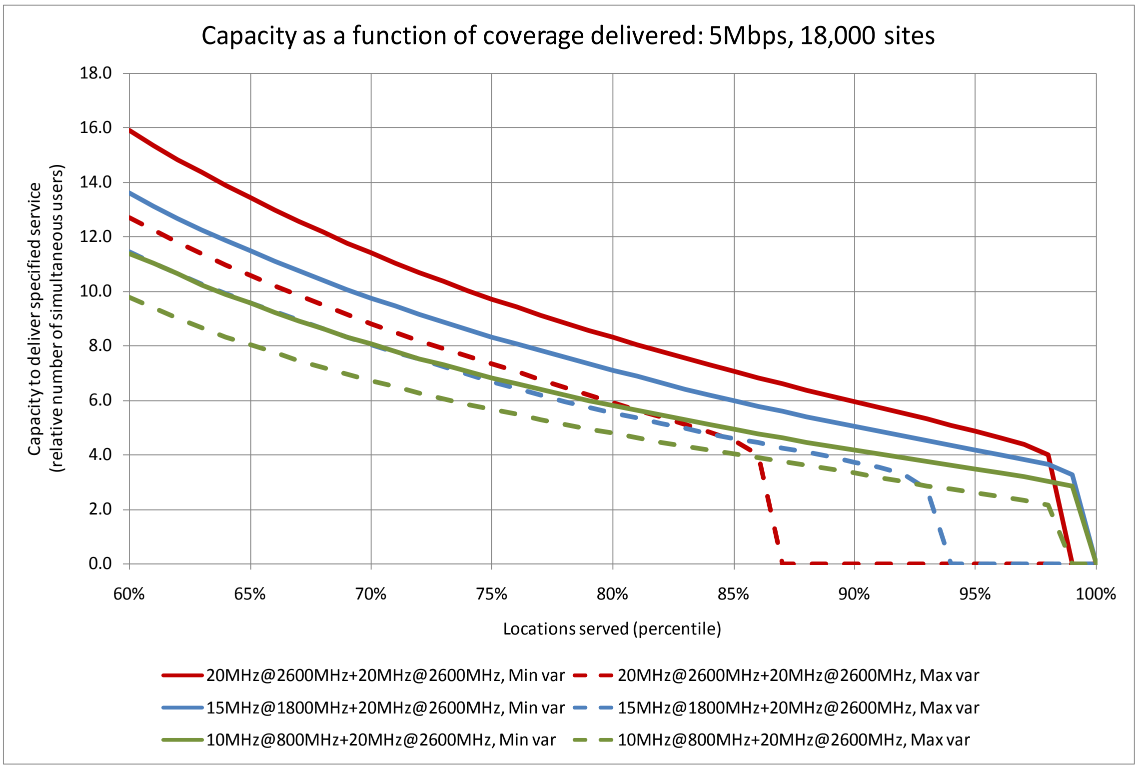
Figure 13: Relative capacity as a function of coverage delivered: 5Mbps, 18,000 sites – West London



Networks with two carriers operating in different frequency bands

A14.147 Figure 14 below illustrates the capacity results for multi-frequency networks with two carriers for a 5.0 Mbps guaranteed data-rate.

Figure 14: Relative capacity as a function of coverage delivered: 5Mbps, 18,000 sites – West London

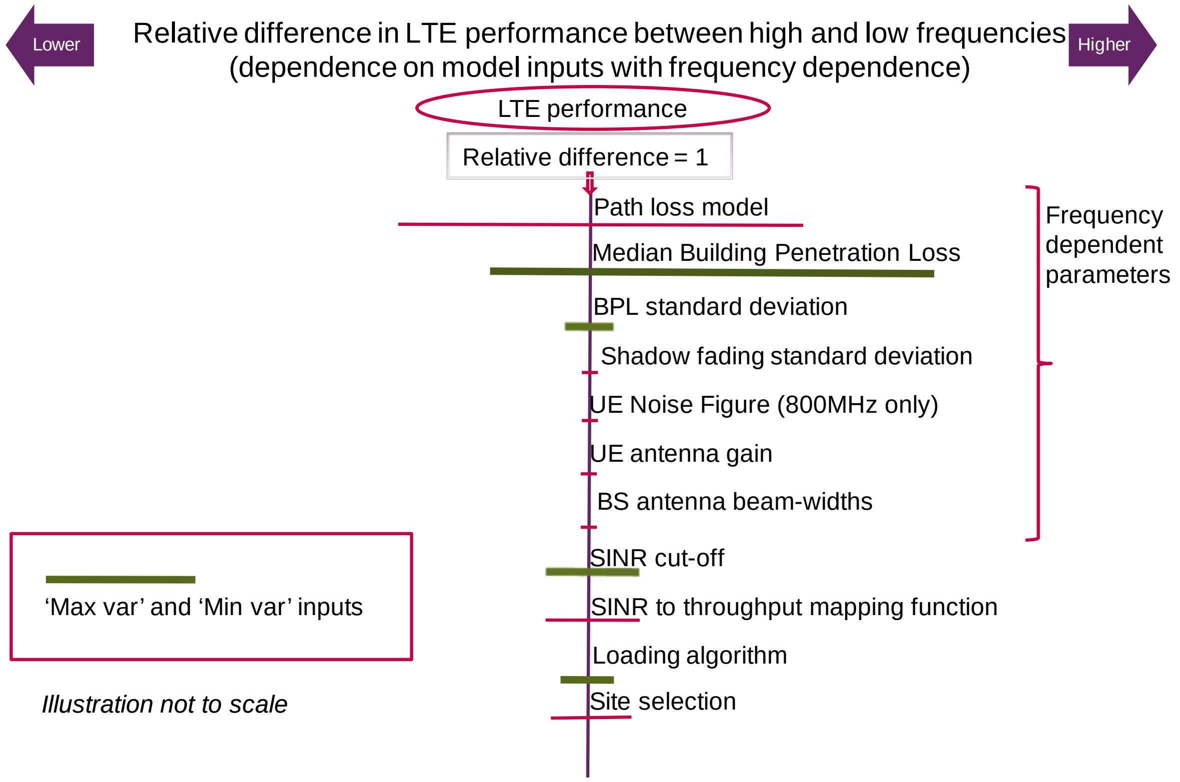


Variability in our modelling

A14.148 As discussed in paragraph A14.6 above, there is considerable uncertainty around many of the parameter values and assumptions we have used in our modelling.

A14.149 Figure 15 below provides an illustration of the wide range of uncertainties that we have considered in relation to our model, particularly those likely to affect the relative performance between frequencies. This illustration by no means includes every single source of uncertainty that might be applicable to the model but it does show those that we believe are likely to have the greatest impact on the interpretation of our results.

Figure 15: Illustration of uncertainties



A14.150 The length of the horizontal bars is indicative of our current view of the size of the relative performance difference between 800 MHz and 2600 MHz as a function of the uncertainty associated with each input parameter (or input algorithm). The length of each bar to the right means a higher relative difference in performance in response to a change in the relevant input parameter and the length of the bar to the left means a lower relative difference in performance. Note that the diagram should be interpreted in a qualitative manner: it is not to scale.

A14.151 As illustrated in Figure 15, median BPL is an important uncertainty in the relative difference between frequencies. This together with BPL standard deviation, SINR cut-off and choice of loading algorithm are key parameters are included in the 'Max var' and 'Min var' cases used for presentation of the main results in this consultation. These parameters are discussed in detail in paragraphs A14.156 to A14.172, in which we also consider the relevant sensitivities.

A14.152 We also present, in paragraphs A14.173 to A14.178, a discussion of the sensitivity of the results to the choice of SINR to throughput mapping function. We show that in absolute terms the mapping function has a significant impact on the single-user throughput mapping function. However, the effect on the relative performance is more moderate as reflected in Figure 15.

A14.153 As indicated in paragraphs A14.21 and A14.65, we have used the Extended Hata model for calculation of path loss. The Extended Hata Model is based upon a range of path loss measurements and has been subject to extensive peer review both within academia and industry. It is widely accepted and has been used by regulatory bodies, CEPT and ITU in the conduct of various studies. We consider it the best model available to Ofcom to model performance for this consultation.

A14.154 The values chosen for a number of other parameters used for the performance modelling used in the March 2011 consultation were commented on in the responses to that consultation. We address the impact of UE noise figure at 800 MHz, UE antenna gain, BS antenna beam-widths and shadow fading (location variability) standard deviation in Annex 15 of this consultation where some relevant results are presented. We consider that our modelling is relatively insensitive to these particular parameters.

A14.155 Some uncertainties in our choice of parameter values (or ranges) will always remain, simply because they fall into a category where a wide range of values are considered reasonable. Other uncertainties arise because we are required to make an assessment of the performance of current implementations or likely improvements in performance over the lifetime of the technology. Overall, there are many sources of uncertainty and, and we have modelled the uncertainties associated with a number of these parameters, however we welcome stakeholder feedback on any aspect of the modelling, parameter choices and our treatment of uncertainty.

‘Min var’ and ‘Max var’

A14.156 As mentioned in paragraph A14.151, to reflect the major areas of uncertainty we have chosen to model a range of values for certain key parameters:

a) SINR cut-off

b) Median building penetration loss

c) Building penetration loss standard deviation

d) Resource allocation - calculation of non-serving cell interference based on (non-standard) scheduler allocation of resource blocks.

A14.157 To illustrate this range we have chosen to group the parameter values into two cases: those that tend, in most circumstances, to minimise the relative performance variation between frequencies (our ‘Min var’ case) and those that tend, in most circumstances, to maximise the relative performance variation (our ‘Max var’ case). The model is then run twice to produce results for these two cases. Table 14 below shows the combination of parameters we have used for the ‘Min var’ and ‘Max var’ cases.

Table 14: ‘Min var’ and ‘Max var’ parameters

Parameter	Min var	Max var	Comment
SINR cut-off	-10 dB	-5 dB	The lowest SINR value for which a viable downlink service can be received (based on the performance of the most sensitive control channels)
BPL standard deviation	800 MHz: 4.0 dB 1800 MHz: 5.4 dB 2600 MHz: 6.0 dB	800 MHz: 8.0 dB 1800 MHz: 10.8 dB 2600 MHz: 12.0 dB	The standard deviation of the propagation loss

			incurred in penetrating into buildings
Median BPL	Lower absolute value and zero frequency dependency	Higher absolute value and strong frequency dependency	The median value of the propagation loss incurred in penetrating into buildings.
Resource allocation algorithm	Random	Intelligent	The intelligent algorithm attempts to optimise the allocation of the resource blocks on the serving cell and its neighbouring cells so as to minimise interference, while the random algorithm distributes user data randomly amongst resource blocks

A14.158 Strictly speaking, there are two different types of parameter that make up our 'Min var' and 'Max var' sets. The ranges for SINR cut-off and resource allocation algorithm represent an uncertainty in our knowledge about how an operator might manage their network. In principle, with more information we could reduce or possibly eliminate these sources of uncertainty and we would welcome any additional information from operators. However, the ranges for BPL standard deviation and median BPL represent the current uncertainty around the nature of propagation into buildings due to the myriad of different paths, locations, building types, construction materials, internal layouts and the relative importance of those locations for customers who are sensitive to differences in service quality etc. Even with perfect knowledge of every possible parameter we could never build a practical model that would eliminate these uncertainties (though, potentially, with better knowledge it could be reduced somewhat).

A14.159 In this annex the gap between the 'Min var' and 'Max var' curves is an indication of some of the principal sources of uncertainty in our model's prediction of performance. We have not modelled every uncertainty in a quantitative manner. The gap illustrates the extent of knowledge we, as a regulator, can have about LTE network performance, the inherent uncertainty in propagation into buildings and the choices operators may make in relation to implementation of intelligent resource scheduling algorithms and influencing SINR cut-off by, for example, increasing power in control channels[48]. For any particular location, we believe that it is more likely than not that performance will lie somewhere between our 'Min var' and 'Max var' lines, but we are not making any specific judgement as to the likely distribution of results within this range. Operators will have better knowledge about these

[48] It is likely that operators will have greater knowledge (and hence less uncertainty) about many of these factors which influence LTE network performance. However, they will still face a level of uncertainty even for the factors that they have direct influence over – for instance the efficacy of intelligent resource scheduling algorithms and their ability to reduce SINR cut-off by increasing power to certain control channels is to some extent uncertain.

factors but they will likely still have a degree of uncertainty and this uncertainty may influence their network planning.

A14.160 In order to examine the sensitivity of the modelling to each element of the 'Min var' and 'Max var' cases, we have conducted sensitivity studies on impact of each element individually. Our focus was upon single-user throughput curves for all frequencies and for all combinations of the inputs shown in Table 15.

Table 15: Inputs for sensitivity studies

Sites	Bandwidth	Depths	Network loadings
8000	2 x 10 MHz	Outdoors / 1m	15%
18000		15 m	85%

Median building penetration loss

A14.161 To examine the sensitivity of the results to median building penetration loss we based our comparison upon:

- **Medium rate median BPL** Values of median BPL which lie mid-way between our *lower bound median BPL* and *upper bound median BPL* parameters.
- **Medium BPL SD** Values of BPL standard deviation which lie mid-way between *low BPL standard deviation* and *high BPL standard deviation*.

A14.162 Medium rate median BPL and Medium BPL SD are in approximate alignment with the values used in the March 2011 consultation document.

A14.163 Some clear trends emerge from the results:

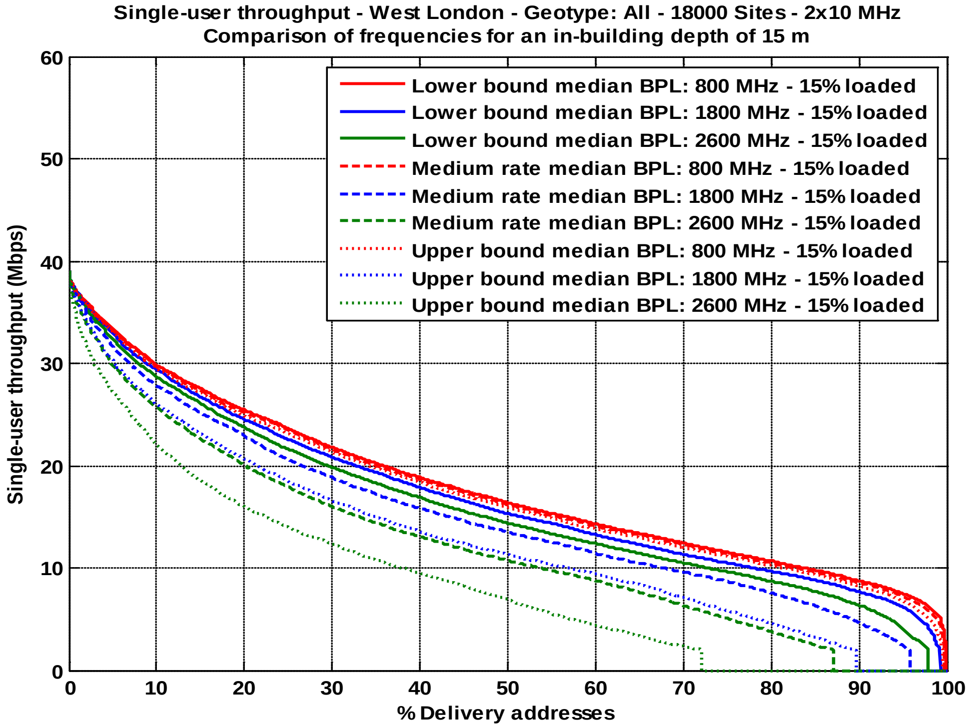
- In comparison to the medium rate BPL, *lower bound median BPL* increases the throughputs and *upper bound median BPL* decreases the throughputs. This is as we would expect: the larger the building penetration loss the lower the performance.
- The higher frequency throughputs show more sensitivity to our adopted range of median building penetration loss values than the lower frequencies. Specifically, the difference between the throughputs for *lower bound median BPL* and *upper bound median BPL* increases with increasing frequency. This is true even for a notional depth of 1 m, and is as we would expect because the external wall loss is higher for the higher frequencies. For notional depths of 15 m the sensitivity is even greater and is particularly apparent in terms of the coverage available for even the lowest throughputs (the point at which the curves meet the x-axis). This reflects the frequency dependency of the specific attenuation coefficient (the rate in dB/m at which the median building penetration loss increases with depth).
- Increasing the network loading from 15% to 85% significantly decreases the difference between the throughputs for *lower bound median BPL* and *upper bound median BPL*. This is in line with the increased loading leading to an increase in interference from non-serving sectors. The increased interference means that for most locations the building penetration loss has less of an influence in the calculation of SINR implying that the throughput curves for *lower bound median BPL* and *upper bound median BPL* tend to lie closer together. However the difference in the coverage available for the lowest throughputs (for

lower bound median BPL and *upper bound median BPL*) is only slightly smaller for 85% loading in comparison to 15% loading. This is because, as the noise in the test terminal receiver becomes more dominant in difficult to serve locations, the building penetration loss has more influence in the calculation of SINR and influence of network loading is reduced.

- As the number of sites is increased from 8000 to 18,000 the difference between the throughputs for *lower bound median BPL* and *upper bound median BPL* slightly decreases. This reflects the increased site density leading to increases in both the serving sector received power and the power received from non-serving sectors, which leads to the noise term in the calculation of SINR playing a less dominant role and accordingly variations in building penetration loss are not so apparent. The difference in the coverage available for the lowest throughputs (for *lower bound median BPL* and *upper bound median BPL*) is smaller for 18,000 sites compared with 8,000 sites. This is because; in difficult to serve locations, as the noise in the test terminal receiver becomes less dominant relative to interference (with increased site numbers) the building penetration loss has a less dominant influence in the calculation of SINR.

A14.164 Figure 16 shows an example of the relevant results for 18,000 sites, 15% network loading and a notional depth of 15m. The curves clearly demonstrate a high sensitivity of the results to our adopted range of median building penetration loss values for 1800 MHz and 2600 MHz.

Figure 16: Example showing the sensitivity of the results to median BPL



Building penetration loss standard deviation

A14.165 To examine the sensitivity of the results to building penetration loss standard deviation, and in line with our examination of median building penetration loss sensitivity studies, we based our comparison upon:

- **Medium rate median BPL** Values of median BPL which lie mid-way between *lower bound median BPL* and *upper bound median BPL*.

- **Medium BPL SD** Values of BPL standard deviation which lie mid-way between *low BPL standard deviation* and *high BPL standard deviation*.

A14.166 Some clear trends emerge from the results:

- In the majority of cases, the adoption of *low BPL standard deviation* decreases the throughputs and *high BPL standard deviation* increases the throughputs. This is as we would expect given the shape of the SINR to throughput mapping function: in general, the larger the building penetration loss standard deviation the higher the performance. However, the curves do not have a high sensitivity to building penetration loss standard deviation (at least over the range we have used for our 'Min var' and 'Max var' cases).

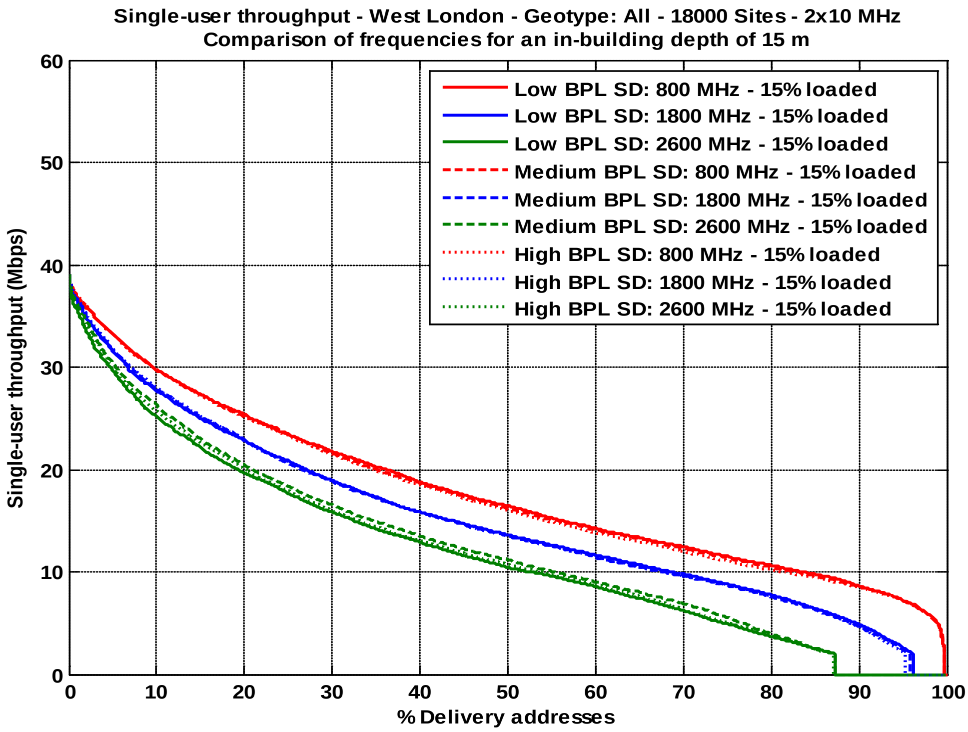
- The higher frequency throughputs show more sensitivity to our range of building penetration loss standard deviation values than the lower frequencies. The magnitude of the difference between the throughputs for *high BPL standard deviation* and *low BPL standard deviation* increases with increasing frequency and this is larger for notional depths of 15 m compared to notional depths of 1 m. The coverage available for lowest throughputs (the point at which the curves meet the x-axis) is not particularly sensitive to building penetration loss standard deviation.

- Increasing the network loading from 15% to 85% slightly decreases the difference between the throughputs for *high BPL standard deviation* and *low BPL standard deviation*. This is in line with the increased loading leading to an increase in interference in most locations from non-serving sectors.

- As the number of sites is increased from 8,000 to 18,000 the magnitude of the difference between the throughputs for *high BPL standard deviation* and *low BPL standard deviation* slightly decreases. This reflects the increased site density leading to increases in both the serving sector received power and the power received from non-serving sectors, which leads to the noise term in the calculation of SINR playing a less dominant role and accordingly variations in building penetration loss are not so apparent

- Figure 17 shows an example of the relevant results for 18,000 sites, 15% network loading and a notional depth of 15m. The curves clearly demonstrate a low sensitivity of the results to our range of median building penetration loss values.

Figure 17: Example showing the sensitivity of the results to BPL standard deviation



SINR cut-off

A14.167 We examined the sensitivity of the single-user throughput results to the SINR cut-off (used in association with the SINR to throughput mapping function). Our comparisons were against results obtained using 'Max var' and 'Min var', noting that we have defined 'Min var' to use a cut-off of -10 dB and 'Max var' to use a cut-off of -5 dB. For this sensitivity study we made the following comparisons:

- 'Max var' with a -5 dB cut-off in comparison to 'Max var-like' with a -10 dB cut-off
- 'Min var' with a -10 dB cut-off in comparison to 'Min var-like' with a -5 dB cut-off

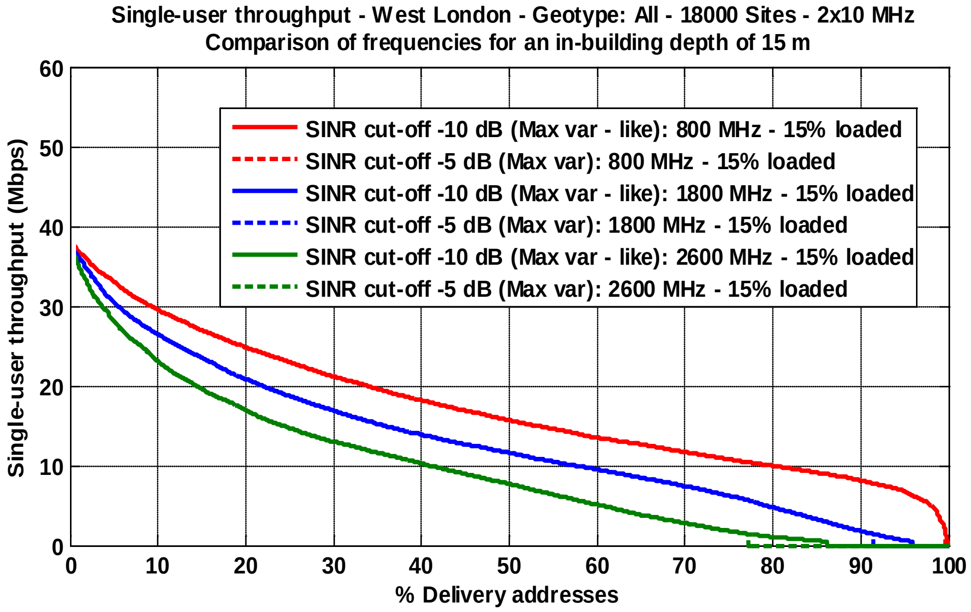
A14.168 The other more general inputs were as given in Table 15.

A14.169 Some clear trends emerge from the results:

- The impact of the choice of SINR cut-off is most apparent at the limit of coverage for the lowest throughputs i.e. the point at which the curves meet the x-axis.
- The 'Max var'/'Max var-like' results are more sensitive to SINR cut-off than the 'Min var'/'Min var-like' results, a finding which aligns with higher building penetration loss values implying more challenging signal quality conditions i.e. lower SINR values.
- As expected, the impact is significantly larger for a notional depth of 15 m than for a notional depth of 1 m.
- The impact of choice of SINR cut-off is relatively insensitive to network loading or number of sites.

- Figure 18 shows an example of the relevant 'Max var'/Max var-like' results for 18,000 sites, 15% network loading and a depth of 15m. The curves demonstrate the sensitivity of the results to SINR cut-off. It can clearly be seen that, for this example, adoption of a -5 dB cut-off, in comparison to a -10 dB cut-off, reduces coverage for the lowest throughputs for 2600 MHz by 8%.

Figure 18: Example showing the sensitivity of the results to SINR cut-off



Loading algorithm

A14.170 We examined the sensitivity of the single-user throughput results to the choice of loading algorithm. Our comparisons were against results obtained using 'Max var' and 'Min var', noting that 'Min var' uses the random loading algorithm and 'Max var' uses the intelligent loading algorithm. For this sensitivity study we made the following comparisons:

- 'Max var' with the intelligent loading algorithm in comparison to 'Max var - like' with the random loading algorithm
- 'Min var' with the random loading algorithm in comparison to 'Min var - like' with the intelligent loading algorithm

A14.171 The other more general inputs were as given in Table 15.

A14.172 Some clear trends emerge from the results:

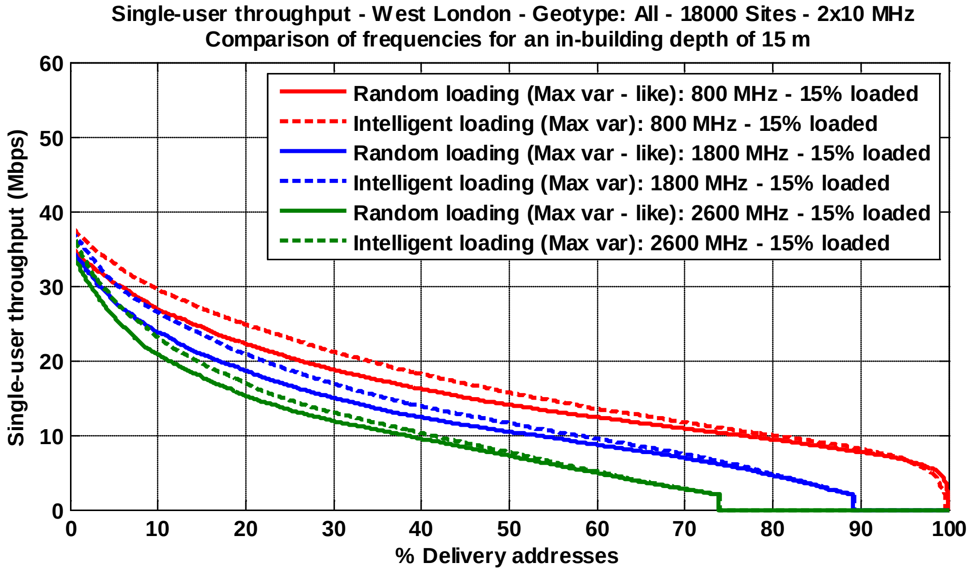
- At low network loading (15%) the intelligent loading algorithm gives better single-user throughput performance than the random loading algorithm. This is in accord with the allocation of resource blocks being such that, for intelligent loading, the resource blocks used in sectors of type α, β and γ (see paragraph A14.75) do not overlap in frequency if the network loading is below 33%. It is also apparent that at low loading the coverage achievable at the lowest throughputs is almost unaffected by the choice of loading algorithm.
- At high network loading (85%) the random loading algorithm gives better performance than the intelligent loading algorithm. In contrast to low loading, at

high loading the coverage achievable at the lowest throughputs is affected by the choice of loading algorithm, with the random loading algorithm giving a higher coverage than the intelligent loading algorithm. This effect is more pronounced for notional 15 m depth as compared with a notional 1 m depth, and is more pronounced for 8000 sites in comparison with 18,000 sites.

- The 'Max var' results are more sensitive to the choice of loading algorithm than the 'Min var' results, particularly for notional depths of 15m.

- Figure 19 shows an example of the relevant 'Max var'/'Max var-like' results for 18,000 sites, 15% network loading and a notional depth of 15m. The curves demonstrate the sensitivity of the results to network loading. It can clearly be seen that, for this example, adoption of the intelligent loading algorithm generally improves the throughputs.

Figure 19: Example showing the sensitivity of the results to loading algorithm



SINR to throughput mapping function

A14.173 Our results rely on mapping SINR to throughput (a measure of user data-rate in Mbps) for a 2 x 2 (transmit x receive) antenna configuration. Though we have used a particular mapping function that we believe is a reasonable representation of the likely performance of real LTE networks when they are deployed ('realistic' mapping function – see paragraphs A14.90 to A14.96), the actual performance real LTE networks will achieve over time remains uncertain. It is possible that for a particular SINR value the data-rate that a real network could support might be significantly greater or less than the value given by the function we are using, and we give this consideration through examination of results using the 'theoretical' mapping function as described earlier (see paragraphs A14.97 to A14.101).

A14.174 We examined the sensitivity of the single-user throughput results to the choice of SINR to throughput mapping function. Our comparisons were against results obtained using 'Max var' and 'Min var', noting that both of these use the 'realistic' mapping function. For this sensitivity study we made the following comparisons:

- 'Max var' with the 'realistic' mapping function in comparison to 'Max var - like' with the 'theoretical' mapping function

- ‘Min var’ with the ‘realistic’ mapping function in comparison to ‘Min var - like’ with the ‘theoretical’ mapping function

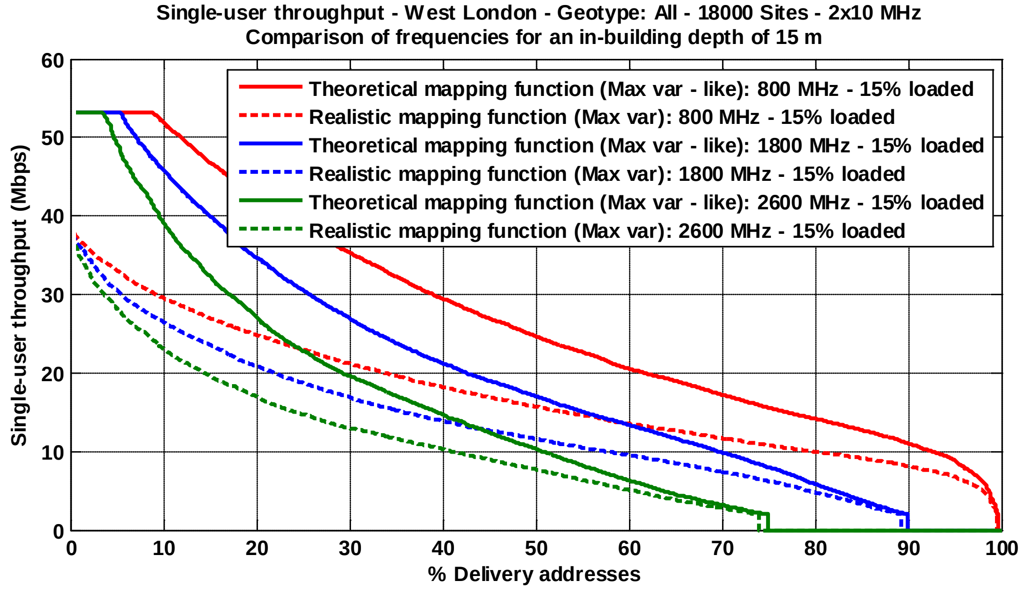
A14.175 The other more general inputs were as given in Table 15.

A14.176 The expected clear trend in the results is that the throughputs are consistently improved by use of the ‘theoretical’ mapping function compared with the ‘realistic’ mapping function. The improvement is such that for low network loading (15%) the throughputs reach a plateau for the best served locations: this being associated with the SINR point in the mapping function beyond which the maximum throughput is achieved.

A14.177 The impact of choice of mapping function on the coverage for low throughputs is minimal i.e. there is very little impact upon the point at which the curves meet the x-axis.

A14.178 Figure 20 shows an example of the relevant ‘Max var’/’Max var-like’ results for 18,000 sites, 15% network loading and a notional depth of 15m. The curves clearly demonstrate the high sensitivity of the results to the adopted SINR to throughput mapping function. However, as we believe that our ‘realistic’ mapping function is likely to give results closer to actual LTE networks in the real world (at least for the short to medium term) and given that we are focussing most on the difference in performance between frequencies rather than absolute performance we are content to rely on the ‘realistic’ mapping functions for our main results in Annexes 6 and 7.

Figure 20: Example showing sensitivity of results to SINR to throughput mapping function



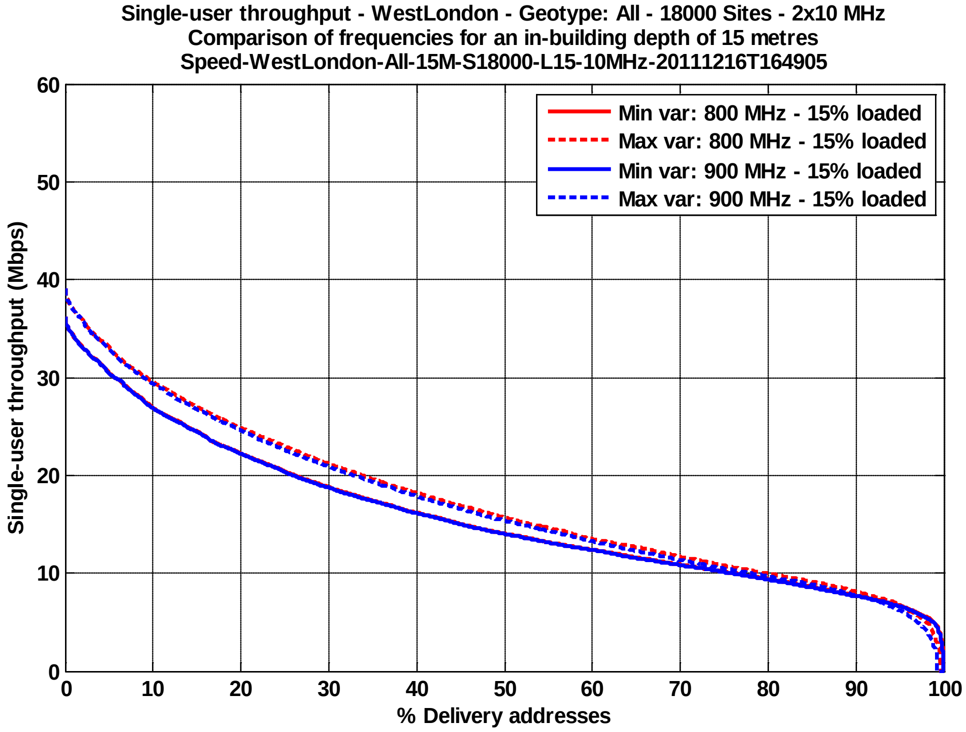
Frequency

A14.179 As stated in paragraph A7.113 in Annex 7, “For the purposes of this analysis we have assumed that 900 MHz performs identically to 800 MHz and that 2100 MHz performs identically to 1800 MHz.”

A14.180 In Figure 21 and Figure 22 below we show the results of a comparison of single-user throughput results for 800 MHz vs 900 MHz and 1800 MHz vs 2100 MHz. These are for the case of a network with the equivalent of 18,000 sites nationally loaded to 15% for a notional depth of 15m. Generally we see a similar picture regardless of site count, loading and notional depth.

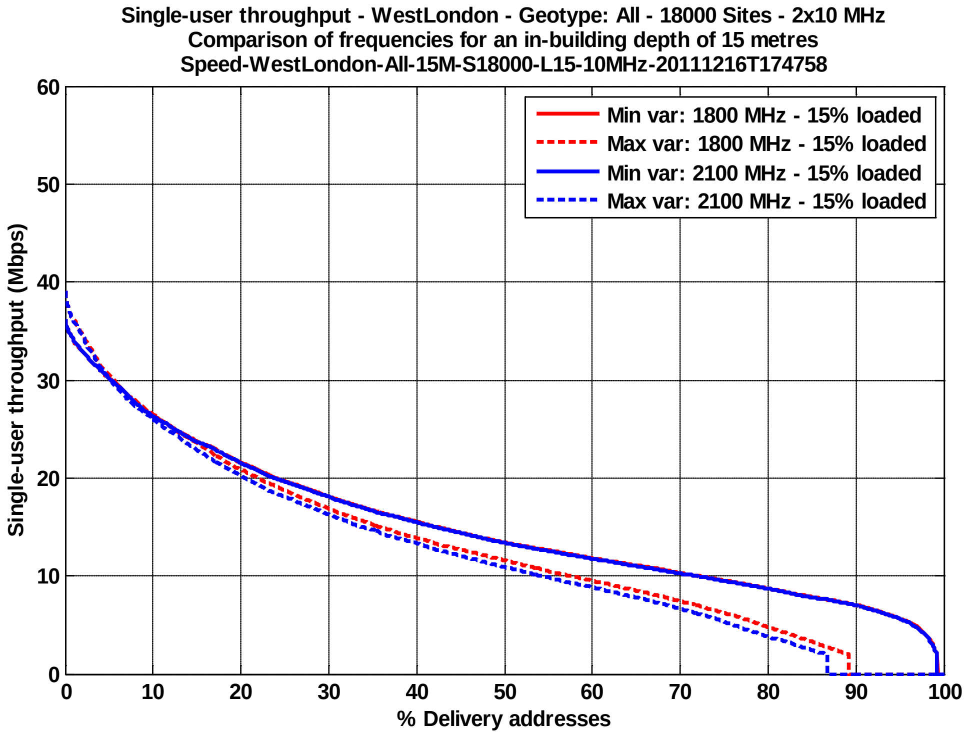
A14.181 For the 800 MHz vs 900 MHz case (Figure 21) we see very little difference in the performance of networks at the two frequencies. As would be expected, 800 MHz performs very slightly better than 900 MHz in the 'Max var' case but the difference is not significant.

Figure 21: Single-user throughput - comparison of 800 MHz vs 900 MHz



A14.182 For the 1800 MHz vs 2100 MHz case (Figure 22) we see a slightly greater difference in the performance of networks at the two frequencies. Again, as expected, 1800 MHz performs slightly better than 2100 MHz in the 'Max var' case. The consequence of this is that any 1800 MHz results in Annexes 6 and 7 that are proxies for the performance of networks operating at 2100 MHz are likely to be slightly over optimistic for the 'Max var' case though we don't consider the difference significant and are content that performance at 1800 MHz is a fair proxy for performance at 2100 MHz.

Figure 22: Single-user throughput - comparison of 1800 MHz vs 2100 MHz



Parameters and assumptions

A14.183 Our parameters and assumptions are given in Table 16.

Table 16: Parameters and assumptions

Ref.	**Parameter/ Assumption**	**Value or range modelled**	**Units**	**Comment**
Simulation area				
0	100 km x 100 km area	West of London NW corner (412300, 250500) NE corner (552300, 250500) SW corner (412300, 110500) SE corner (552300, 110500) Cambridge NW corner (490000, 340000) NE corner (630000, 340000) SW corner (490000, 200000) SE corner (630000, 200000)	(eastings, northings)	The eastings and northings range includes the 20 km buffer zone
Synthetic base station networks				
1	Base station locations	Based on random selection from a generated super-set of sites equivalent to a UK national network of 20,000 sites.	(eastings, northings)	Representative of national networks of various site counts - see paragraphs A14.18 to A14.19
UE test points				
2	UE locations	Postcode unit locations extracted from Code-Point® data	(eastings, northings)	The Postcode unit locations have a local density commensurate with user density

Ref.	Parameter/ Assumption	Value or range modelled	Units	Comment
3	User weighting applied to UE test points	Number of domestic delivery points associated with the Postcode unit location.		Applying a weighting of the number of domestic delivery points to the results for each UE test point provides a weighting that to a first approximation takes into account population density.
Base station parameters				
4	Sectors per site	3		Industry practice
5	Radiated power (EIRP) per 180 kHz LTE resource block	47	dBm	Derived from the maximum value permitted by the proposed technical licence conditions for 800 MHz and 2600 MHz[49]
6	Antenna gain	-		Not explicitly used as we are assuming a fixed EIRP for the downlink modelling.
7	Antenna horizontal 3 dB beam-width	65	degrees	A fixed value for all frequencies based on the Kathrein 742 265 multi-band antenna – interpolated to the mid-point between 800 MHz and 2600 MHz
8	Antenna vertical 3 dB beam-width	7.5	degrees	A fixed value for all frequencies based on the Kathrein 742 265 multi-band antenna – interpolated to the mid-point between 800 MHz and 2600 MHz
9	Antenna down-tilt	variable	degrees	Optimised for frequency and average distance to nearest neighbouring sites

49 http://stakeholders.ofcom.org.uk/consultations/technical-licence-conditions/

Ref.	Parameter/ Assumption	Value or range modelled	Units	Comment
10	Antenna height	variable	m	Distribution representative of existing mobile operators networks - see paragraphs A14.18 to A14.19
UE parameters				
11	Antenna gain (mean effective gain)	-1.1 dBi @800MHz 0.0 dBi @ 1800 MHz +0.5dBi @ 2600 MHz	dBi	Take into account antenna efficiency increasing with frequency as suggested by Vodafone.
12	Antenna height	1.5	m	Standard assumption
13	Body loss (relative to free space)	5.0	dB	Assumption (consistent with previous Ofcom work)
14	Receiver noise figure	10 (800 MHz) 10 (1800 MHz) 9 (2600 MHz)	dB	Derived from 3GPP TS 36.101[50]
Propagation				
15	Location variability (outdoor)	Varies dependent on frequency and clutter	dB	See paragraph A14.25.
16	Location variability (outdoor) cross-correlation coefficient	1.0 (inter-sector) 0.5 (inter-site)		See [[51]]

[50] http://www.3gpp.org/ftp/Specs/html-info/36101.htm
[51] "Advice to Government on the consumer and competition issues relating to liberalisation of 900MHz and 1800MHz spectrum for UMTS", Annex 5, Ofcom, 25 October 2010

Ref.	Parameter/ Assumption	Value or range modelled	Units	Comment
17	Building penetration loss variability	Building penetration loss standard deviation values as given in Table 14: 'Min var' and 'Max var' parameters	dB	See paragraphs A14.52 to A14.56
18	Building penetration loss cross-correlation coefficient	1.0 (inter-sector) 0.5 (inter-site)		Assumption – common with 15
19	Median building penetration loss	Varies according to frequency, clutter characteristics and BPL scenario. See Table 14: 'Min var' and 'Max var' parameters and paragraphs A14.31 to A14.50	dB	See paragraphs A14.31 to A14.51
20	Propagation path loss model	Extended Hata		From [52]
21	Clutter definitions	Infoterra clutter database	50 m x 50 m resolution	
Calculation of throughput				

[52] ERC Report 68 and http://tractool.seamcat.org/raw-attachment/wiki/Manual/PropagationModels/ExtendedHata/Hata-and-Hata-SRD-implementation_v2.pdf

Ref.	Parameter/ Assumption	Value or range modelled	Units	Comment
22	Network loading as applied to non-serving sector interference power in calculation of SINR.	Intelligent allocation of resource blocks was assumed for ‘Max var’ and random allocation of resource blocks was assumed for ‘Min var’. - see paragraphs A14.67 to A14.81		The network loading scheme is taken into account in estimating the probability of interference due to usage of interfering resource blocks in non-serving sectors.
23	SINR to throughput mapping function	‘Realistic’ mapping function as given in paragraphs A14.90 to A14.96	Throughput units of bps/Hz	
24	SINR cut-off	For ‘Max var’ we use an SINR cut-off of -5 dB and for ‘Min var’ we use an SINR cut-off of -10 dB	dB	
25	System overheads	20%		The mapping function used does not include system overheads and these are accounted for separately in the calculation of the available throughputs.
Calculation of capacity				
26	Inclusion of frequency domain packet scheduling	FDPS is only included in the calculation of capacity		See paragraphs A14.112 to A14.115