Consultation on assessment of future mobile competition and proposals for the award of 800 MHz and 2.6 GHz spectrum and related issues

Annexes 7-13

Consultation

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Contents

Annex 7

LTE Modelling – Key Results

A7.1 In this annex we set out the results of our technical modelling of LTE networks. For details of that modelling see Annex 8.

Summary of key results

A7.2 The answers to a number of technical questions are an important input to our assessment of likely future competition in mobile markets:

a) Can an operator without sub-1GHz spectrum, but with higher frequency spectrum, build an LTE network whose performance matches that of an LTE network using 2x20 MHz of sub-1GHz spectrum?

b) Can an operator with only 2x5 MHz or 2x10 MHz of sub-1GHz spectrum, but together with some higher frequency spectrum (for example 1800 MHz spectrum), build an LTE network whose performance matches that of an LTE network built by an operator with 2x20 MHz of sub-1GHz spectrum? And how much higher frequency (1800 MHz) spectrum do they need?

c) If an operator has only 2x5 MHz or 2x10 MHz of sub-1GHz spectrum, is it enough for them to have access to sufficient 2.6GHz spectrum in order to match the performance of a network built using 2x20 MHz of sub-1GHz spectrum, or do they need access to 1800 MHz spectrum?

d) And what if the largest sub-1GHz carrier that any operator deploys is only 2x15 MHz rather than 2x20 MHz?

A7.3 In all cases the metrics of performance that we consider are:

- Coverage – the proportion of the population within an area to which it is technically possible to deliver a service with a particular downlink speed (if all the resources of the serving cell were dedicated to a single customer), as a function of the number of network sites (and in some cases the loading on the network);[1]

- Speed – for a given number of sites and network loading,[2] the downlink throughput (if 85% of the resources of the serving cell were dedicated to a single customer) attained or exceeded by a particular proportion of the population;[3]

[1] Note that this measure is of coverage and not capacity. In order to serve a customer at the very edge of coverage of a cell, the network will have to dedicate all of the resources of that cell to that single customer and will not be able to serve any other customers simultaneously in the same cell.

[2] The loading is defined here as the percentage of available resources (frequency and time) used to deliver download service to users. The specified loading applies to all cells within the modelled network except the serving cell, which is taken to be using 85% of its available resources to deliver service to users.

[3] Again, this is a measure of what is technically possible, not of the capacity of the network. In order to deliver the given speed to a customer at the edge of coverage (for that speed), the network will have to dedicate 85% of the resources of the cell serving that customer to that single customer, and will not be able to serve any other customers simultaneously in the same cell.

- Capacity – for a given downlink speed and network loading, the number of sites needed to provide enough capacity to simultaneously serve a certain proportion of the population within an area with the given downlink speed.

A7.4 All of the results in this annex are from a model of the performance of mobile networks providing service to a 100km x 100km area to the west of London (see Annex 8 for further details). We consider this area to be a not unreasonable proxy for the more populous areas of the UK – urban, suburban and populous rural – but it is probably not a particularly good proxy for less populous areas. We anticipate however that competition between national wholesalers will focus predominantly on network performance in more populous areas, where the vast majority of customers spend most of their time, and consequently consider it not unreasonable to base our analysis on these results.

A7.5 Results are based on LTE networks deploying 2x2 MIMO on macro-sites and are calculated assuming users are relatively deep within buildings (depth 2+: see Annex 8 for further details about the modelling approach and parameters)

Can an operator without sub-1GHz spectrum, but with higher frequency spectrum, build an LTE network whose performance matches that of an LTE network using 2x20 MHz of sub-1GHz spectrum?

A7.6 We compare the modelled performance of three networks, using in each case the same bandwidth of spectrum (2x20 MHz contiguous), but at different frequencies: 800 MHz, 1800 MHz and 2.6 GHz.

A7.7 Looking first at coverage, we see that for any given number of sites and guaranteed downlink data-rate, the model predicts that a network operating at 800MHz will be able to reach a consistently higher proportion of the population[4] than networks operating at 1800 MHz or 2.6 GHz. We also see that the predicted gap in coverage between networks using different frequencies widens somewhat as the guaranteed downlink data-rate increases (compare the difference in coverage at 1.2Mbps with the difference in coverage at 4Mbps).[5]

[4] Note that the model looks at the quality of service provided indoors (inside buildings) rather than outdoors, since there is evidence that most mobile broadband usage occurs indoors rather than outdoors.

[5] The network loading in these figures is at 85% of available resources, except in the 4.0 Mbps case where both 15% and 85% are compared.

Figure A7.1

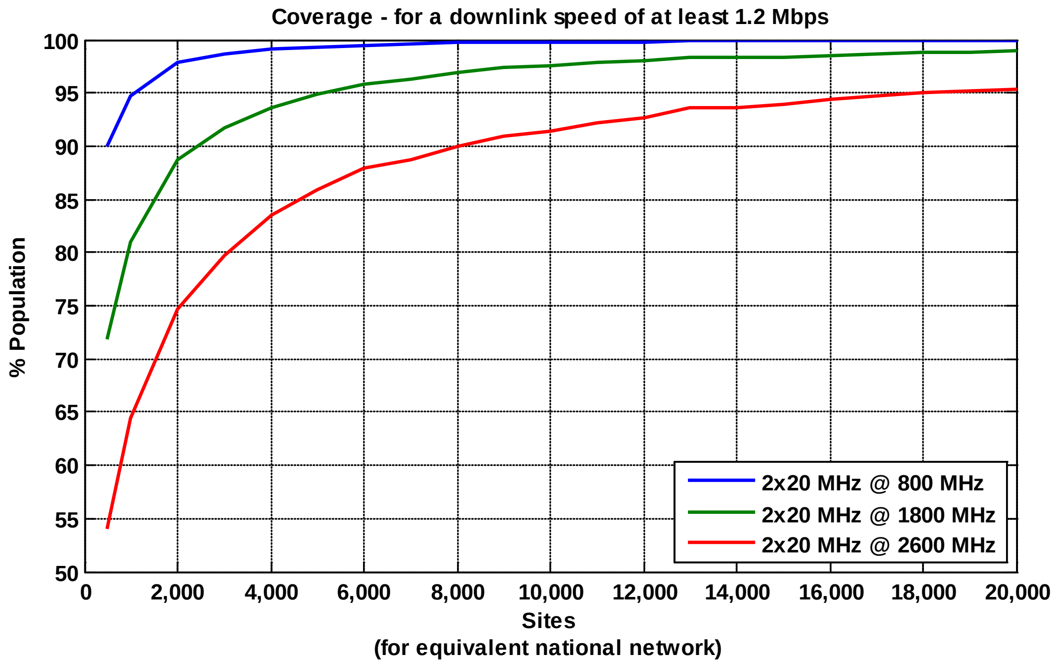


Figure A7.2

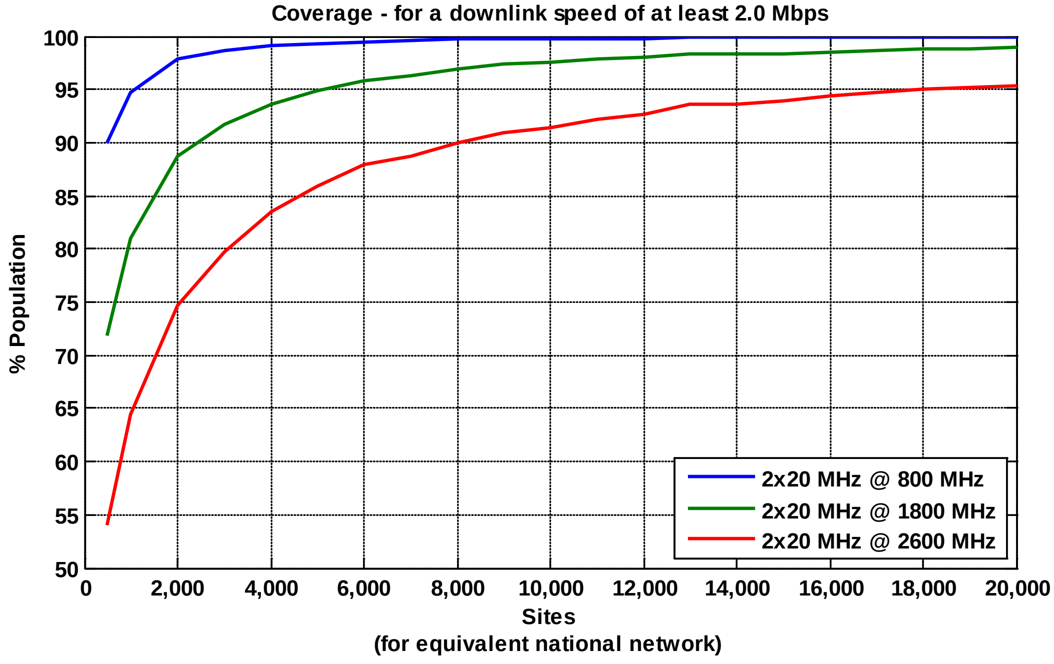
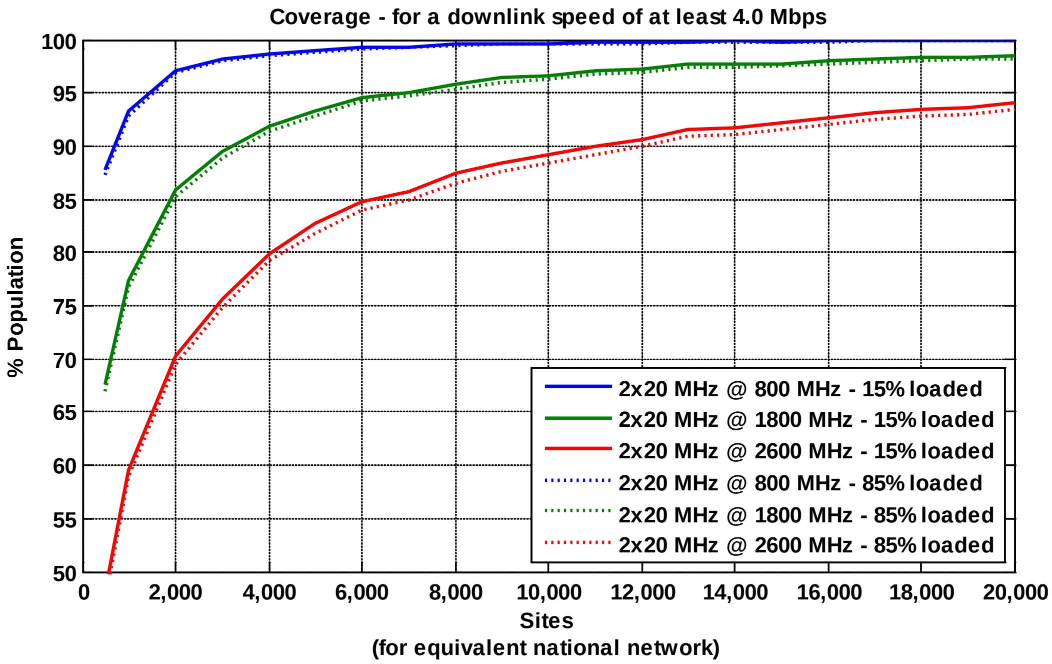


Figure A7.3



A7.8 Looking at these graphs in another way, we see that the predicted number of sites needed to achieve a given level of coverage, for a given guaranteed downlink data-rate is consistently higher for networks using 1800 MHz or 2.6 GHz than for a network using 800 MHz. For lower levels of coverage, below 90% say at 2Mbps, the difference in the number of sites required is perhaps moderate, in particular in respect of 1800 MHz spectrum. However, for higher levels of coverage the gap is wider, and for 2.6 GHz in particular the number of sites required to provide coverage above say 95% at a downlink data-rate of 2.0Mbps starts to look unfeasibly large.

A7.9 Turning next to speed (single-user throughput), we see that the model predicts quite a big difference in the maximum speed that can be provided to any given proportion of the population between a network using 800 MHz spectrum (highest speed) and one using 2.6 GHz spectrum (lowest speed) if the networks are lightly loaded (15% loaded). However, the speed advantage offered by an 800 MHz network, whilst not disappearing completely, becomes relatively less for most customers as the networks become more heavily loaded.

A7.10 However, the model shows this effect over the whole range of network sizes modelled and it is relatively insensitive to network sizes above the equivalent of about 5,000 sites (though differences in speed get less as the number of sites the network has increases). Below about 5,000 sites coverage effects start to dominate but a speed advantage is still very much apparent for lower frequency networks.

Figure A7.4

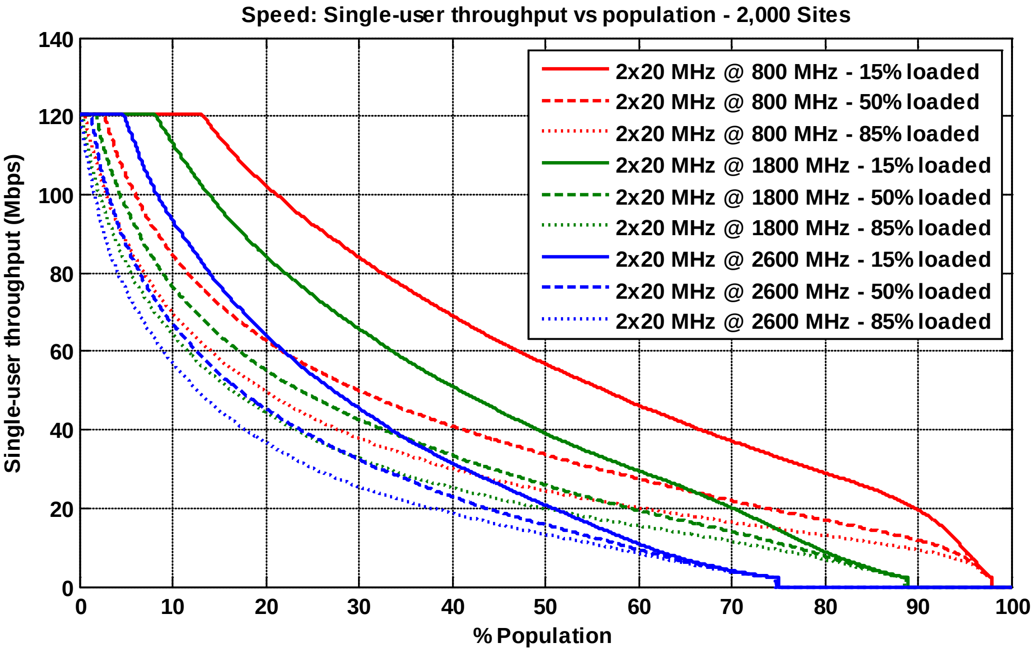


Figure A7.5

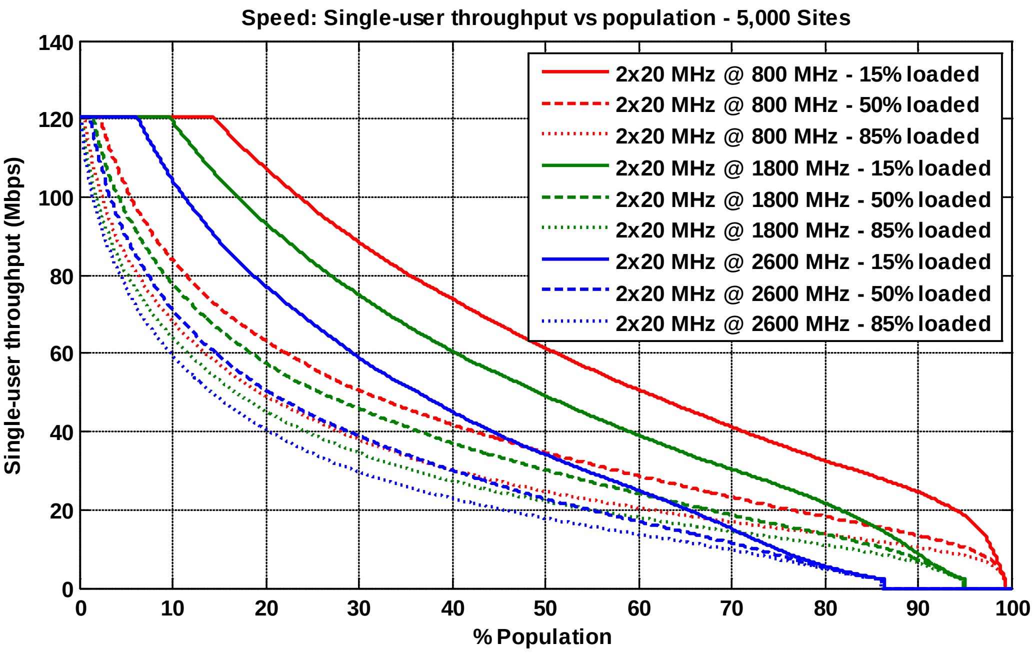


Figure A7.6

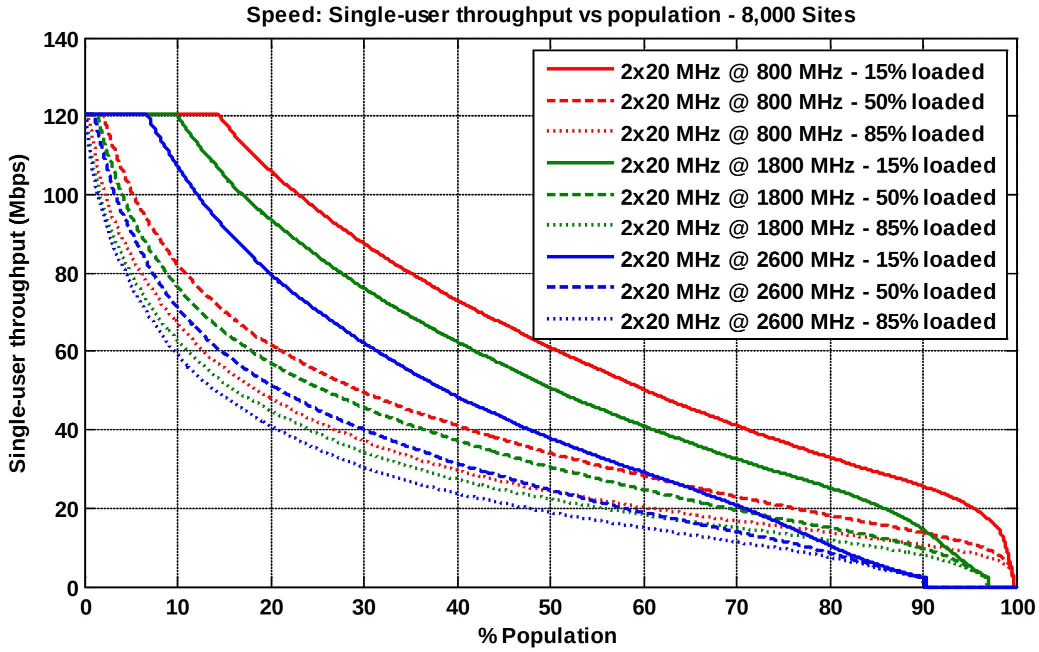
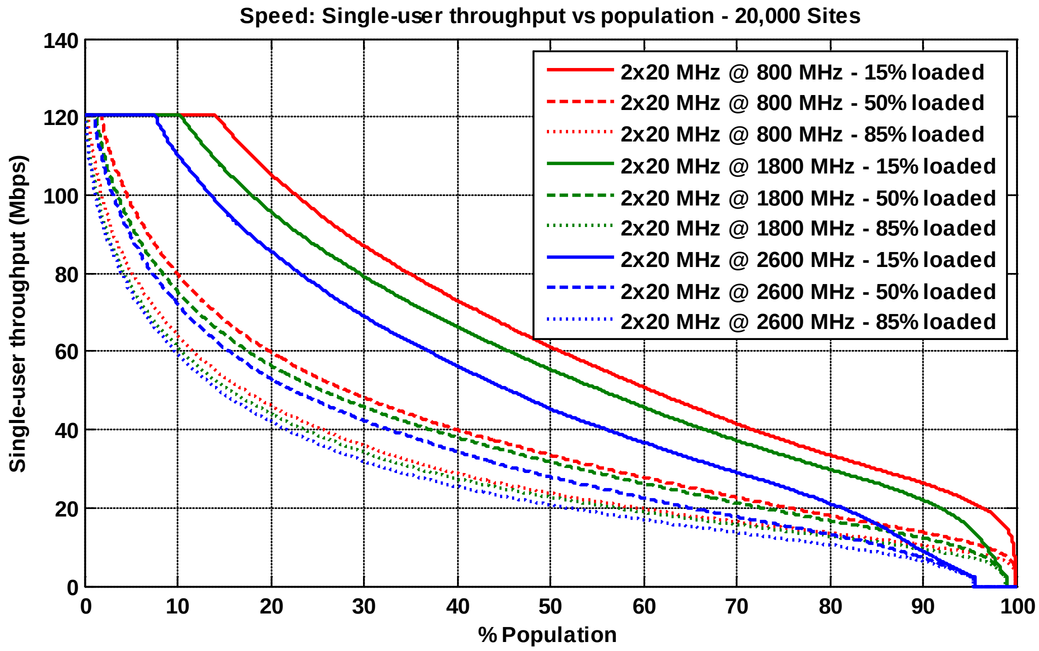
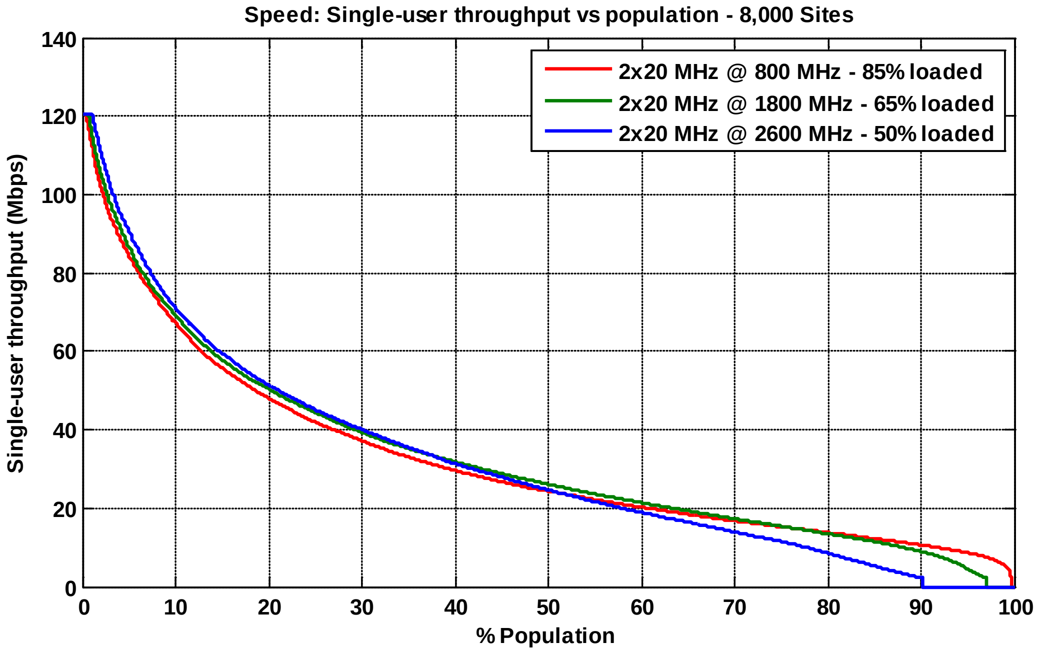


Figure A7.7



A7.11 The model suggests therefore that the operator of a higher frequency network might be able to match the speed offered by a lower frequency network by operating at a somewhat lower loading (albeit this would have consequences for the capacity of the network unless the operator either had more spectrum or more sites) – for example either a 2.6 GHz network operated at 50% loading or a 1.8 GHz network operated at 65% is predicted to achieve a similar maximum speed for most customers as does an 800 MHz network operated at 85% loading.

Figure A7.8



A7.12 What the model results show clearly however is that even with a reduction in loading there remains a gap between the performance of an 800 MHz network and a network using a higher frequency (whether 1800 MHz or 2.6 GHz) at the edge of coverage, with this gap being wider in the case of 2.6 GHz than in the case of 1800 MHz spectrum.

A7.13 Finally, comparing the predicted capacities of the three networks at the loadings compatible with matching single-user throughput, we see that whilst the 800 MHz network has somewhat higher capacity than either the 1800 MHz or 2.6 GHz networks, the difference is in all cases less than a doubling of capacity, and is almost a constant ratio of capacity between networks over a range of network sizes and downlink data-rates.

Figure A7.9

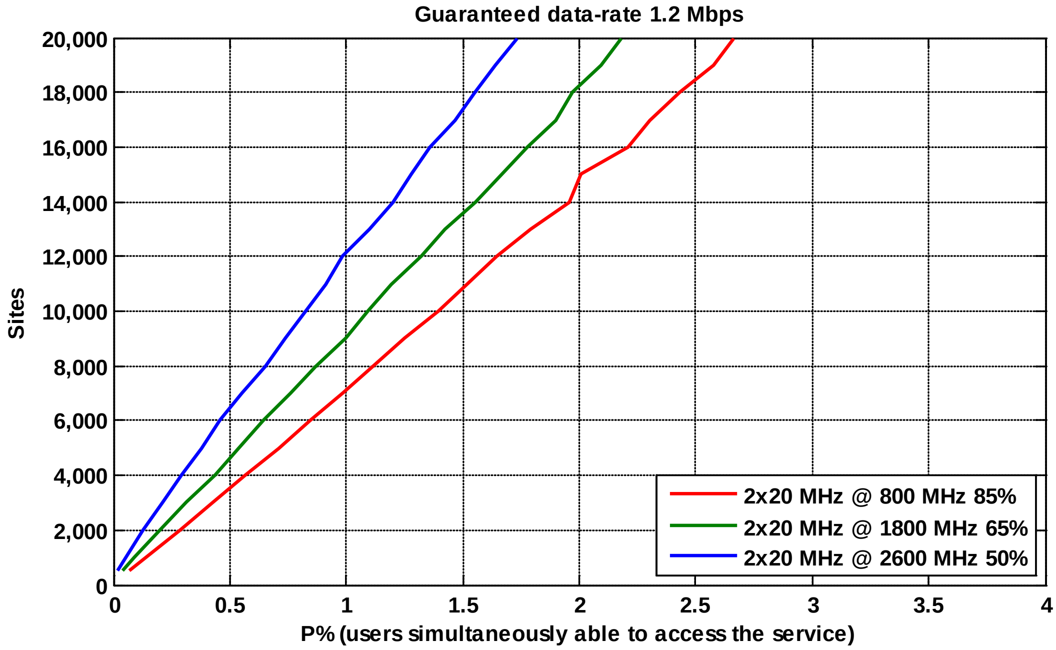


Figure A7.10

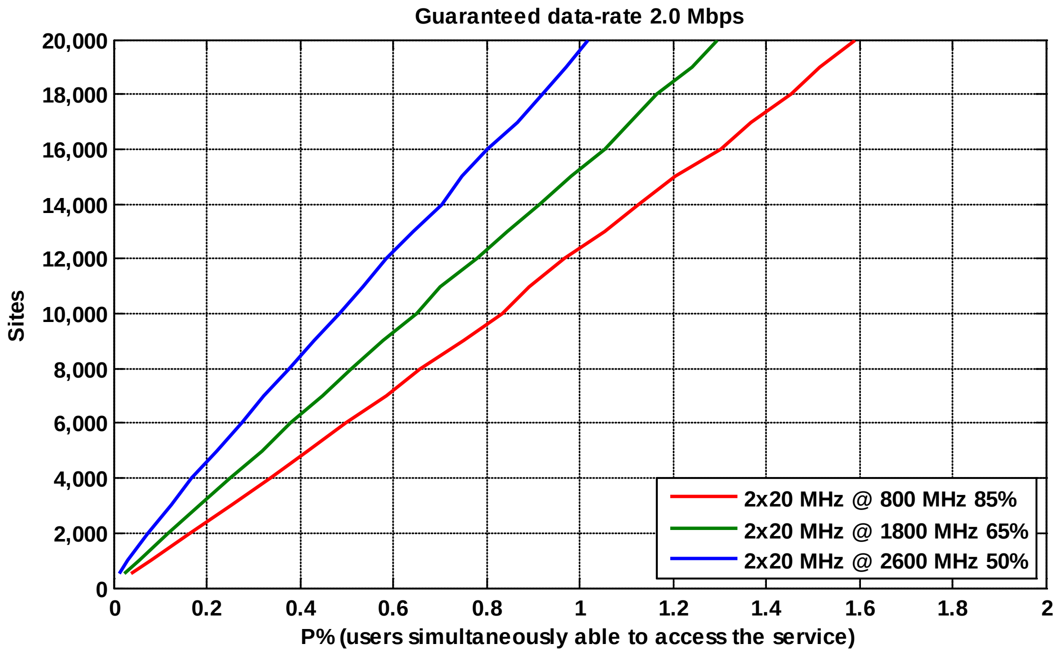
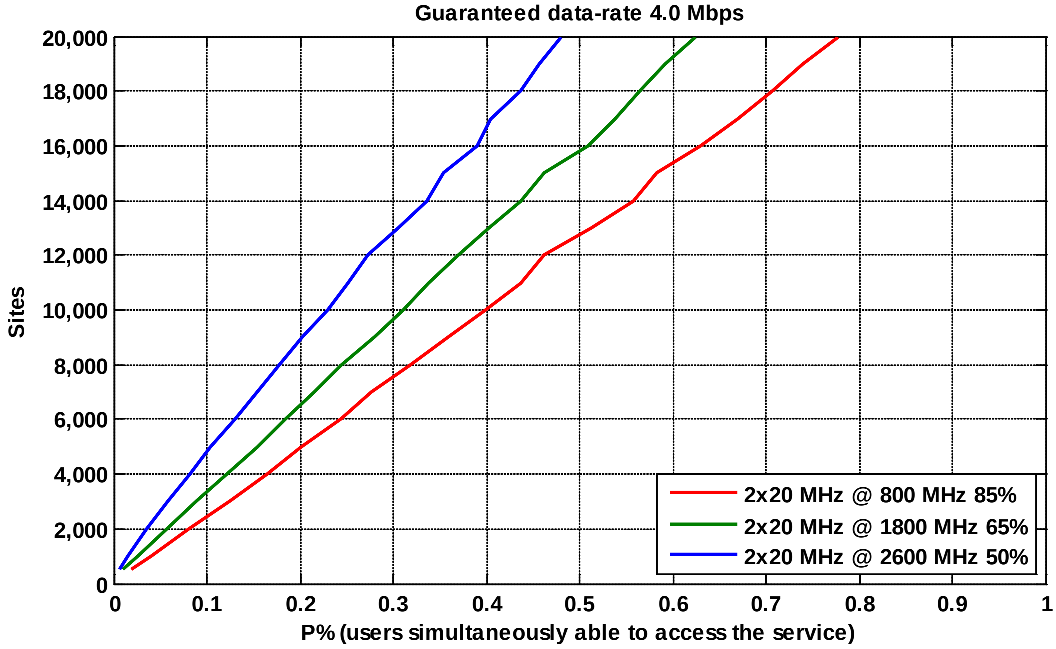


Figure A7.11



A7.14 In summary therefore, we see that the model predicts a difference in coverage between networks using different frequencies with the same number of sites. In some circumstances it may be possible to match the coverage of an 800 MHz network when using higher frequencies through the deployment of more sites, but in other circumstances this may be impractical. To the extent that 800 MHz provides a speed (single-user throughput) advantage over higher frequencies, this may be matched for the majority of customers by operating a higher frequency network at lighter loading (at the expense of potential capacity), but the model predicts that such matching will not be possible at the edge of coverage given equal numbers of sites. Finally, whilst the model predicts some difference in capacity between networks using the different frequencies at the maximum loadings compatible with matching single-user throughput, these do not appear to be particularly large.

Can an operator with only 2x5 MHz or 2x10 MHz of sub-1GHz spectrum, but together with some higher frequency spectrum (for example 2x15 MHz of 1800 MHz spectrum), build an LTE network whose performance matches that of an LTE network built by an operator with 2x20 MHz of sub-1GHz spectrum?

A7.15 To answer this question we look at the predicted performance of three networks using different amounts of 800 MHz spectrum:

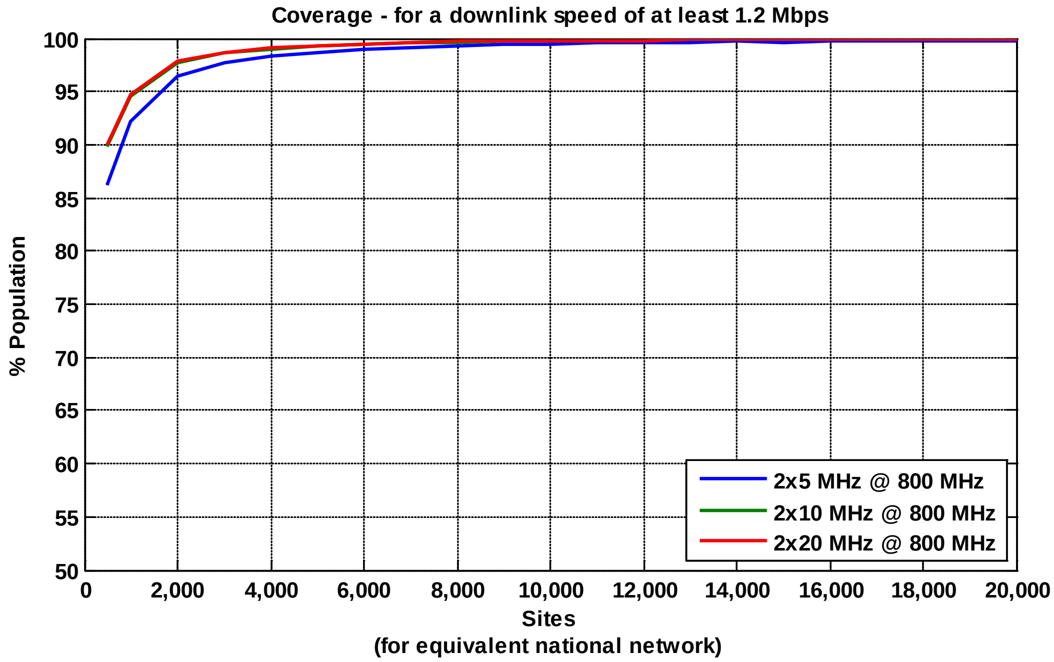
a) 2x5 MHz @ 800 MHz + 2x15 MHz @ 1800 MHz;

b) 2x10 MHz @ 800 MHz + 2x15 MHz @ 1800 MHz;

c) 2x20 MHz @ 800 MHz.

A7.16 Looking first at coverage, we see that for a guaranteed downlink data-rate of 2Mbps or less, there is very little difference in the coverage provided by the three networks, and even for a downlink data-rate of 4Mbps the difference in coverage is quite small provided that the 800 MHz layer of the multi-frequency networks is only lightly loaded. It is only when we look at higher guaranteed downlink data-rates, such as 8Mbps, that we start to see a significant difference in coverage between the networks[6], irrespective of the network loading, with the network having only 2x5 MHz of 800 MHz spectrum struggling to provide this sort of speed to much more than 80% of the population irrespective of loading[7].

Figure A7.12



[6] The modelling carried out does not explicitly account for the minimum SINR needed to achieve synchronisation, it is possible that this could affect the data-rate at which a difference in coverage between the networks starts to become significant.
[7] Note again that the model is looking at indoor coverage; outdoor coverage should be significantly better than this.

Figure A7.13

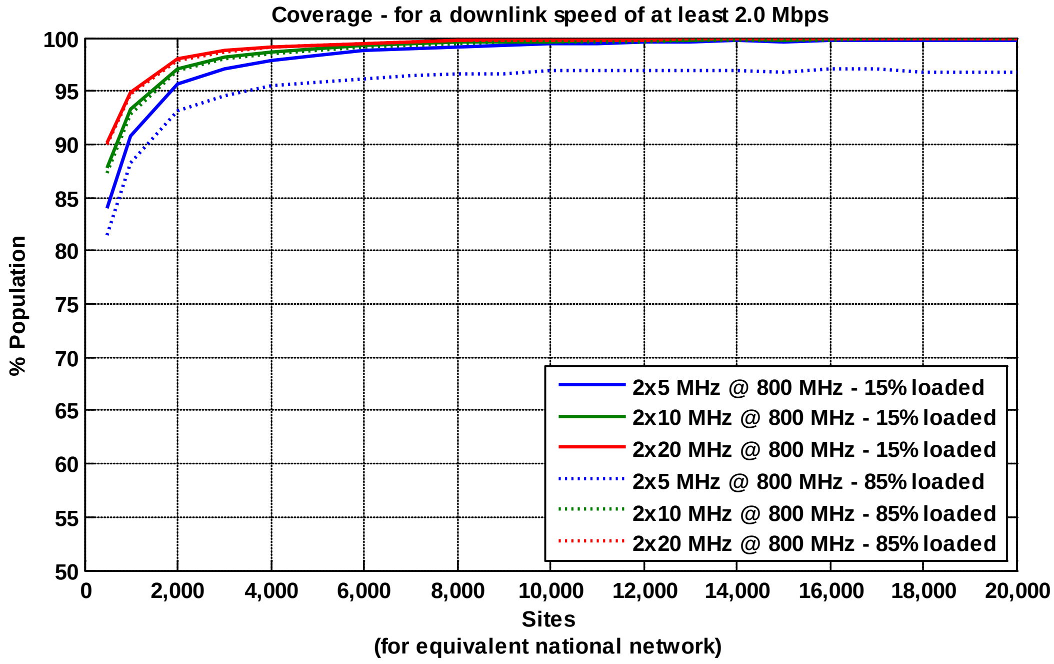


Figure A7.14

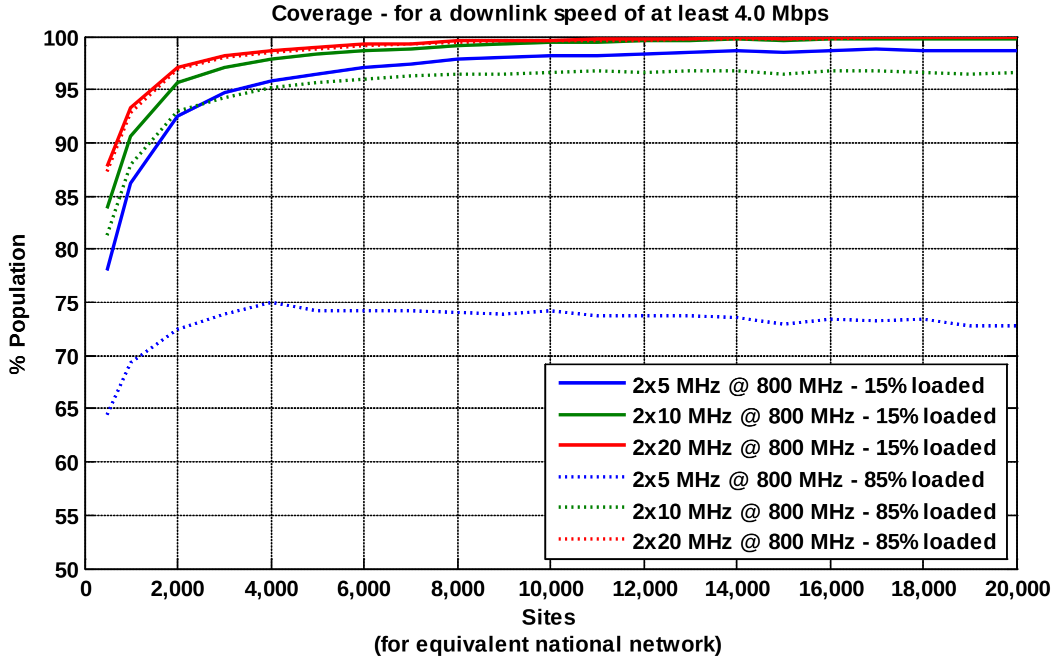
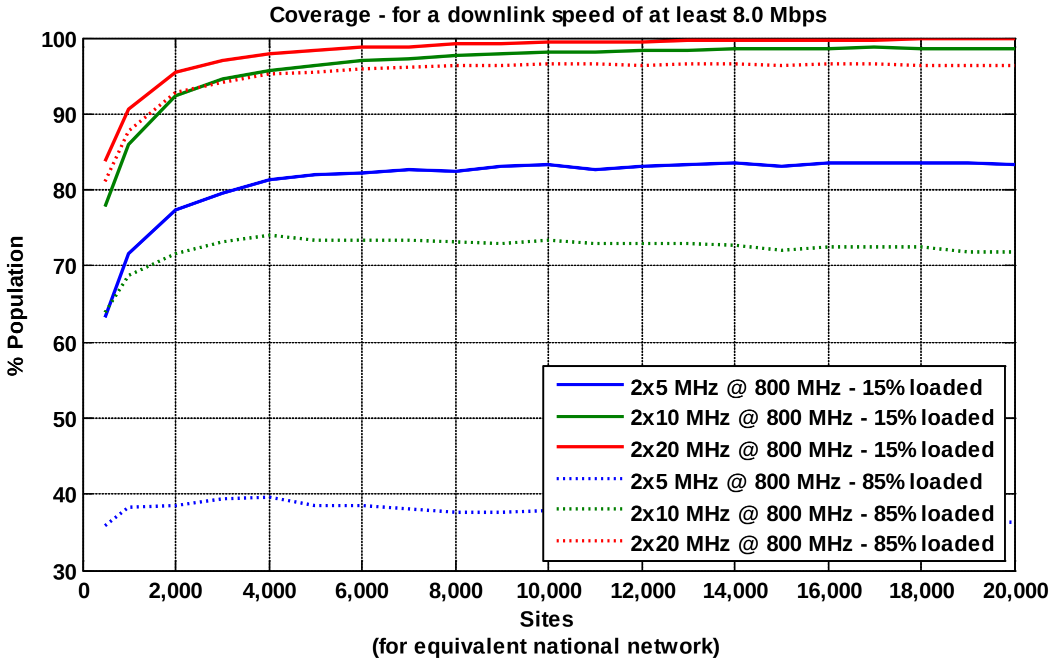


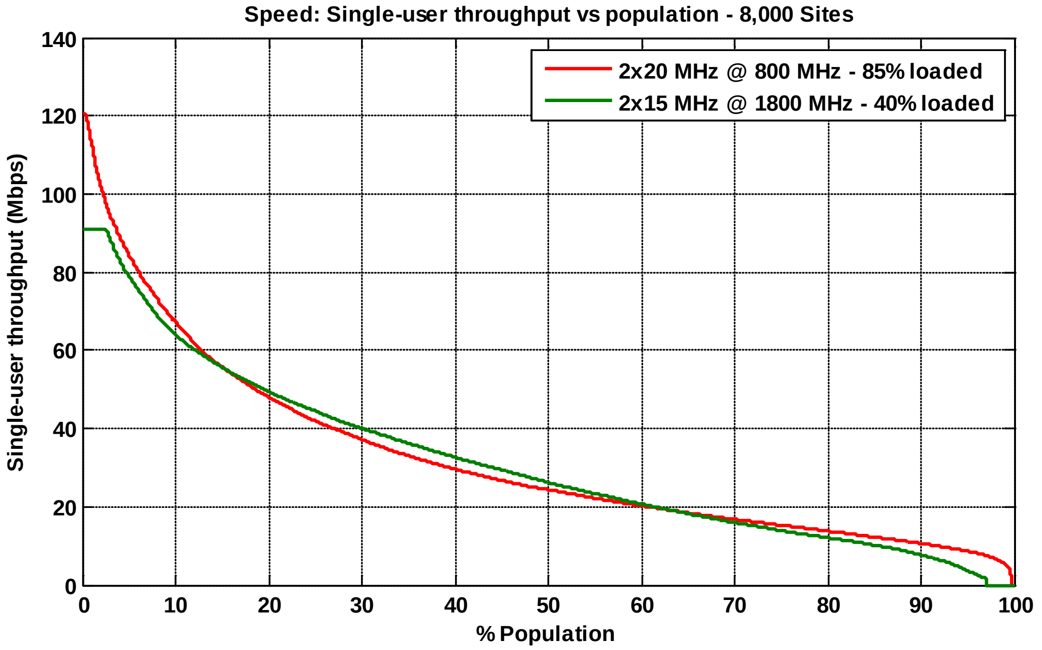
Figure A7.15



A7.17 Looking at coverage for a heavily loaded 2x5 MHz carrier at 800 MHz for downlink speeds of 4 Mbps and above, we see a slight reduction in coverage as site numbers increase above about 4,000. This is an artefact of the modelling process due to subtle effects caused by vertical antenna patterns and imperfect down-tilt optimisation and is not significant for the discussion.

A7.18 Moving on to consider maximum speed (single-user throughput), we first consider to what extent a network layer using 2x15 MHz of 1800 MHz spectrum might be able to match the maximum speed deliverable by a network using 2x20 MHz of 800 MHz spectrum if the 800 MHz network is fully loaded (85% loaded) but the 1800 MHz layer is more lightly loaded. What the model predicts is that for most customers a 2x15 MHz 1800 MHz layer operating at 40% loading would be able to match the maximum speed of a 2x20 MHz 800MHz network operating at 85% loading.

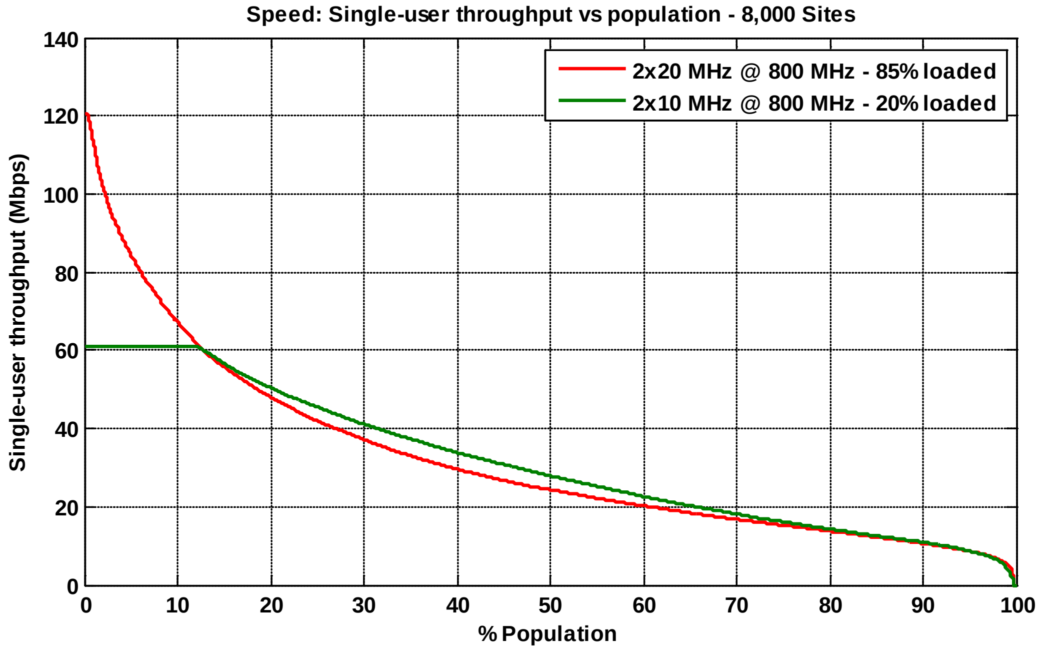
Figure A7.16



A7.19 The gaps in performance of a 2x15 MHz 1800 MHz layer are at the very centre of each cell where the absolute peak data-rate that a 2x15 MHz carrier can deliver is only three quarters of that which a 2x20 MHz carrier can deliver, and at the edge of coverage where the performance of a 2x15 MHz 1800 MHz layer drops off relative to that of a 2x20 MHz 800 MHz network. We therefore next look at the extent to which the 800 MHz layer in a multi-frequency network might be able to fill this latter gap.

A7.20 What we see here is that if the 800 MHz layer is only lightly loaded (say 20% loaded) then a network with 2x10 MHz of 800 MHz spectrum is predicted to pretty well match or even better the speed of a network with 2x20 MHz of 800 MHz spectrum which is heavily loaded (85% loaded), certainly at the edge of coverage, and actually over most of the area.

Figure A7.17

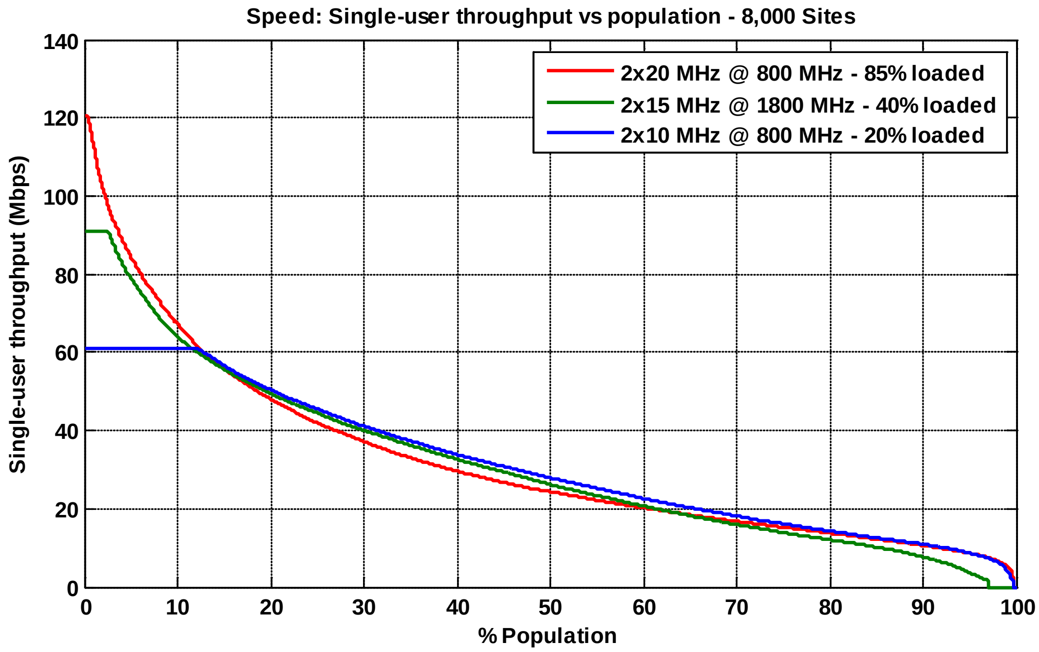


A7.21 Combining the use of 1800 MHz spectrum and 800 MHz spectrum in a 'doughnut' arrangement[8] is therefore predicted to allow an operator with 2x10 MHz of 800 MHz spectrum plus 2x15 MHz of 1800 MHz spectrum to pretty well match the speed that an operator with 2x20 MHz of 800 MHz spectrum can provide over almost the entire area.[9]

[8] Using the larger bandwidth of higher frequency spectrum to serve customers near the centre of each cell (with good signal quality) and the smaller bandwidth of lower frequency spectrum to serve customers nearer the edge of each cell (with poorer signal quality).

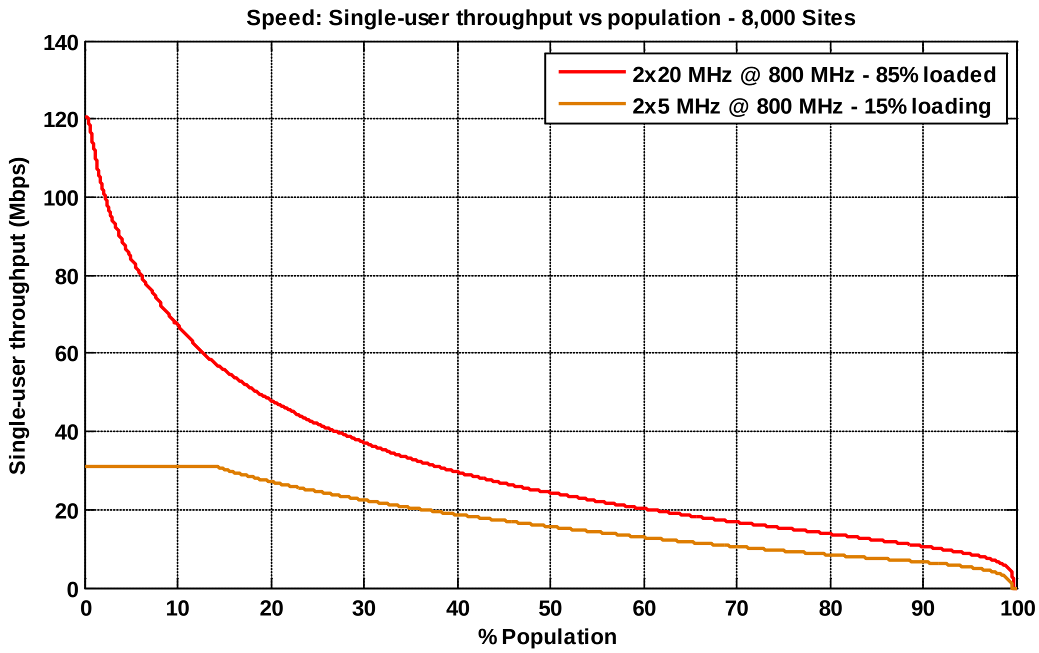
[9] This analysis is something of a simplification since our modelling of single-user throughput is based on an assumed uniform distribution of customers within each cell, whereas if a doughnutting arrangement is used the distribution of customers on each layer will be non-uniform; customers on the higher-frequency layer will tend to be closer to the centre of the cell and customers on the lower-frequency layer will tend to be closer to the edge of the cell. In practice therefore it may be possible to sustain a higher loading of the higher-frequency layer, but may be necessary to operate the lower-frequency layer at a lighter loading to achieve the same speed.

Figure A7.18



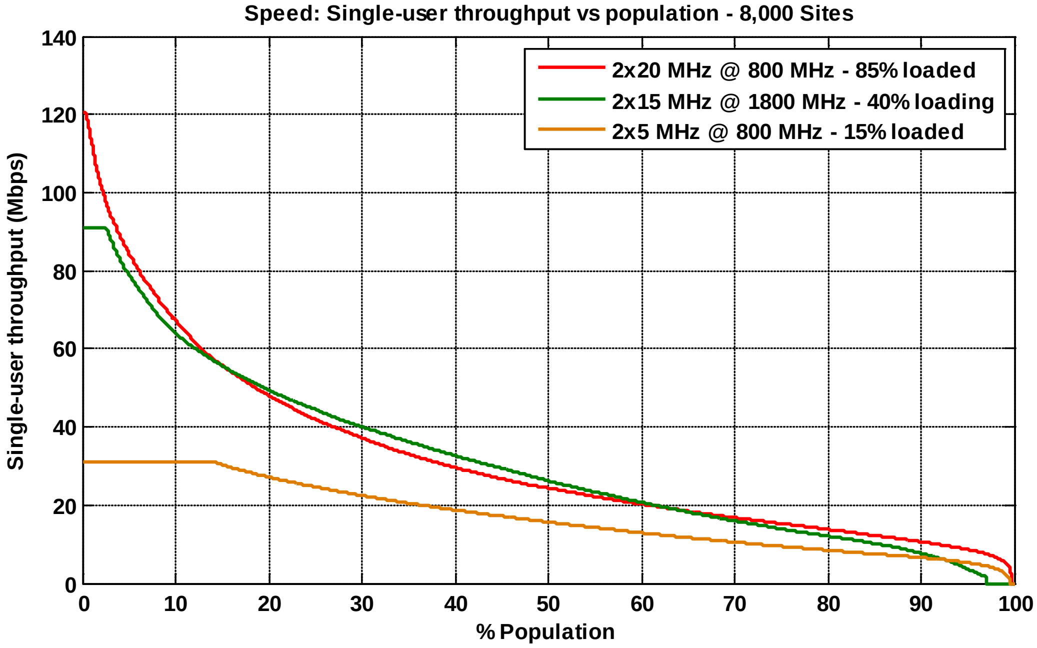
A7.22 In the case of a network with only 2x5 MHz of 800 MHz spectrum, even if lightly loaded, there remains some gap in the maximum speed that the network can deliver to customers at the edge of coverage, but the network can, none the less, deliver a service with a reasonable downlink data-rate to almost the same set of customers as the network with 2x20 MHz of 800 MHz spectrum.

Figure A7.19



A7.23 In this case the 'doughnutting' of frequencies is predicted to give near comparable maximum speeds to most customers, but with some drop off in speed at the very edge of coverage.

Figure A7.20



A7.24 Looking at the capacity of these different networks when operating at the maximum loadings compatible with matching single-user throughput, we see that, unsurprisingly, the 2x20 MHz 800 MHz network operating at 85% loading has a rather higher capacity (ability to simultaneously serve customers for a given number of sites) than do either of the modelled multi-frequency networks. Operators of such multi-frequency networks would therefore be constrained in their ability to simultaneously serve large numbers of customers if the modelled spectrum was all that they had available to them, and they were to operate with a similar number of sites as any operator with 2x20 MHz of sub-1GHz spectrum.

Figure A7.21

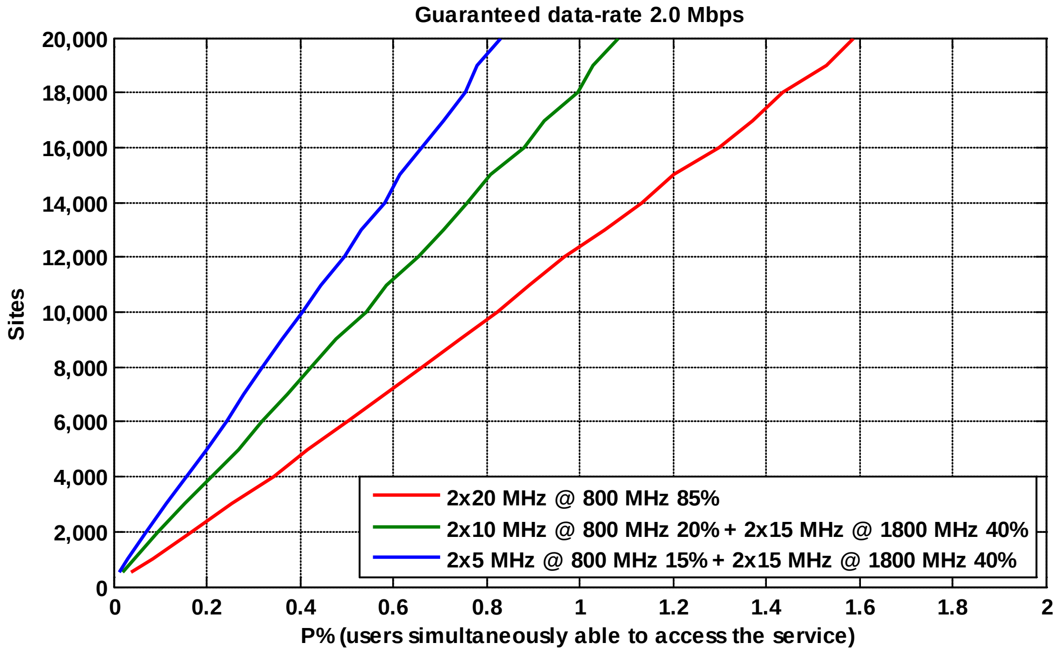
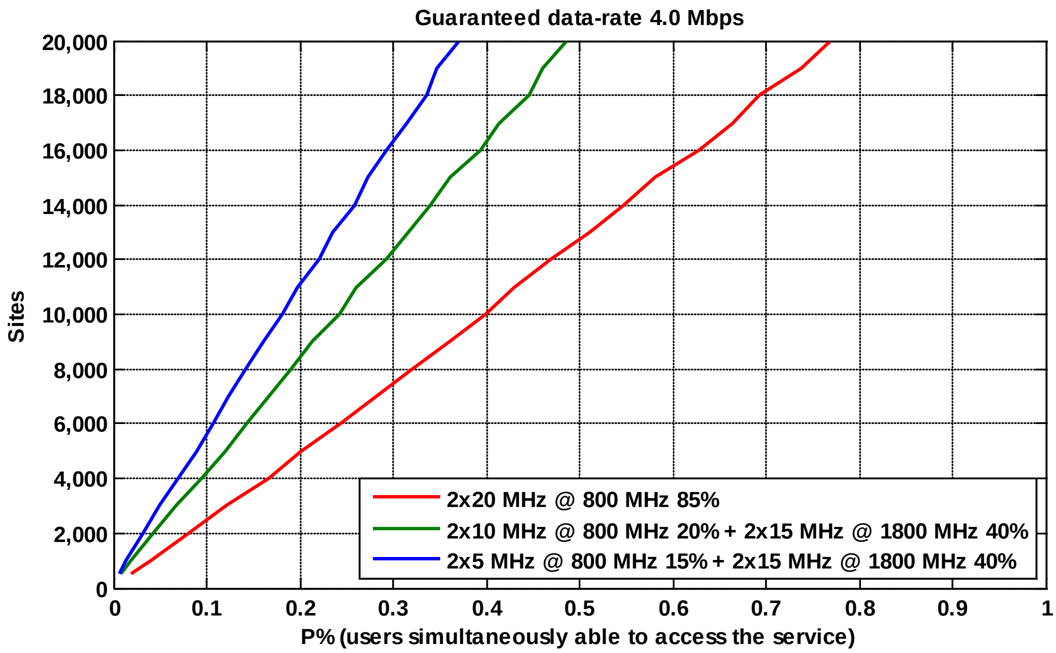


Figure A7.22



A7.25 In summary therefore, multi-frequency networks with a limited amount of sub-1GHz spectrum and also a limited amount of above-1GHz spectrum can never the less go a long way towards matching the coverage and maximum speed deliverable by a network with only sub-1GHz spectrum using the same number of sites, provided that the multi-frequency networks are not loaded to the same extent as the sub-1GHz only network. This requirement for lighter loading does however mean that, all other things being equal, such multi-frequency networks will not be able to serve the same number of customers as a sub-1GHz only network with a similar amount of spectrum.

A7.26 It may be that such differences in capacity would not preclude an operator with only a limited amount of sub-1GHz spectrum from having a material impact on competition – such an operator may be an effective competitor, notwithstanding the more limited number of customers that they can serve. But there may also be ways in which an operator with only limited sub-1GHz spectrum could increase the capacity of their network. One way would be for them to have more higher frequency spectrum – see below. Another way might be to make greater use of other technologies, such as femtocells and WiFi, to off-load traffic from their macro-cell network, both as a general means of increasing capacity, and potentially as a way of providing coverage and capacity in some more difficult to serve locations, thereby releasing capacity on the lower frequency macrocell layer that can then be used to improve the quality and capacity of service in other hard to serve locations. It is therefore by no means clear that operators need to have macrocell networks with even comparable capacities, let alone identical capacities, in order for them to be effective competitors.

How much difference does it make if an operator with sub-1GHz spectrum has access to 2x20 MHz of 1800 MHz spectrum, rather than just 2x15 MHz?

A7.27 If an operator with 2x5 MHz or 2x10 MHz of 800 MHz spectrum had access to 2x20 MHz of 1800 MHz spectrum, rather than just 2x15 MHz, they would be able to run their 1800 MHz layer at a higher loading (e.g. 65% loaded) and still match the speed of a network with 2x20 MHz of 800 MHz spectrum (assumed to be operating at 85% loading).

Figure A7.23

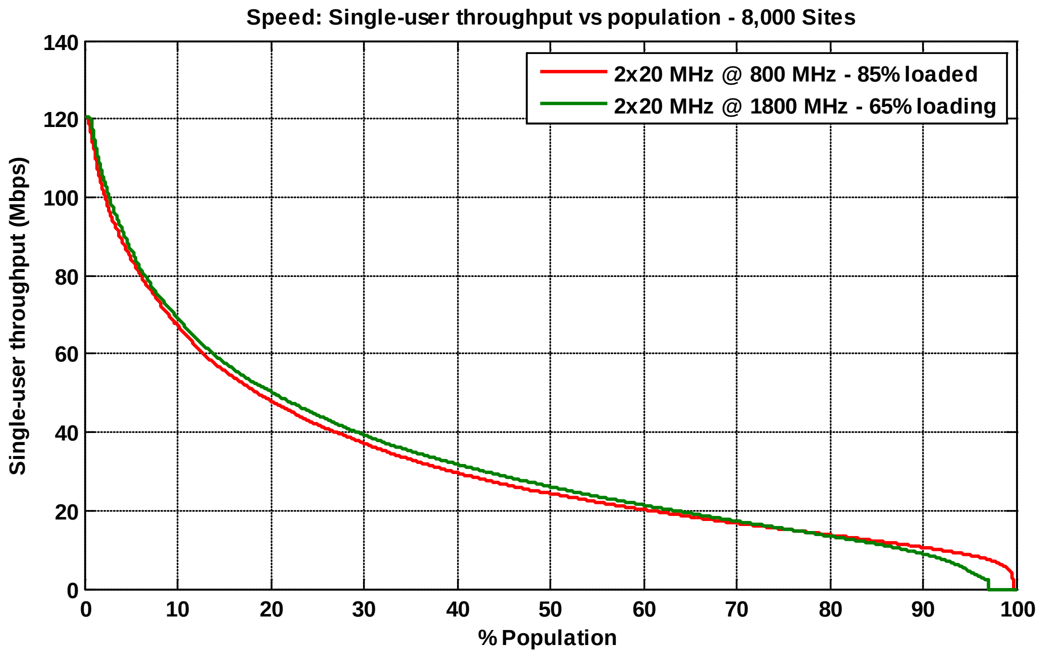


Figure A7.24

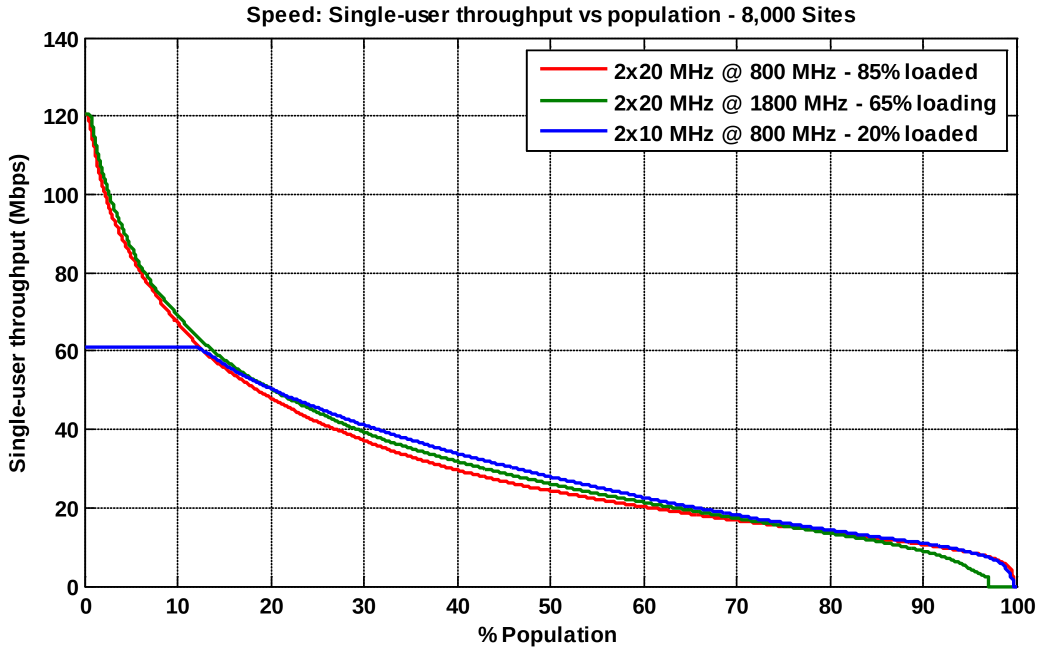
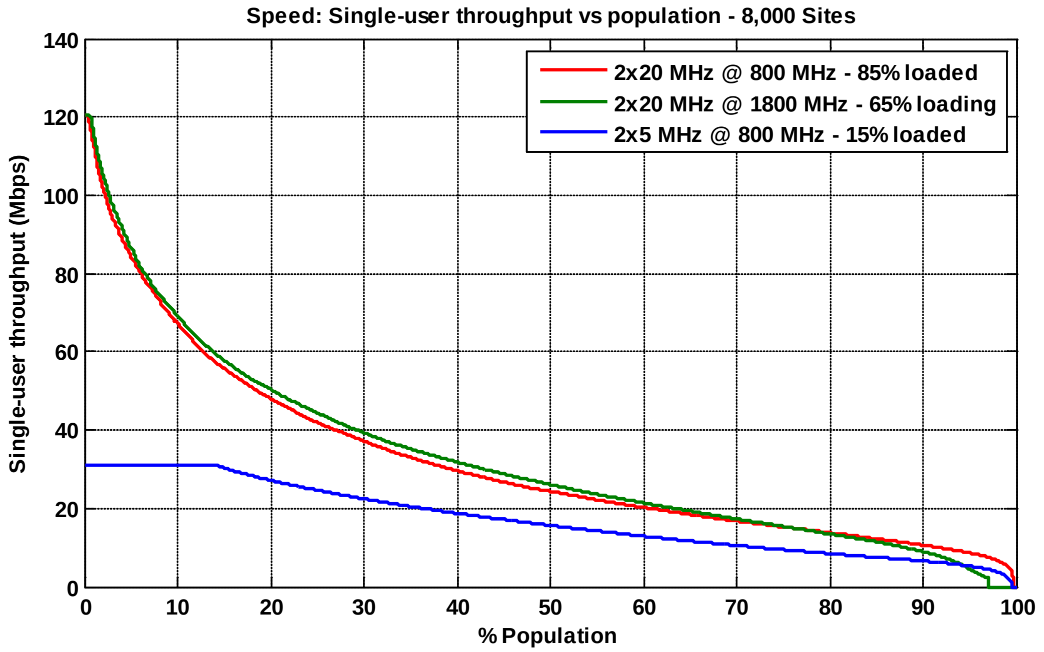
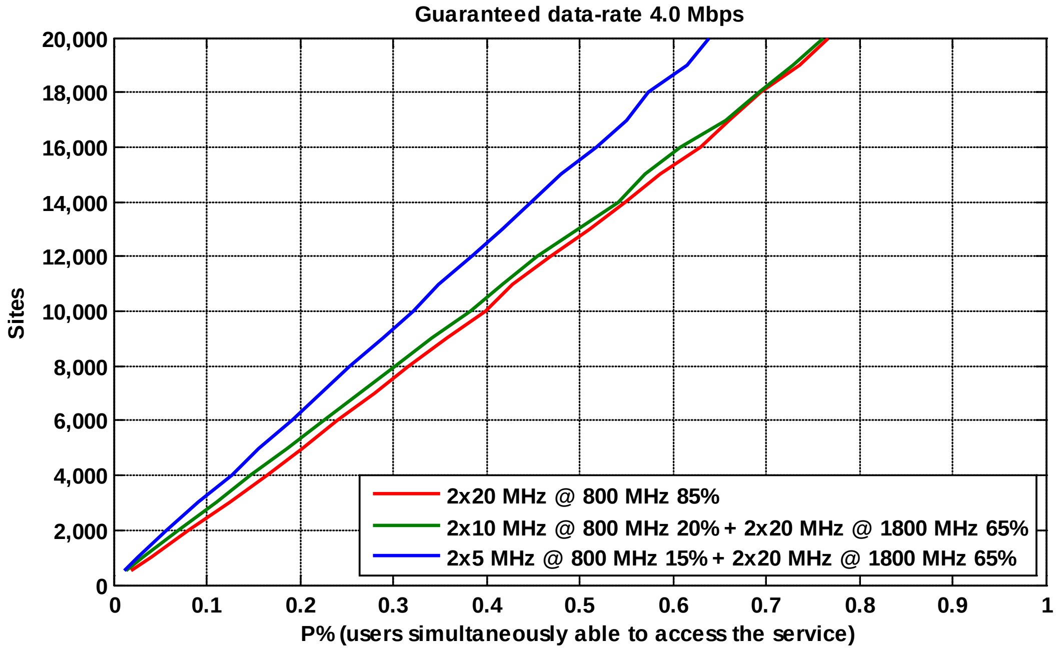


Figure A7.25



A7.28 The capacity of such networks would moreover be closer to that of a 2x20 MHz 800 MHz network operating at 85% loading; indeed in the case of a network with 2x10 MHz of 800 MHz operating at 20% loading plus 2x20 MHz of 1800 MHz operating at 65% loading (as required to match single-user throughput), the capacity would be almost identical to that of a network with 2x20 MHz of 800 MHz operating at 85% loading.

Figure A7.26

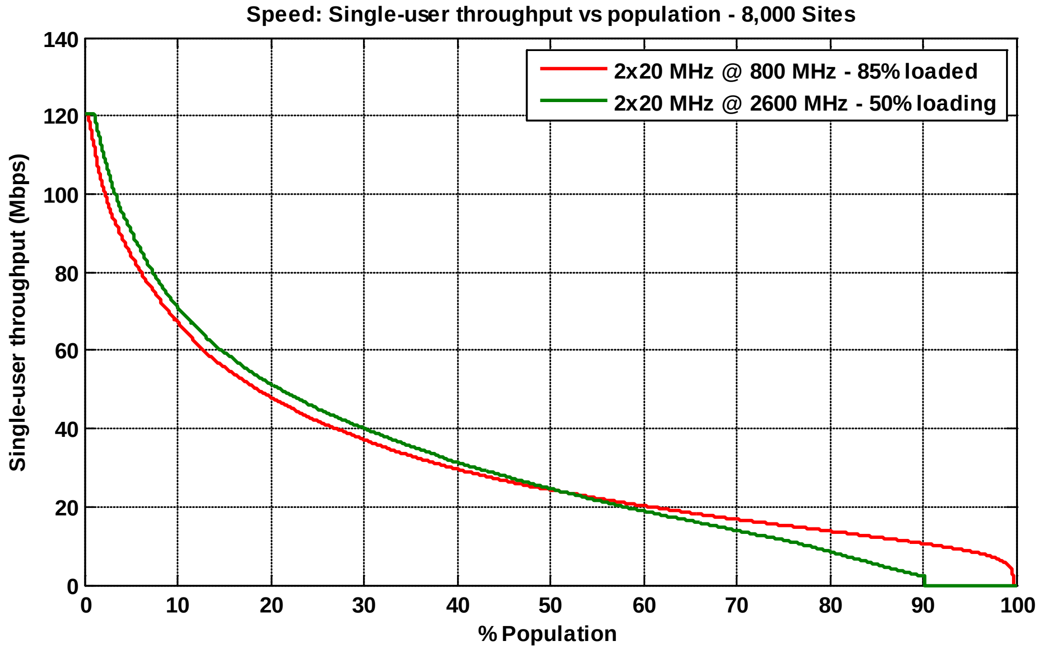


If an operator has only 2x5 MHz or 2x10 MHz of sub-1GHz spectrum, is it enough for them to have access to sufficient 2.6GHz spectrum when it comes to their ability to build a network whose performance matches that of one built using 2x20 MHz of sub-1GHz spectrum, or do they need access to 1800 MHz spectrum?

A7.29 Since the limit of coverage that a network can provide is almost entirely determined by the characteristics of the lowest frequencies that an operator holds, it makes no material difference to the coverage that an operator can provide whether the higher frequency spectrum they hold is 1800 MHz or 2.6 GHz.

A7.30 Turning next to speed, the model predicts that for the majority of customers a network using 2x20 MHz of 2.6 GHz spectrum can deliver a maximum downlink data-rate comparable to that of a network using 2x20 MHz of 800 MHz spectrum, provided that the 2.6 GHz network is operating at 50% loading whilst the 800 MHz network operates at 85% loading. However, the maximum speed that the 2.6 GHz network can deliver drops off more quickly towards the edge of coverage than does an equivalent 1800 MHz network.

Figure A7.27



A7.31 As before, it is predicted that this gap in speed at the edge of coverage can be filled to a greater or lesser extent by an 800 MHz layer operating at less than full loading, albeit the 800 MHz layer has to fulfil this role over a larger proportion of the area in this case than when the higher frequency spectrum is 1800 MHz. Again a 2x10 MHz 800 MHz layer operating at 20% loading can pretty well match the maximum speed of a 2x20 MHz 800 MHz layer operating at 85% loading and a 2x5 MHz 800MHz layer operating at 15% loading can provide a service with a reasonable downlink data-rate to almost the same set of customers as the network with 2x20 MHz of 800 MHz spectrum.

Figure A7.28

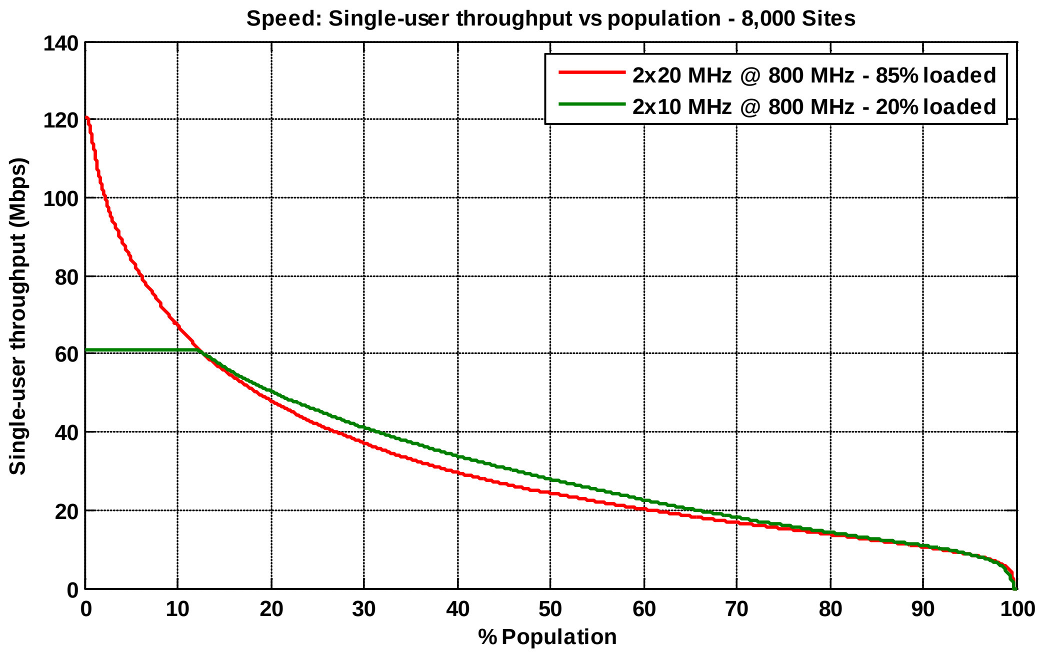
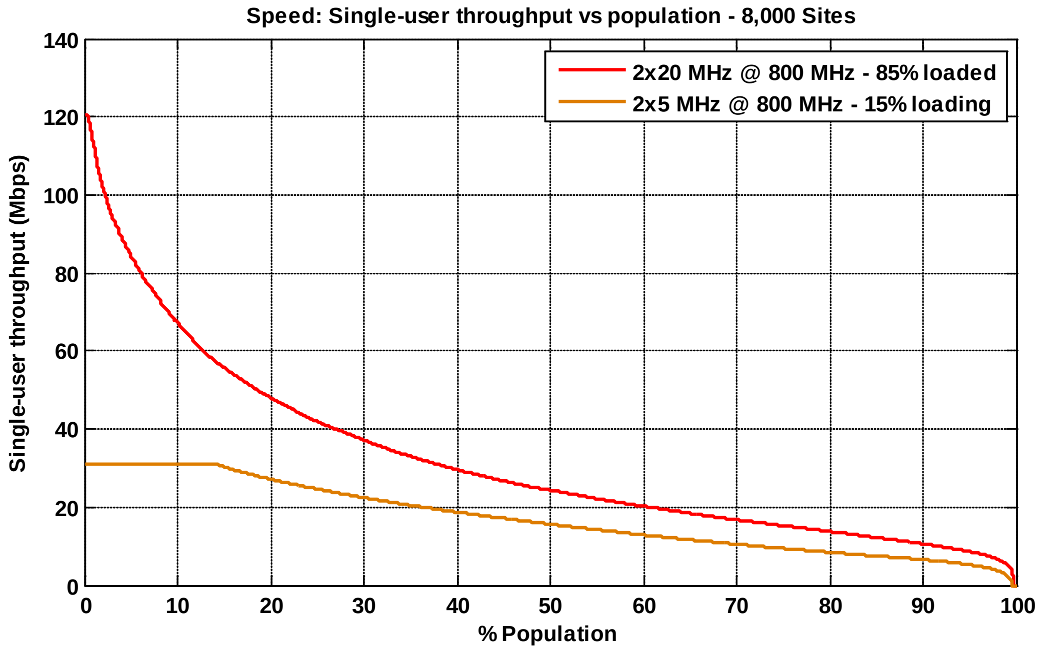


Figure A7.29



A7.32 Combining these results to look at the predicted performance of multi-frequency networks employing frequency 'doughnutting'[10], we see that a network with 2x10 MHz of 800 MHz spectrum plus 2x20 MHz of 2.6 GHz spectrum is predicted to be able to match or better the maximum speed performance of a network with 2x20 MHz of 800 MHz spectrum across almost the entire area. A network with only 2x5 MHz of 800 MHz spectrum plus 2x20 MHz of 2.6 GHz spectrum is able to match the maximum speed of a 2x20 MHz 800 MHz network across most of the area, and can provide a reasonable speed over almost the whole area, but cannot exactly match the maximum speed of a 2x20 MHz 800 MHz network towards the edge of coverage[11].

[10] See previous footnote re the simplification adopted here.

[11] Again recalling that the model looks at in-building coverage; the performance of the networks outdoors should be materially better than this.

Figure A7.30

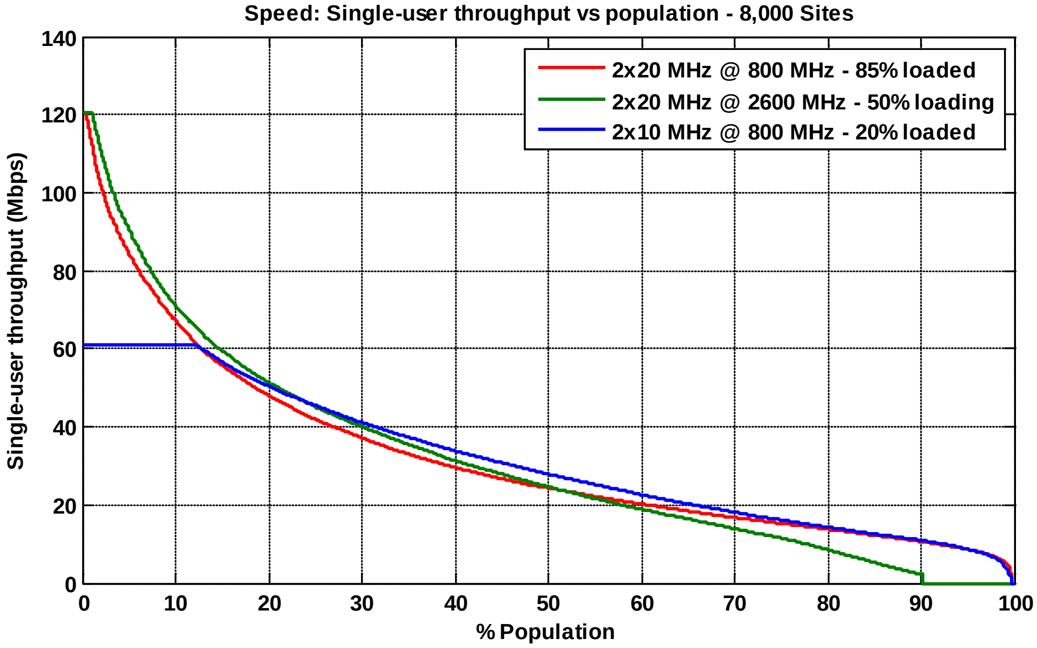
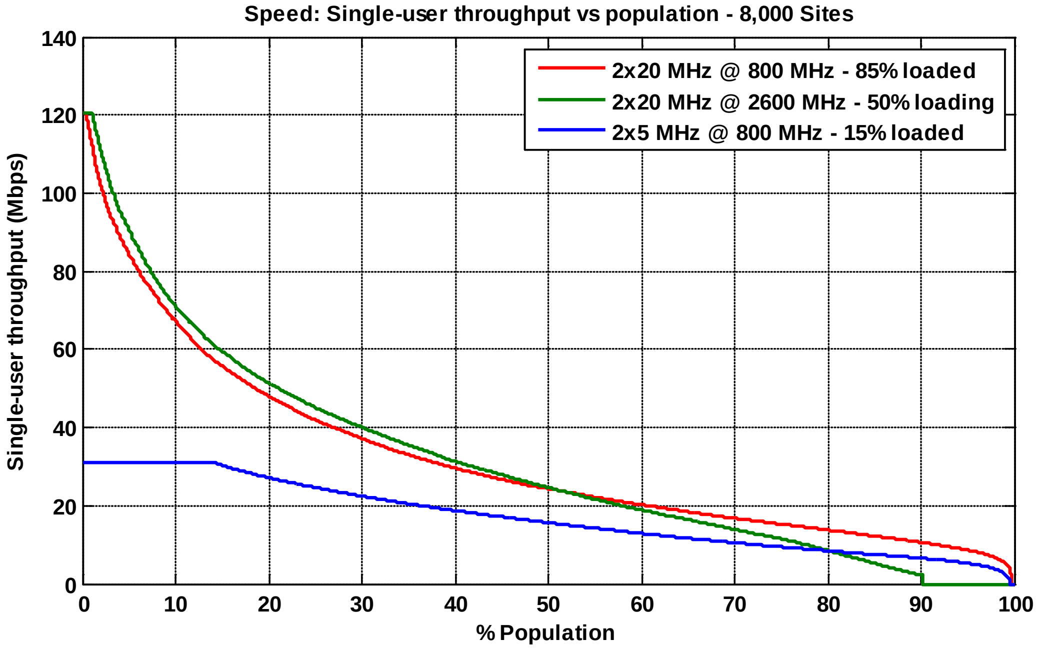
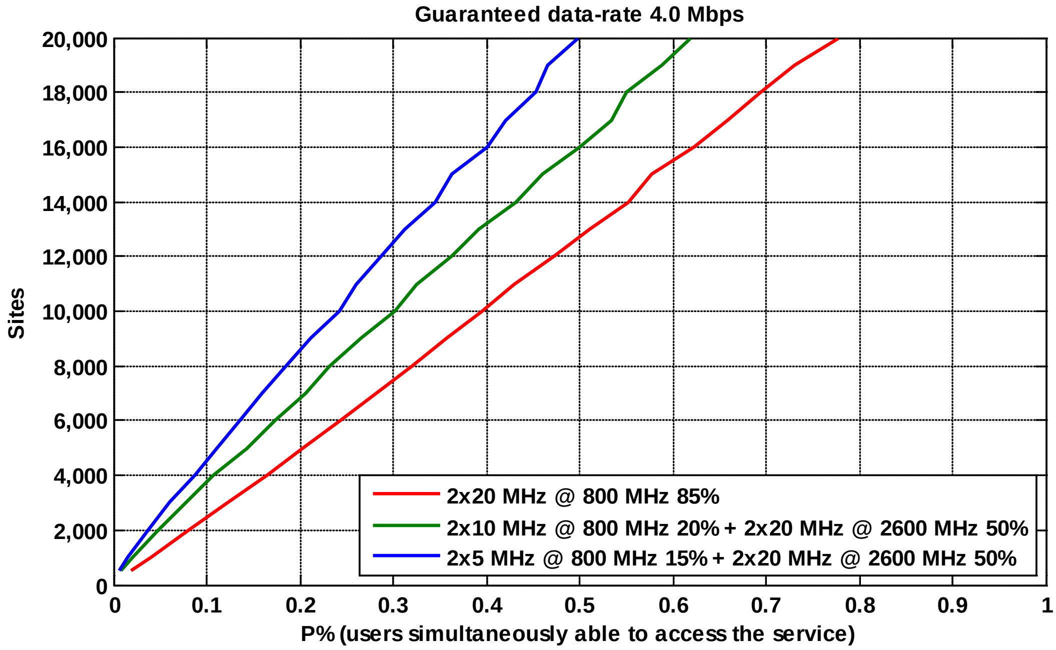


Figure A7.31



A7.33 Turning to the relative capacity of such networks, we see again that the 2x20 MHz 800 MHz network has a capacity advantage relative to the two multi-frequency networks when operated at the maximum loadings compatible with matching single-user throughput, but that this advantage is nearly constant in proportion over a wide range of network sizes, and amounts to less than a doubling of capacity.

Figure A7.32

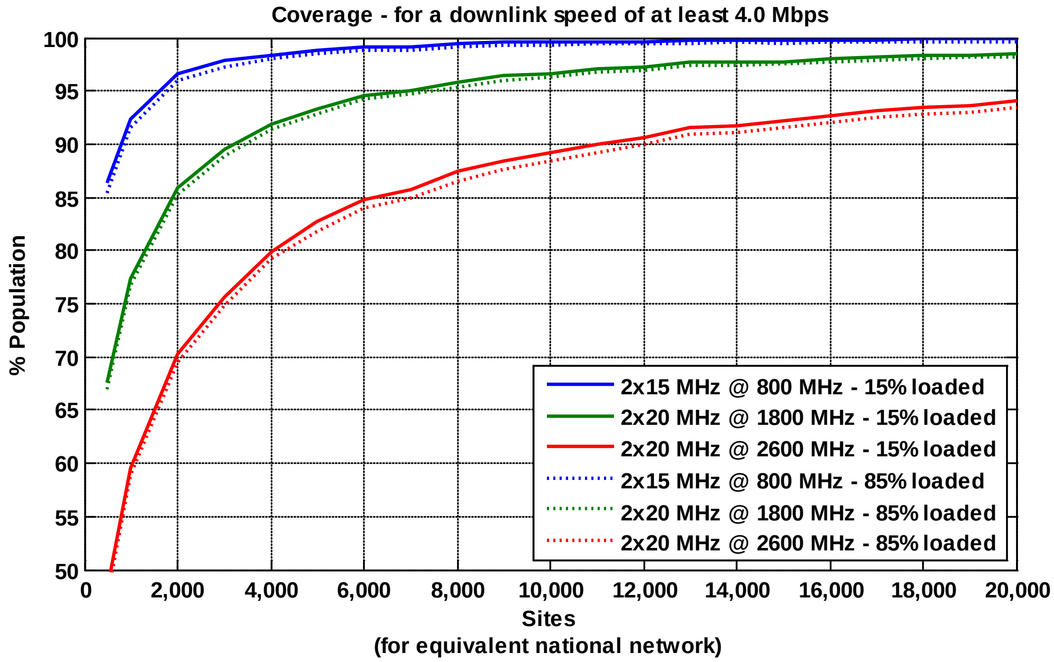


What if the largest holding of sub-1GHz spectrum is only 2x15 MHz?

A7.34 All of the above analysis is predicated on the operator with the largest amount of sub-1GHz spectrum having a 2x20 MHz contiguous carrier. We now consider what the model predicts the situation would be if the largest sub-1GHz carrier was only 2x15 MHz.

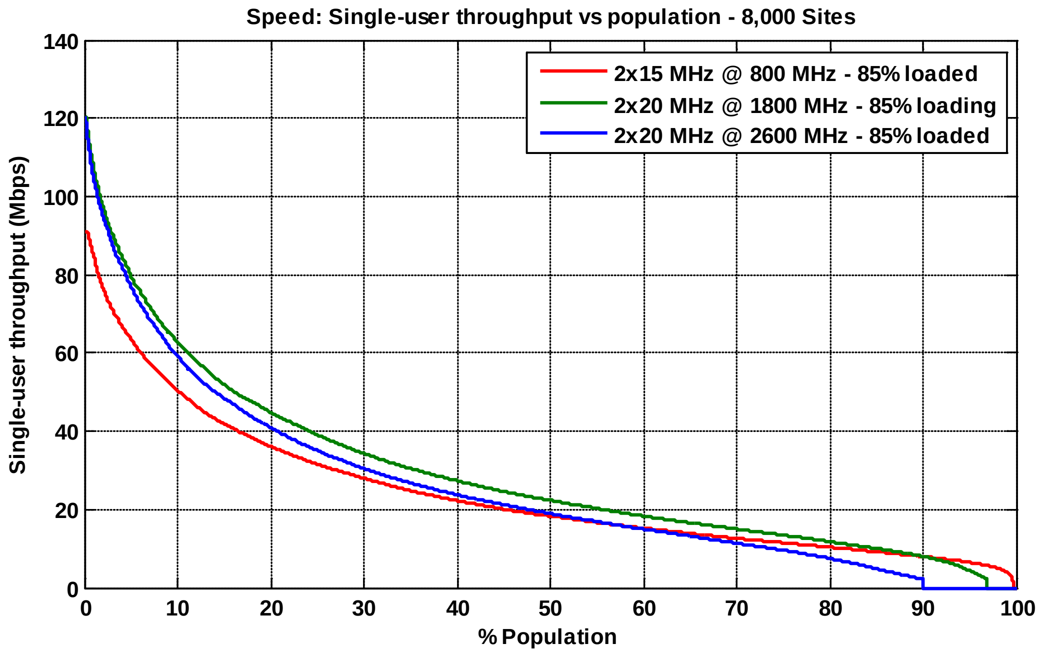
A7.35 Considering coverage first, we see that even with only 2x15 MHz of 800 MHz spectrum, a network with sub-1GHz spectrum still provides significantly better coverage than networks using only higher frequencies, irrespective of loading.

Figure A7.33



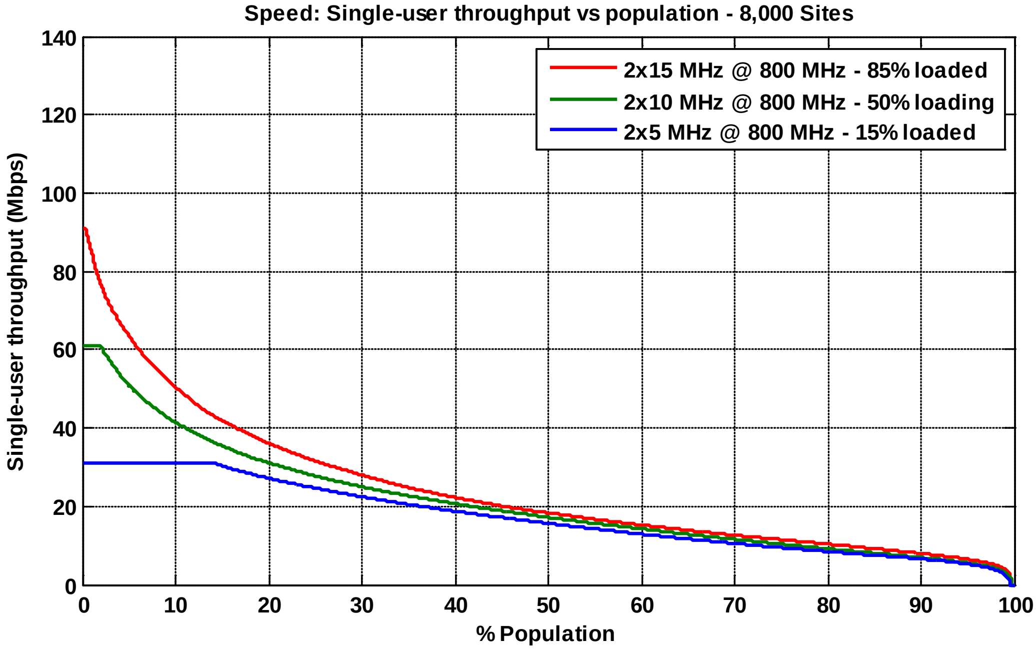
A7.36 Turning next to maximum speed, we see that, expect at the edge of coverage, networks using 2x20 MHz of either 1800 MHz or 2.6 GHz spectrum can more than match the maximum speed of a 2x15 MHz 800 MHz network, even when fully loaded.

Figure A7.34



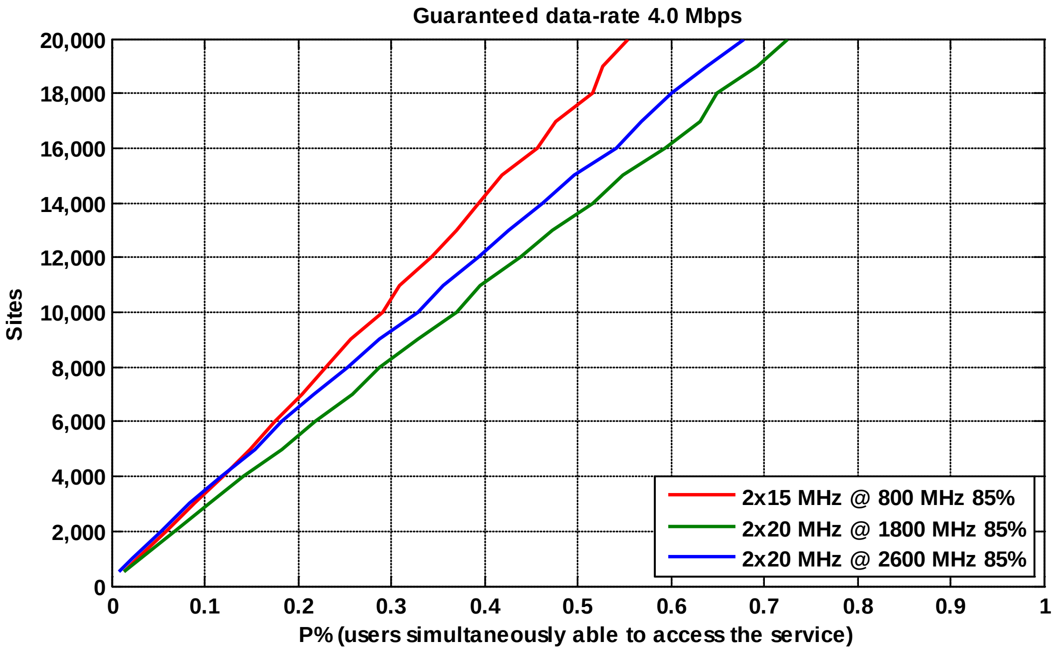
A7.37 And at the edge of coverage even a network with only 2x5 MHz of 800 MHz spectrum, if lightly loaded (15% loaded), can all but match the maximum speed of a network with 2x15 MHz of 800 MHz spectrum if fully loaded (85% loading). A network with 2x10 MHz of 800 MHz can afford to operate such a layer at moderate loading (50% loading) and still all but match the maximum speed of a network with 2x15 MHz of 800MHz spectrum if that network is fully loaded (85% loading).

Figure A7.35



A7.38 Looking at the capacity of these networks, the model predicts that even without the additional capacity provided by the lower frequency layers of the multi-frequency networks, networks with 2x20 MHz of higher frequency spectrum, whether 1800 MHz or 2.6 GHz, can more than match the capacity of a network with only 2x15 MHz of 800 MHz spectrum.

Figure A7.36



A7.39 In conclusion therefore, the model predicts that a multi-frequency network combining 2x5MHz of 800MHz spectrum (operated at 15% loading) with 2x20 MHz of 2.6 GHz spectrum (operated at 85% loading) can on all measures, all but match, or even better, the performance of a network using 2x15 MHz of 800 MHz spectrum alone (operated at 85% loading).

Annex 8

LTE Modelling Methodology

Introduction

A8.1 This Annex describes how we have modelled LTE networks operating in the 800 MHz, 1800 MHz and 2600 MHz bands. It comprises the following sections:

- *Modelling Approach*, which describes the model we have used for generating the results reported in Annex 7;

- *Coverage Obligation,* which describes how we have derived the coverage threshold values proposed in Section 6;

- *Parameters and Assumptions*, which tabulates the parameters used within the modelling; and

- *References.*

A8.2 In addition to the description of modelling we set out below, we are making available in the SINR distributions we have generated using the model in form of spreadsheets which can be downloaded from our website (see http://www.ofcom.org.uk/static/combined-award/sinr.html). We also intend to make the code for the model available during the consultation period.

Modelling Approach

A8.3 This section describes the modelling approach we have adopted to analyse and compare the performance of LTE networks operating in the 800 MHz, 1800 MHz and 2600 MHz bands.

A8.4 The key results presented in Annex 7 have been derived using what we have termed a ‘non-uniform’ mode.

A8.5 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 sectors 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.

A8.6 A high level description of the model is as follows:

- a synthetic base station network of a particular size is established covering the simulation area plus a buffer zone 20 km deep surrounding the simulation area. The base station network is constructed so that it (as far as possible) has similar characteristics (in terms of site density vs. population density, antenna heights, etc.) as the current mobile macro site networks.

- for a hypothetical test terminal (UE) located at each UK census output area population weighted centroid (within the simulation area), the signal to interference plus noise ratio (SINR) is calculated taking into account signals from sites within the base station network within a certain distance of the centroid location up to a maximum of the 20 closest sites.

- using the SINR values together with a suitable mapping function and taking into account system overheads the average downlink single-user throughput for each population weighted centroid is established.

- the three steps above are repeated to establish a range of SINR and single-user throughput distributions for a range of base station network sizes, network loadings, carrier bandwidths and building penetration depths[12] at the three frequencies under consideration (800 MHz, 1800 MHz and 2600 MHz).

- from the single-user throughput distribution statistics within the simulation area, the three metrics of performance that we consider in Annex 7 are calculated:

    - *Coverage* – the proportion of the population within an area to which it is technically possible to deliver a service with a particular downlink speed (if all the resources of the serving sector were dedicated to a single customer), as a function of the number of network sites (and in some cases the loading on the network)

    - *Speed* – for a given number of sites and network loading, the downlink throughput (if 85% of the resources of the serving cell were dedicated to a single customer) attained or exceeded by a particular proportion of the population

    - *Capacity* – for a given downlink speed and network loading, the number of sites needed to provide enough capacity to simultaneously serve a certain proportion of the population within an area with the given downlink speed

A8.7 The parameters and assumptions used to generate the key results in Annex 7 are as follows:

- Building penetration depth 2+[13]

[12] The results reported in Annex 7 are all for a single building penetration depth. A limited set of results for other depths have also been investigated and these results are reported in this annex.

[13] In previous publications on mobile spectrum issues Ofcom has used the notation 'depth 0', 'depth 1' 'depth 2: base case' and 'depth 2: rising faster with frequency' to denote building penetration depths which are increasingly difficult to reach. In this consultation we have adopted a new depth which we

- Base station network distributions (locations and antenna heights) representative of existing mobile operators' macro networks

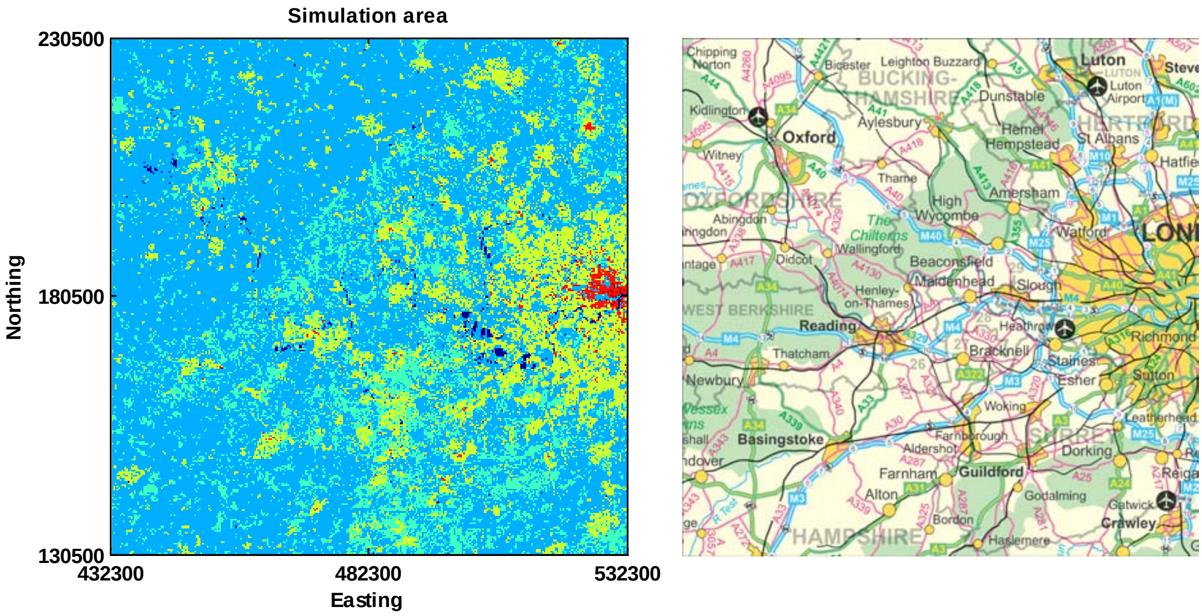
- SINR distribution calculated for UK census output population weighted centoids with clutter for each centroid taken from Ofcom's 50 x 50 metre clutter database

- 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 the 3GPP specs but with horizontal and vertical 3dB beamwidths taken from a real multi-band antenna covering 800 – 2100 MHz and extrapolated to cover 2600 MHz – down-tilts optimised for operating frequency and neighbouring base station distribution

A8.8 The geographic area over which LTE network performance was simulated was a 100 km by 100 km north/south aligned square centred on 482300:180500, see Figure A8.1 below.

Figure A8.1: Simulation area



A8.9 Table A8.1 below gives the breakdown of the simulation area 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.

are calling 'depth 2+' which represents a building penetration depth midway between the 'depth 2: base case' and 'depth 2: rising faster with frequency'.

Table A8.1: Population by clutter type

Clutter	Simulation Area	England	Scotland	Wales	NI	UK
Rural	1,358,704	12,432,176	1,111,763	1,243,263	936,148	15,723,350
Suburban	6,501,147	35,234,141	3,533,484	1,581,088	699,129	41,047,842
Urban	548,939	1,347,311	372,773	77,451	44,740	1,842,275
D Urban	28,311	60,056	10,121	561	3,582	74,320

A8.10 Table A8.2 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 A8.2: Population percentage per clutter type

Clutter	Simulation Area	England	Scotland	Wales	NI	UK
Rural	16.10%	25.33%	22.11%	42.84%	55.60%	26.79%
Suburban	77.05%	71.80%	70.27%	54.48%	41.53%	69.94%
Urban	6.51%	2.75%	7.41%	2.67%	2.66%	3.14%
D Urban	0.34%	0.12%	0.20%	0.02%	0.21%	0.13%

A8.11 It is clear that the simulation area is not 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. It has a greater proportion of the population in Dense Urban, Urban and Suburban areas and less in Rural areas. However, given that we believe competition between national wholesalers will focus predominantly on network performance in more populous areas, the simulation area seems a reasonable choice to base our technical results on.

A8.12 21 different network sizes were simulated representing networks with 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10000, 11000, 12000, 13000, 14000, 15000, 16000, 17000, 18000, 19000 and 20000 sites nationally (GB).

A8.13 These networks covered the simulation area plus a buffer zone of 20 km (to avoid edge effects). Figures A8.2, A8.3 and A8.4 below provide an illustration of six of these networks from the smallest to the largest.

Figure A8.2: 500 and 4,000 site networks

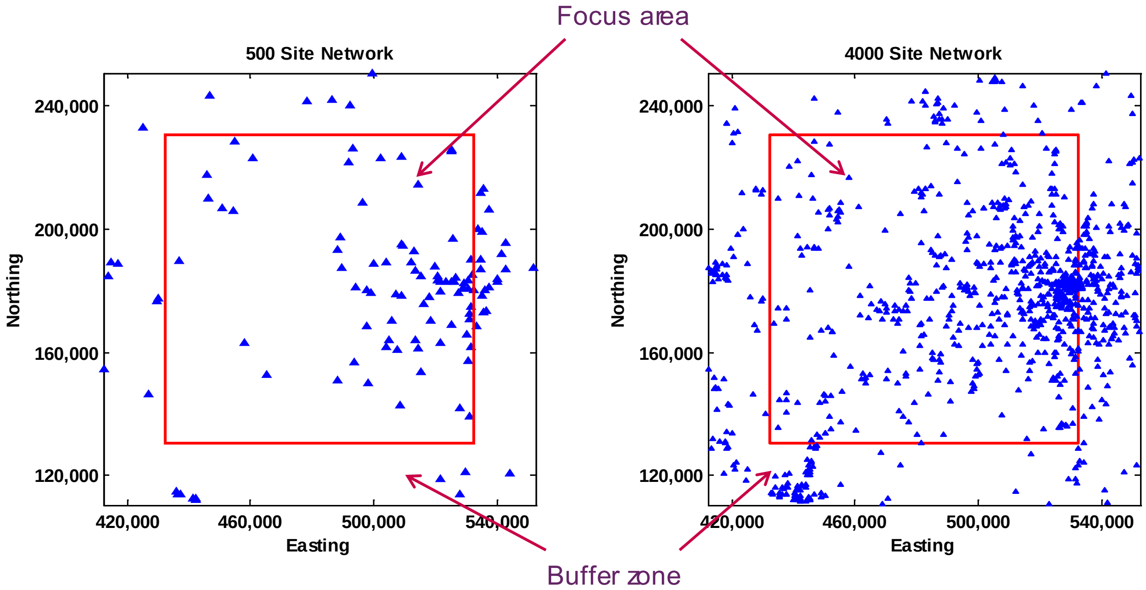


Figure A8.3: 8,000 and 12,000 site networks

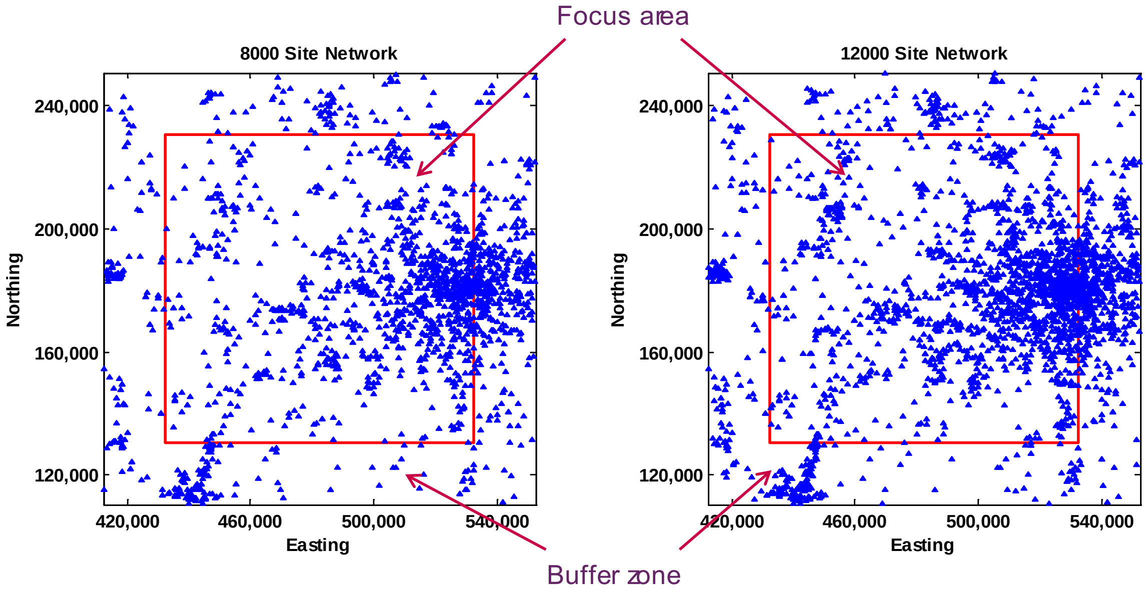
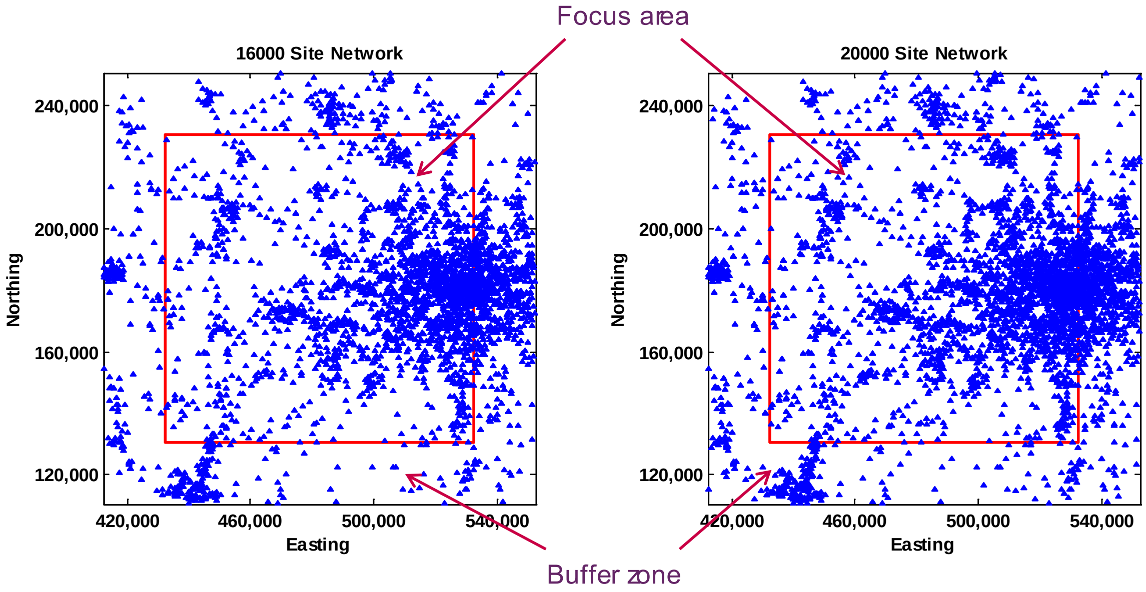


Figure A8.4: 16,000 and 20,000 site networks



SINR Distribution Model

A8.14 The following text describes in detail the steps involved in each simulation run to generate an SINR distribution:

A8.15 A base station network of the required size is established across the simulation area (focus area) plus 20 km buffer zone by sub-sampling a 'reference' network representing a national network with 20,000 sites. The 'reference' network having been carefully constructed so that its characteristics (e.g. site to population density, antenna height distributions, etc) are similar to those of current mobile operators' networks.

A8.16 For each UK census output area population weighted centroid within the simulation area:

- its clutter category (Dense Urban, Urban, Suburban and Rural) is established based on Ofcom's 50 x 50 metre clutter database entry for the centroid location;
- a set of 21 random variables is generated. These values are drawn from the normal distribution with mean 0 and standard deviation σs and represent the shadow fading values in decibels. The first value in the set represents the local shadow fading component for the location and the next 20 represent the shadow fading component for the 20 base station sites closed to that location; and
- a further set of 21 random variables is also generated. These values are drawn from the normal distribution with mean m_{bpl} and standard deviation σ_{bpl} and represent the building penetration loss values in decibels. The first value in the set represents the local building penetration loss component for the location and the next 20 represent the building penetration loss component for the 20 base station sites closed to that location.

A8.17 The shadow fading standard deviation σ_{S} (in decibels) is derived from the empirical relationship given by formula (1) below taken from [2]:

$$\sigma_S = 0.65\ \log(f_c)^2 - 1.3\log(f_c) + A \qquad (1)$$

A8.18 The value of A being 5.2 dB for Dense Urban and Urban clutter and 6.6 dB for other clutter categories.

A8.19 The mean building penetration loss (BPL) m_{bpl} used depends on the clutter at the UE location and the specific scenario under investigation. For the purposes of this consultation, we have defined two building penetration depths reflecting a wide range of building types and user locations within buildings:

- Depth 1 represents the conditions for users who are, on average, considered to be at an average depth within buildings and/or buildings which have, on average, moderately high penetration losses;
- Depth 2+ represents the conditions for users, who are, on average, considered to be deep inside buildings and/or in buildings which have, on average, relatively high penetration losses (e.g. users who are near the core of a building well away from external walls and windows)[14].

A8.20 The values used (in decibels) are based on values used in previous Ofcom publications [3] and [4], extrapolated or interpolated as appropriate. They are reproduced in Table A8.3 below.

Table A8.3: Mean BPL values

Building penetration depth scenario	**Depth 1**				**Depth 2+**			
Clutter*	DU	U	S	R	DU	U	S	R
800 MHz	-11.2	-9.2	-7.2	-7.2	-13.6	-11.6	-9.6	-9.6
1800 MHz	-13.3	-11.3	-9.3	-9.3	-18.8	-16.8	-14.8	-14.8
2600 MHz	-15.0	-13.0	-11.0	-11.0	-23.1	-21.1	-19.1	-19.1

*The clutter categories in the table above are as follows: DU = Dense Urban; U = Urban; S = Suburban; and R = Rural

A8.21 The standard deviations of the BPL σ_{bpl} used are taken from Table A8.4 below.

Table A8.4: BPL standard deviations

Building penetration depth scenario	**Depth 1**	**Depth 2+**
800 MHz	6.0	7.0
1800 MHz	6.0	9.0
2600 MHz	6.0	9.0

[14] In previous spectrum publications on mobile spectrum issues Ofcom has used the notation 'depth 0', 'depth 1' 'depth 2: base case' and 'depth 2: rising faster with frequency' to denote building penetration depths which are increasingly difficult to reach. In this consultation we have adopted a new depth which we are calling 'depth 2+' which represents a building penetration depth midway between the 'depth 2: base case' and 'depth 2: rising faster with frequency'.

A8.22 For each simulation snapshot a UE is placed at one of the UK census output area population weighted centroids within the simulation area.

A8.23 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.

A8.24 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 (2) and (3) below which are taken from [7]:

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

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

A8.25 The values of $\varphi_{3\mathrm{dB}}$, $\theta_{3\mathrm{dB}}$, and bore-sight gain are derived from a typical multi-band antenna from the Kathrein catalogue (742-265) extrapolated to cover the 2600 MHz band; $\mathrm{A_m}$ = 25 dB; $\mathrm{SLA_v}$ = 20 dB.

A8.26 The individual antenna down-tilt values θ_{tilt} for each site are set according to equation (4) below:

$$\theta_{\mathrm{tilt}} = \arctan\left({}^{H_{\mathrm{BS}}}/{}_{2\mathrm{x}ISD_{\mathrm{m}}}\right) + \left({}^{\theta_{3\mathrm{dB}}}/{}_{3}\right) \quad (4)$$

A8.27 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. This equation has been derived by trial and error. It should be noted that the simulation results are relatively insensitive to down-tilt, though due to the narrower vertical beam-widths higher frequencies are slightly more sensitive than lower frequencies. Though not perfectly optimal for all combinations of network size and frequency band under consideration, equation (3) has been found to provide a reasonable compromise for the calculation of down-tilts across the simulation area.

A8.28 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 centroid location in A8.15) assuming a shadow fading and building penetration cross correlation coefficients of 0.5 according to the method in section 3.2.4 of [5].

A8.29 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 from [6] (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.

A8.30 The sector with the smallest coupling loss is designated as the 'serving' sector and its site is designated as the 'serving' site.

A8.31 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 (see paragraph A8.27). 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 [5].

A8.32 Network or system loading is accounted for, when calculating P_{other}, by multiplying the interference power from each sector by the relevant factor as described below:

- 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 at a particular time. It is therefore assumed that, in a given sector, users will be on *orthogonal* channels and there will be no intra-cell interference.

- The model assumes that sectors of the same site are loaded in an *intelligent* way. By this we mean that the radio resource algorithm is assumed to allocate resource blocks in order to minimise 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 however it is assumed that sites allocate their resource blocks in the same fashion as each other.

- 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 cell 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 can be entirely eliminated. It also means that 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).

- For interference analysis purposes, we can effectively place sectors into two sets (even though in practice there will be three sets, one for each set of primary sub-group of resource blocks):

  - A: those assigned the same primary sub-group of resource blocks as the 'serving' sector – i.e. 1/3 of all sectors in the network; and

  - B: those assigned a different primary sub-group of resource blocks to the 'serving' sector – i.e. 2/3 of all sectors in the network (this group includes the other sectors of the 'serving' site).

- For practical reasons, sectors with the same azimuth as the 'serving' sector are placed in set A, all other sectors are placed in set B. This arrangement ensures that sectors immediately adjacent to the 'serving' sector will be in set B thus minimising interference.

- On the assumption that sectors allocate resource blocks from their primary sub-group at random, the interference percentage received from other sectors from set A is given by:

$$I_{\text{A}} = LF_{\text{own :A}} \times LF_{\text{other :A}} \tag{5}$$

- Where $LF_{\text{own:A}}$ is dependent on the loading of the 'serving' sector and $LF_{\text{other:A}}$ is dependent on the loading of all the other sectors in the network. It is assumed that, on average, the network is loaded to a certain percentage but that the 'serving' sector, at any instance of time, can be loaded to a different level (in most instances it is assumed the 'serving' sector is loaded to 85% of maximum, i.e. it is, in practice, fully loaded).

- Similarly, the interference percentage received from other sectors from set B is given by:

$$I_{\text{B}} = LF_{\text{own :B}} \times LF_{\text{other :B}} \tag{6}$$

- For sectors from set A, the relevant loading factors are given by:

$$LF_{\text{own :A}} = \begin{cases} 3 \times Loading_{\text{own}}\,, \ \text{for } Loading_{\text{own}} < \frac{1}{3} \\ 1, \ \text{for } Loading_{\text{own}} \geq \frac{1}{3} \end{cases} \tag{7}$$

  - and

$$LF_{\text{other :A}} = \begin{cases} 3 \times Loading_{\text{other}}\,, \ \text{for } Loading_{\text{other}} < \frac{1}{3} \\ 1, \ \text{for } Loading_{\text{other}} \geq \frac{1}{3} \end{cases} \tag{8}$$

- For sectors from set B, the relevant loading factors are given by:

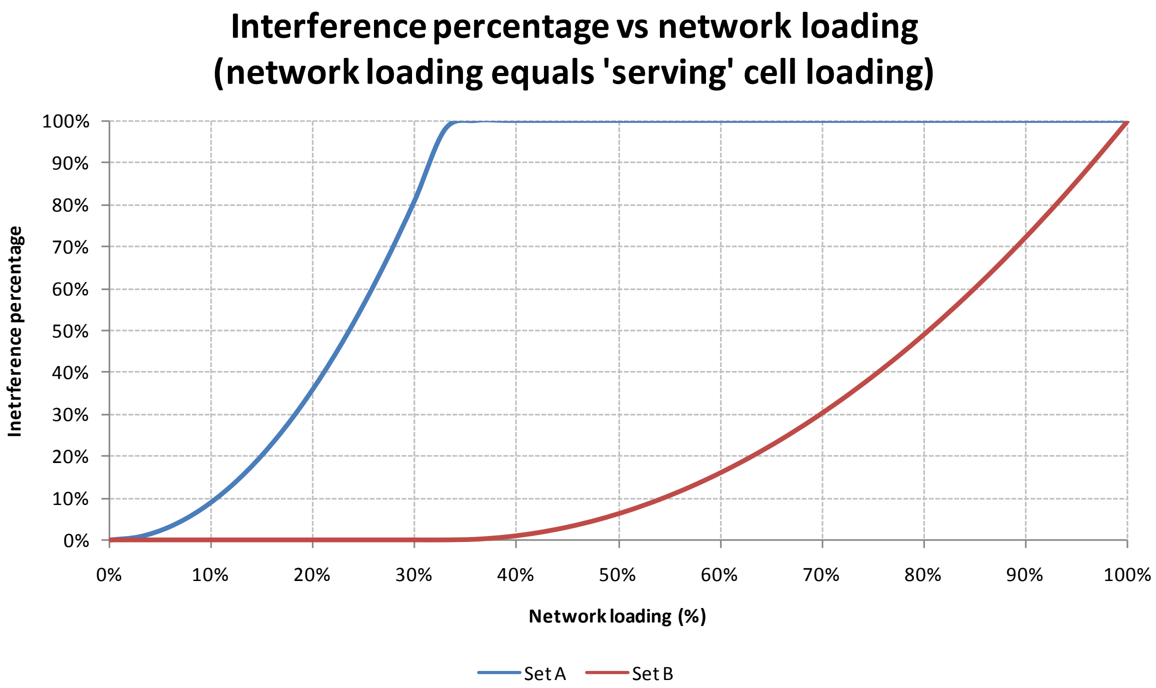
$$LF_{\text{own :B}} = \begin{cases} 0, \ \text{for } Loading_{\text{own}} < \frac{1}{3} \\ \frac{3}{2} \times (Loading_{\text{own}} - \frac{1}{3}), \ \text{for } Loading_{\text{own}} \geq \frac{1}{3} \end{cases} \tag{9}$$

  - and

$$LF_{\text{other :B}} = \begin{cases} 0, \ \text{for } Loading_{\text{other}} < \frac{1}{3} \\ \frac{3}{2} \times (Loading_{\text{other}} - \frac{1}{3}), \ \text{for } Loading_{\text{other}} \geq \frac{1}{3} \end{cases} \tag{10}$$

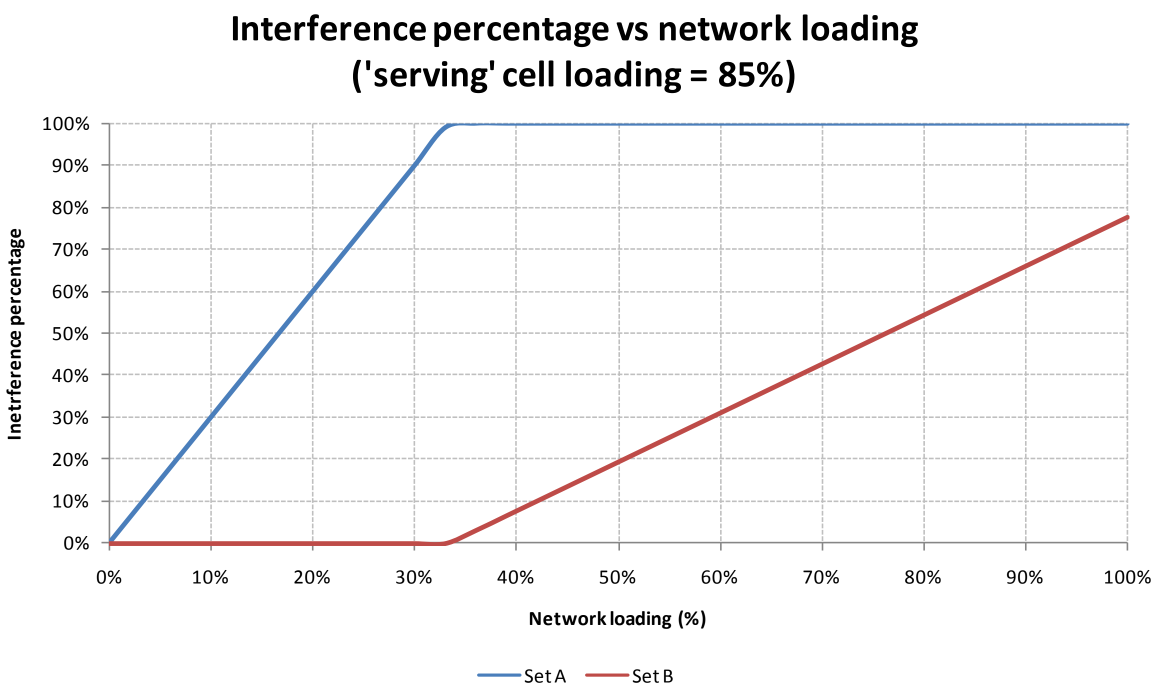
A8.33 Figure A8.5 below illustrates the results for the case where the network loading and 'serving' sector loading are equal. When the network is relatively lightly loaded, say 15%, the interference percentage from sectors in set A is about 20% and from set B is zero. When the network is heavily loaded, say 85%, the interference percentage from sectors in set A is 100% and from set B is about 60%.

Figure A8.5



A8.34 Figure A8.6 below illustrates the results for the case where the network loading varies but the 'serving' sector loading is fixed at 85%. When the network is relatively lightly loaded, say 15%, the interference percentage from sectors in set A is about 45% and from set B is zero. When the network is heavily loaded, say 85%, the interference percentage from sectors in set A is 100% and from set B is about 60%.

Figure A8.6



A8.35 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 A8.30.

A8.36 The SINR at the UE location is calculated according to

$$SINR = \frac{P_{\text{wanted}}}{P_{\text{other}} + P_{\text{noise}}} \tag{11}$$

A8.37 Where P_{noise} is the noise power at the UE given by kTB multiplied by the noise figure of the UE: k being Boltzmann's constant; T the temperature (290 degrees); and B the bandwidth (i.e. 180 kHz for 1 resource block).

A8.38 The steps from A8.15 to A8.36 are repeated for every UK census output area population weighted centroid within the simulation area (28,009 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.

A8.39 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

A8.40 For each SINR distribution a corresponding throughput (single-user throughput) distribution can be calculated using a suitable mapping function. The SINR to throughput mapping function used is an attenuated and truncated form of the Shannon bound and is taken from Annex A of [8]. It is expressed (in bps/Hz) as follows:

$$Thr = \begin{cases} 0, & \text{for } SINR < \mathrm{SINR_{min}} \\ \alpha.\mathrm{S}(SINR), & \text{for } \mathrm{SINR_{min}} < SINR < \mathrm{SINR_{max}} \\ \mathrm{Thr_{max}}, & \text{for } SINR > \mathrm{SINR_{max}} \end{cases} \tag{12}$$

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

$$\mathrm{S}(SINR) = \log_2(1 + SINR) \tag{13}$$

And 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

A8.41 The values of these parameters, from Annex A of [8], are given in Table A8.5 below.

Table A8.5

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

A8.42 It should be noted that various different SINR to throughput mapping functions are available in the literature. Generally these scale differently for different channel models, however the shape of these functions are similar to each other. The particular function chosen is taken from the 3GPP specifications [8] and is also the same as that used by the SEAMCAT tool.

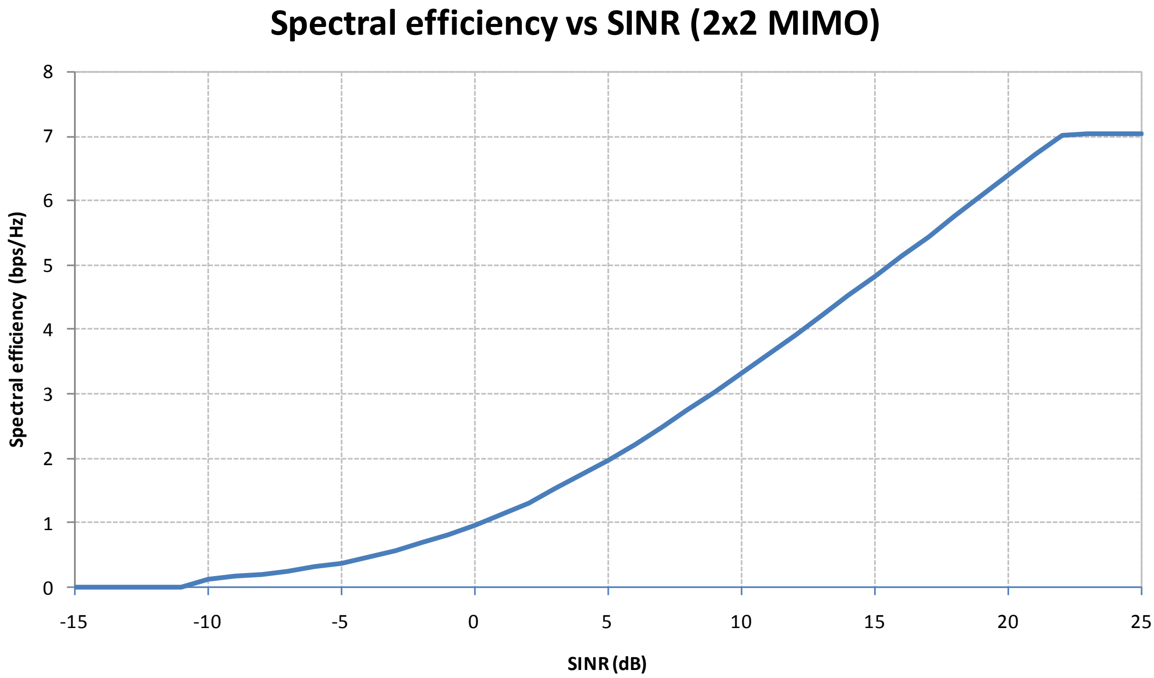
A8.43 Throughput is also adjusted to account for the following overheads:

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

A8.44 The combined effect of these overheads varies slightly with carrier bandwidth (with narrower bandwidths having slightly higher overheads) but is in practice very close to 20% for a 2x2 MIMO system. Thus the throughput distributions calculated according to equation (12) are reduced by an appropriate factor to account for overheads.

A8.45 Figure A8.7 below illustrates the overall effect of the equations (12) and (13) as applied to a 2x2 MIMO downlink after overheads (assumed to be exactly 20% for the purposes of the illustration) are accounted for. This figure is presented in terms of spectral efficiency (bps/Hz) vs. SINR.

Figure A8.7



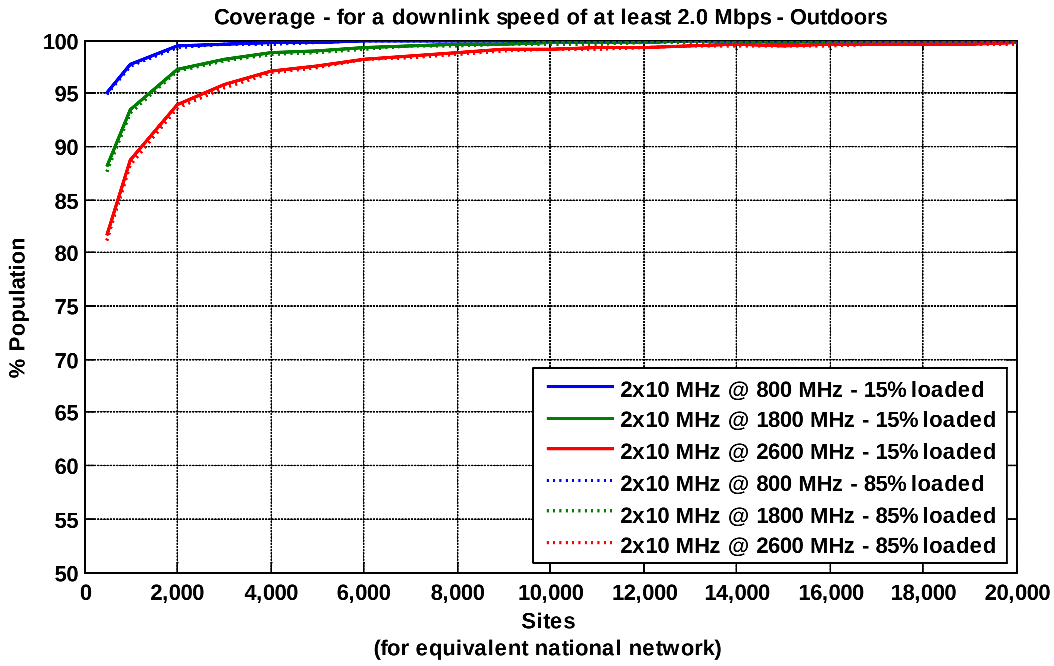
A8.46 Because overheads vary slightly with channel bandwidth, a different throughput distribution needs to be calculated for each channel bandwidth under consideration.

Coverage

A8.47 For each centroid location we have the population of that centroid. The population coverage for a particular guaranteed minimum data-rate associated with a particular combination of frequency, channel bandwidth, base station network size, network loading and building penetration depth is calculated by summing the population of each centroid whose calculated data-rate is equal to or greater than the guaranteed minimum data-rate.

A8.48 Figure A8.8 below illustrates the coverage results for a 2 Mbps minimum guaranteed data-rate for outdoor users for the full range of sites simulated for a 10 MHz carrier.

Figure A8.8

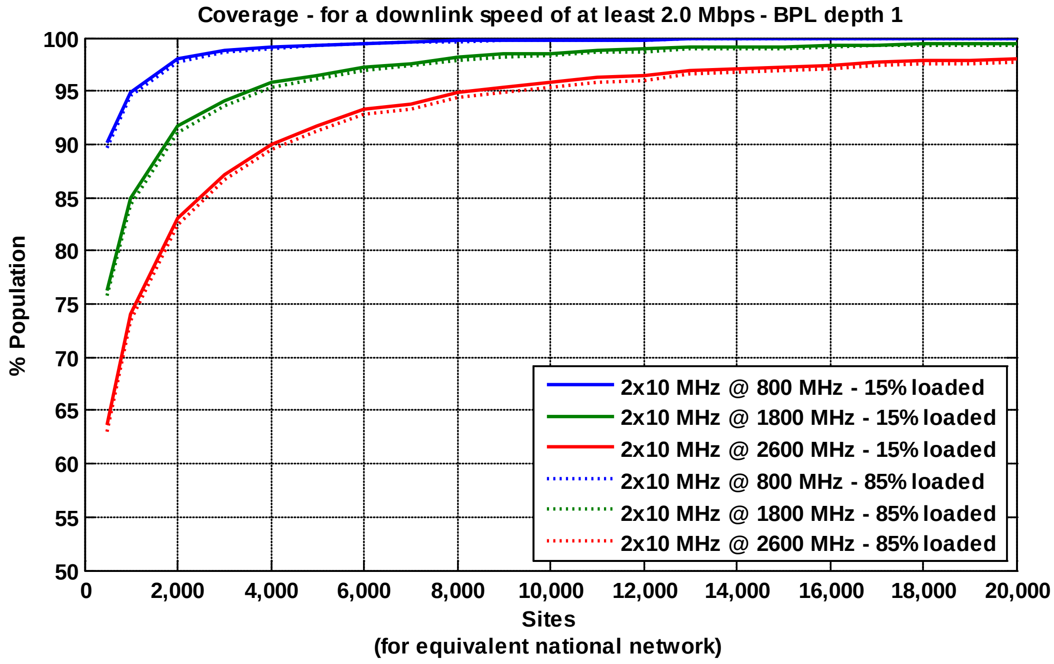


A8.49 Figure A8.8 should be interpreted as follows: the x-axis represents the size of the networks modelled in terms of the number of sites an equivalent national network covering Great Britain would have (the actual number of sites within the simulation area being a only a fraction of these). So 2,000 in Figure A8.8 represents a national network with 2,000 sites. The y-axis shows the percentage of the population able to receive a minimum downlink speed of at least the target data-rate (in this case 2.0 Mbps). Thus we see that for a 2600 MHz network loaded to 15% of maximum (i.e. using 15% of the available resource blocks - solid red line), approximately 94% of the population within the simulation area are predicted to receive a downlink speed of 2.0 Mbps or better when the network has 2,000 sites.

A8.50 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.

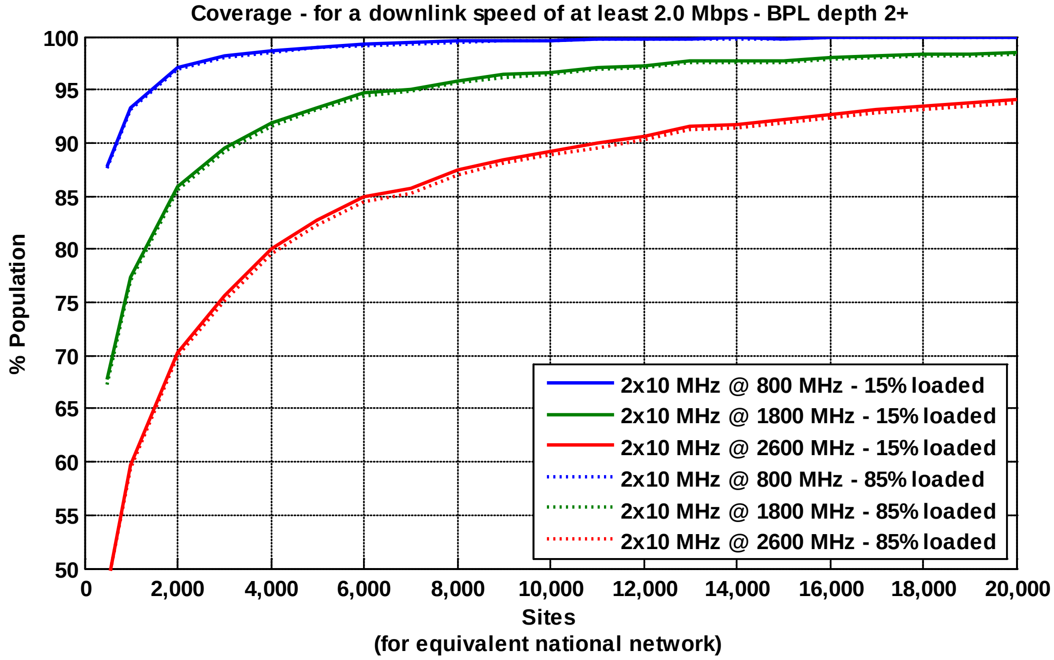
A8.51 Figure A8.9 below illustrates the coverage results for a 2 Mbps minimum guaranteed data-rate for users indoors at depth 1 for the full range of sites simulated for a 10 MHz carrier. Comparing Figure A8.8 and Figure A8.9, as might be expected, the model predicts that the percentage of the population covered when users are indoors at depth 1 is less that when users are outdoors.

Figure A8.9



A8.52 Figure A8.10 below illustrates the coverage results for a 2 Mbps minimum guaranteed data-rate for users indoors at depth 2+ for the full range of sites simulated for a 10 MHz carrier. This time, comparing Figure A8.9 and Figure A8.10, again as might be expected, the model predicts that the percentage of the population covered when users are much deeper indoors (at depth 2+) is less that when users are less deep (depth 1).

Figure A8.10

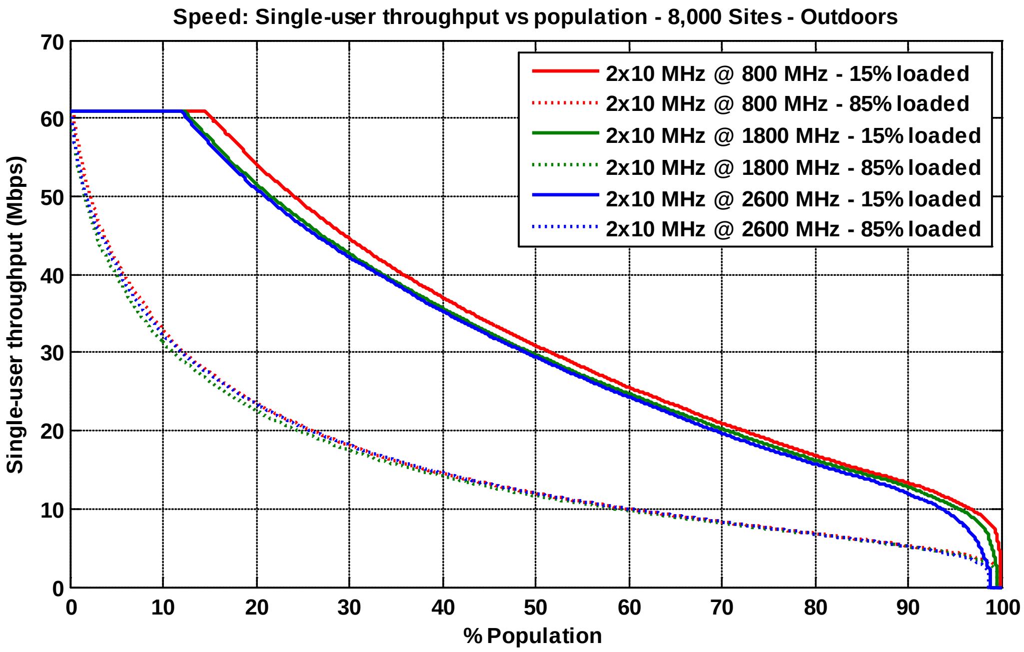


Speed

A8.53 The speed of a network, for a particular combination of frequency, channel bandwidth, base station network size, network loading and building penetration depth is obtained directly from the 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 cumulative population (expressed as a percentage of the total population in the simulation area) that can receive at least that throughput.

A8.54 Figure A8.11 below illustrates the speed results for outdoor users for a national network with 8,000 sites simulated for a 10 MHz carrier.

Figure A8.11



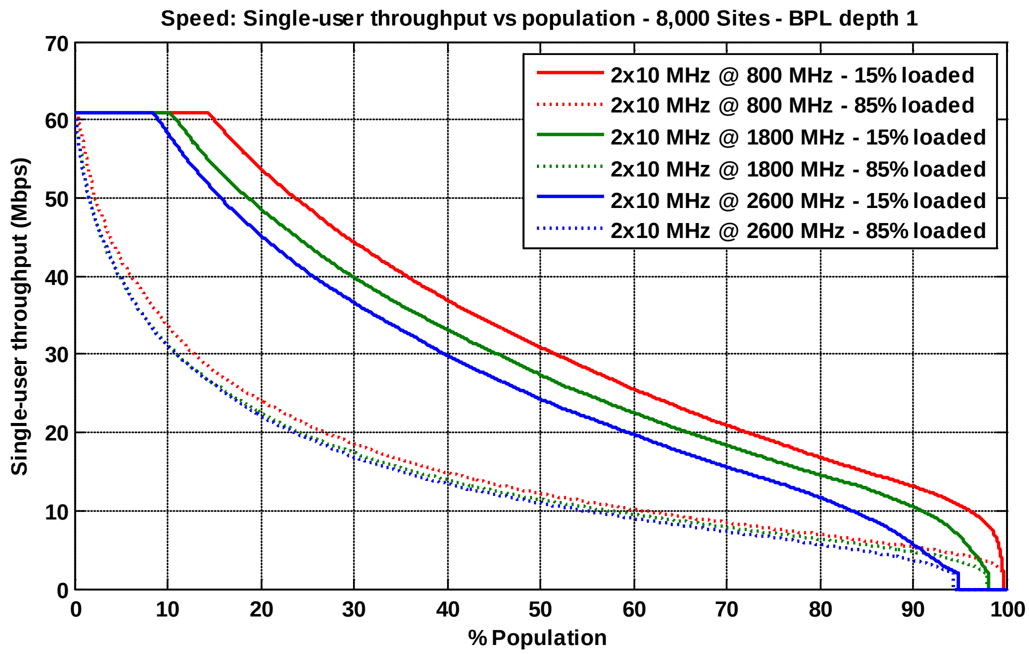
A8.55 Figure A8.11 should be interpreted as follows: the x-axis indicates the percentage of the population within the area simulated ordered such that those having the best signal conditions are to the left, and those with the worst to the right. So “20%” in Figure A8.11 represents the 20% of the population who 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 20% of locations). The y-axis shows the throughput attained or exceeded at all of these locations when a single user consumes the full capacity of the serving cell. Thus we see that for a lightly loaded 2600 MHz network (15% loaded – solid blue line), a single-user downlink speed of just over 50 Mbps or better can be delivered to the first 20% of the population. By contrast, a heavily loaded 2600 MHz network (85% loaded – dotted blue line) can deliver only about 23 Mbps or better to the first 20% of the population. Just over 20 Mbps or better can be delivered to 70% of the population by a lightly loaded 800 MHz network (solid red line).

A8.56 As can be seen, the model predicts that for outdoor users within the simulation area, there is very little difference in performance between a network with the equivalent of 8,000 sites nationally when operating at 800 MHz, 1800 MHz and

2600 MHz. However, a lightly loaded network (15% loaded) has a throughput performance that is significantly better than a loaded network (85% loaded).

A8.57 Figure A8.12 below illustrates the coverage results for users indoors at depth 1 for a national network with 8,000 sites simulated for a 10 MHz carrier.

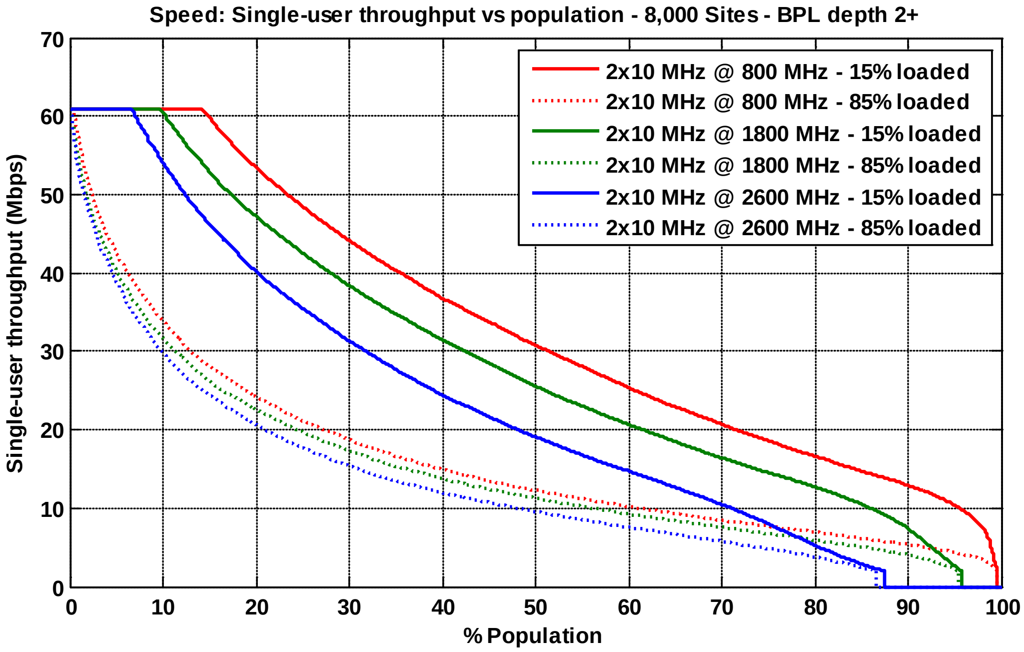
Figure A8.12



A8.58 When users are indoors at depth 1, the model now shows a number of differences to the outdoor case. First, when operating at 800 MHz, an 8,000 site network has consistently better throughput performance than an equivalent network operating at 1800 MHz or 2600 MHz. This is most pronounced when the networks are lightly loaded (15% loaded). Secondly, looking at Figure A8.12, the model predicts that a network operating at 2600 MHz clearly has poorer coverage than one operating at 800 MHz; the 2600 MHz lines (blue) intersect the x-axis at about the 95% value whereas the 800 MHz lines (red) intersect the x-axis at almost the 100% value – the 1800 MHz lines (green) are approximately mid way between the other two. It is also apparent that coverage is largely independent of network loading (at least for the guaranteed minimum data-rate illustrated here – 2 Mbps).

A8.59 Figure A8.13 illustrates the coverage results for users indoors at depth 2+ for a national network with 8,000 sites simulated for a 10 MHz carrier.

Figure A8.13



A8.60 From Figure A8.13 we can now see that the model predicts an even greater difference in single user performance between the three frequency bands when the network is loaded both lightly (15%) and heavily (85%). Though it is still evident that the differences are more pronounced for a lightly loaded network. Coverage differences are also more apparent, with 2600 MHz covering only about 87% of the population in the simulation area, 1800 MHz about 96% and 800 MHz 99%.

Capacity

A8.61 For the capacity calculations, we assume that the SINR distributions calculated at the network level are also, on average, representative of the SINR distribution at the cell level. We also assume that users are uniformly distributed within each cell.

<u>Networks with a single carrier operating in a single frequency band</u>

A8.62 We calculate the capacity of a cell with a single carrier operating in a single frequency band as follows:

A8.63 We pick a point on the SINR distribution at random (using a uniform distribution). This represents a single user. We then, using the same throughput to SINR mapping function as described above, calculate the number of resource blocks needed to serve this user at the guaranteed data-rate specified. If this is less than the number resource blocks available in the cell[15] the user is deemed served.

A8.64 If the first user can be served, another point on the SINR distribution is picked at random, representing a second user. We calculate the number of resource blocks needed to serve this user at the guaranteed data-rate. If the total number of resource blocks needed to serve both the first and second user is less than the

[15] The total number of resource blocks available is dependent on carrier bandwidth and cell loading. For a 10 MHz carrier there are a total 50 resource blocks. If the cell is 50% loaded the number of resource blocks available is 50 x 0.5 = 25.

number of resource blocks available in the cell the second user is also deemed served.

A8.65 The process of adding a user at random and checking if the total number of resource blocks needed by this user and all previous users to receive a service at the guaranteed data-rate is repeated until no more users can be added. This gives us the number of simultaneous users that the cell can support in this iteration (snapshot) of the model.

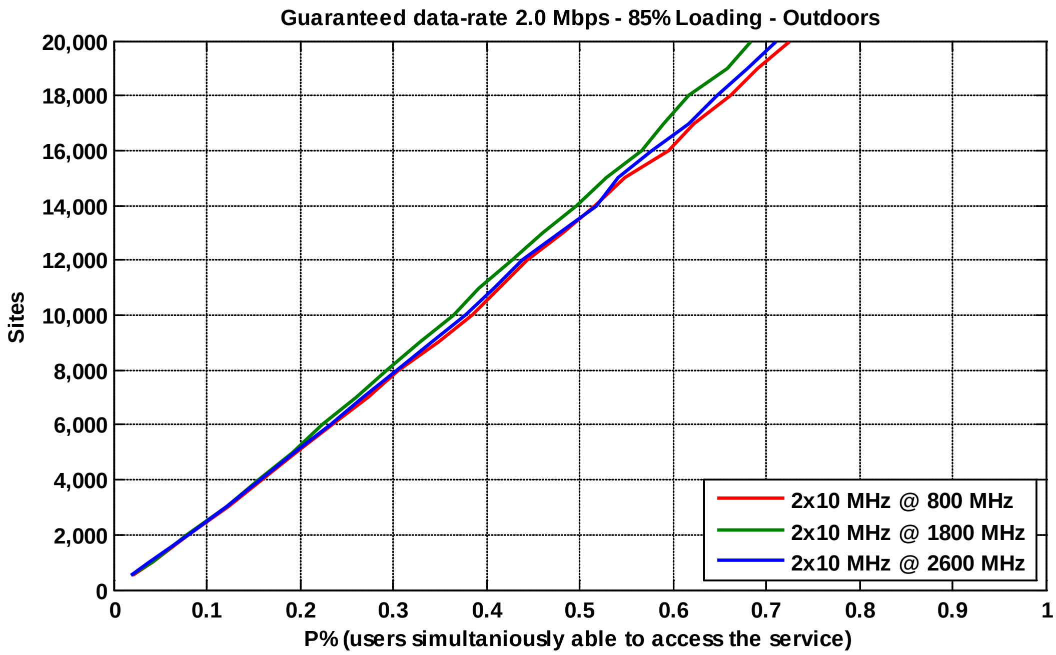
A8.66 We then repeat the whole process (steps A8.62 to A8.64) until we have a total of 10,000 snapshots to build up a distribution. The average of this distribution is the average number of simultaneous users a cell can support for the given loading.

A8.67 The capacity of the network for the given loading and guaranteed data-rate is then calculated by multiplying the average number of simultaneous users a cell can support (for the given loading) by the total number of cells (or sectors) in the network (remembering that there are 3 sectors per site, an 8,000 site network will have 24,000 sectors).

A8.68 For each frequency of interest, we calculate the network capacity for the 21 different network sizes mentioned in A8.8. Results are displayed as a percentage of the population (P%) that the network can simultaneously serve at the given guaranteed data-rate by dividing the capacity of the network by the total population.

A8.69 Figure A8.14 below illustrates the capacity results for outdoor users simulated for a 10 MHz carrier, a 2.0 Mbps guaranteed data-rate and a loading of 85%.

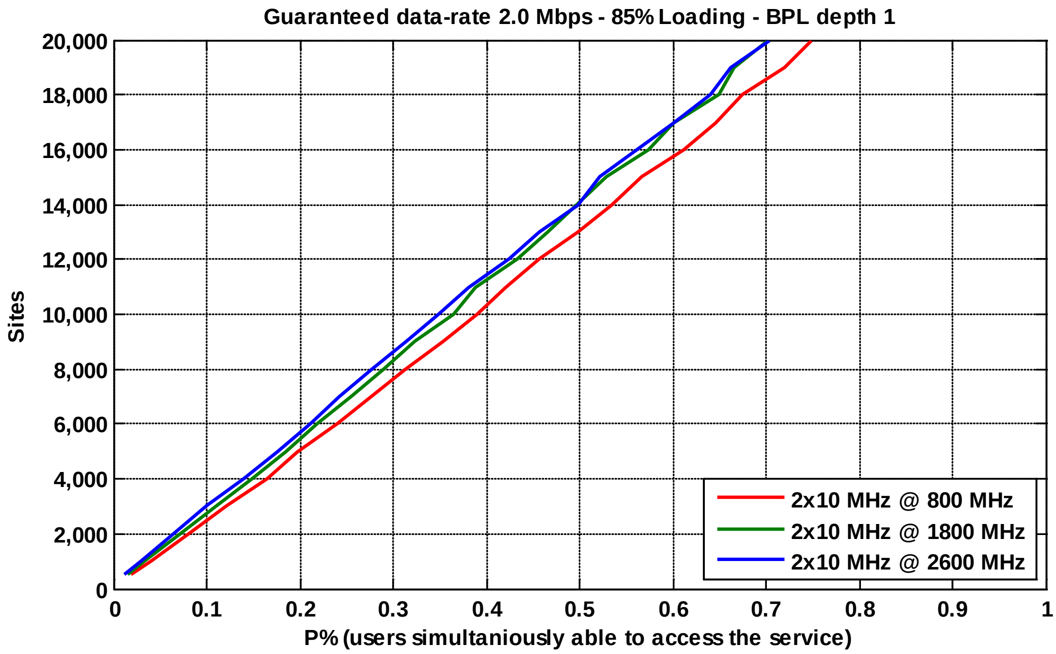
Figure A8.14



A8.70 Figure A8.14 should be interpreted as follows: the x-axis indicates the percentage of the population within the area simulated who are able, on average, to simultaneously receive a guaranteed data-rate of 2.0 Mbps when the network is loaded to 85% (i.e. 85% of the available resource blocks are being use in each cell in the network). The y-axis shows the number of sites for an equivalent national network. So, the model predicts that for a national network with 4,000 sites operating with a 10 MHz carrier, within the simulation area, approximately 0.16% of the population would be able to simultaneously access a 2.0 Mbps downlink service when the network is heavily loaded (85%) – regardless of the frequency band of operation. For a larger network sizes, a small difference in capacity with frequency is apparent but it is relatively small.

A8.71 Figure A8.15 below illustrates the capacity results for users indoors at depth 1 simulated for a 10 MHz carrier, a 2.0 Mbps guaranteed data-rate and a loading of 85%.

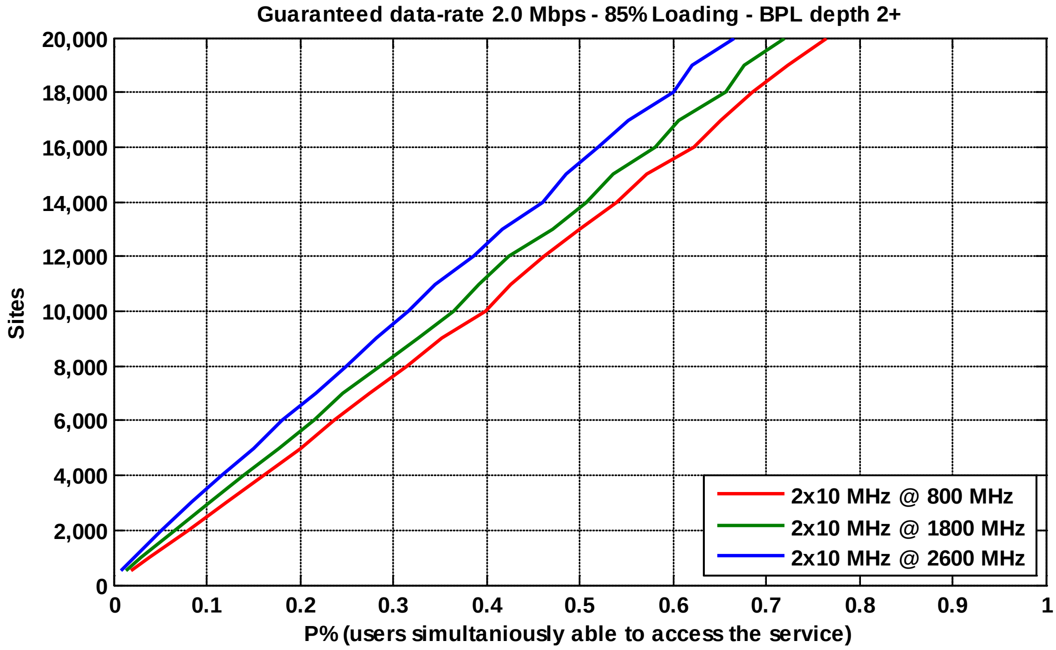
Figure A8.15



A8.72 At depth 1 the model predicts that 800 MHz has a capacity advantage over both 1800 MHz and 2600 MHz but, again, even for large network sizes, the advantage is relatively small.

A8.73 Figure A8.16 below illustrates the capacity results for users indoors at depth 2+ simulated for a 10 MHz carrier, a 2.0 Mbps guaranteed data-rate and a loading of 85%.

Figure A8.16



A8.74 At depth 2+ it is clear that the model predicts a greater capacity advantage for 800 MHz compared to higher frequencies.

Networks with two carriers operating in different frequency bands

A8.75 We calculate the capacity of a with a network with two carriers operating in different frequency bands as follows:

A8.76 We pick a point on the SINR distribution of the higher frequency at random (using a uniform distribution). This represents a single user. We then, using the same throughput to SINR mapping function as described above, calculate the number of resource blocks needed to serve this user at the guaranteed data-rate specified. If this is less than the number resource blocks available on the carrier at the higher frequency in the cell[16] the user is deemed served.

A8.77 If the first user can be served, another point on the SINR distribution of the higher frequency is picked at random, representing a second user. We calculate the number of resource blocks needed to serve this user at the guaranteed data-rate. If the total number of resource blocks needed to serve both the first and second user is less than the number resource blocks available from the carrier at the higher frequency in the cell the second user is also deemed served.

A8.78 The process of adding a user at random and checking if the total number of resource blocks needed by this user and all previous users to receive a service at the guaranteed data-rate using the carrier at the higher frequency is repeated until users can no longer be added to the higher frequency carrier.

[16] The total number of resource blocks available is dependent on carrier bandwidth and cell loading. For a 10 MHz carrier there are a total 50 resource blocks. If the cell is 50% loaded the number of resource blocks available is 50 x 0.5 = 25.

A8.79 At this point, we see if the first user who cannot be served using the higher frequency carrier can be accommodated by the lower frequency carrier, again by using the SINR to throughput mapping function to calculate the number of resource blocks needed to serve this user and comparing this to the number available on the carrier at the lower frequency.

A8.80 We carry on adding users at random and first checking if they can be supported at the higher frequency and then moving on to check if they can be supported at the lower frequency until no more users can be supported at either frequency. This gives us the total number of simultaneous users that the cell can support on both frequencies in this iteration of the model (snapshot).

A8.81 We then repeat the whole process (steps A8.75 to A8.79) for a total of 10,000 snapshots to build up a distribution. The average of this distribution is the average number of simultaneous users a cell can support using the two carriers available to it for the given loading (note the two carriers may have a different loading)[17].

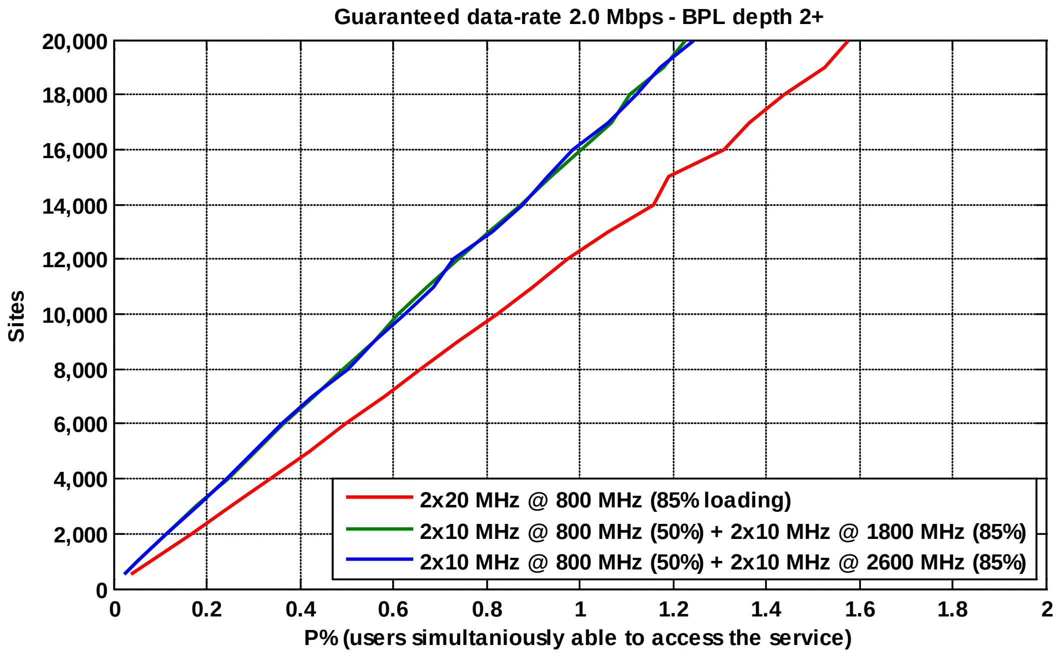
A8.82 The capacity of the network for the given spectrum portfolios, loadings and guaranteed data-rate is then calculated by multiplying the average number of simultaneous users a cell can support by the total number of cells.

A8.83 For each spectrum portfolio of interest, we calculate the network capacity for the 21 different network sizes mentioned in A8.8. Results are displayed as a percentage of the population (P%) that the network can simultaneously serve at the given guaranteed data-rate by simply dividing the capacity of the network by the total population.

A8.84 Figure A8.17 below illustrates the capacity results for users indoors at depth 2+ simulated for a three different spectrum portfolios, for a 2.0 Mbps guaranteed data-rate.

[17] It should be noted that this above process is unlikely to be totally optimal as it only assigns users to a carrier based on the conditions at the time that user is added. An approach that looks at all users together and assigns them on the basis of assigning every user with the good signal conditions (i.e. higher SINRs) to the higher frequency carrier whilst pushing the remaining users with lower signal conditions to the lower frequency might result in a better overall outcome. However, this likely to require users to be frequently pushed back and forth between the two carriers as and when they come and go and as their signal conditions change as they move about. Such frequent changes would clearly add a significant signalling overhead and is unlikely to be practical to implement (at least fast enough to maintain an optimal distribution of users between carriers).
It should also be noted that the above process is unlikely to maintain a uniform distribution of users across the cell for each individual frequency. Therefore the underlying SINR distributions (which are based on the assumption that users are evenly distributed) may not be entirely applicable. However, dealing these effects would require a much more complicated model and we believe that our current approach provides a reasonable approximation for the purposes of this consultation.

Figure A8.17



A8.85 At depth 2+ the model predicts that 1800 MHz used with 800 MHz has no capacity advantage over 2600 MHz used with 800 MHz but both have inferior capacity compared with two carriers at 800 MHz.

Coverage Obligation

A8.86 In section 6 we define a potential coverage obligation in terms of the following:

- the provision of an electronic communications network that is capable of providing mobile telecommunications services with a sustained downlink speed of not less than 2 Mbps;
- with a 90% probability of reception indoors;
- to an area within which at least 95% of the UK population lives.

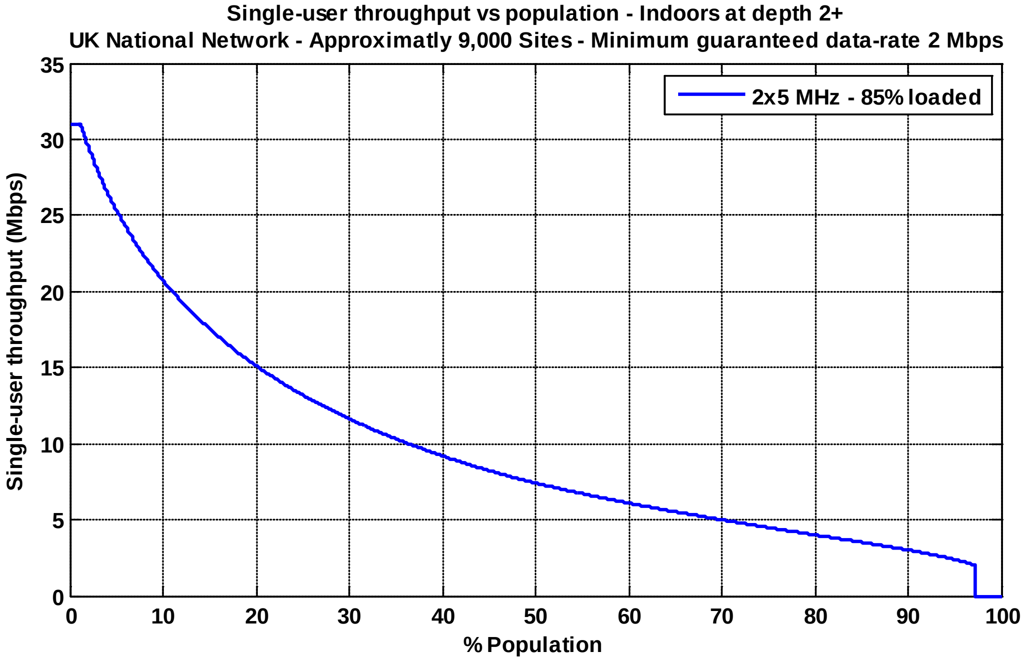
A8.87 We also say that we believe this service could be achieved by upgrading existing 2G mobile network sites or by establishing a network of a similar size and configuration.

Estimating coverage from a network of existing sites

A8.88 In order to justify this claim we have modelled the coverage performance of an LTE network with approximately 9,000 macro sites deployed across the UK using a similar modelling approach to that described above. However, instead of modelling just a sample 100 x 100 km area we have modelled the entire UK. This modelling has been carried out for a single network size (approximately 9,000 sites) and assuming a single network loading of 85%. We also assume a 2x5 MHz carrier and 2x2 MIMO.

A8.89 The results of this modelling are in Figure A8.18.

Figure A8.18



Example of how we might assess compliance

A8.90 The following provides an example of how we might assess compliance with a coverage obligation. This example has been derived on the basis of an operator providing a minimum guaranteed data-rate of 2 Mbps to users indoors at depth 2+ using LTE technology, with a single 5 MHz carrier in the 800 MHz band and the deployment of 2x2 MIMO[18].

A8.91 The -4.7 dB SINR target is taken from the SINR to throughput mapping function described above (see Figure A8.7) as applied to a 5 MHz carrier.

A8.92 To derive the target wanted signal strength (P_{wanted}) we make the assumption that, at the edge of cell, power from the 'serving' sector is on average equal to the interference power from other sectors in the network (i.e. $P_{\text{wanted}} = P_{\text{other}}$).

A8.93 From equation (11) we have $SINR = P_{\text{wanted}}/(P_{\text{other}} + P_{\text{noise}})$, substituting P_{wanted} for P_{other} and rearranging gives:

$$P_{\text{wanted}} = \frac{SINR \times P_{\text{noise}}}{(1 - SINR)} \tag{14}$$

A8.94 P_{noise} for a single 180 kHz resource block is -111.4 dBm. We know that $SINR_{\text{target}}$ = -4.7 dB therefore equation (14) means that the wanted power (per resource block), P_{wanted}, must be equal to or greater than -114.3 dBm.

A8.95 The wanted power computed in A8.92 is the power indoors at depth 2+. However, we want to know what the target power outdoors needs to be that would enable a 2 Mbps indoors at depth 2+. According to Table A8.3 and Table A8.4, mean building

[18] This example is specific to these assumptions. The actual parameters used to assess compliance will need to be established taking into account what the operator actually deploys (e.g. technology, frequency band, bandwidth, MIMO order etc.)

penetration losses and their standard deviation vary by clutter. We therefore need to specify the clutter environment which we will use as the basis for defining the target outdoor wanted power. As can be seen from Table A8.2 the majority of the UK population live in suburban areas (approximately 70%). We have therefore chosen to use building penetration values based on suburban clutter. The mean building penetration loss ($BPL_{\text{sub:d2}}$) for suburban clutter and depth 2+ is 7.2 dB and its standard deviation (SD_{bpl}) is 7 dB. We are also assuming a 90% coverage confidence.

A8.96 The equivalent outdoor wanted power threshold is given by equation 15 below:

$$P_{\text{wanted :outdoor}} = P_{\text{wanted :indoor}} + \left(SD_{\text{bpl}} \times \text{cf}\right) + BPL_{\text{sub :d2}} \qquad (15)$$

A8.97 Where cf is the coverage confidence factor given by the inverse of the normal distribution function for 90% (i.e. 1.28). This gives a target outdoor wanted power of -98.2 dBm or greater per resource block.

A8.98 Therefore, in this example, compliance is achieved for a network where:

- the SINR is equal to or greater than -4.7 dB in locations where at least 95% of the population of the UK live; and
- the received wanted power is equal to or greater than -98.2 dBm in outdoor locations where at least 95% of the population of the UK live.

Parameters and assumptions

Ref.	Parameter	Value or range modelled	Units	Comment
Base station				
1	Sectors per site	3		Industry practice
2	Radiated power (EIRP) per 180 kHz LTE resource block	45	dBm	Standard value
3	Antenna horizontal 3 dB beam-width	68 @ 800 MHz 67 @ 1800 MHz 62 @ 2600 MHz	degrees	Kathrein 742 265 multi-band antenna – extrapolated to 2600 MHz
4	Antenna vertical 3 dB beam-width	10.5 @ 800 MHz 5.2 @ 1800 MHz 4.5 @ 2600 MHz	degrees	Kathrein 742 265 multi-band antenna – extrapolated to 2600 MHz

5	Antenna down-tilt	variable	degrees	Optimised for frequency and average distance to nearest neighbouring sites
6	Antenna height	variable	m	Distribution representative of existing mobile operators networks
UE				
7	Antenna gain (mean effective gain)	0.0	dBi	
8	Antenna height	1.5	m	Standard assumption
9	Body loss (relative to free space)	5.0	dB	Assumption (consistent with previous Ofcom work)
10	Receiver noise figure	10 (800 MHz) 10 (1800 MHz) 9 (2600 MHz)	dB	3GPP TS 36.101
System				
11	Coverage Confidence	90% over cell area.	%	Industry data
12	Location variability (outdoor)	Varies dependant on frequency and clutter according to equation (1)	dB	See equation (1) above
13	Location variability (outdoor) cross-correlation coefficient	1.0 (inter-sector) 0.5 (inter-site)		See [4]
14	Building penetration loss variability	See Table A8.4	dB	Assumption, values refined in light of stakeholder comments on [3] and further Ofcom consideration
15	Building penetration loss cross-correlation coefficient	1.0 (inter-sector) 0.5 (inter-site)		Assumption – common with 13

16	Mean building penetration loss	Varies according to frequency, clutter characteristics and BPL scenario. See Table A8.3	dB	From [3]

References

[1] "LTE for UMTS - OFDMA and SC-FDMA Based Radio Access", Holma and Toskala, John Wiley and Sons

[2] "Antennas and Propagation for Wireless Communication Systems", S. Saunders & A. Aragon-Zavala, John Wiley and Sons

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

[4] "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

[5] IEEE 802.16m-08/004r5, "Evaluation Methodology Document (EMD)"

[6] "SEAMCAT implementation of Extended Hata and Extended Hata-SRD models", http://tractool.seamcat.org/raw-attachment/wiki/Manual/PropagationModels/ExtendedHata/Hata-and-Hata-SRD-implementation_v1.pdf

[7] 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

[8] 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

A8.99 The model described above has been developed using Matlab version 7.11.0.584 (R2010b).

Annex 9

Proposed Auction Rules

Introduction

A9.1 This annex provides a set of proposed rules for the auction of licences to use frequencies in the 800MHz, 2.6GHz and potentially other bands, for stakeholders to comment on, based on the illustrative packaging proposals set out in the main section of the document. In summary, the proposed auction has the following features.

a) Spectrum will be awarded using a combinatorial clock auction (CCA) format, the same format used in the 10-40GHz and L-band spectrum awards and proposed for the stand-alone award of the 2.6GHz band. The auction will progress in two distinct stages – a Principal Stage and an Assignment Stage.

b) The Principal Stage will allocate the spectrum available in the auction to bidders, based on bids made in the primary bid stage and the supplementary bids stage.

c) The primary bids stage will consist of a number of primary bid rounds during which each bidder can submit a single package bid based on lot prices prevailing in that round. The bid amount for primary bids is equal to the sum of the round prices of all lots included in the package.

d) This will be followed by a supplementary bids stage consisting of a single round of bidding during which bidders may submit bids for packages of lots with an associated bid amount specified by the bidder. During this round, bidders may increase their bids for packages they bid on in the primary bid rounds and make bids for packages for which they did not previously bid, subject to restrictions on the bid amount that can be specified for each package ("relative caps", discussed in paragraphs A9.67 to A9.72), which depend on the bidding behaviour of the bidder during the primary bids stage.

e) In determining the winners of the Principal Stage, all primary and supplementary bids submitted by all bidders will be considered. The winning outcomes will be constrained to satisfy a competition constraint, designed to promote outcomes where a sufficient number of parties hold sufficient spectrum after the auction to be credible national wholesale operators. The implementation of the competition constraint is through a reservation of spectrum to ensure that a number of bidders win as much spectrum of the relevant type as at least one of a set of pre-defined minimum spectrum portfolios.

f) Where lots of spectrum allocated to bidders are not linked to specific frequencies and where there is more than one block of specific frequencies to which winning bidders could be assigned consistent with the spectrum allocations determined in the Principal Stage, the specific frequencies assigned to each winning bidder will be determined in the Assignment Stage. This will consist of a single round of bidding where winners of lots not assigned to specific frequencies can submit bids for one or more of the alternative sets of frequencies that they may be assigned based on their winning packages.

A9.2 The bids of individual bidders during the Principal Stage will be limited by an eligibility points system and bidder-specific spectrum caps (discussed in paragraphs

A.39 to A.49). The calculation of these caps will take account of existing holdings of mobile spectrum that participants may have. As explained in section 8, we do not expect relinquishment into the auction of spectrum that is currently licensed beyond the 2x15MHz of 1800MHz spectrum to be divested by Everything Everywhere, which may be awarded through the auction if Everything Everywhere has not completed that divestment prior to the start of the auction.

A9.3 An Electronic Auction System (EAS) will be used for running the auction. This system will provide bidders with an interface that will provide real-time information about the status and progress of the auction and the necessary forms to check and submit bids, and will process bids for the identification of winning bidders and the calculation of associated base prices. More information on similar electronic auction systems used by Ofcom for previous auctions is available on the Ofcom website.[19]

Available spectrum and lot structure

A9.4 A description of the proposed lot structure for the spectrum that will be available for allocation in the auction is set out in Table 1 below. This consists of all spectrum in the 800MHz and 2.6GHz bands, and some spectrum that may also be included in the auction depending on circumstances relating to Everything Everywhere's divestment of 1800MHz spectrum in line with its merger undertakings (European Commission merger procedure case reference COMP/M.5650). For the purpose of this annex and for illustrative purposes, we assume that there is no spectrum reservation for concurrent low power use at 2.6GHz.

Category A: The 800 MHz band

A9.5 The 800 MHz band consists of 2x30 MHz of contiguous spectrum. This band will be made available in its entirety in the auction as 6 lots of 2x5 MHz of spectrum. This spectrum will be allocated using four separate lot categories:

i) Category A1 contains two generic lots. These lots relate to the lowest 2x10 MHz in the 800MHz band (791-796 MHz paired with 832-837 MHz and 796-801 MHz paired with 837-842 MHz).

ii) Category A2 contains one generic lot. This lot is linked to frequencies within the 2x10 MHz in the centre of the 800 MHz band (either 801-806 MHz paired with 842-847 MHz or 806-811 MHz paired with 847-852 MHz).

iii) Category A3 contains one generic lot. This lot is linked to the same frequencies as the lot in Category A2, but has an associated coverage obligation (discussed in section 6 of the consultation).

iv) Category A4 contains two generic lots. These lots relate to the highest 2x10 MHz in the 800 MHz band (811-816 MHz paired with 852-857 MHz and 816-821 MHz paired with 857-862 MHz).

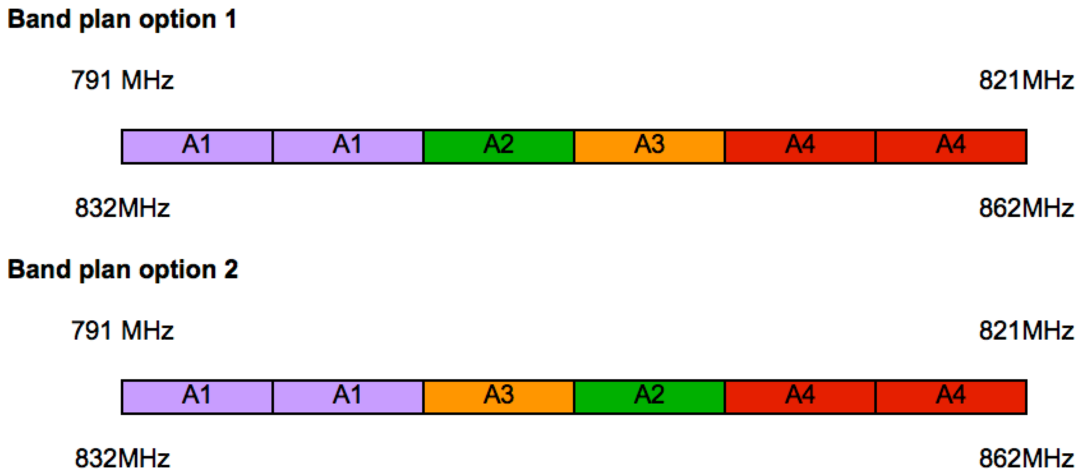
A9.6 Note that the two lots in the middle of the band, A2 and A3, are generic so as to allow a coverage obligation to be fixed to a specific lot category in the middle of the

[19] See for example, for the L-band award, http://stakeholders.ofcom.org.uk/binaries/spectrum/spectrum-awards/completed-awards/714758/keydocs/bidders.pdf, or for the 10/40GHz award http://stakeholders.ofcom.org.uk/binaries/spectrum/spectrum-awards/completed-awards/10-28-32-40-ghz-awards/10-40GHzseminar.pdf and http://stakeholders.ofcom.org.uk/binaries/spectrum/spectrum-awards/completed-awards/10-28-32-40-ghz-awards/auctioninfo.pdf.

band (A3), while retaining as much flexibility as possible as to frequency, to facilitate contiguous assignment of spectrum to winners of lots in the 800 MHz band.

A9.7 The alternative band plans given the lot structure described above are illustrated below.

Figure A9.1: Alternative band plans in the 800 MHz band

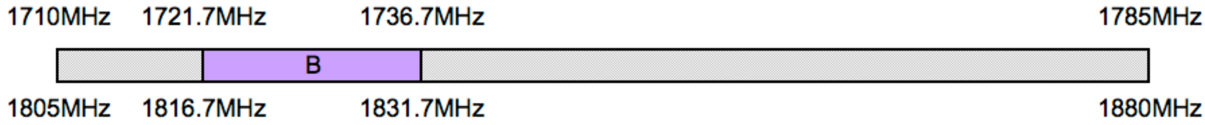


Category B: Spectrum in the 1800 MHz band

A9.8 The 1800 MHz band consists of 2x75 MHz of contiguous spectrum. Of this spectrum, 2x15 MHz of contiguous frequencies may be made available in the auction as a single 2x15 MHz lot. Where this spectrum is made available in the auction, the following lot category would be included in the auction lot structure.

- Category B contains one specific lot of 2x15 MHz linked to frequencies at the lower end of the band (1721.7-1736.7 MHz paired with 1816.7-1831.7 MHz).

Figure A9.2: Spectrum in the 1800MHz band that may be included in the auction



Categories C, D and E: spectrum in the 2.6 GHz band

A9.9 All spectrum in the frequency range 2500-2690 MHz is available for award. The centre band (2570-2620 MHz) will be offered as a single contiguous block of 50 MHz of unpaired spectrum (Category E). The remaining spectrum (2500-2570 MHz and 2620-2690 MHz) will be offered as paired spectrum in lots of 2x10 MHz, each comprising two blocks of 10 MHz with a separation of 120 MHz (duplex spacing between uplink and downlink frequencies).

A9.10 As part of the 2x70 MHz of paired spectrum, 2x60 MHz (2500-2560MHz paired with 2620-2680 MHz) will be offered exclusively for high power use in 2x10 MHz blocks. These lots will be in Category C.

A9.11 The remaining 2x10 MHz (2560-2570 MHz paired with 2680-2690 MHz) will be offered as *either* for high power use by a single user (a seventh lot in Category C) or for concurrent low power use by up to ten users (up to 10 lots in Category D for concurrent use of a single block of 2x10 MHz). Which use these 2x10 MHz are put to will depend on the bids made and will be determined at the end of the Principal Stage as part of the winner determination process.

A9.12 Therefore, spectrum in the 2.6 GHz band will be offered in three separate lot categories.

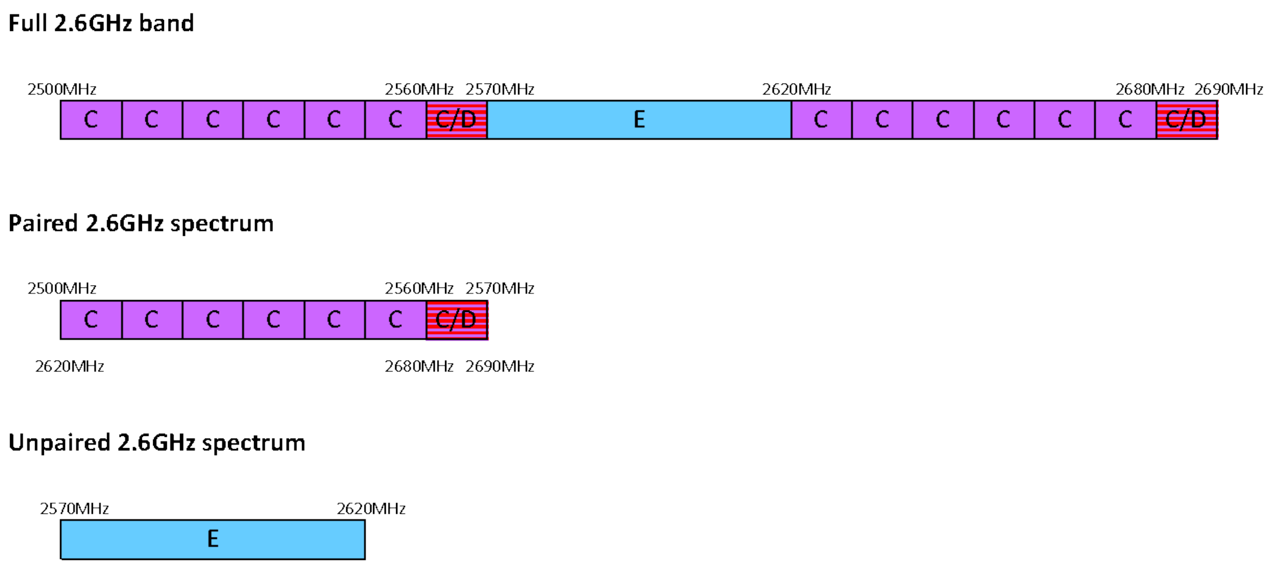
i) Category C contains up to seven lots of 2x10 MHz in the range 2500-2570 MHz paired with 2620-2690 MHz.

ii) Category D contains up to ten lots for concurrent low power use in the range 2560-2570 MHz paired with 2680-2690 MHz;.

iii) Category E consists of one single lot of 50 MHz of unpaired spectrum between 2570 MHz and 2620 MHz.

A9.13 If any Category D lots are allocated at the end of the Principal Stage, then no more than six lots in Category C will be allocated, and these will be assigned in the frequency range 2500-2560 MHz paired with 2620-2680 MHz. If seven Category C lots are allocated at the end of the Principal Stage, then no lots will be allocated in Category D, and in this case the Category C lots will be assigned in the range 2500-2570 MHz paired with 2620-2690 MHz. The 2.6 GHz band plan is illustrated below showing these two possibilities.

Figure A9.3: The full 2.6 GHz band and categories of paired and unpaired 2.6 GHz spectrum for a given approach to concurrent low power use



Lot structure: All lot categories

A9.14 Table A9.1 below provides a summary of the spectrum to be made available in the auction (based on specific assumption regarding EE's divestment at 1800 MHz and the approach to concurrent low power use, for illustrative purposes) .

Table A9.1: Lot structure for all lot categories

Category and band	Lot type	No. of lots	Lot size	Proposed eligibility per lot
A1: 800MHz (bottom 2 lots)	Generic	2	2x5MHz	30
A2: 800MHz (middle lot – no coverage obligation)	Generic as to frequency	1	2x5MHz	30
A3: 800MHz (middle lot – WITH coverage obligation)	Generic as to frequency	1	2x5MHz	30
A4: 800MHz (top 2 lots)	Generic	2	2x5MHz	30
B: 1800MHz (Divested prior to auction as per EC merger requirements)	Specific	1	2x15MHz	15
C: 2.6GHz Paired for individual high power use (bottom 6 lots or all 7 lots)	Generic	6 or 7	2x10MHz	10
D: 2.6GHz Paired, for concurrent low power use(1 block of 2x10MHz)	Specific	0 or up to 10	2x10MHz	1
E: 2.6GHz Unpaired, for individual high power use	Specific	1	50MHz	20

Deposits, reserve prices and eligibility points

A9.15 Illustrative eligibility points for lots that will likely be made available in the auction are set out in Table A9.1 above. Section 8 sets out more information on reserve prices. The mechanics of the eligibility points system during the auction are described in paragraphs A9.39 to A9.45.

A9.16 Prior to the start of the auction, there will be deposit requirements as discussed in section 9. Deposits will need to be consistent with the number of eligibility points a bidder wishes to be eligible to bid for in the first primary bid round and must be received in full by Ofcom. Ofcom may require that these deposits be increased at certain points during the auction. Spectrum licences will only be awarded to winners in the auction provided that Ofcom receives the full winning price of the associated lots within a pre-specified timeframe after the auction. Full details of deposit requirements, the consequences of not meeting such deposit requirements and the details on the return of deposits to unsuccessful bidders will be specified in the Information Memorandum and Regulations for this award.

Application and qualification

A9.17 As discussed in section 9, there will be specific requirements to apply to participate in the award process and then qualify as a bidder. We expect to implement similar provisions to those used in recent awards and will specify the provisions in the Information Memorandum and Regulations for this award.

Opt-in to compete to be a guaranteed spectrum winner

A9.18 In the first primary bid round, any bidder who at the deadline for applications did not already hold at least as much spectrum of the relevant types as at least one of the minimum spectrum portfolios will, in addition to their normal primary round bid, be able to elect to submit a bid in that round for each and every one of the different packages of spectrum that would result in them holding at least one of the minimum spectrum portfolios after the auction if that bid were to be a winning bid (‘minimum spectrum portfolio compatible packages’). The bid amount of those bids will in each case be the reserve price of the lots in the relevant package. Such bidders will only be able to elect to submit all such bids or none of them, they will not be able to elect to submit only some of them. Such bidders will also need to ensure that they have sufficient eligibility in the first primary bid round to submit each of these bids – if they have insufficient eligibility to make any one of these bids in the first primary bid round then they will not be permitted to elect to submit any of these bids.

A9.19 Bidders who elect to submit such bids will then be in competition with each other, but not with bidders who did not elect to submit such bids, or were ineligible to elect to submit such bids, to be guaranteed winners of at least a minimum spectrum portfolio compatible package. When determining the winners of the principal stage, Ofcom will ensure that sufficient of these bidders win a package of spectrum that is at least as large as that necessary for them to hold a minimum spectrum portfolio after the auction, such that at least four distinct licensees hold spectrum portfolios after the auction that are at least this large, unless insufficient bidders elect to submit such bids, in which case Ofcom will ensure that all bidders who do elect to submit such bids are winners, and win a package of spectrum at least sufficient for them to hold a minimum spectrum portfolio after the auction.

A9.20 Note that such bidders are by no means limited to winning only enough spectrum to satisfy the requirement to hold a minimum spectrum portfolio. It is entirely possible for those bidders to bid for and win more spectrum than this, and also to submit higher bids for some or all of their minimum spectrum portfolio compatible packages.

Primary bid rounds

A9.21 The primary bid rounds follow a clock auction format. The auction proceeds in discrete rounds, with all bidders submitting a single bid within a common fixed time window (subject to the provisions for bidder-specific rights to extend a round, details of which are not considered here but will be provided in the Information Memorandum).

A9.22 Bids submitted in the primary rounds are referred to as primary bids. A primary bid consists of a package of lots and a bid amount calculated automatically. Before the start of a round, the auctioneer announces a round price per lot for each lot category. During the round, bidders specify the package that they wish to bid for in the round by selecting the number of lots in each category they would be willing to purchase given the prices specified. The bid amount is the sum of the round prices associated with the lots contained in the primary bid in the round the primary bid is submitted.

A9.23 Primary bid rounds continue until there is a round when there is no excess demand in any lot category or, in exceptional circumstances, when the auctioneer decides to end the primary rounds early. The auction then proceeds to the supplementary bids round.

Scheduling primary bid rounds

A9.24 Ofcom will specify in advance of the auction the minimum notice period that will be provided before the start of a primary bid round and a minimum round duration. When a round start time is notified, bidders will also be given information about:

a) the duration of the round;

b) the round prices that will apply to lots in each category; and

c) their eligibility to bid in the round (expressed as a number of eligibility points).

Primary round prices

A9.25 Round prices announced by the auctioneer are prices per lot for each lot category.

A9.26 In the first primary bid round, the round price for each lot category will be set equal to the reserve price per lot for that lot category. In subsequent rounds, under normal circumstances, price increments will be applied to individual lot categories independent of one another and based on the level of excess demand for that lot category. The typical rule governing the price per lot within a lot category is that:

a) the round price for lots in a category in excess demand in the previous round will be increased; and

b) the round price for lots in a category not in excess demand will remain unchanged.

A9.27 In order to determine whether a lot category has excess demand at the end of a round, Ofcom will calculate the aggregate demand for that lot category as the sum of lots in that lot category specified in the packages of all bidders submitted in the round. A category is deemed to have excess demand if aggregate demand strictly exceeds the (maximum) number of lots available in the lot category.

A9.28 For paired spectrum in the 2.6 GHz band (Categories C and D), the calculation of excess demand will take account of the overlap between these two categories. Therefore, in addition to the assessment of whether there is excess demand for each one of these categories individually, Ofcom will also determine whether there is excess demand for paired 2.6 GHz lots overall, meaning that the combined demand for paired 2.6 GHz lots across Categories C and D exceeds the total supply of lots. Therefore, if the demand for lots in Category C exceeds six, and the demand for lots in Category D exceeds zero, then there is excess demand for paired 2.6 GHz lots overall, and therefore there is excess demand for lots in both categories (C and D).

A9.29 When there is excess demand for lots in a given lot category, round prices are increased by a price increment set at the discretion of the auctioneer. Under normal circumstances, price increments will be set independently for each lot category. A maximum price increment of 100% of the previous round price shall apply for all lot categories. We expect that price increments will typically be between 5% and 20% of the prevailing round price. All round prices will be in multiples of a thousand pounds.

Submitting bids during primary bid rounds

A9.30 All lots in the auction are available for bidding on in each primary round.

A9.31 In each primary bid round, each bidder may submit at most one primary bid.

A9.32 In order to submit a primary bid, the bidder must specify the number of lots in each lot category that a bidder wishes to acquire at the prevailing round prices. The combination of lots selected by the bidder needs to satisfy the constraints set out in paragraphs A9.39 to A9.45 on activity rules and paragraph A9.46 on spectrum caps. There are also contiguity requirements for the different categories of 800 MHz spectrum as set out in paragraph A9.51.

A9.33 To enter a bid, bidders need to select the number lots that they wish to acquire in each of the categories in the electronic bid form provided by the auctioneer through the EAS used for running the auction.

A9.34 The submission procedure is a two-step process. In the first step, bidders enter a bid in the electronic bid form. The bid is then checked by the system for validity. If the bid entered is invalid, the bidder will be informed of why the bid is invalid and directed to return to the electronic bid form. If the bid entered is valid, the bidder will be presented with a bid submission form providing:

a) a summary of the bid checked;

b) any applicable warnings in relation to potential reductions of eligibility for subsequent rounds (explained in paragraphs A9.39 to A9.45 below); and

c) the option to either submit the bid or to return to the bid form to modify the bid.

A9.35 It is not possible for bidders to choose the bid amount of a bid during the primary bid rounds. The primary bid amount is the sum of round prices for all the lots included in the package selected by the bidder. Therefore, the bid amount of a primary bid is determined as follows:

a) for each category, the number of lots in that category included in the package will be multiplied by the round price for that category; and

b) these values will be added up across all lot categories.

A9.36 A bid containing zero lots is called a ‘zero bid’.

A9.37 In the first primary round, each bidder must submit a bid for a package containing at least one lot. In subsequent rounds, bidders have the option to submit a ‘zero bid’.

A9.38 If a bidder fails to submit a bid within the round, the EAS will automatically enter a zero bid on the bidder’s behalf.

Activity rule and eligibility points

A9.39 Each category of lots in the auction has an associated number of eligibility points per lot.

A9.40 Any bid for a package has an associated level of 'activity', which is calculated as the sum of the eligibility points of all lots included in the package. The activity of a bidder in a primary bid round is equal to the number of eligibility points associated with the bid the bidder submits.

A9.41 In any primary bid round of the auction, the bidder's activity cannot exceed their eligibility (expressed as a number of eligibility points) in that round.

A9.42 The initial eligibility for each bidder will depend on the size of their deposit made prior to the first round of the auction. The minimum deposit would provide the bidder with two eligibility points and would allow it to bid for one concurrent low power lot in our illustration.

A9.43 After the first primary bid round, the eligibility of a bidder to bid in a round is equal to the activity of that bidder in the previous round. Therefore, a bidder can only bid for a package with an associated eligibility that is no greater than the bidder's activity in the previous round.

A9.44 Over successive primary bid rounds, a bidder's eligibility can be maintained or be reduced, but can never be increased. As the primary bid rounds progress, bidders may bid for different combinations of lots, provided that the activity level of each such bid is not greater than the eligibility for that bidder. Therefore, it is possible that a bidder's activity in some lot categories may increase, provided that the bidder's activity in other categories is sufficiently reduced so that the overall activity level of the bidder does not increase.

A9.45 A bidder whose eligibility has fallen to zero cannot submit any further primary bids.

Spectrum caps and bidding restrictions

Spectrum caps

A9.46 All bids are liable to be subject to one or more spectrum caps. The proposed caps are:

i) 2x27.5 MHz for spectrum under 1GHz for all bidders, including existing spectrum holdings of the bidder (the "Sub-1GHz Cap"); and

ii) 2x105 MHz for spectrum in the 800 MHz, 900 MHz, 1800 MHz, 2.1 GHz (paired) and 2.6 GHz (paired and unpaired) bands for all bidders, including existing spectrum holdings of the bidder (the "Overall Cap").

A9.47 The spectrum subject to the Sub-1GHz Cap includes all spectrum in the 800 MHz and 900 MHz bands.

A9.48 The spectrum subject to the Overall Cap includes:

a) all spectrum in the 800 MHz, 900 MHz, 1800 MHz, and 2.1 GHz (paired) bands, plus

b) all high-power use paired spectrum in the 2.6 GHz band (Lot category C); plus

c) 2x20 MHz equivalent in respect of the 2.6GHz centre band (Lot category E).

A9.49 No bidder may submit any bid for a package of spectrum that would result in them exceeding any spectrum cap if the bid were to be a winning bid.

Bidding restrictions

A9.50 There is a contiguity requirement for bids in the 800 MHz band. This means that a bidder cannot bid on lot categories linked to frequencies in the 800 MHz band (A1, A2, A3, A4) that are not adjacent to one another and as such would result in a non-contiguous assignment. For example, it is not possible to bid for a package that includes only A1 and A4 lots.

A9.51 A Bidder may bid for at most one lot in Category D (concurrent low power use 2.6 GHz paired spectrum).

Submission of primary round bids in exceptional circumstances

A9.52 Details of the circumstances and procedures linked to the permission of a bidder to submit a bid or bids via channels other than the EAS will be detailed in the Information Memorandum.

Primary bid round results information provided to bidders

A9.53 At the end of each primary bid round, Ofcom will reveal to each bidder:

a) the level of demand and excess demand for lots in each category;

b) information about the bid submitted by the bidder in the last completed round;

c) the eligibility of the bidder in the next round (if there is need for an additional round); and

d) the highest bid amount submitted by the bidder to date (which is relevant for any deposit calls).

A9.54 There is not full transparency of all bids made in the last round by all bidders; only aggregate and excess demand in each category are revealed.

A9.55 If there is a need for an additional round, Ofcom will notify bidders of the new round prices (including price increases for the relevant lot categories) and the start time and duration of this round.

A9.56 The EAS includes an auction history tool that will allow bidders to view and download information about demand and excess demand in each lot category in previous rounds, and about their own bids.

A9.57 We may also publish information on our website from time to time during the primary bid rounds, for example at the end of each day of bidding. Such information would likely cover excess demand and round prices for each lot category.

End of the primary bid rounds

A9.58 The primary bid rounds end when there is a round in which there is no excess demand in any of the lot categories.

A9.59 At this point, Ofcom will announce that the primary bid rounds have ended and that the auction will progress to the supplementary bids round.

A9.60 Ofcom has the discretion to end the primary rounds early (i.e. while there is still excess demand in one or more lot categories). In this case, the auction will proceed directly to the supplementary bids round.

Supplementary bids round

A9.61 The supplementary bids round consists of a single round of bidding that follows the primary bid rounds.

A9.62 In the supplementary bids round, bidders may submit multiple, mutually exclusive bids, subject to the constraints set out in paragraphs A9.46 to A9.51, and the constraint that any package they bid for cannot have an associated eligibility greater than the bidder's initial eligibility.

A9.63 The bid amounts for bids submitted in the supplementary bids round are at the discretion of the bidder, subject to the constraints detailed in paragraphs A9.67 to A9.72.

A9.64 The supplementary bids round provides an opportunity for bidders to:

a) submit bids for packages that they are willing and eligible to bid for, but on which they did not bid in the primary bid rounds; and

b) increase the amount bid for packages that they bid for in the primary bid rounds.

A9.65 All bids received from bidders in both the primary bid rounds and the supplementary bids round are considered for the determination of winning bidders, winning bids, and prices to be paid by winning bidders.

Scheduling the supplementary round

A9.66 After the completion of the primary bid rounds, Ofcom will announce the start time and duration of the supplementary round. Minimum advance notice and minimum duration of this round will be set out in the Information Memorandum.

Restrictions on supplementary bids

A9.67 There is no limit on the number of supplementary bids that a bidder can submit (although it can only make one bid for each particular package of lots).

A9.68 The bid amount for each supplementary bid must exceed the higher of:

a) the sum of the reserve prices for all lots included in the package; and

b) the bidder's highest primary bid for that package (if the bidder has submitted a primary bid for the package).

Relative cap

A9.69 Each bidder has a 'final primary package' (FPP). The FPP of a bidder is the package that the bidder bid for in the final primary bid round. The FPP of a bidder who submitted a zero bid (actively, or defaulted by the system) in the final primary bid round is the zero package (the package containing zero lots).

A9.70 The supplementary bid amount for the FPP is not capped provided that the FPP is not the zero package. The bid amount for the zero package is always 0.

A9.71 Supplementary bid amounts for all packages other than the FPP are subject to a relative cap. The cap on a package A is set to:

a) the amount of the highest bid (made in either a primary bid round or the supplementary bids round) for package B, where B is the package that the bidder bid for in the last primary round in which the bidder was eligible to bid for package A; plus

b) the price difference between the two packages (price of package A minus price of package B) at the round prices prevailing in the last round that the bidder was eligible to bid for package A.

A9.72 The implication of this rule is that all supplementary bids for packages other than the FPP will be subject to relative caps that ultimately relate to the supplementary bid amount submitted for the FPP (though possibly through a number of steps).

Generating supplementary bids

A9.73 The EAS includes a supplementary bids management tool that bidders can use to maintain and revise a list of provisional supplementary bids throughout the primary and supplementary rounds. This system also incorporates information about the bids submitted by the bidder in the primary bid rounds, and the constraints on supplementary bids deriving from primary bids. This information is updated as the bidder submits further bids, when the results of the relevant primary bid round are approved. The supplementary bid management tool also informs bidders of the relative caps that result from the provisional supplementary bids already entered in the system.

A9.74 The management tool is provided purely for the convenience of bidders. No supplementary bids can be submitted until the supplementary bids round is in progress. Supplementary bids entered into the supplementary bids management tool will not be automatically submitted during the supplementary bids round, but must be actively submitted by the bidder. Provisional bids entered into the system using this tool will not be visible to Ofcom or any other bidder.

Submitting supplementary bids

A9.75 Supplementary bids are submitted using the EAS during the supplementary bids round. The submission procedure is a two-step process, similar to the procedure for submitting primary bids.

A9.76 In the first step, bidders enter a list of supplementary bids into the system (this can be done using the supplementary bid management tool or using a file upload facility, where the file uploaded should contain the supplementary bids that the bidder wishes to submit in a pre-specified format). The list of supplementary bids is checked by the system for validity against all applicable constraints. If any of the supplementary bids entered is invalid, the bidder will be informed of why the bid is invalid and directed to return to the supplementary bid management tool to modify the invalid bids (or upload a new bids file).

A9.77 If all the supplementary bids in the list are valid, the bidder will be presented with a submission form providing:

a) a summary of the bids checked;

b) the number of supplementary bids checked;

c) the highest bid amount over all bids checked;

d) any applicable warnings in relation to very large bid amounts or primary bids for which the bidder has not modified the supplementary bid amount; and

e) the option either to submit the list of supplementary bids or to return to the supplementary bids form to modify the list of bids.

A9.78 Any provisional supplementary bids stored by a bidder using the management tool, together with the bids they made for packages in the primary bid rounds (including reserve price bids for minimum spectrum portfolio compatible packages made by bidders in the first primary bid round), will be available as a starting point for compiling a list of supplementary bids during the supplementary bids round. A bidder may add, revise or delete its supplementary bids as required. However, bidders cannot delete any primary bids. Bidders are also provided with details of any constraints on their maximum bids for nominated packages and an explanation of the calculation of the supplementary bid amount caps that apply to each package. The constraints are displayed as maximum bids for particular packages *given bids on all other packages*. There is a “chain” effect on relative cap constraints such that changing a bid for one package may affect the level of the cap on other packages. All bid amounts must be in multiples of a thousand pounds.

Determining the winners of the Principal Stage

Ensuring effective competition: Minimum spectrum portfolios

A9.79 The outcome of the auction will be required to satisfy a competition constraint. The competition constraint will require that at least N bidders are allocated a package of spectrum such that their total holding of mobile spectrum after the auction includes at least a minimum amount of spectrum from a list of pre-identified minimum spectrum portfolios, consistent with the proposals from our competition assessment. These N bidders need to be selected from amongst the group of bidders who elected to submit a reserve price bid for each and every one of their minimum spectrum portfolio compatible packages in the first primary bid round. Bidders who did not elect to submits such bids in the first primary bid round, or were ineligible to do so, do not contribute towards the satisfaction of the competition constraint.

A9.80 N will be the lesser of:

i) the number of bidders that elected to submit a reserve price bid for each and every one of their minimum spectrum portfolio compatible packages in the first primary bid round; and

ii) four, less the number of distinct licensees who at the deadline for applications already held at least as much spectrum of the relevant types as at least one of the minimum spectrum portfolios.

A9.81 An example may help to illustrate how N is determined.

A9.82 Suppose that two licensees at the deadline for applications already held at least as much spectrum of the relevant types as at least one of the minimum spectrum portfolios. Five bidders elected to submit a reserve price bid for each and every one of their minimum spectrum portfolio compatible packages in the first primary bid round, and one bidder did not elect to submit such bids in the first primary bid round. In this case N is the smaller of:

- Five, equal to the number of those that elected to submit a reserve price bid for each and every one of their minimum spectrum portfolio compatible packages in the first primary bid round; and

- Two, equal to four minus the two licensees who at the deadline for applications already held at least as much spectrum of the relevant types as at least one of the minimum spectrum portfolios.

A9.83 The one bidder that did not elect to submit such bids in the first primary bid round, and the two that were ineligible to do so, do not contribute towards the satisfaction of the competition constraint and N is equal to two.

A9.84 In this example the number of bidders who elected to submit a reserve price bid for each and every one of their minimum spectrum portfolio compatible packages in the first primary bid round (equal to five) exceeds the number of those needed to satisfy the competition constraint (equal to two). Therefore it will be competition in the auction that selects the bidders that contribute to meet the competition constraint. Notice that we require those bidders who wish to compete to be a guaranteed winner of spectrum, to submit a reserve price bid in respect of each and every one of their minimum spectrum portfolio compatible packages. This is necessary because otherwise, if such bidders could pick and choose which minimum spectrum portfolio compatible packages they were willing to accept, it may be impossible for us to allocate a large enough number of such bidders a suitable spectrum package to meet the competition constraint, as a result of those bidders having incompatible and conflicting demands. Ofcom wishes to ensure that the competition constraint can be met if there are enough bidders interested in doing so.

A9.85 Furthermore, the requirement that such bidders make a reserve price bid for each and every one of their minimum spectrum portfolio compatible packages ensures that the competition constraint cannot be used by such bidders to leverage that constraint to ensure that they win a larger package. In particular, such bidders will be competing on a level playing field with other bidders for any additional spectrum above and beyond the minimum necessary for them to hold a minimum spectrum portfolio after the auction.

Compatible combinations of winning bids

A9.86 In determining the winning bids, all valid bids made during the primary bid rounds and the supplementary bids round will be considered.

A9.87 A combination of bids will be eligible to be the winning combination of bids (a ‘compatible combination of bids’) if:

i) the combination of bids includes at most one bid from each bidder;

ii) the total number of lots in each lot category included in the bids within the combination is no greater than the total number of lots available in that lot category; and

iii) the combination of bids includes a minimum spectrum portfolio compatible bid from at least N bidders, where N is the smaller of--

- the number of bidders who elected to submit a reserve price bid for each and every one of their minimum spectrum portfolio compatible packages in the first primary bid round; and
- four less the number of operators who at the deadline for applications already held at least as much spectrum of the relevant types as at least one of the minimum spectrum portfolios.

Winning combination of bids

A9.88 The winning combination of bids will then be the compatible combination of bids for which the total sum of all bid amounts is greatest.

A9.89 An algorithm will be used to determine the combinations of bids that meet the criteria set out in paragraph A9.87. If there is only one combination of bids that meet these criteria, this will be the winning outcome that determines the winning bids and winning bidders.

A9.90 If there is more than one combination of bids that satisfy the criteria set out in paragraph A9.87 for which the total sum of the bid amounts is equal highest, the winning combination of bids will be that combination amongst these which includes the greatest amount of spectrum within the bids measured in terms of eligibility points. If there is still a tie between compatible bid combinations based on these criteria, the winning combination will be selected at random from amongst those tied winning combinations.

Determining base prices for winning bids in the Principal Stage

A9.91 Following the determination of winning bids in the Principal Stage, Ofcom will proceed to determine the base prices, that is, the minimum prices to be paid by winning bidders for the bid packages they have been allocated.[20]

A9.92 A separate base price is determined for each winning bid (and thus for each winning bidder).

A9.93 Base prices are calculated such that if all winners had specified a bid amount equal to the base price of their winning bid, and reduced the bid amount of all other bids they submitted by the same extent, then:

a) the outcome of the winner determination process would be the same as the outcome of the Principal Stage; and

b) no winner could have lowered their winning bid amount any further without changing the outcome of the winner determination process.

A9.94 Base prices are determined jointly for all winners in a single calculation. A unique set of base prices is found by applying the following conditions.

[20] These are minimum prices because bidders may have to pay an additional price in order to win particular frequencies through the Assignment Stage.

i) **First condition:** the base price of a winning bid must be no less than the total of the reserve prices of the lots in the winning bid package, but no greater than the winning bid amount.

ii) **Second condition:** the set of prices must be sufficiently high that there is no alternative bidder, or group of bidders, who expressed through their bids a willingness to pay more than any winner or group of winners and whose bids would be compatible with the competition constraint. If there is only one set of prices that meet the first and second conditions, these are the base prices for the Principal Stage.

iii) **Third condition:** if there are many sets of prices that fulfil the first and second condition, only those set(s) of prices that minimise(s) the sum of prices across winning bidders are selected. If there is only one set of prices satisfying these three conditions, these are the base prices for the Principal Stage.

iv) **Fourth condition:** if there are many sets of prices that satisfy the first three conditions, the (unique) set of such prices that minimises the total distance (as defined in annex 10) between the price for each winner and the linear reference price for that winner are the base prices.

A9.95 Annex 10 sets out in detail the proposed methodology for calculating base prices.

A9.96 These conditions determine a unique base price for each winning bidder that is not greater than their winning bid and not smaller than the reserve price for their winning bid package.

End of the Principal Stage

A9.97 Once Ofcom has determined the winning bids, the winning bidders and the base prices, the outcome of the Principal Stage will be announced to bidders. The following information will be released to all bidders:

a) the identity of the winning bidders;

b) the number of lots won in each of the categories by each winning bidder; and

c) the base price to be paid by each winning bidder.

A9.98 Following this, specific frequencies are assigned to all winners based either on the allocation of specific lots in the Principal Stage or the outcome of a follow-up process of assignment described in the following sub-section.

Assignment Stage

A9.99 The Principal Stage will be followed by an Assignment Stage, which will allocate specific frequencies available within certain lot categories to the winning bidders of lots in such lot categories. The Assignment Stage will consist of a single round of bidding, the assignment round, which will allow winners to express preferences for the specific frequencies at which their lots might be located by submitting assignment bids for alternative assignment options. At the end of this stage, winning bidders will be assigned specific frequencies equal in bandwidth to the lots in each lot category that they were allocated in the Principal Stage. Where a number of winners of the Principal Stage compete for the same frequency range in the Assignment Stage, the bidder who is allocated a contested frequency range may have to pay an additional price no greater than its assignment bid.

A9.100 In order for a lot category to appear in the assignment round:

a) there must be more than one lot in the lot category; and

b) there must be at least two alternative assignment options for winners of spectrum in the lot category once the ‘contiguity rule’ has been applied.

Contiguity rule

A9.101 The contiguity rule imposes a restriction on assignment options such that where a bidder is allocated lots in lot categories that are adjacent to one another, assignment options will be limited to those that ensure that such a bidder’s frequency assignment is in one contiguous block in each band.

A9.102 Based on the lot structure of the auction assumed in this annex, this rule is relevant for the 800MHz band only.

a) If a bidder is allocated lot A2 or A3 and one lot in A4, this bidder will automatically be assigned frequencies linked to blocks 4 and 5 in the 800 MHz band (806-816 MHz paired with 847-857 MHz).

b) Similarly, if a bidder is allocated lot A2 or A3 and one lot in A1, this bidder will automatically be assigned frequencies linked to blocks 2 and 3 in the 800 MHz band (796-806 MHz paired with 837-847 MHz).

A9.103 The contiguity requirements for the 2.6 GHz band are that all lots in an assignment of paired lots in category C (high power) needs to be contiguous.

Bidding in the assignment round

A9.104 In the assignment round, winners in the Principal Stage that have been allocated at least one lot which has not automatically been assigned to specific frequencies are presented with the alternative frequency ranges available to them based on the package they have won in the Principal Stage. During the assignment round, these winners have an opportunity to make an assignment bid in respect of each of the specific frequency ranges they could be assigned. Bidders that have been awarded one or more lots in a lot category in the Principal Stage are guaranteed to win one of the specific frequency ranges in the relevant lot category equal in bandwidth to the lots allocated to them in the Principal Stage regardless of the assignment bids they make. As such, bidders in the assignment round are free to choose not to make any bids during the round if they so wish.

A9.105 Each bidder will be provided with an electronic bid form listing the alternative frequencies ranges available to them given the lots they won in the Principal Stage and the effect of the contiguity rule. Bidders may bid an amount for one or more of the assignment options. Bid amounts must be expressed in whole pounds.

A9.106 If a bidder does not enter a bid for one or more assignment options, it will be deemed to have entered a bid of zero for those assignment options.

Determining winners in the Assignment Stage

A9.107 The winning bids from the assignment round will be determined for each lot category by selecting the combination of assignments of specific frequency ranges to winners that yields the greatest sum of winning Assignment Stage bid amounts. In the event of a tied outcome with more than one assignment producing the same total value of winning bid amounts, the tie will be broken by selecting one of the tied outcomes at random.

Determining additional prices for winning bids in the Assignment Stage

A9.108 Following the determination of winning assignment bids in the Assignment Stage, Ofcom will proceed to determine the additional prices, that is, the amounts (over and above the base prices) to be paid by winning bidders for the specific frequencies they have been assigned.

A9.109 A separate additional price is determined for each winning bid (and thus for each winning bidder).

A9.110 Additional prices are calculated such that if all winners had specified a bid amount equal to the additional price for their winning bid, and reduced the bid amount of all other assignment stage bids they submitted by the same extent-

a) the outcome of the winner determination process would be the same as the outcome of the Assignment Stage; and

b) no winner could have lowered their winning bid amount any further without changing the outcome of the winner determination process.

A9.111 Additional prices are determined jointly for all winners in a single calculation similar to that used to determine base prices (see paragraph A9.94 above).

End of the Assignment Stage

A9.112 Following the completion of the assignment round, each winning bidder will be told:

a) the exact frequency ranges awarded to them; and

b) the total price to be paid by them, which will be the sum of the base price for their winning bid in the Principal Stage and the additional price (if any) for their winning bid in the Assignment Stage.

A9.113 Bidders are required to pay the total price of their bid (minus funds deposited with Ofcom during the course of the auction process if not forfeit) within a pre-specified timeframe, before a licence for frequencies assigned to the bidder in the auction is granted.

Completion of the award process

A9.114 Following the payment of licence fees and the grant of licences, Ofcom will complete the award process by publishing on its website details of all bids made in the Principal Stage and Assignment Stage by each Bidder, the names of all licensees, the details of the frequencies comprised in the licences awarded and the licence fees paid. We will also publish the names of any winning bidders that did not comply with the deposit requirements applicable in the award and have been excluded from the award process in accordance with the auction rules. Where relevant, we will also publish details of the frequencies that would otherwise have been assigned to excluded bidders and the licence fees that they would have been required to pay.

A9.115 If one or more lots are not awarded as part of the award process, we will retain the discretion to award the remaining lots through a separate award process.

Annex 10

Pricing methodology for base price determination and annual licence fee derivation

Introduction

Second price approach

A10.1 Ofcom's previous spectrum awards have used a combinatorial clock auction (CCA) format in which a 'second price' rule was used to determine prices paid by winners. This rule means that a bidder typically does not pay what it bid. Instead, a winner pays the lowest amount such that, had the bidder bid this lower amount instead, it would still have won the same package.[21] Therefore, the rule is based on the economic principle of opportunity cost: that a winner (or any group of winners) should pay for the lost value to those denied spectrum by virtue of that bidder winning.

A10.2 This second price rule is based on winners paying both individually and collectively a sufficient amount that losers cannot argue, on the basis of the bids they made, that they should have won. Therefore, the rule uses a generalised notion of opportunity cost that sets a floor for how much each and every subset of winning bidders must pay. This principle is called *core pricing.*

A10.3 Subject to these floors set by opportunity cost and winners paying at least the reserve price for their winning packages, the rule used previously then requires that the total amount paid by winners is minimised. This means that winners pay no more than necessary (both individually and collectively) such that losers cannot argue that they should have won. Prices for winners that satisfy this condition are called *minimum revenue core (MRC) prices.*

A10.4 There may be many possible MRC prices. In such cases, a rule for selecting one set of MRC prices (a single price for each winner) is required. In auctions to date, Ofcom has used the Vickrey-nearest rule when selecting from amongst the MRC prices to find base prices. This rule establishes a reference point – the Vickrey prices – and the set of prices amongst the MRC prices closest to this reference point is chosen.

A10.5 Vickrey prices are the opportunity cost that each individual winning bidder imposes on others by virtue of winning. They are equal to the higher of the reserve price for the bidder's winning package and the value of the bidder's winning bid less the amount by which the total value of all winning bids would be reduced if that bidder's bids were omitted.

[21] This is an informal description. Strictly, this is a simultaneous restriction on all prices. For winning each bidder, the winning bid is reduced to the level described and all other losing bids of that bidder are reduced by the same amount as the winning bid. The winning bids should remain winning given these changes. In addition, there is a general requirement that prices are at least equal to the reserve prices.

Characterising base prices

A10.6 In previous CCAs, Ofcom has characterised the MRC prices through three nested conditions on the base prices:

i) **First condition:** the base price of a winning bid must be greater than or equal to the total reserve prices of the lots in that winning bid, but less than or equal to the amount bid.

ii) **Second condition:** the base prices must be sufficiently high that there is no alternative bidder, or group of bidders, whose bids indicate that they are prepared to pay more than the base price of any winner or total of the base prices of any group of winners and whose bids would be compatible with the competition constraint. If there is only one set of prices that meet the first and second conditions, these are the base prices for the principal stage.

iii) **Third condition:** If there are many sets of prices that fulfil the first and second condition, only those sets of prices that minimise the sum of prices across winning bidders are considered. If there is only one set of prices satisfying these three conditions, these are the base prices for the principal stage.

A10.7 In the case where the above three conditions do not determine a single unique set of base prices, Ofcom has used a **fourth condition** to break this tie by choosing from among the sets of prices that do satisfy the above three conditions that set of prices which is closest in Euclidean distance (i.e. minimise the sum of squares of differences) to the individual opportunity costs (Vickrey prices). These are then the base prices for the principal stage. This rule for selecting a set of base prices from the MRC is referred to as the Vickrey-nearest rule.

Suitability of the Vickrey-nearest rule for this award

A10.8 Since the implementation of these awards, Ofcom has reviewed the suitability of this rule for determining base prices in light of developments in the academic literature in analysing the bidding incentives that this approach to determining second prices creates and also in light of certain requirements on it relating to this award.[22]

A10.9 Academic work in this area suggests that in certain cases the Vickrey-nearest rule for selecting a set of base prices from the MRC may provide bidders with incentives to reduce their bid amounts. However, the concerns are strongest in simple settings where there is a high degree of certainty that a bidder will be part of a group of bidders who will collectively face a floor on what they must pay determined by their collective opportunity cost. In the context of application of the Vickrey-nearest rule to reasonably complex auctions where there is significant uncertainty about how other bidders will behave, this situation is less likely. Therefore, the practical implications may be less severe than the theory might at first suggest. Nevertheless, this is a potential concern about the Vickrey-nearest rule that might justify the adoption of a different rule.

A10.10 However, there is a perhaps more pertinent reason for considering a slightly different approach to pricing in the context of this award. One requirement of the

[22] For more information about the incentive effects see Erdil, A. and P. Klemperer, 2009, A new payment rule for core-selection package auctions, working paper available online at http://www.nuff.ox.ac.uk/users/klemperer/cspa-23-9-2009.pdf.

Government's Direction to Ofcom is that after the auction we revise the level of annual licence fees that apply to 900 MHz and 1800 MHz licences so that they reflect full market value, and in so doing have particular regard to the sums bid for licences in this auction. We therefore need to extract from the sums bid for licences in this auction an estimate of the value of different frequencies, as expressed through those bids. The Vickrey-nearest rule however only determines a base price for each winner, it provides no estimate of the value of different frequencies within the packages won. We have therefore considered whether a different pricing rule, which continues to apply the minimum revenue core principle but which adopts a different approach to breaking any tie between different sets of MRC prices, might be more appropriate in this case.

A10.11 The alternative rule that we have developed, and which is set out in further detail below, seeks to identify linear lot prices which are closest in a particular sense to market clearing prices for the winning outcome (and if there is more than one such set of linear lot prices, to select those that are closest to the reserve prices in relative terms), whilst generating the same total (minimum) revenue as MRC prices. Having identified this (unique) set of 'linear reference prices', the alternative rule then uses these in place of Vickrey prices to break any tie that there might be in the identification of base prices from within the MRC.

A10.12 One advantage of this rule would be that, if it turned out that there existed linear lot prices that were market clearing, and in the MRC, then base prices would be determined by those linear lot prices. In other words, each winning bidder would pay the same amount as every other winning bidder for each lot of the same type. By contrast, under the Vickrey-nearest rule, even in these circumstances different winning bidders could pay different amounts for the same combination of lots. However, even if exactly market clearing linear lot prices do not exist for a particular auction outcome, it is likely that base prices derived using this linear reference rule would none the less be closer to uniform than base prices derived using the Vickrey-nearest rule. And in either case, we would have an estimate of the value placed on each distinct type of lot, by both winning and losing bidders, in the form of the linear reference price for each type of lot, which we might then use as the basis for setting annual licence fees that reflected full market value, having particular regard to the sums bid for licences in the auction.

A10.13 We are therefore minded, subject to the views of stakeholders and the results of further analysis and testing, to adopt the linear reference price approach to breaking ties amongst sets of minimum revenue core prices, for the purpose of determining base prices in this auction, in preference to the Vickrey-nearest rule.

The linear reference price method

Overview

A10.14 The proposed linear reference price method finds a particular set of linear prices that are, in a particular sense, closest to market clearing prices at which each bidder could not argue that they should have won something different from what they did win, on the basis of their bids (including losing bidders having not won anything). It cannot however be guaranteed that a set of linear prices can be found to match market clearing prices exactly, hence the approach is to choose linear prices that satisfy this condition as best as possible. We therefore allow an 'excursion' for each bidder which quantifies the maximum extent to which any particular set of linear lot prices fails to explain the auction outcome for that bidder.

A10.15 Specifically, in the case of winning bidders this excursion is the maximum amount by which the payoff of any of their losing bids (difference between amount bid and price of bid) exceeds the payoff of their winning bid, for the particular set of linear lot prices being considered (with the excursion being zero if the payoff for their winning bid is at least as great as the payoff for all of their losing bids). Similarly, in the case of losing bidders the excursion is the greatest amount by which any of their (losing) bids exceeds the price of that bid, given those same linear lot prices, in other words the maximum payoff amongst their (losing) bids (again with the excursion being zero if none of their (losing) bids has a positive payoff). In other words, in both cases, the excursion for each bidder is the maximum extent to which the proposed linear lot prices are unable to explain the auction outcome for that bidder.

A10.16 The first requirement that we impose on the linear reference prices is that the total of the linear reference prices for all lots sold should be the same as the total revenue from all sets of prices in the MRC; in other words that the total revenue that would be generated if the lots won were priced at the linear reference prices would be the same as the total revenue that will be generated from the final base prices when those come from the MRC. Thus we ensure that the final linear reference prices will in one sense represent the average of the base prices paid by winning bidders.

A10.17 The second requirement that we impose on the linear reference prices is that they should be one of those sets of linear lot prices which minimise the total of the excursions across all bidders.

A10.18 The effect of this condition is that the linear reference prices are approximate market clearing prices. They are prices at which the outcome of the auction is approximately consistent with the bidders choosing the package they have been awarded if faced with a common per lot price for each category, so demand and supply are balanced. However, we can only achieve approximate consistency, as there are cases in which it is not possible to match demand and supply using only linear prices that are common across all bidders.

A10.19 If there is more than one set of linear lot prices which minimise the sum of excursions, the linear reference prices are the set of linear lot prices from amongst this group which are closest to reserve prices in relative terms. This condition is guaranteed to identify a unique set of linear reference prices in all cases.

Technical description

Notation

A10.20 There are K categories of lots for allocation labelled $k = 1,\ldots,K$ and there are s_k lots awarded in category k.

A10.21 There are I bidders labelled $i = 1,\ldots,I$. Bidder i makes bids (β_{ij}, x_{ij}) where β_{ij} is the bid amount of the j$^{\text{th}}$ bid and x_{ij} is the package of lots bid for. Conventionally, each bidder's set of bids includes a zero bid (i.e. a bid of amount zero for an empty package) representing the possibility of that bidder losing. Let $(\beta_i^\star, x_i^\star)$ be the winning bid of bidder i (which will be the zero bid in the case of losing bidders).

A10.22 Let α_k denote the linear reference price of a lot in category k and α the vector of linear reference prices. Let ρ_k be the reserve price for lot category k and ρ the vector of reserve prices.

Minimisation of sum of maximum excursion over all bidders

A10.23 The first step in the determination of linear reference prices is to find the vectors of linear lot prices which are solutions to the following linear programme:

$$\min_\alpha \sum_{i=1}^{I} \max_j \left[(\beta_{ij} - \alpha \cdot x_{ij}) - (\beta_i^* - \alpha \cdot x_i^*) \right]$$
$$s.t.$$
$$\sum_{i=1}^{I} \alpha \cdot x_i^\star = R$$
$$\alpha_k \geq \rho_k \forall k$$

where R is the total revenue requirement on the linear reference prices that is the minimum revenue over core prices (i.e. the common revenue associated with all MRC price vectors).

A10.24 This linear programme identifies the sets of linear lot prices that minimise the total over bidders of the maximum excursion for each bidder, subject to the total price of the winning packages at these linear lot prices equating to the total revenue of prices in the minimum revenue core and the linear lot prices being higher than their respective reserve prices.

A10.25 If there is more than one set of linear lot prices which minimise the sum of maximum excursions over bidders, the linear reference prices are chosen to be that set which minimise the sum of squared differences relative to reserve prices:

$$\min_\alpha \sum_{k=1}^{K} s_k (\alpha_k - \lambda \rho_k)^2$$
$$s.t.$$
$$\alpha_k \geq \rho_k \forall k.$$

where s_k is the total number of lots awarded in category k and

$$\lambda = \frac{\sum \alpha_k s_k}{\sum \rho_k s_k}$$

is the common multiple that needs to be applied to the reserve prices to obtain revenue R.

Determination of base prices using the linear reference price rule

Overview

A10.26 Having determined linear reference prices as above, the base price determination would then select the set of base prices which fulfil the following four conditions:

i) **First condition:** the base price of a winning bid must be no less than the total of the reserve prices of the lots in the winning bid package, but no greater than the winning bid amount.

ii) **Second condition:** the set of base prices must be sufficiently high that there is no alternative bidder, or group of bidders, who expressed through their bids a willingness to pay more than any winner or group of winners and whose bids would be compatible with the competition constraint. If there is only one set of prices that meet the first and second conditions, these are the base prices for the principal stage.

iii) **Third condition:** If there are many sets of prices that fulfil the first and second condition, only those set(s) of prices that minimise(s) the sum of base prices across winning bidders are selected. If there is only one set of prices satisfying these three conditions, these are the base prices for the principal stage.

iv) **Fourth condition:** If there are many sets of prices that satisfy the first three conditions, the (unique) set of such prices that minimises the sum of squared differences between the price for each winner and the linear reference price for that winner are the base prices.

A10.27 Relative to the Vickrey-nearest rule previously used by Ofcom, only the last condition of the base price determination changes through the use of a different reference point.

Technical description

Notation

A10.28 We will use the same notation as before and set out in paragraphs A10.20 to A10.22. In addition, let p_i be the base price for bidder i.

Identification of minimum–revenue core prices

A10.29 Core prices are prices p_i for each bidder i which satisfy the following conditions:

$$\sum_{i \in C} (\beta_i^\star - p_i) \leq V(I) - V(I \setminus C) \forall C \subset I$$
$$p_i \leq \beta_i^\star \forall i$$
$$p_i \geq \rho \cdot x_i^\star \forall i$$

A10.30 The first condition says that each coalition of bidders C pays at least its collective opportunity cost. The second requirement is that prices do not exceed bids and the third that they exceed the cost of the package won at reserve prices.

A10.31 Let M be the set of price vectors $(p_1, \dots, p_I)$ satisfying these conditions and which also minimise the total revenue $\sum p_i = R$. These price vectors are the MRC prices (and R will be the common minimum revenue across all these MRC prices).

Selection of minimum-revenue core prices using the linear reference price rule

A10.32 To select from the set of MRC price vectors, we minimise the Euclidean distance from the reference point set by pricing the winning packages at the linear reference prices:

$$\min_p \sum_{i=1}^{I} (p_i - \alpha \cdot x_i^\star)^2$$
$$s.t.$$
$$(p_1, \dots, p_I) \in M$$

A10.33 All price vectors in the minimum revenue core M have total revenue R. Pricing the winning packages at the linear reference prices also produces total revenue R. Therefore, geometrically, the problem is one of finding the closest point in M to the winning prices implied by the linear reference prices within the plane of all prices raising revenue R. This problem has a unique solution for the base prices.

Annex 11

Proposals for revising annual licence fees for 900 MHz and 1800 MHz spectrum

A11.1 In this Annex we describe the proposed strategy to implement article 6(1) and 6(2) of the Direction regarding the revision of annual licence fees for 900MHz and 1800MHz licences. .[23] We expect to undertake the implementation of article 6(3) regarding the introduction of annual licence fees in respect of the 2.1GHz band nearer the time that annual licence fees will be payable on those licences, if the amendments which we are currently proposing to make, subject to licensee consent, are made.[24]

A11.2 Article 6 (1) and 6(2) of the Direction set out respectively the following requirements.

> *(1) After completion of the Auction OFCOM must revise the sums prescribed by regulations under section 12 of the WTA for 900MHz and 1800MHz licences so that they reflect the full market value of the frequencies in those bands.*
>
> *(2) In revising the sums prescribed OFCOM must have particular regard to the sums bid for licences in the Auction.*

A11.3 Throughout this annex, we refer to the revised charges for 900MHz and 1800MHz licences derived in accordance with the requirements of the Direction as annual licence fees or "ALF".

High level approach

Full market value

A11.4 Article 6 of the Direction requires us to set ALF for licences in the 900 MHz and 1800 MHz bands to reflect full market value. We consider that full market value is the price that would arise in a well functioning spectrum market. This would be the market clearing price when supply equals demand.

A11.5 We interpret the term "full market value" to mean that we do not discount our estimate of the price that would occur in a well functioning market, nor do we set it conservatively compared with the available market information.

A11.6 Finally, we note that the approach we are proposing to set ALFs in this consultation is different from our approach to setting AIP.[25] This is because the Direction

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[23] At present, licensees in the 900 MHz and 1800 MHz bands pay fees set under Administrative Incentive Pricing (AIP) principles. These fees were originally set in 1998 by the Radiocommunications Agency and Ofcom last reviewed them in 2004-2005. Currently, under AIP, annual fees are approximately £3.6 million per 2x5 MHz block in the 900 MHz band and £2.8 million per 2x5 MHz block in the 1800 MHz band. See the Wireless Telegraphy (Licence Charges) Regulations 2005 (UK statutory instrument 2005 No. 1378).

[24] See http://stakeholders.ofcom.org.uk/binaries/consultations/2100-MHz-Third-Generation-Mobile/summary/main.pdf

[25] See http://stakeholders.ofcom.org.uk/binaries/consultations/srsp/statement/srsp-statement.pdf

explicitly requires us to set ALF so as to reflect full market value and requires us to have particular regard to the sums bid for licences in the auction.

Source of information for the derivation of full market value

A11.7 We have identified a number of different sources of information that could be used to determine the full market value of the 900 MHz and 1800 MHz spectrum. These are:

a) bids made and licence fees paid in the auction for 800 MHz and 2.6 GHz spectrum;

b) licence fees paid in auctions in other countries for the same or similar spectrum;

c) estimates derived from technical and cost modelling; and

d) information derived from spectrum trades for 900 MHz and 1800 MHz spectrum in the UK or potentially in other countries.

A11.8 We have analysed the strengths and weaknesses of each of the above sources of information and present here our provisional conclusions.

A11.9 The bids made and the auction prices of 800 MHz and 2.6 GHz spectrum should give fairly good information on the full market value of 900 MHz and 1800 MHz spectrum . The auction will take place relatively close to the time at which 800 MHz and 2.6 GHz spectrum will be used and we can expect the timing of that use largely to coincide with the use of 900 MHz and 1800 MHz spectrum. Also while there are some differences between the bands (see further below at A11.21 to A11.29) the auctioned spectrum is likely to be reasonably close substitute for 900MHz and 1800 MHz spectrum. However, if the auction is not sufficiently competitive then it will not be a good indicator of the full market value of 900 MHz and 1800 MHz spectrum. The prices derived from it would not be indicative of the price that would emerge in a well functioning market. We believe that in the circumstances of setting ALF the relevant way to consider if the auction is sufficiently competitive is to consider whether the information that can be delivered from it is likely to be more accurate than that which could be derived from alternative sources for the purpose of setting ALF.

A11.10 International auction prices of spectrum in the same or comparable spectrum bands may give reasonable indications of the full market value of 900 MHz and 1800 MHz spectrum.[26] However this data would need to be treated carefully in light of differences between international and UK markets and also to take into account whether the auctions were competitive.

A11.11 Estimates derived from technical and cost modelling may be feasible, but they are subject to a considerable margin for error, especially in relation to technologies that are in the early stages of commercial deployment such as LTE. Accordingly, our view is that we should only use them alone if there is no credible alternative.

A11.12 Data from trades may be used to inform estimates of full market value however it is not clear whether we would be able to access this information, either because of lack of transactions or because of lack of knowledge, given that it is not compulsory

[26] An example of comparable international auction is given by the recent mobile spectrum auction in Germany.

for parties to reveal transaction prices. But even if we would have this information, in this context it is likely that trades will not reveal the full market value of the spectrum. This is because, since ALF will continue to apply regardless of the trade, the buyer of a licence may be expected to adjust the price they paid for the spectrum to reflect expected future annual licence fee payments.

A11.13 Given these considerations, our provisional conclusion is that the use of the amounts bid and licence fees paid in the auction are likely to provide the most reliable basis on which we can estimate the full market value of 900 MHz and 1800 MHz spectrum. This is because, if the auction is sufficiently competitive, auction results would reflect the prices that would emerge in a well functioning market and with respect to the other sources of information, auction bids and prices would be subject to a relatively smaller margin for error.

A11.14 We recognise that this provisional conclusion will have to be reviewed after the auction when we will be able to judge properly whether the information revealed by the auction does indeed provide the most reliable basis for revising ALF. We will consult again on this question after the auction but believe that it is likely to be helpful for stakeholders to understand in advance of the auction our possible approach and therefore have included a discussion in this consultation.

Competitiveness of the auction

A11.15 We currently consider it likely that the auction will be sufficiently competitive, given (a) current indications of stakeholders' interest in the spectrum, (b) the bands' likely importance for future mobile broadband services and (c) our proposed auction design. Nonetheless, there remain risks (such as lower participation than the market would be expected to support) that the auction is not sufficiently competitive. When we consider the position after the auction if we determine that the auction was not sufficiently competitive, additional analysis will be needed to identify the data and the most appropriate methodology to revise fees so that they reflect full market value.

A11.16 At present, we believe that next best alternative information is likely to be to use the prices paid in other international auctions for similar spectrum to assess full market value of the relevant spectrum in the UK.

A11.17 Since there is no unique methodology to determine the degree of competition in an auction, this will to a significant degree be a matter of our judgement. There is however some data we would expect to look at from the auction of 800MHz and 2.6 GHz to aid us in making this judgement, these are:

a) *Initial eligibility ratio*, - the eligibility ratio is the ratio of the total eligibility demanded at the start of the auction to the eligibility of the total supply on offer. Eligibility points are a measure of spectrum quantity weighted by the relative value of lots.[27] They are a means to enforce rules on bidding in the auction, and to help with efficient price discovery. With a fixed supply of spectrum, the total eligibility associated with that supply is also fixed and known at the start of the auction. In the first round of the auction, the sum of the eligibility associated with all bids made is a measure of demand from all bidders in that round. The ratio of eligibility of all bids in the first round and the total eligibility for the supply is a simple measure of excess demand and by extension of competition in the

[27] More desirable lots, such as sub-1GHz lots, have a higher eligibility to help reflect relative values when bidders switch between lot categories.

auction. Auctions with a ratio above 3 indicate that the total demand in the first round, measured through eligibility points, is 3 times higher than total supply. In this case, auctions are typically viewed as likely to be highly competitive[28] since bidders reveal a strong demand for a relatively scarce supply. On the other hand auctions with a ratio below 2 may indicate that competition is weak. However, this ratio is only a snapshot of excess demand in the first round.

b) *Number of rounds* – if the clock phase closes quickly, this could be an indicator of low demand or of scarce competition.

c) *Rate of decrease of activity* –if the auction has a long tail of activity on just a few lots, a high number of rounds may not indicate that competition is spread evenly throughout the auction. Activity could be unevenly spread over groups of lots and we will take into account this dimension to evaluate the competitiveness of the auction.

d) Finally, using benchmarks from other countries may provide a useful indicator of whether the outcome of the auction is competitive, although we need to recognize that there are likely differences between UK and other countries' mobile markets and award processes.[29]

Detailed implementation

A11.18 If we consider the auction of the 800 MHz and 2.6 GHz spectrum to be sufficiently competitive, we propose to implement the Direction in three key steps.

a) First we propose to derive average (linear) price information for each lot category in the auction using the methodology described in Annex 10.

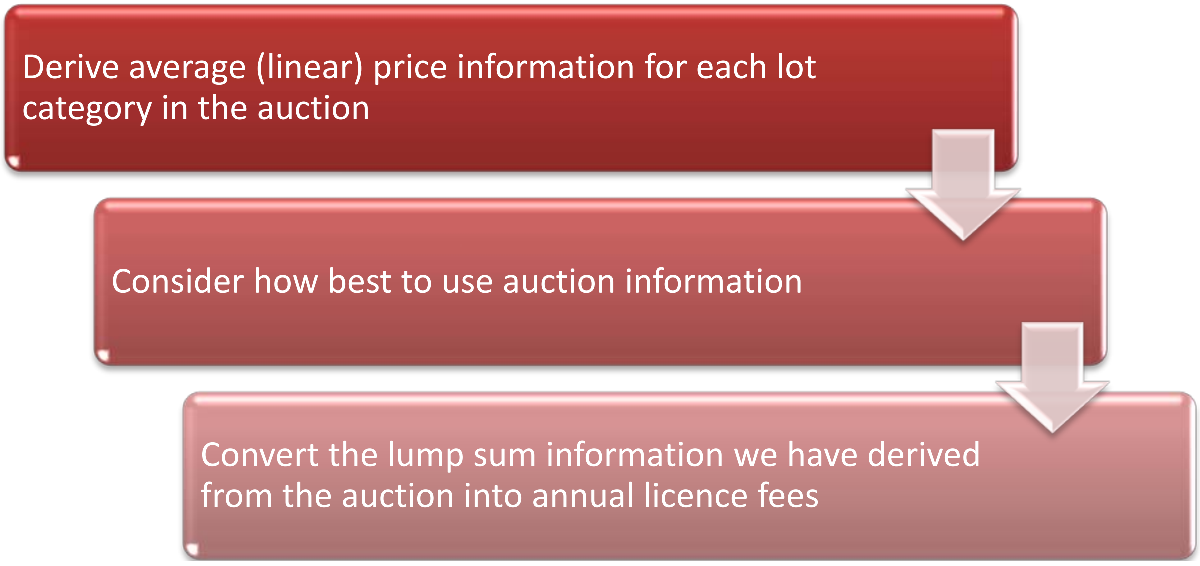
b) Second we will consider how best to use this information, and whether any adjustments are necessary, for example to reflect differences between spectrum bands, to estimate the market value of 900 MHz and 1800 MHz spectrum.

c) Third we will convert the lump sum information we have derived from the auction into annual licence fees.

[28] See for example Professor Peter Cramton's report on the L-band auction, p.3 at http://stakeholders.ofcom.org.uk/binaries/spectrum/spectrum-awards/completed-awards/714758/Report_by_Professor_Peter_C1.pdf.

[29] For the purposes of checking the competitiveness of the auction we could consider other international auction such as the awards of 800 MHz spectrum in EU countries such as example in Germany, Sweden and Ireland, and perhaps the 700 MHz auction in US.

Figure A11.1: overview of process to set ALF



Identify appropriate information from the auction

A11.19 We propose to use the methodology set out in Annex 10 to derive average price information for each lot category in the auction. This will provide a useful set of information which we can use to estimate the full market value of 900 MHz and 1800 MHz spectrum.

Spectrum information

A11.20 As explained in section 8 we do not propose to allow relinquishment of 900 MHz and 1800 MHz spectrum in the auction. This would mean that price information derived from the auction will be for 800 MHz and 2.6 GHz spectrum and therefore we need to consider how this information can be used to estimate the full market value of 900 MHz and 1800 MHz spectrum.[30]

<u>900 MHz full market value</u>

A11.21 We have considered different elements that may affect the degree of substitutability of 800 MHz and 900 MHz spectrum. These are:

a) Propagation differences: our analysis shows that the propagation differences between the two bands are almost identical and therefore they are unlikely to give rise to significant differences in full market values;

b) The differences in licence term: the 800 MHz spectrum licences are proposed to be on an indefinite period with an initial term of 20 years compared with the 900 MHz licences which are indefinite subject to revocation on 5 years' notice. This implies that holders of licences for 800 MHz spectrum holders will have a longer period of certainty regarding the right to use the spectrum which may make the 800MHz licences more valuable than the 900MHz licences. On the other hand,

[30] If our approach to relinquishment changes so this is allowed and also that operators chose to relinquish spectrum then we envisage we will use the same pricing methodology to determine average prices for categories relating to relinquished spectrum. These additional categories can then be used in the averaging methodology in appropriate way.

bidders for 800 MHz spectrum in the auction will take a risk regarding the value of the licences by committing to pay a sum for an asset whose value will realise in the future. 900 MHz licence holders instead, by paying ALF have always the possibility to hand back the spectrum if they consider that its value is lower than the ALF payable. This may mean that 900 MHz licences are more valuable than 800 MHz licences. We believe that it would be very difficult to quantify any differences to any reasonable degree of accuracy. Moreover, as these two effects work in different directions, the differences may off-set one another;

c) Differences in international harmonisation between bands and handsets availability: the two bands are both internationally harmonised, and while UMTS 900 handsets are available today and are already widely taken up, handsets capable of using LTE800 are likely to reach the market before handsets capable of using LTE900. Some indicators therefore may suggest that 800MHz spectrum would be more valuable than 900 MHz, and vice versa. On balance, we do not consider that there is robust information to conclude whether 800 MHz or 900 MHz is more valuable due to international harmonisation and handset availability;

d) Coverage obligations: our current proposal is to include in one of the 800 MHz licences a coverage obligation as described in section 6 of this document. By contrast 900 MHz licences do not have any coverage obligations. However, given the current proposal for the 800 MHz coverage obligation we do not believe that this would lead to very significant differences in the value of the spectrum.

e) DTT Interference: as described in section 8 there may be possible limitations on the lots in one of the 800 MHz category to reduce interference into adjacent DTT use; for this reason we have suggested that it may be that only three of the categories of 800 MHz lot would count towards the minimum spectrum portfolios for the purposes of the competition constraint.

A11.22 Given the above considerations we propose that there should be consistency between the categories that are used for the purpose of the competition constraint and for the derivation of ALF. Accordingly, we propose to use the three categories of 800 MHz lot that would count towards the minimum spectrum portfolios for the purposes of the competition constraint, as set out in section 8, to estimate the full market value of 900 MHz spectrum. We propose to average the price per MHz across the three lot categories to produce a single price per MHz that we will then use as our estimate of the full market value of 900 MHz spectrum.

1800 MHz full market value

A11.23 The position regarding 1800 MHz spectrum is more difficult in our view than regarding 900 MHz spectrum. This is because neither 800 MHz nor 2.6 GHz spectrum is as close a substitute for 1800 MHz spectrum as 800 MHz spectrum is for 900 MHz spectrum.

A11.24 Our technical analysis (see Annex 7 for details) suggests that 1800 MHz spectrum may have advantages over 2.6 GHz spectrum in terms of the quality and coverage of the services that can be offered. This may be the case even when the 1800 MHz and 2.6 GHz frequencies are used in combination with sub 1GHz spectrum. Our analysis also suggests that 800 MHz spectrum has significant advantages over 1800 MHz spectrum. Given our understanding of the technical work, we consider that prices for 2.6 GHz spectrum are likely to understate the value of 1800 MHz whereas 800 MHz would overstate the value.

A11.25 There are also other elements that may affect the comparability of the frequencies:

a) The differences in licence terms: The same considerations as above apply in relation to differences in the licences for 1800 MHz and 800 MHz and 2.6 GHz spectrum.

b) Differences in international harmonisation between bands and handsets availability: the 1800 MHz and 2.6 GHz bands are both internationally harmonised and a good selection of handsets is likely to be available for both. In particular we expect that handsets capable of LTE technology will be deployed in both paired 2.6GHz and 1800 MHz spectrum bands.

c) Coordination with radars: as explained in Section 4 it is possible that there will be technical restrictions on 2.6 GHz licences necessary to protect radars.

A11.26 Given the above we have identified five possible approaches to estimate the full market value of 1800 MHz:

a) Use 2.6 GHz price information derived from the auction without adjustment;

b) Use 800 MHz price information derived from the auction without adjustment;

c) Use 2.6 GHz price information derived from the auction with an uplift;

d) Use 800 MHz price information derived from the auction with a discount;

e) Use an average of 800 MHz and 2.6 GHz price information derived from the auction.

A11.27 As noted above the difficulty with options a) and b) are that neither band provides a reasonably close comparator which means that it is likely that our estimates of full market value using those approaches could be fairly inaccurate.

A11.28 Under options c) and d) the challenge is to find a reliable basis for determining the uplift or discount. We could base the adjustment on some relatively crude estimate derived from technical modelling of the differences between the frequency bands or possibly using information on the differences between prices paid between the two bands in auctions in other countries. However we have some concerns about the reliability of doing this due to the difficulty first in accurately estimating the difference in technical capability, and second and more importantly interpreting these in terms of differences in monetary value. The relative difference in prices paid in other auctions might provide a simpler basis for adjusting values, but there is only one source of information we are aware of and it is hard to know how accurately that information might reflect the difference between the bands in the UK.

A11.29 Option e) seems to us to be the best approach in the circumstances. This reflects our understanding of the technical characteristics of the bands which suggests that 1800 MHz lies between 800 MHz and 2.6 GHz. Given that the risks of regulatory failure associated with deriving adjustment values could be considerable, a simple average may not in practice be significantly less accurate, but would be clearer, simpler and less costly to derive. We propose to estimate the full market value of 1800 MHz as follows:

a) calculate average price per MHz for lots in the 2.6 GHz FDD for high power use category (category C1 in our packaging proposals in section 8);

b) calculate the average price per MHz for 800 MHz lots as explained above;

c) then calculate a simple average of those two prices to give an average per MHz price that would be our estimate of the full market value of 1800 MHz.

Converting upfront payments to annual payments

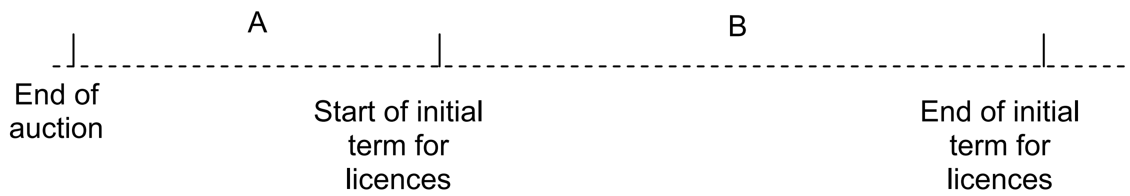
A11.30 The full market values derived according to the methodology above[31] will then be converted in annual payments.[32]

A11.31 As a first step we consider the length of period over which to spread the full market values established from the auction.

A11.32 The amounts bid for the licences will primarily reflect the value of the spectrum over the initial term.[33] For this reason we propose to spread the full market value as derived from the auction over the period of time that corresponds to the licences' initial term. As discussed in Section 7, we propose to use an initial term of 20 years.

A11.33 The second step is to consider the adjustment that could be needed in case there could be a difference between the date when the acquirer pays for the spectrum and the date when the licence initial term would start. Under our current proposals (see section 7) this would not be required but it is possible that this could change and therefore we set out below how we propose the issue could be addressed. The issue would arise if bidders paid for spectrum before the date of its availability and therefore committed funds that they could otherwise have invested elsewhere. The consequence is that we may need to adjust the price revealed in the auction upwards to identify the real value attributed to the spectrum.

Figure A11.2: timeline from end of auction to end of initial licence term



A11.34 In this case, as illustrated in the figure above, the time after the auction could be divided in two periods:

a) Period A, corresponding to the time period between the end of the auction and the start of the licence initial term for those licences granted in the auction; and

b) Period B, corresponding to the initial term of the licences for those licences granted in the auction.

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[31] We note that also some other sources of information, as international data, may be expressed as lump sums amounts and therefore would require the same operation as described below.

[32] We have considered the possibility of collecting ALF in a single upfront payment as for auction payments, however we considered that it would be disproportionate to charge a one-off payment in this circumstance.

[33] Note that any value beyond the initial term islikely to be heavily discounted in the price paid in the auction.

A11.35 The formula we propose to use to make this adjustment is:

$$PV(AP) = AP * (1 + r)^{ta}$$

A11.36 Where AP is the full market price of a certain quantity of spectrum as derived from the auction, $PV(AP)$ represents the value of AP adjusted to reflect the difference between the payment of the auction price and spectrum availability, r is the discount factor and it is equal to the real pre tax cost of capital, and *ta* represents the time length of period A.[34]

A11.37 r represents the discount rate. We propose to use the real pre tax cost of capital of a notional efficient mobile operator. It would also be possible to use a post-tax cost of capital and adjust for expected differences in tax treatments for ALF and auction payments. This would make the calculation more complex and would require us to make more assumptions about tax treatments. For this reason we suggest using a pre-tax cost of capital.

A11.38 In our March 2011 Mobile Call Termination statement, we estimated the cost of capital of a notional efficient mobile operator. For the purpose of setting ALF we have considered whether the relevant cashflows would have different systematic risk to that cost of capital. In our 2005 Cost of Capital Review,[35] we set out the circumstances in which assessing risk for particular cashflows is likely to be greater,[36] If evidence were presented that there was a strong case for assessing this risk specifically, then it may be appropriate to use a different cost of capital. In the absence of such evidence, we currently propose to use the cost of capital used in the Mobile Call Termination charge controls at the time of the ALF determination. .

A11.39 Once we have adjusted the auction prices according to the equation above, we spread the value obtained over the initial term of the licence from which the value has been derived. This is done according to the formula:

$$ALF = PV(AP)\frac{r}{1 - (1 + r)^{-tb}}$$

A11.40 Where tb is equal to the duration of period B (i.e. 20 years).

A11.41 We propose to set ALF in constant real terms. This means we will set ALF in the first year and in subsequent years it will increased in line with inflation.[37] In the absence of information on the profile of the value of spectrum over time, we consider a constant real profile to be a reasonable approach.

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[34] Below we explain in more detail why we use the constant real pre tax cost of capital as interest rate. Note also that ta represents the length of the period between the payment of the licence fee and the start of the licence. In the example above it is assumed that bidders pay soon after the auction.
[35] Statemetn published on 18 August 2005 at http://stakeholders.ofcom.org.uk/consultations/cost_capital2/statement/.
[36]In the" 2005 Cost of Capital Review" we say that the case for assessing risk on a project-specific basis is likely to be stronger under the following circumstances: there are strong *a priori* reasons to believe that the systematic risks would differ, there is evidence which can be used to assess variations in risk, and finally if correctly identifying variations in risk, and reflecting this in an adjusted rate of return, is likely to bring about significant gains for consumers. See also http://stakeholders.ofcom.org.uk/binaries/consultations/cost_capital2/statement/final.pdf.
[37] An example of an inflation measure is the Retail Price Index (RPI). This is the measure we use for inflation when we set charge controls.

A11.42 We expect to start charging the ALF as soon as practically possible following the implementation procedure described below.[38]

Subsequent reviews of ALF

A11.43 In the SRSP statement of December 2010, we concluded that we would generally seek views from stakeholders on the need for a review when we consult on Ofcom's Annual Plan. However, we may on occasion undertake a fee review where there is a clear and urgent need without including this in the Annual Plan.

A11.44 In the SRSP we also proposed "to conduct a fee review only where the evidence suggests that a review would be justified, including evidence of a likely and sufficiently material misalignment between the current rates and the opportunity cost of the spectrum for fees based on AIP, or between the current rates and our spectrum management costs for cost-based fees".

A11.45 In this case, the ALF values for 900 MHz and 1800 MHz will be set to reflect the full market value of the spectrum, which in this consultation we propose to derive from the bids in the auction (if sufficiently competitive). If this is the case, the auction would be likely to provide the best quality of information on the value of 900 MHz and 1800 MHz spectrum at that time. We propose that once we have revised the level of ALF for retained 900 MHz and 1800 MHz spectrum, we would only be likely to conduct revisions to the level of ALF in the case of clear evidence of significant changes in long term circumstances that suggested that the value of this spectrum had varied materially and we were able to derive a more reliable estimate.

A11.46 In particular, we do not plan to review fees using information from spectrum trades. This is for a number of reasons. Firstly, trading prices do not have to be revealed to us. Secondly, even if trading prices were disclosed to us, many spectrum trades occur as a part of a business sale in which spectrum is not valued separately. Thirdly, if there is only a small number of trades, transaction prices are likely to be sensitive to the particular circumstances of the trades concerned and may require careful consideration as indicators of market value. Most importantly, linking ALF directly to trading prices for mobile spectrum may distort incentives to trade, which would raise potential concerns for the long term efficiency of spectrum use and resulting consumer benefits.

Next Steps

A11.47 Our proposal is to review the overall approach for the implementation of article 6(1) and 6(2) of the Direction in light of responses to this consultation and set out our views on these matters in our statement ahead of the combined award.

[38] Note that ALF may be charged in period A. As explained above we are aware that prices in a competitive auction give direct information on full market value of spectrum in period B, however we believe that it would be appropriate to use the figure also for fees paid in period A. This is due to a number of reasons. First, because the Direction requires us to review the fees: "after completion of the Auction" suggesting that no delays should occur. Second, because the length of period A is likely to be relatively short and this would make the full market value in period A and period B strongly comparable. Third, because ALF derived using auction prices reflecting full market value of spectrum available in period B is likely to be the best available information to derive full market value of spectrum already available and in use in period A. Fourth, because licensees should be able to predict the likely order of magnitude of the fee increment (e.g. using benchmarks from auctions in other countries) and therefore would be able to adjust their business plans accordingly without undue delay.

A11.48 Soon after the end of the auction, we expect to conduct a review of the auction to determine whether an approach based on using the data derived from it is appropriate for the purpose of setting ALF. Our position will be then be set out in a further consultation document which we will follow with a statement and the necessary regulations.

Annex 12

Technical licence conditions

Introduction

A12.1 This annex sets out Ofcom's current thinking on the technical licence conditions that should apply in the licences for the 800 MHz and 2.6 GHz spectrum. We are in the process of carrying out technical work to assess adjacent band protection requirements, which could lead to additional technical conditions or a modification of the conditions presented here.

800 MHz

A12.2 The 800 MHz RSC Decision sets out the technical parameters that must apply to the use of the 790 to 862 MHz band for networks other than high-power broadcasting networks.

A12.3 The limit at any frequency is given by the highest (least stringent) value of (a) the baseline requirements, (b) the transition requirements, and (c) the in-block requirements (where appropriate). The technical conditions are presented as upper limits on the mean equivalent isotropically radiated power (EIRP) or total radiated power (TRP)[39] over an averaging time interval, and over a measurement frequency bandwidth. In the time domain, the EIRP or TRP is averaged over the active portions of signal bursts and corresponds to a single power control setting. In the frequency domain, the EIRP or TRP is determined over the measurement bandwidth specified in the tables.

A12.4 The technical licence conditions that we are developing are outlined below. They are fully consistent with the parameters in the 800 MHz RSC Decision.

In-block limits for base stations:

A12.5 The 800 MHz RSC Decision does not make an in-block EIRP limit obligatory for base stations. However, Member States may set limits and, unless otherwise justified, such limits would normally lie within the range 56 dBm/5MHz to 64 dBm/5MHz.

A12.6 The established practice for licences that we have issued in the 900 MHz, 1800 MHz and 2.1 GHz frequency bands is to include a maximum base station EIRP. For the 800 MHz band, including the 5 MHz measurement bandwidth will also ensure that the in-block power density applies consistently to the range of possible channel bandwidths that could be deployed in this spectrum.

A12.7 We plan to set an in-block power limit for base stations as outlined in Table A12.1.

[39] TRP is a measure of how much power the antenna actually radiates. The TRP is defined as the integral of the power transmitted in different directions over the entire radiation sphere.

Table A12.1: In-block requirements – base station in-block emission limit

Maximum mean in-block power	61 dBm/(5 MHz) EIRP

A12.8 We may need to impose further restrictions on in-block power for protection of DTT reception, which could result in a reduction in the power limit below that specified in Table A12.1. We are continuing to study this issue and we will include our proposals when we consult on the technical licence conditions.

Out-of-block limits for base stations:

Table A12.2: Baseline requirements – base station out-of-block EIRP limits

Frequency range of out-of-block emissions	Maximum mean out-of-block EIRP	Measurement bandwidth
Frequencies used for uplink (832 to 862 MHz)	–49.5 dBm	5 MHz

Table A12.3: Transition requirements – base station out-of-block EIRP limits per antenna[40] over downlink frequencies (791 to 821 MHz)

Frequency range of out-of-block emissions	Maximum mean out-of-block EIRP	Measurement bandwidth
–10 to –5 MHz from lower block edge	18 dBm	5 MHz
–5 to 0 MHz from lower block edge	22 dBm	5 MHz
0 to +5 MHz from upper block edge	22 dBm	5 MHz
+5 to +10 MHz from upper block edge	18 dBm	5 MHz
Remaining downlink frequencies	11 dBm	1 MHz

Table A12.4: Transition requirements – base station out-of-block EIRP limits per antenna[41] over frequencies used as guard band

Frequency range of out-of-block emissions	Maximum mean out-of-block EIRP	Measurement Bandwidth
790 to 791 MHz	17.4 dBm	1 MHz
821 to 832 MHz	15 dBm	1 MHz

A12.9 The 800 MHz RSC Decision defines three cases for requirements on base station out-of-block emissions below 790 MHz, as shown in Table A12.5.

[40] For one to four antennas.
[41] For one to four antennas.

Table A12.5: Baseline requirements – base station out-of-block EIRP limits over frequencies below 790 MHz

Case		Condition on base station in-block EIRP, P dBm/10 MHz	Maximum mean out-of-block EIRP	Measurement bandwidth
A	For TV Channels where broadcasting is protected	P ≥ 59	0 dBm	8 MHz
		36 ≤ P < 59	(P-59) dBm	8 MHz
		P < 36	-23 dBm	8 MHz
B	For TV Channels where broadcasting is subject to an intermediate level of protection	P ≥ 59	10 dBm	8 MHz
		36 ≤ P < 59	(P-49) dBm	8 MHz
		P < 36	-13 dBm	8 MHz
C	For TV Channels where broadcasting is not protected	No conditions	22 dBm	8 MHz

A12.10 Cases A, B, and C listed in Table A12.5 can be applied per broadcasting channel and/or per region so that the same broadcasting channel may have different levels of protection in different geographic areas and different broadcasting channels may have different levels of protection in the same geographic area. Member States shall apply the baseline requirement in case A in circumstances where digital terrestrial broadcasting channels are in use at the time of deployment of terrestrial systems capable of providing electronic communications services. Member States may apply the baseline requirements in cases A, B or C in circumstances where the relevant broadcasting channels are not in use at the time of deployment of terrestrial systems capable of providing electronic communications services. They shall take into account that case A and B reserve the option of bringing relevant broadcasting channels into use for digital terrestrial broadcasting at a future date, while case C is appropriate where there are no plans to bring the relevant broadcasting channels into use.

A12.11 We expect to set out a baseline requirement below 790 MHz as shown in Table A12.6, which uses the Case A limits. We do not plan to use the Case B and Case C limits in our technical conditions.

Table A12.6: Baseline requirements – base station out-of-block EIRP limits over frequencies below 790 MHz

Frequency range of out-of-block emissions	Condition on base station in-block EIRP, P dBm/10 MHz	Maximum mean out-of-block EIRP	Measurement bandwidth
470 to 790 MHz	P ≥ 59	0 dBm	8 MHz
	36 ≤ P < 59	(P-59) dBm	8 MHz
	P < 36	-23 dBm	8 MHz

Additional requirements

A12.12 We also expect to include obligations on licensees to take additional measures to protect DTT reception. We are in the process of carrying out significant technical work to consider the technical conditions that should apply in adjacent bands and in the 800 MHz band following the award. This work is on-going and we will include our detailed proposals when we consult on the technical licence conditions.

Technical conditions for terminal stations (TS)

Table A12.7: In-block requirements – TS BEM in-block emission limit

Maximum mean in-block power	23 dBm[42]

A12.13 Member States may relax the limit in Table A12.7 for specific deployments, e.g. fixed terminal stations in rural areas, providing that protection of other services, networks and applications is not compromised and cross-border obligations are fulfilled.

A12.14 We currently plan to use the limit in Table A12.7 with no relaxation.

2.6 GHz

A12.15 The 2.6 GHz RSC Decision sets out a number of technical parameters that must apply to the use of the band.

A12.16 The technical conditions are presented as upper limits on the mean equivalent isotropically radiated power (EIRP) or total radiated power (TRP)[43] over an averaging time interval, and over a measurement frequency bandwidth. In the time domain, the EIRP or TRP is averaged over the active portions of signal bursts and corresponds to a single power control setting. In the frequency domain, the EIRP or TRP is determined over the measurement bandwidth specified in the tables.

A12.17 The technical licence conditions that we are developing are outlined below. They are fully consistent with the parameters in the 2.6 GHz RSC Decision.

Unrestricted block limits for base stations

A12.18 The emission limits for an unrestricted spectrum block are built up by combining Tables A12.8, A12.9 and A12.10 in such a way that the limit for each frequency is given by the higher value out of the baseline requirements and the block specific requirements.

[42] This power limit is specified as EIRP for terminal stations designed to be fixed or installed and as TRP for terminal stations designed to be mobile or nomadic. EIRP and TRP are equivalent for isotropic antennas. It is recognised that this value is subject to a tolerance of up to +2 dB, to take account of operation under extreme environmental conditions and production spread.
[43] TRP is a measure of how much power the antenna actually radiates. The TRP is defined as the integral of the power transmitted in different directions over the entire radiation sphere.

Table A12.8: Baseline requirements – base station out-of-block EIRP limits

Frequency range of out-of-block emissions	Maximum mean out-of-block EIRP	Measurement bandwidth
Frequencies allocated to FDD down link and ± 5 MHz outside the range of frequency blocks allocated to FDD down link. (2615 to 2690 MHz)	4 dBm	1 MHz
Frequencies in the range 2470-2720 MHz not covered by the definition above.	-45 dBm	1 MHz

Table A12.9: Block specific requirements —unrestricted base station in-block EIRP limit

Frequency range of in-block emissions	Maximum mean in-block power
Paired downlink frequencies	61 dBm/(5 MHz) EIRP
Downlink use of standard unpaired frequencies	61 dBm/(5 MHz) EIRP

Table A12.10: Block specific requirements — base station out-of-block EIRP limits

Frequency range of out-of-block emissions	Maximum mean out-of-block EIRP	Measurement bandwidth
Start of band (2500 MHz) to -5 MHz from lower block edge	Baseline requirement level	
-5 MHz to -1 MHz from lower block edge	4 dBm	1 MHz
-1 MHz to -0.2 MHz from lower block edge	+ 3 + 15(Δ_F + 0.2) dBm	30 kHz
-0.2 MHz to 0 MHz from lower block edge	3 dBm	30 kHz
0 MHz to 0.2 MHz from upper block edge	3 dBm	30 kHz
0.2 MHz to 1 MHz from upper block edge	+ 3 - 15(Δ_F – 0,2) dBm	30 kHz
1 MHz to 5 MHz from upper block edge	4 dBm	1 MHz
5 MHz from upper block edge to end of band (2690 MHz)	Baseline requirement level	
Where: Δ_F is the frequency offset from the relevant block edge (in MHz)		

A12.19 We are currently considering whether to make spectrum available for low-power shared access. If we decide to make proposals for such use, we will include additional proposals when we consult on the technical licence conditions.

Restricted block limits for base stations

A12.20 To manage interference between paired and unpaired use, restricted blocks are required at 2570 to 2575 MHz and at 2615 to 2620 MHz. A 5 MHz restricted block would also be required between unpaired licensees in adjacent frequency blocks, unless the 2570 to 2620 MHz spectrum were awarded as a single block.

A12.21 The emission limits for a restricted spectrum block are built up by combining Tables 4.8 and 4.11 in such a way that the limit for each frequency is given by the higher value out of the baseline requirements and the block specific requirements.

Table A12.11: Block specific requirements — base station in-block EIRP limit for restricted unpaired frequencies

Frequency range of in-block emissions	Maximum mean in-block power
Downlink use of restricted unpaired frequencies	25 dBm/(5 MHz) EIRP

Restricted block limits for base stations with additional restrictions on antenna placement

A12.22 In cases where antennas are placed indoors or where the antenna height is below a certain height, a Member State may use alternative parameters in line with Table A12.12, provided that at geographical borders to other Member States Table A12.9 applies and that Table A12.11 remains valid nationwide.

A12.23 Our provisional conditions on antenna placement that would allow the use of the technical parameters in Table A12.12 are:

i) antennas that are placed indoors and are at a height no greater than 10m above ground level; and

ii) antennas that are placed outdoors and are at a height no greater than 4m above ground level.

A12.24 We are considering whether to carry out further analysis on the suitability of these values, so the proposals that we bring forward when we consult on technical conditions may include a revised set of restrictions for the use of the limits in Table A12.12.

Table A12.12: Block specific requirements — base station out-of-block EIRP limits for restricted block with additional restrictions on antenna placement

Frequency range of out-of-block emissions	Maximum mean out-of-block EIRP	Measurement bandwidth
Start of band (2500 MHz) to -5 MHz from lower block edge	-22 dBm	1 MHz
-5 MHz to -1 MHz from lower block edge	-18 dBm	1 MHz
-1 MHz to -0.2 MHz from lower block edge	$-19 + 15(\Delta_F + 0.2)$ dBm	30 kHz
-0.2 MHz to 0 MHz from lower block edge	-19 dBm	30 kHz
0 MHz to 0.2 MHz from upper block edge	-19 dBm	30 kHz
0.2 MHz to 1 MHz from upper block edge	$-19 - 15(\Delta_F – 0,2)$ dBm	30 kHz
1 MHz to 5 MHz from upper block edge	-18 dBm	1 MHz
5 MHz from upper block edge to end of band (2690 MHz)	-22 dBm	1 MHz
Where: Δ_F is the frequency offset from the relevant block edge (in MHz)		

Additional requirements on base station emissions

A12.25 We also expect to include obligations on licensees to take additional measures to protect radar use in the spectrum above 2700 MHz. We will include our proposals on this when we consult on the technical licence conditions.

In-block limits for terminal stations

A12.26 Table A12.13 sets out the power limits for mobile or nomadic terminal stations in paired or unpaired frequencies.

Table A12.13: In-block requirements – terminal station in-block emission limit

	Maximum mean in-block power
Total radiated power	31 dBm/(5 MHz)

A12.27 In cases where terminal stations or user stations are permanently installed at a fixed location an alternative maximum mean power of 35 dBm/(5 MHz) for uplink use of both paired and unpaired frequencies applies.

Annex 13

Glossary of abbreviations

2G
Second–generation mobile phone standards and technology.

3G
Third-generation mobile phone standards and technology.

3GPP
The 3rd Generation Partnership Project. A collaboration between groups of telecommunications associations, to make a globally applicable third-generation (3G) mobile phone system specification within the scope of the International Mobile Telecommunications-2000 project of the International Telecommunication Union (ITU).

4G
Four generation mobile phone standards and technology.

AIP
Administered incentive pricing.

ALF
Annual licence fee.

ATC
Air traffic control.

BPL
Building penetration loss.

CCA
Combinatorial clock auction.

CENELEC
European Committee for Electrotechnical Standardisation.

CEPT
European Conference of Postal and Telecommunications Administrations.

CPE
Customer premises equipment.

CTIA
International Association for the Wireless Telecommunications Industry.

dBm
Decibels above one milliwatt; a logarithmic representation of radio frequency power with respect to one Watt.

DDR
Digital Dividend Review.

DECT
Digital Enhanced Cordless Telecommunications. An access technology used in private cordless telephone equipment.

DSO
Digital switchover.

DTT
Digital Terrestrial Television.

EAS
Electronic auction system.

EIRP
Equivalent Isotropically Radiated Power.

ETSI
European Telecommunications Standards Institute.

EU
European Union.

FDD
Frequency Division Duplex. A transmission method where the downlink/downstream path and uplink/upstream path are separated by frequency.

GCF
Global Certification Forum.

GHz
Gigahertz.

GPS
Global Positioning System.

GSA
Global Mobile Suppliers Association.

GSM
Global System for Mobile Communications.

GSM-R
Global System for Mobile Communications (GSM) on Railways.

HSDPA
High-Speed Downlink Packet Access

IEEE
Institute of Electrical and Electronics Engineers.

Kbps
Kilo (thousand) bits per second. A measure of the speed of transfer of digital information.

km
Kilometre

LTE
Long Term Evolution.

m
Metre.

Mbps
Megabit per second. A measure of the speed of transfer of digital information.

MHz
Megahertz.

MIMO
Multiple-input and multiple-output.

MNO
Mobile network operator.

MOD
Ministry of Defence.

MRC
Minimum revenue core.

MVNO
Mobile Virtual Network Operator.

PMSE
Programme-making and special events.

RAN
Radio access network.

RSC
Radio Spectrum Committee of the European Commission.

SMRA
Simultaneous Multi-Round Ascending auction.

SINR
Signal to interference plus noise ratio.

SRD
Short range device.

STB
Set top box.

TD LTE
Time Division LTE.

TDD
Time Division Duplex. A transmission method that uses the same channel for the uplink and downlink but separates them by time slots.

TRP
Total radiated power.

UE
User equipment.

UMTS
Universal Mobile Telecommunications System.

VoLTE
Voice over LTE.

WAPECS

Wireless Access Policy for Electronic Communications Services.

WiFi
Commonly used to refer to wireless local area network (WLAN) technology, specifically that conforming to the IEEE 802.11 family of standards. Such systems typically use one or more access points connected to a wired Ethernet network which communicate with wireless network adapters in end devices such as PCs. It was originally developed to allow wireless extension of private LANs but is now also used as a general public access technology via access points known as "hotspots".

WiMAX
WiMAX is the colloquial name given to wireless metropolitan area network (WMAN) technology, specifically that conforming to the IEEE 802.16 family of standards.