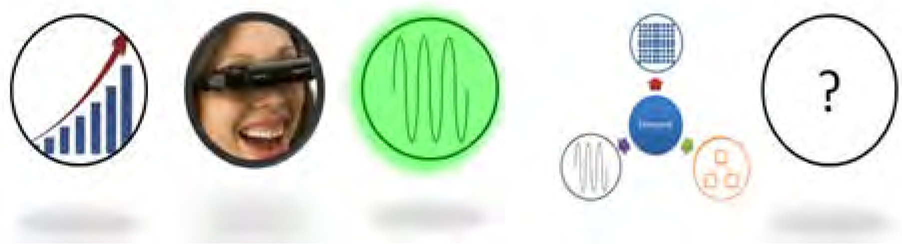
RW spectrum requirements for mobile broadband - appendices V2-0.docx

Appendices to final report



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About Real Wireless

Real Wireless is a leading independent wireless consultancy, based in the U.K. and working internationally for enterprises, vendors, operators and regulators – indeed any organization which is serious about getting the best from wireless to the benefit of their business.

We seek to demystify wireless and help our customers get the best from it, by understanding their business needs and using our deep knowledge of wireless to create an effective wireless strategy, implementation plan and management process.

We are experts in radio propagation, international spectrum regulation, wireless infrastructures, and much more besides. We have experience working at senior levels in vendors, operators, regulators and academia.

We have specific experience in LTE, UMTS, HSPA, Wi-Fi, WiMAX, DAB, DTT, GSM, TETRA – and many more.

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Overview of these appendices

These appendices have been produced in support of the final report main body delivered by Real Wireless to Ofcom under the "Study on the future spectrum demand for terrestrial mobile broadband applications".

These appendices contain:

- Appendix A – which details our simulation and modelling methodology for spectrum estimates in this study and updates made to the ITU-R M.1768-1 model obtained from ITU-R working party 5D.
- Appendix B – which details our assumptions on spectrum availability in the UK over time
- Appendix C – which details our analysis of UK specific mobile broadband demand
- Appendix D – which details our critique of ITU recommended values for service and market related parameters for the ITU-R M.1768-1 model
- Appendix E – which details our critique of ITU recommended values for network and technology related parameters for the ITU-R M.1768-1 model
- Appendix F – which details our assumed traffic distribution across intermediary devices in our demand analysis
- Appendix G – which summarises CFI responses from stakeholders and our actions against these

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1. Appendix A – Our approach to using the ITU-R M.1768-1 model, updates made and calibration approach

1.1 Updates to the ITU-R M.1768-1 model

Several changes in the worksheets and code were carried out on the received version of the ITU-R M.1768-1 model, v2-5 Feb 2013 from the ITU-R working party 5D website [53]. These changes were to support outputs for five spot-years (2010, 2015, 2020, 2025, 2030), instead of three (2010, 2015, 2020), and to estimate the spectrum of RATG3. Minor changes were required so that the cases of shared and dedicated spectrum estimates were calculated, and so as to expedite the macros.

1.1.1 Spectrum estimate for RATG3

The received version of ITU-R M.1768-1 model, v2-5 Feb 2013, does not calculate the amount of spectrum required for licence exempt (LE) communication links. This section identifies the quantities that are calculated with the current methodology and describes the process we followed to derive the required spectrum estimates for RATG3. Figure 1 displays the flow chart that is followed by the current methodology.

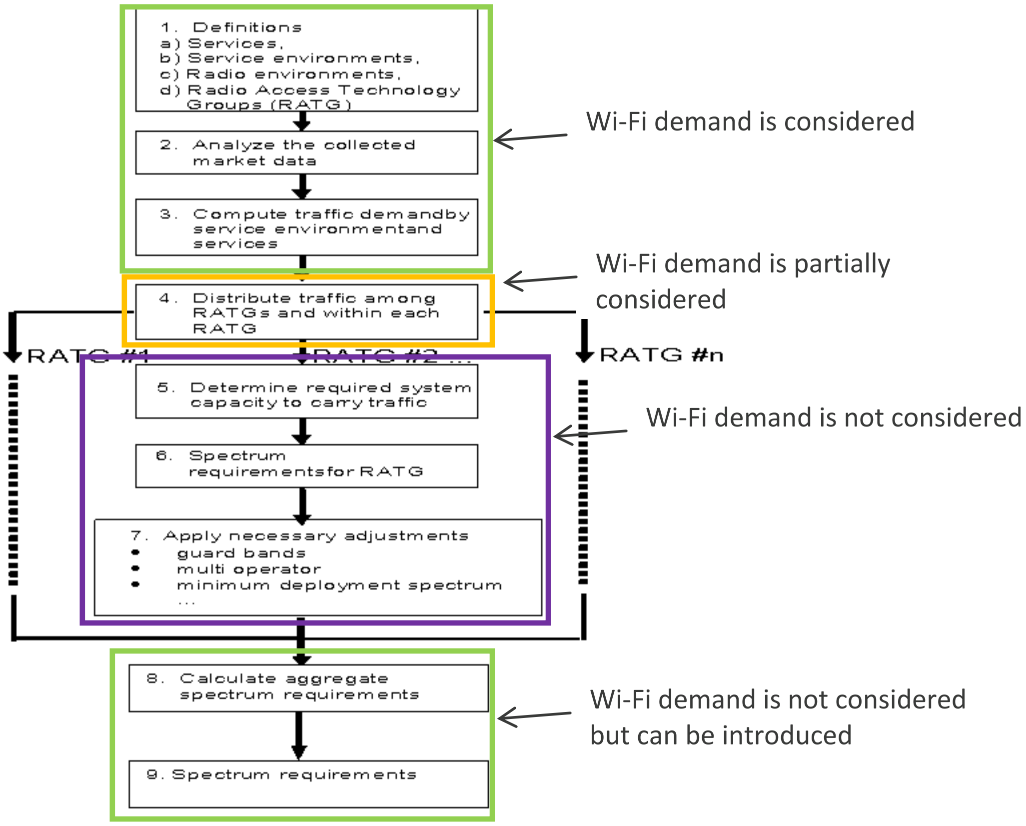


Figure 1: Flow chart of the ITU-R M.1768-1 methodology for the calculation of spectrum

1.1.2 Quantities relevant to LE that the methodology calculates

The received version of the ITU-R M.1768-1 model, v2-5 Feb 2013, calculates the ratios that the demand density (given in kbit/s/km2) should be distributed across the RATGs. RATG 3 corresponds to short range LE technologies such as Wi-Fi and its future enhancements. The ratios are calculated within the model so that the amount of demand density that is carried into the licensed spectrum of RATG 1 and 2 is found and hence spectrum estimates for these RATGs can be calculated. Figure 1 identifies which steps in the model flowchart explicitly take into account the RATG3 demand.

For example, with the default parameters the downlink (DL) demand density for SC 4, Conversational services with peak rates between 16 and 144kbit/s (e.g. calls), and SE 6, rural, in 2020 is split according to the percentages summarised in Table 1. In this example 24% of the traffic is routed through the RATG3 layer with 20% of this via RATG3i hotspots of 5m range and 4% via wider area RATG3 coverage of 23m range.

RATG 1				RATG 2				RATG 3				RATG 4				Σ
Macro	Macro	Pico	Hot Spot	Macro	Macro	Pico	Hot Spot	Macro	Macro	Pico	Hot Spot	Macro	Macro	Pico	Hot Spot	
4%	-	-	5%	37%	-	5%	25%	-	-	4%	20%	-	-	-	-	100%

Table 1 Example split of demand amongst RATGs and Radio Environments

The received version of ITU-R M.1768-1 model, v2-5 Feb 2013, does not proceed with any further steps for RATG3 spectrum estimation beyond this calculation of the demand density split by RATG and Radio Environment.

1.1.3 Changes to the model to include LE spectrum calculation

As mentioned earlier, the received version of ITU-R M.1768-1 model, v2-5 Feb 2013, calculates the amount of demand density that is allocated to RATG3 which includes Wi-Fi and its enhancements. This is controlled by the percentage of demand density that is expected to be carried over RATG3, which is a model input. The missing algorithmic steps beyond this to estimate spectrum requirements for RATG3 are similar to those for RATG 1 and 2, which have been implemented for the derivation of the required licensed spectrum in the model already.

Below is a list of the algorithmic steps needed for the RATG 3 spectrum estimate. Note that the calculation steps prior to the list to generate demand density are not included in this list because these are already existent in the ITU model.

1. First we calculate the traffic values (kbit/s/cell) for each RATG3 cell type based on multiplication of the traffic density (kbit/s/km2) with the traffic density split by RATG and Radio Environment and with the RATG3 sector areas (km2/cell). A different traffic value is expected for packet- and circuit-switched, unicast and multicast Service Categories in different Service Environments, Radio Environments and years in uplink and downlink. It is noted that although licence exempt networks deal with the traffic with a packet-based architecture, several services that are requested from them are circuit-switched. These circuit-switched services are covered in step 2.
2. For circuit-switched services the traffic value unit is session arrivals/s/cell instead of kbit/s/cell. However the conversion can be easily done using the average

session data rate. This can be done at the stage where Queuing Theory is applied to derive the requested system capacity.

3. Next the coverage density can be aggregated over areas of the same teledensity, i.e. dense urban RATG3 capacity density = SE1 + SE2 + SE3 RATG3 capacity density, suburban RATG3 capacity density = SE4 + SE5 RATG3 capacity density, rural RATG3 capacity density = SE6 RATG3 capacity density. A similar step is performed for RATG 1 and 2. For packet-switched services this leads to traffic values for unicast and multicast Service Categories in different teledensities, Radio Environments and years for RATG3 in the uplink and downlink in kbit/s/cell.
   Note that since a separate run of the model was used for LE spectrum estimates for home, office, and public areas, that the user density of some SEs is set to zero. As a consequence, the traffic volume density that is calculated at this step is also zero. Thus for example in home runs, dense urban RATG3 capacity density = SE1 RATG3 capacity density, suburban RATG3 capacity density = SE4 RATG3 capacity density, rural RATG3 capacity density = SE6 RATG3 capacity density.
4. The previous step of aggregation across Service Environments of same teledensity can be applied to circuit-switched services. The results in traffic values for unicast and multicast Service Categories in different teledensities, Radio Environments and years for RATG3 for the downlink and uplink in Erlang/cell.
5. The required RATG3 capacity (kbit/s/cell) can next be calculated for packet-switched, unicast and multicast Service Categories in different teledensities, Radio Environments and years in uplink and downlink using the Queuing Theory calculation block. The required RATG3 capacity (kbit/s/cell), independent of Service Category, is the output of the Queuing Theory calculation block so that the quality of service criteria of the driver Service Categories are fulfilled, whereas the quality of service criteria of the rest of Service Categories are over fulfilled. Thus the required RATG3 capacity (kbit/s/cell) can be calculated for packet-switched, unicast and multicast services in different teledensities, Radio Environments and years in the uplink and downlink. A similar step is carried out for RATG 1 and 2.
6. The previous step of Queuing Theory application can be applied to circuit-switched services. The result is traffic values for unicast and multicast Service Categories in different teledensities, Radio Environments and years for RATG3 for the downlink and uplink in kbit/s/cell. The required RATG3 capacity (kbit/s/cell), independent of Service Category, is the maximum capacity amongst the capacities for each Service Category. Thus the required RATG3 capacity (kbit/s/cell) can be calculated for circuit-switched, unicast and multicast services in different teledensities, Radio Environments and years in uplink and downlink.
7. In this step we can aggregate the required RATG3 system capacity (kbit/s/cell) for the uplink and downlink. The result is the required RATG3 capacity (kbit/s/cell) for packet- and circuit-switched, unicast and multicast services in different teledensities, Radio Environments and years. A similar step is carried out in RATG 1 and 2.
8. The spectrum required for RATG3 (MHz/cell or just MHz) can be then calculated assuming a spectral efficiency that is relevant to RATG3 communication links. The spectral efficiency is discussed in appendix E. The required RATG3 capacity (kbit/s/cell) is first aggregated between packet- and circuit-switched services and the sum is then divided by the RATG3 spectral efficiency. The result is spectrum

required for RATG3 (MHz) for unicast and multicast services in different teledensities, Radio Environments and years. A similar step is carried out in RATG 1 and 2.

9. In this step we can calculate the spectrum required for RATG3, regardless of unicast or multicast service, by summation. The result is spectrum required for RATG3 (MHz) in different teledensities, Radio Environments and years. A similar step is carried out in RATG 1 and 2.
10. The spectrum required for RATG3 that is calculated in the previous step is unadjusted for several inefficiencies. These are the guard band between operators, the minimum spectrum deployment per operator and radio environment, the granularity for spectrum allocation, and the number of RATG3 operators. The result of this step is spectrum required for RATG3 (MHz) in different teledensities, Radio Environments and years, adjusted for deployment inefficiencies. A similar adjustment step is carried out in RATG 1 and 2.
11. In this step we can aggregate the required spectrum for RATG3 (MHz) across Radio Environments. The result is the adjusted spectrum required for RATG3 (MHz) in different teledensities and years. A similar action is carried out in RATG 1 and 2.
12. The required spectrum for RATG3, independent of teledensity, is equal to the maximum across different teledensities. A similar action is carried out in RATG 1 and 2.
13. Finally we post process the model results to take into account practical deployment limitations of RATG3 LE technologies such as the supported bandwidths of Wi-Fi and the number of concurrent channels required in any given location to avoid interference given the LE nature of RATG3. We make these adjustments assuming the same split of LE devices across 802.11 protocols and between the 2.4 and 5GHz frequency bands as discussed in appendix E for deriving RATG3 spectral efficiencies and application rates.

1.1.4 Other changes

The received version of the ITU-R M.1768-1 model, v2-5 Feb 2013, supports spectrum estimates in only three spot-years. Changes were required in the table structures across the model's sheets to add two more spot-years so as to extend the estimation period to the required time duration, up to 2030. The same increment in time was adopted as in the received version of the model, one estimate every five years. Changes were also required in the macro code, where loops had to be extended and indices to tables introduced or corrected. Several sheets, and their named variables, that correspond to the two introduced spot-years had to be created.

In order to calculate the 'dedicated' and 'shared' spectrum estimates several tables were introduced from row 108 onwards in the worksheet Main. These tables are populated with formulas, without burdening the runtime. Using formulas in the model was generally avoided, because the table structures do not allow dragging formulas across, and because formulas are slower than VBA macro code.

In order to expedite runtimes we introduced switches between automatic and manual calculation modes during the macro execution. These switches are required for synchronisation between formulas and macros, because some calculation steps take place with use of formulas, whereas others are exclusively dealt with within the macro code.

1.2 Model calibration for estimating the spectrum

The ITU-R M.1768-1 model distributes the traffic amongst different Radio Environments with the macro MainModule.DistributeTrafficButton. At the end of this process the worksheet Dist-Ratio-Matrix contains information about the traffic distribution ratios.

On several occasions the whole or part of the traffic that is requested from the network remains undistributed. This is an expected output based on unavailability of appropriate infrastructure to provide service to this traffic. This is can occur for example from the combination of high mobility traffic and high data rates. Here macrocells are the only Radio Environment that can deliver service to high mobility traffic but their support for high data rate services is limited by the extent of carrier aggregation and adequate resources.

The traffic that remains undistributed after the distribution process in effect means that the traffic volume density that the model uses for the spectrum estimate is not necessarily equal to that which would correspond to the demand inputs. In other words, a percentage of the input demand does not make it through the traffic distribution and therefore a calibration process is required so as to match the model's distributed traffic volume density against the traffic volume density that is envisioned from the market analysis. More information on the market analysis can be found in our demand analysis in appendix C.

During the calibration process the entries of worksheet AreaTrafficVolume are read and summed independently for DL and uplink (UL) across Service Categories. Note that the DL sum needs to include the multicast traffic. Then the sums are adjusted for undistributed traffic, since the entries of worksheet AreaTrafficVolume include both distributed and undistributed parts of the traffic. The result of the adjustment is compared against the traffic volume density from the market analysis, after conversion to match the same unit of measure, TB per month per km2.

The error between the traffic volume density of model and market analysis is used to adjust the trial multiplier value of the min and max market user density values in the worksheet Market-Input. Although the model's traffic volume density is a nonlinear function of the min and max market licensed user density, for the range of the multiplier of all simulations it was found that the response is close to linear so that only a few calibration iterations were required. The trial value of each new iteration is simply based on the previous iteration value, and changed at the same percentage as the calibration error.

Note that the trial multiplier is independent for urban, suburban and rural SE-SC combinations and also separate for the two link directions (DL and UL), since the market analysis provides a separate traffic volume value for DL/UL and teledensity. Also note that in licence exempt runs, where for example home-only traffic is input to the model, the trial multiplier affects only those SEs that are categorised as home, i.e. SE1, SE4 and SE6. Figure 2 shows the schematic of the model processes, and the position of the min/max of market studies where the trial multiplier is applied.

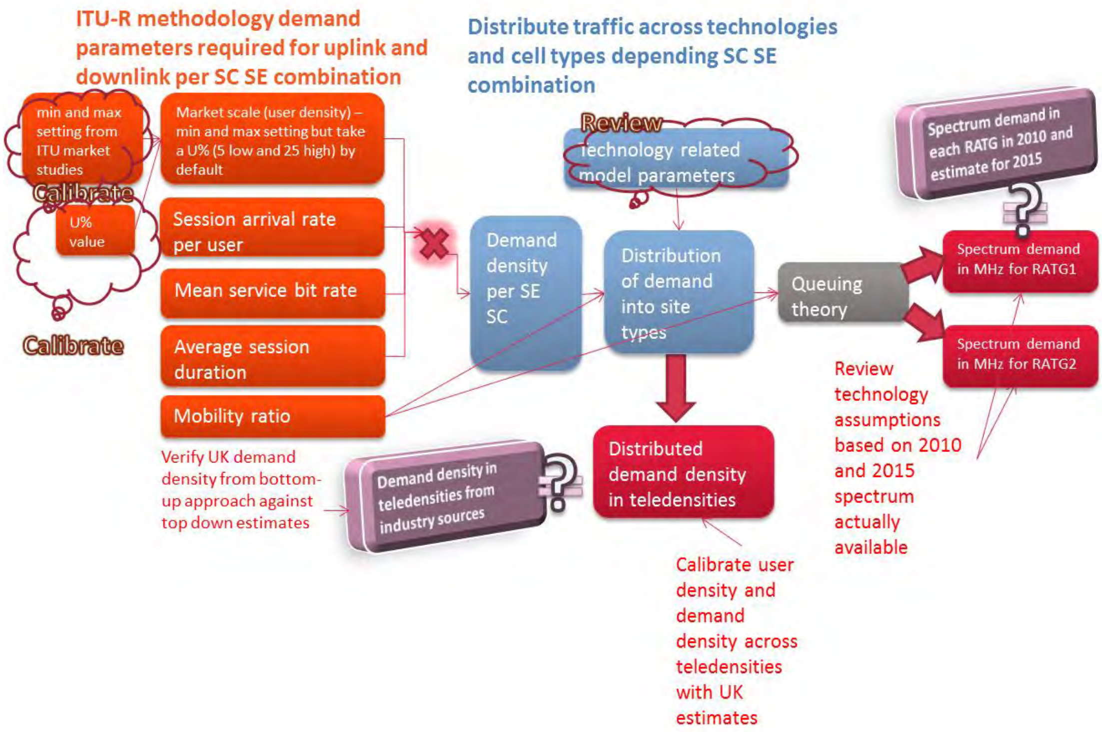


Figure 2: Overview of calibration processes added to the model

1.3 Model use in licensed and licence exempt runs

The received version of ITU-R M.1768-1 model, v2-5 Feb 2013, distributes the traffic amongst licensed and licence exempt spectrum routes. However, the traffic distribution by RATG takes place after preceding traffic distributions, so that the split of traffic into licensed and licence-exempt is distorted. Furthermore, we found that the proportion of total wireless broadband traffic traffic that goes through RATG1 and RATG2, when home networking devices are included as well as traditional portable devices, is a very small proportion of the total traffic, e.g. 1-2% of the total modelled traffic is on licensed spectrum. This causes issues in the model as inserting non-integer numbers in v2-5 Feb 2013 is not accepted.

For the reasons above two separate runs of the model provide the licensed and licence-exempt spectrum estimates. Also, the v2-5 Feb 2013 version of the model does not support a variable max application rate for RATG3 for each spot-year. Thus a separate run is carried out for each spot-year for RATG3. Lastly, in licence-exempt spectrum a separate run was carried out for home, office and public areas, since separate market survey data are used for calibration in these localised demand scenarios.

2. Appendix B – Assumptions regarding UK spectrum availability and usage from 2010 to 2030

In the main body final report we compare our licensed and licence exempt spectrum results against our view of likely UK mobile broadband spectrum usage and supply between 2010 and 2030.

This appendix outlines our assumptions behind these spectrum estimates for both the licensed and licence-exempt bands.

2.1 Licensed spectrum availability

As outlined in the final report main body in reviewing the spectrum requirements produced by the ITU model, we have compared these against our view of spectrum planned to be released in the UK between 2010 and 2030 if current UK plans for spectrum releases are followed. Our view of this supply of UK mobile broadband spectrum over time is shown in Figure 3.

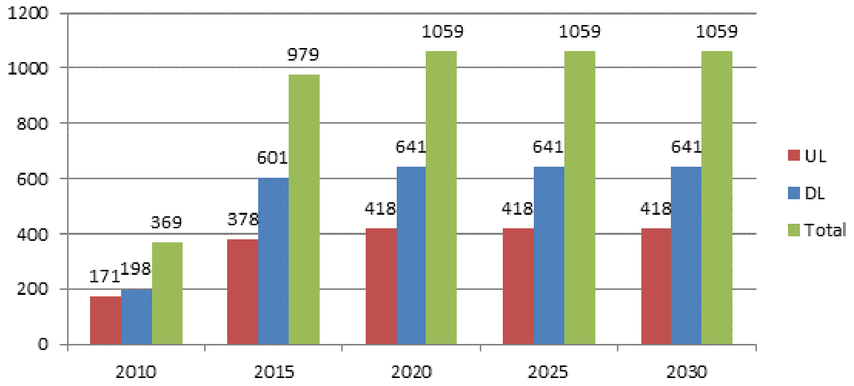


Figure 3: Our estimate of anticipated supply of mobile broadband spectrum for the UK without further ITU designations

Table 2 summarises the paired and unpaired spectrum bands that we have considered in our supply of UK spectrum. Note that all of the bands shown in Table 2 are ITU allocated for mobile services and so our assumed spectrum supply quantity for the UK over time is based purely on UK centric release/award plans for these bands rather than any further ITU decisions on the usage of these bands. We note that the 3.6-3.8 GHz mobile allocation is on a secondary basis by the ITU but is currently held by UK Broadband for fixed wireless services use in the UK.

Paired spectrum	Unpaired spectrum
800 MHz	1452-1492 MHz
900 MHz	2100 MHz (1900 -1920 MHz)
1800 MHz	2100 MHz (2010-2025 MHz)
2100 MHz	2300 MHz
2600 MHz	2600 MHz
3400 – 3600 MHz	3600- 3800 MHz

Table 2: Paired and unpaired frequency bands under consideration

The amount of spectrum available in the UK within each of these bands and the likely timing of when this spectrum will become awarded is shown in Figure 4 and Figure 5. The assumptions behind the volume of spectrum available and the timing of availability of this spectrum across these bands are detailed in sections 2.1.1 and 2.1.2. These are largely based on the medium baseline spectrum release scenario that we considered in our UHF study for Ofcom [1] with some minor updates to reflect developments since this study was completed in March 2012.

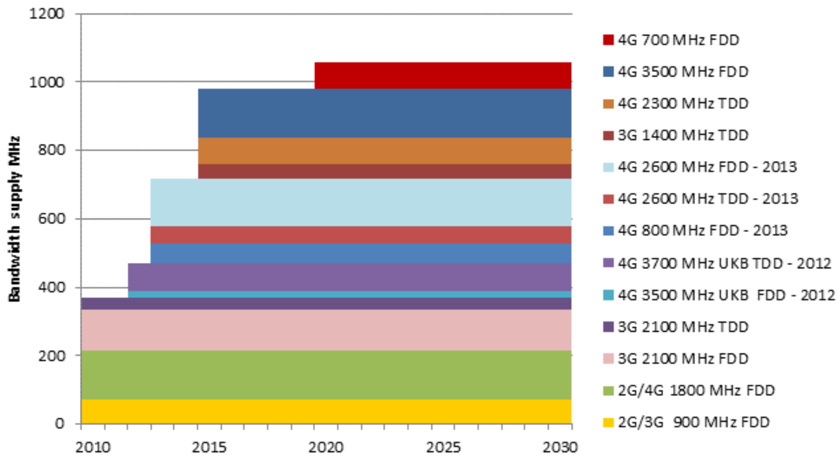


Figure 4: Our assumed baseline for licensed broadband spectrum supply in the UK out to 2030

	Frequency Band	Bandwidth, MHz			MHz Available for downlink in year 20xx								
Technology	Band	DL	UL	Total	2010	2011	2012	2013	2014	2015	2020	2025	2030
	Paired, harmonised												
4G DL	700 MHz	30									40	40	40
4G UL	700 MHz		30	80							40	40	40
4G DL	800 MHz	30						30	30	30	30	30	30
4G UL	800 MHz		30	60				30	30	30	30	30	30
2G/3G DL	900 MHz	35			35	35	35	35	35	35	35	35	35
2G/3G UL	900 MHz		35	70	35	35	35	35	35	35	35	35	35
2G/4G DL	1800 MHz	72			72	72	72	72	72	72	72	72	72
2G/4G UL	1800 MHz		72	144	72	72	72	72	72	72	72	72	72
3G DL	2100 MHz	60			60	60	60	60	60	60	60	60	60
3G UL	2100 MHz		60	120	60	60	60	60	60	60	60	60	60
4G DL	2600 MHz	70						70	70	70	70	70	70
4G UL	2600 MHz		70	140				70	70	70	70	70	70
4G DL	3500 MHz	10					10	10	10	10	10	10	10
4G UL	3500 MHz		10	20			10	10	10	10	10	10	10
4G DL	3500 MHz	70								70	70	70	70
4G UL	3500 MHz		70	140						70	70	70	70
TOTAL		267	267	534	334	334	354	554	554	694	774	774	774
	Unpaired, harmonised												
3G DL	1400 MHz	35.6								35.6	35.6	35.6	35.6
3G UL	1400 MHz		4.4	40						4.4	4.4	4.4	4.4
3G DL	2100 MHz	31.15			31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.2	31.2
3G UL	2100 MHz		3.85	35	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85
4G DL	2300 MHz	71.2								71.2	71.2	71.2	71.2
4G UL	2300 MHz		8.8	80						8.8	8.8	8.8	8.8
4G DL	2600 MHz	44.5						44.5	44.5	44.5	44.5	44.5	44.5
4G UL	2600 MHz		5.5	50				5.5	5.5	5.5	5.5	5.5	5.5
4G DL	3500 MHz	71.2						71.2	71.2	71.2	71.2	71.2	71.2
4G UL	3500 MHz		8.8	80				8.8	8.8	8.8	8.8	8.8	8.8
TOTAL		520.65	298.35	819	35	35	35	165	165	285	285	285	285

	DL	UL	2010	2015	2020	2025	2030
Spectrum baseline	630.65	408.35					
DL			198	601	641	641	641
UL			171	378	418	418	418
Total			369	979	1059	1059	1059

Figure 5: Detailed breakdown of frequency bands assumed to be available at each year in licensed spectrum supply estimates

Note that looking back at 2010 we know that not all UK mobile broadband spectrum that was licensed was actually used by networks in practice. For example, some TDD spectrum at 2.1 GHz that could have been used by UMTS networks was licensed but not used due to the UK's focus on FDD based cellular networks currently. Looking ahead to 2015 from today (2013) we can also anticipate which licensed bands are likely to be used in practice by the UK's mobile broadband networks.

Therefore when sense checking our spectrum estimates produced by the ITU-R M.1768-1 model we can compare our spectrum estimates against that amount of mobile broadband spectrum that was likely to be heavily utilised in the UK at 2010 and 2015. Throughout this study we assume that this was:

- 334 MHz in 2010 based on all 900 MHz, 1800 MHz and the FDD portion of the 2100 MHz bands being likely to be heavily used. We assume that the TDD portion of the 2100 MHz bands were not used heavily used at this time.
- 534 MHz in 2015 as we include 200 MHz of additional FDD spectrum from the 4G spectrum auction of 800 MHz and 2600 MHz but do not include UK Broadband's spectrum at 3.5 GHz as it is not deployed nationwide.

2.1.1 Assumptions on paired spectrum availability over time

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

Quantity	Timing
• Gross quantity available is over 90 MHz based broadly on likely available spectrum from the boundary 700 – 790 MHz according to the quantity given in FCC band plan [2] since there is no agreed quantity identified yet for Europe. • Net quantity incorporates the potential use of: o 1 MHz guard band from 694 – 695 MHz o 40 MHz UL portion o 11 MHz duplex gap o 40 MHz DL portion o 5 MHz guard band from 786 MHz to 791 MHz • This results in 2 x 40 MHz of total usable spectrum.	• In Ofcom's UHF strategy consultation last year and more recent Call for Inputs the earliest date proposed for releases of spectrum at 700MHz is 2018.We therefore include spectrum from this band from 2020 onwards in our timeline of spectrum supply.

Table 3: Quantity and timing of 700 MHz band

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

Quantity	Timing
• Gross quantity available is 72 MHz based on Commission Decision 2010/267/EU [3]. • Net quantity incorporates the use of: o 11 MHz duplex gap o 1 MHz guard band at 790 MHz • This results in 2 x 30 MHz of total usable spectrum.	• Based on the award of this band in the 4G spectrum auction in 2013 we assume availability and usage of this band from 2013 onwards.

Table 4: Quantity and timing of 800 MHz band

900 MHz frequency band (880 MHz – 915 MHz paired with 925 MHz – 960 MHz)

Quantity	Timing
• Gross quantity available is 70 MHz based on Ofcom Interface Requirement IR 2014 Public Wireless [4] Networks (Aug 2005). • Net quantity is equal to gross quantity with all duplex gaps and guard bands already taken into account with 2 x 35 MHz available in total.	• This band is licensed to mobile operators in the UK and widely used for GSM and UMTS networks today and so we include 2x35MHz for this band in both our spectrum usage and supply scenarios.

Table 5: Quantity and timing of 900 MHz band

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

Quantity	Timing
• Gross quantity available is 150 MHz based on Interface Requirement IR2014 [4] Public Wireless Networks (Aug 2005). • Net quantity will be 144 MHz including the 2 x 15 MHz released to the market. All duplex gaps and guard bands already taken into account with 2 x 72 MHz available in total.	• This band is licensed to mobile operators in the UK and widely used for GSM networks. However, EE have now launched LTE in 2x15 MHz of spectrum in 2013. • We include 2x72MHz for this band in both our spectrum usage and supply scenarios.

Table 6: Quantity and timing of 1800 MHz band

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

Quantity	Timing
• Gross quantity available is 120 MHz based on IR 2019 Third Generation Mobile [5]. • Net quantity incorporates the use of guard bands and duplex gaps resulting in 2 x 60 MHz available in total.	• This band is licensed to mobile operators in the UK and widely used for UMTS networks today and so we include 2x60MHz for this band in both our spectrum usage and supply scenarios.

Table 7: Quantity and timing of 2100 MHz band

2600 MHz frequency band (2500 MHz – 2570 MHz paired with 2620 MHz – 2690 MHz)

Quantity	Timing
• Gross quantity available is 140 MHz based on ECC Decision (05)05 [6]. • Net quantity includes a total of 2 x 70 MHz of usable spectrum which takes into account duplex gap and guard bands.	• Based on the award of this band in the 4G spectrum auction in 2013 we assume availability and usage of this band from 2013 onwards.

Table 8: Quantity and timing of 2600 MHz band

3500 MHz frequency band (3480 – 3500 MHz paired with 3580 – 3600 MHz UK Broadband spectrum and 3410 MHz – 3480 MHz paired with 3510 MHz – 3580 MHz)

Quantity	Timing
3480 – 3500 MHz paired with 3580 – 3600 MHz • Gross quantity available is 40 MHz based on Interface Requirement IR2015 [7] (2011) noting amendment of licence to mobile. • Net quantity will be 20 MHz based on the frequency boundary for FDD band 22 in 3GPP 36.101[8] Release 10 September 2011. The boundary is given as 3410-3490 MHz UL and 3510-3590 MHz DL which means 2 x 10 MHz from 3490-3500 MHz and 3590-3600 MHz fall outside the standard resulting in 2 x 10 MHz available for standard use.	• This band is licensed to UK Broadband for mobile Wireless Broadband services however, we understand that their existing LTE network is TDD rather than FDD based and so this band is included in our supply estimate from 2012 onwards but not in our usage estimate until later in 2020. • We assume this band eventually will be used for a future LTE network to complement UK Broadband's existing LTE TDD localised offerings. However, we assume that, given that LTE networks are only emerging in the UK today at 2013, that it will be 2020 before this band might be used widespread across the UK.
3410 MHz – 3480 MHz paired with 3510 MHz – 3580 MHz • Gross quantity available is 140 MHz as stated in DCMS Enabling UK growth – Releasing public spectrum Making 500 MHz of spectrum available by 2020 [9]. • Net quantity will be 140 MHz (2 x 70 MHz) based on 3GPP 36.101 Release 10 September 2011 [8] which identifies 2 x 80 MHz in this whole spectrum band. This also assumes partial release to market and the need for the MOD to retain spectrum for defence purposes.	• This band is currently used for defence purposes but is a high priority for release by the MOD under its release programme. • The Department for Culture Media and Sport (DCMS) reports that the release of this spectrum is likely to be within current Government spending round i.e. March 2015. • We have assumed that 2 x 70 MHz will be available in 2015 based on current plans from Government.

Table 9: Quantity and timing of 3500 MHz band

2.1.2 Assumptions on unpaired spectrum availability over time

The downlink portion for TDD systems differs to that of FDD due to sharing of spectrum resources between the uplink and downlink. Therefore, we have assumed a proportion of traffic generated by the downlink based on a set of TD-LTE frame configurations developed by 3GPP [10]. The chart in Figure 6 shows the ranges of percentage of DL for TD-LTE and we have assumed 89% in the downlink based on the majority of time spent in the downlink to support growing demands for mobile traffic. All downlink spectrum in the following tables have been adjusted by 89% from the total net quantity.

Uplink-downlink configuration	Subframe number										totals		%DL
	0	1	2	3	4	5	6	7	8	9	U	D	
0	D	S	U	U	U	D	S	U	U	U	6	2	25%
1	D	S	U	U	D	D	S	U	U	D	4	4	50%
2	D	S	U	D	D	D	S	U	D	D	2	6	75%
3	D	S	U	U	U	D	D	D	D	D	3	6	67%
4	D	S	U	U	D	D	D	D	D	D	2	7	78%
5	D	S	U	D	D	D	D	D	D	D	1	8	89%
6	D	S	U	U	U	D	S	U	U	D	5	3	38%

Figure 6: TD-LTE frame configurations and % resource allocated to DL. Source: 3GPP [10]

1452 -1492 MHz frequency band

Quantity	Timing
• Gross quantity available is 40 MHz based on ECC DEC 03(02) [11]. • Net quantity incorporates all 40 MHz use for TDD operation as a supplemental downlink. • Note Plum Consulting conducted a study [12] which investigated the economic benefits from use of 1452-1492 MHz for a supplemental mobile downlink for enhanced multimedia and broadband services which we have drawn upon in our assumptions.	• Timing of introducing this spectrum is based on Plum's report which takes into account conclusion of ECC decision end of 2012, inclusion of the band by 3GPP and availability of devices. • We assume the availability of all 40 MHz will be from 2015 to create a supplemental downlink band for mobile broadband use but that there will be a 5 year lag before this new band is fully used (based on a slow ramp up of usage of TDD bands and TDD device penetration in the UK traditionally).

Table 10: Quantity and timing of 1452 - 1492 MHz band

2100 MHz Unpaired frequency band

Quantity	Timing
1900 – 1920 MHz • Gross and net quantity available is 20 MHz based on Interface Requirement IR2019 [5].	• This spectrum is licensed to operators and available for use by them over the whole time frame.
2010-2025 MHz • Gross quantity available is 15 MHz based on Ofcom consultation[13] • Net quantity is equal to gross quantity with all duplex gaps and guard bands already taken into account with 15 MHz available in total.	• As above

Table 11: Quantity and timing of 2100 MHz unpaired band

2300 MHz frequency band

Quantity	Timing
• Gross quantity available is 80 MHz as stated in DCMS Enabling UK growth – Releasing public spectrum Making 500 MHz of spectrum available by 2020 [9].	• This band is currently used for defence purposes but is a high priority for release by the MOD under its release programme. • The DCMS reports that the release of this spectrum is likely to be within current Government spending round i.e. March 2015. • We have assumed that all of the available bandwidth is released by 2015. • Devices already available for use in this band due to the deployment of networks in Asian markets such as China and India according to consultants at Heavy Reading [14].

Table 12: Quantity and timing of 2300 MHz band

2600 MHz frequency band

Quantity	Timing
• Gross quantity available is 50 MHz based on ECC Decision (05)05 [6].	• This band was awarded as part of the UK 4G auction in 2013 so appears in our spectrum estimate from 2013 onwards.

Table 13: Quantity and timing of 2600 MHz band

3600-3800 MHz frequency band

Quantity	Timing
• Gross quantity available is 82 MHz based on current allocation of Fixed Wireless Service to UK Broadband [7]. • Net quantity is equal to 80MHz when guard bands have been taken into account.	• This band is available for mobile services but currently used by UK Broadband for fixed Wireless Broadband services for their LTE TDD services in London, Reading, Swindon and Scunthorpe [15]. • There are deployment constraints due to the numerous satellite earth stations deployed across the UK in the adjacent bands which may limit its full availability • We assume 40 MHz of total spectrum is available from 2013 to 2030.

Table 14: Quantity and timing of 3600 -3800 MHz band

2.2 Licence exempt spectrum availability

In this study we determine the requirements for licence exempt spectrum and, in the same way as the licensed spectrum, we compare this against our assessment of LE spectrum availability for mobile broadband networks over time.

The following sections capture our method and assumptions for identifying the licence exempt spectrum that may help increase the capacity of mobile broadband networks.

2.2.1 All available LE spectrum

Licence exempt spectrum in the UK is derived from international and European allocations that are then translated into UK specific uses and applications across a mix of small and large quantities. LE spectrum is predominantly used for short range services which enable lots of devices to be used together in close proximity on an expectation that there is sufficient coverage and bandwidth to support the desired service.

However, there is an underlying assumption from licence-exempt users that with enough spectrum the quality and performance of LE networks can be sustained to achieve high enough data rates to support mobile broadband services. Wi-Fi is one exemplar of an LE technology that can achieve high data rates within a non-exclusive spectrum band. However, other LE spectrum bands such as PMR 446 are not appropriate for mobile broadband use due to its voice centric and narrowband nature.

In this section we start by presenting all available LE spectrum between 400 MHz and 64 GHz as derived from IR2030 [16] to illustrate the range of potential LE bands available for use in the UK. These are listed in Table 15 with the volume of spectrum at each band shown in Figure 7. Note that this shows the gross amount of spectrum available at each band without taking into account guard bands or the number of channels that the volume of spectrum at various bands would support in practice.

LE frequency band	Application
400 – 446 MHz	• Non-specific short-range devices • Industrial/Commercial Telemetry and Telecommand • Active Medical implants • Medical and biology applications • Vehicle paging alarms • Model control
863-870 MHz	• Non-specific short range devices • Radio determination applications • RFID • Alarms • Radio microphones • Wireless audio applications
2.4-2.483 GHz	• Wideband data transmission systems • Short range indoor data links • Radio determination applications • RFID

	• Wireless audio applications • Wireless Video cameras – Non broadcasting
5 GHz	• Wireless access systems • Wideband data transmission systems • Short range indoor data links • Radio determination applications • Wireless video cameras – Non broadcasting
8.5-10.6 GHz	• Short range indoor data links • Radio determination applications • Road Transport and Traffic Telematics • Radar level gauges • Tank Level probing radar
13.4-14 GHz	• Radio determination applications • RFID
17.1 – 17.3 GHz	• Radio determination applications
24-27 GHz	• Radio determination applications • Road Transport and Traffic Telematics • Tank Level probing radar
59-64 GHz	• Road Transport and Traffic Telematics • Tank Level probing radar

Table 15: LE frequency bands and associated applications

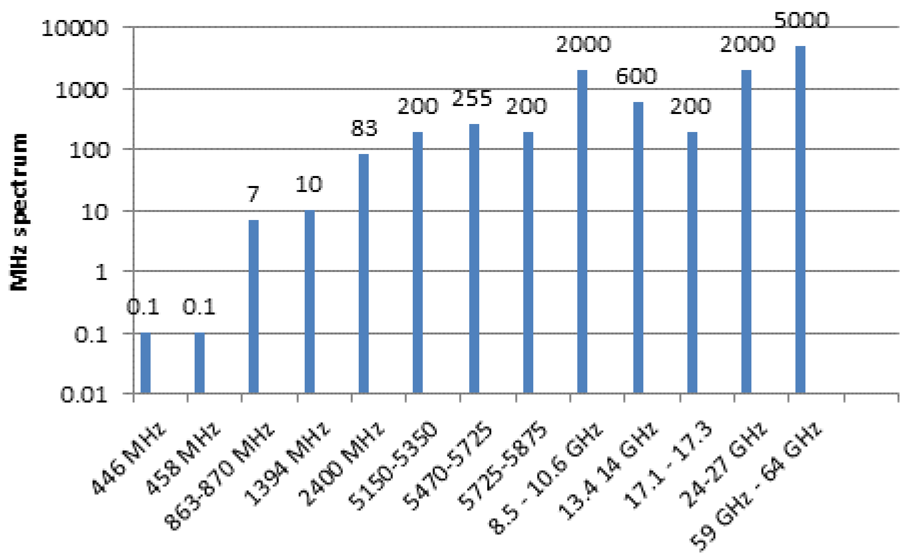


Figure 7: Available LE spectrum as derived from IR 2030 ranging from 300 MHz to 64 GHz

2.2.2 Wi-Fi hotspots spectrum

In the previous section we highlighted all possible available licence exempt frequency bands that are available which have a set of applications used in them.

Given the large role that Wi-Fi networks play today in providing wireless broadband access to many stationary users in both outdoor and indoor environments, we have focussed comparing our estimates of LE spectrum requirements for mobile broadband usage against bands currently used and under discussion to become available for LE usage which would support Wi-Fi hotspots and potentially longer range Wi-Fi picocells over the study timeframe.

Looking first at spectrum availability for LE hotspots, the particular licence-exempt spectrum bands used by Wi-Fi hotspots are the 2.4 GHz and 5 GHz bands. These two bands offer a tiny proportion of LE spectrum when compared against all available LE spectrum yet support a fast growing sector which includes a multitude of new non-mobile devices such as Smart TVs and wireless multimedia devices.

We show in Figure 8 LE bands that we know are available today and currently supported by Wi-Fi devices. These are represented by the solid coloured bars on the graph. The transparent bars with dashed outline on the graph represent potential additional Wi-Fi spectrum that could become available if more 5 GHz spectrum is allocated LE status at the next WRC in 2015. Note that on this graph we only consider the volume of spectrum available at each band which is thought to be usable by Wi-Fi networks. The volume of spectrum available at each band here therefore takes account of guard bands and 20MHz being the smallest channel supported by Wi-Fi networks today.

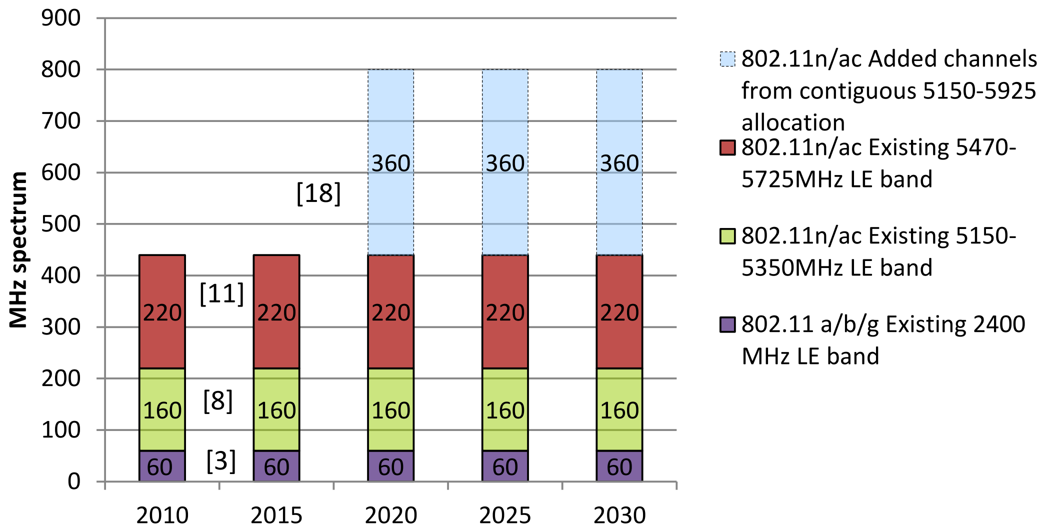


Figure 8: Total potential and available LE spectrum for Wi-Fi hotspots

The current usage of the 2.4GHz and 5GHz bands and proposed newly added spectrum at 5GHz is taken from a recent report on Wi-Fi spectrum usage by Plum Consulting [17] which identifies the quantity of additional Wi-Fi spectrum that could potentially become available in the future.

Theoretically the extension of the 5GHz band to make the currently two separate bands contiguous would make a further 320 MHz of spectrum available. However, due making this band a contiguous run of LE spectrum this removes guard bands limiting the existing separate bands and in practice would make a total of 37 x 20 MHz channels available in total at 5GHz.

Our current study determines from our spectrum requirements analysis whether the proposed additional spectrum at 5GHz is likely to be required based on demand estimates for LE spectrum or if current Wi-Fi spectrum allocations are sufficient to serve the growing demands from Wi-Fi users over the coming 15 to 20 years.

2.2.3 Picocell spectrum

Licence-exempt spectrum could also potentially be used by picocells (or longer range LE access points with increased EIRP limits or using lower frequencies) to target outdoor users either to provide rural broadband coverage or wide spread Wi-Fi coverage such as that which might be deployed in a central urban district such as a town or city centre. The type, quantity and frequency band of the spectrum may not be so straightforward to find in large quantities in all locations as extending LE coverage beyond short ranges starts to introduce increased interference. Therefore, there must be some element of management or defined restrictions to ensure adjacent or close deployments do not cause interference to each other for any potential LE picocell spectrum.

We suggest that TV White Space (TVWS) is a spectrum allocation that would suit LE picocells because of the low frequency band and propagation characteristics that enable a useful range but can still provide bandwidths to deliver mobile broadband performance. The quantity of TVWS spectrum potentially available for this type of application will vary in dense urban, suburban and rural areas depending how heavily the interleaved DTT spectrum is used. In the UK, the current amount of white space spectrum is unknown however, there are plans within Ofcom [18] to make white space spectrum available on a licence-exempt basis. Therefore, the amount of TVWS spectrum assumed available in our study is an example of the potential spectrum that could be available. The numbers used are indicative and sourced from a search within Google's white space spectrum database against dense urban, suburban and rural postcode search of the USA.

In addition we assume a low power overlay in a licensed band, similar to the proposal for 2.6 GHz spectrum in the 4G auction [13]. Although this shared access band was not awarded at 2.6GHz in the latest auction of this spectrum we assume that a similar idea could be applied to other bands in future. The amount of spectrum assumed is based on Ofcom's proposal in the 4G spectrum auction which suggested a dedicated 2 x 20 MHz low power overlay in the 2.6 GHz band. We acknowledge, however, there are no known plans to have any low power shared access channels in any of the new or forthcoming bands but include this as an example of the volume of LE picocell spectrum that might be available at some stage in the future in the UK if such plans were revisited. However, the restrictions on a low power overlay would mean tight control on deployments and an additional burden to all parties involved.

Figure 9 summarises our example of the potential LE picocell spectrum that might be appropriate for the UK in the timescales of our study. Note that we assume that LE picocells access points are not deployed until 2015 as none were currently deployed at the time of this study.

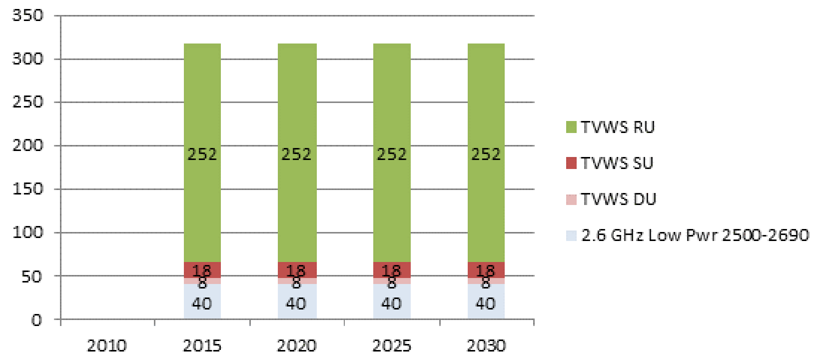


Figure 9: An example of UK LE spectrum availability for picocells (i.e. longer range access points than today's Wi-Fi hotspots) up to 2030

3. Appendix C - UK specific demand for broadband spectrum

This appendix presents our estimates for demand or traffic volumes up to 2030 that we anticipate will be generated on the UK's wireless broadband networks. This includes assessing traffic volumes targeting both licensed spectrum, made up largely of cellular networks, and licence exempt spectrum, dominated today by Wi-Fi usage. This appendix also describes the approach and sources behind our traffic forecast estimates.

Our UK specific demand forecasts are then used to calibrate the user densities within the ITU-R M.1768-1 model so that the distributed demand that the model is estimating spectrum requirements against are specific to the UK market.

This appendix highlights the specific input mobile data traffic parameters researched, it provides the sources, where relevant, from which the numbers have been referenced and also provides summary plots of growth over time from 2010 to 2030 for each of the demand parameters.

The demand parameters that were analysed included:

- Volume of traffic generated by device types
- Penetration of devices amongst the general population
- Location of traffic generated such as at home, in the office or on the move

The blend of each of the above attributes forms the input data used to generate UK specific demand densities per teledensity which can be used to calibrate demand levels across the service environments and service categories in the ITU-R M.1768-1 model as outlined in appendix A.

In this study we have used the up to date forecasts such as the widely quoted forecasts by Cisco[19] and the recent (2012) published forecast by Ericsson[20] which now includes data on the impact of tablet devices such as the iPad and embedded modules which are now becoming a feature of more recent analyses.

3.1 Our UK specific demand is based on a "bottom up" approach which is used to calibrate user densities in the ITU model

In this study we have followed up a bottom up approach to developing demand estimates. This is described in full in section 3.3 but largely involves:

- Understanding demand by device type
- Understanding penetration by device type
- Understanding population densities by teledensity
- Using the above three estimates to determine the number of devices and hence demand in each teledensity

This bottom up analysis is then verified against UK wide mobile data forecasts to ensure that our bottom up estimates appear sensible against these. Our UK specific demand densities are then used to calibrate user densities within the ITU model so that the distributed demand in each teledensity meets those from our forecasts.

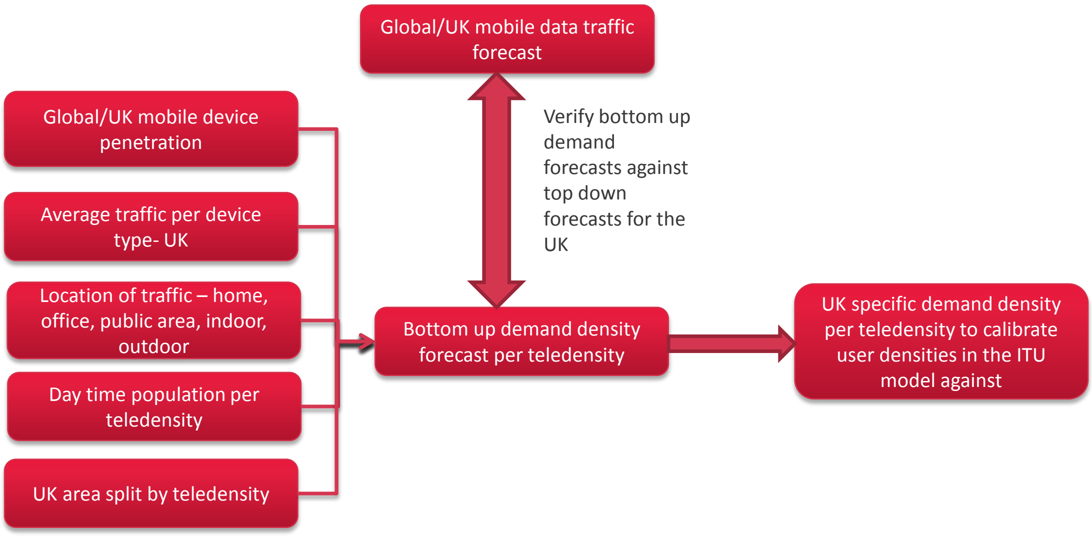


Figure 10: Inputs to "bottom up" demand methodology which are then used to calibrate demand per teledensity in the ITU model

Within the ITU model demand densities are generated per service environment (SE) and service category (SC). Within the timescales of this study we have been unable to generate demand forecasts for each SC and SE combination. In the case of demand for licensed spectrum we instead produce forecasts on a dense urban, suburban and rural basis and use these to calibrate the total distributed demand for the SC and SE combinations falling into these teledensities as illustrated in Figure 11. This assumes that the ITU default distribution of traffic across SEs and SCs within teledensities is appropriate for the UK market. Within this calibration process we adjust the user density in each SE and SC combination via the U% in the model until the distributed demand density in each teledensity matches our UK specific demand density estimates for each of the teledensities. As discussed in appendices D and E we have reviewed and made modifications to other input parameters to the model also but the changes to these parameters are not specifically part of the calibration process for UK specific demand density.

In the case of licence exempt spectrum UK demand estimates are produced on a more granular per SE basis as the distribution of LE traffic amongst SEs may not necessarily track the ITU's assumptions on the distribution of mobile traffic amongst SEs. Also we wanted to model highly localised peak demand scenarios in the LE spectrum analysis which required understanding and calibrating demand in the model on a per SE basis to allow scenarios such as an intensive home networking scenario to be represented. Section 3.2 discusses our approach to LE demand estimation in more detail.

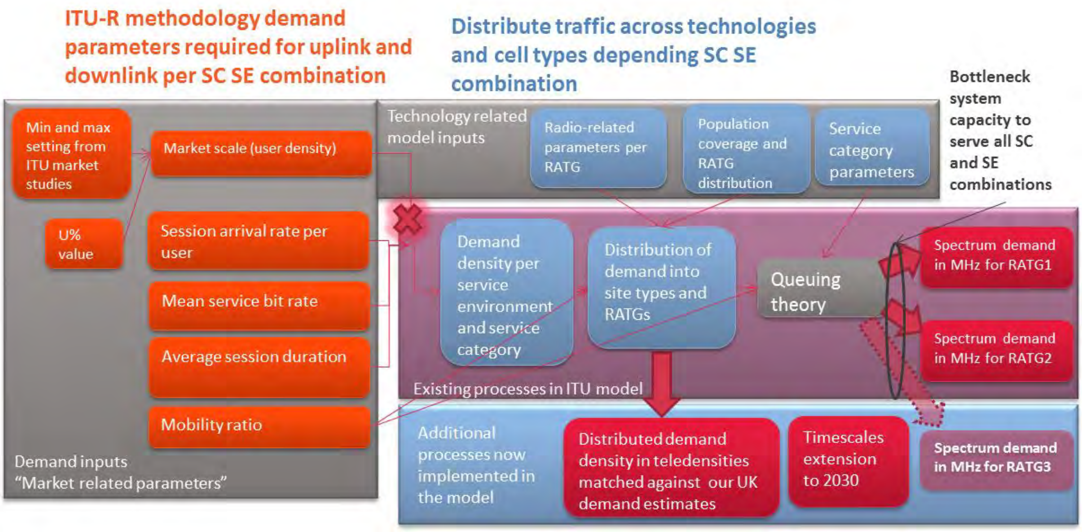


Figure 11: Overview of inputs and processes in ITU-R M.1768 model with distributed demand per teledensity being matched against our UK demand estimates

In producing traffic forecasts via our "bottom up" approach outlined in Figure 10 we have developed a methodology that can take the appropriate traffic inputs gathered from the most relevant data sources and convert these into credible demand scenarios. In this figure the "bottom up" demand estimate comprises the mobile device types, the traffic per device type, time of day users are within a particular teledensity and penetration of devices to derive the user densities across the UK.

In this study we build up our traffic forecasts based on the following key elements:

- Penetration of different device types within the population such as:
  - o Smartphones, Tablets, laptops etc.
- Traffic generated per device type (kB/month)e.g. laptops generate more traffic than smartphones per session
- Location of users during the daytime/night-time across the different teledensities

In a previous study for Ofcom [1] we analysed mobile data traffic across a specific set of devices which are deemed to generate the most significant quantities of traffic across cellular networks. In this study we updated the device types and categorised them into groups of primary device types, which are those devices which are directly used by the users themselves or in the case of M2M machine devices driven by end user needs.

In this study we consider that mobile data traffic is generated by the following primary device types:

- **Smartphones** - These devices are considered to be high end handsets that utilise both touchscreen and non-touchscreen interfaces and are used for mobile data such as video, audio, email etc. amongst other applications such as voice calls. Types of Operating System found in these devices include Android, iOS, Symbian and Windows etc. The volume of traffic generated by these devices is expected to be 3-4x less than that generated by tablets [19].
- **Large Screen Portable devices (type 1) Tablets** – These are considered mobile PC's with large high resolution touchscreens with the ability to surf the web,

stream video, audio, basic editing of documents, email etc. The volume of traffic generated by these devices is expected to be 2-3x less than that of embedded laptops [19].

- **Large Screen Portable devices (type 2) - Embedded laptops** – These are laptop PC's with embedded cellular modules to connect via 3G (or 4G in future) to the Internet. These devices are expected to generate the largest amount of traffic out of all the devices considered. We consider Wi-Fi only laptops in our very high LE demand scenario.
- **Large screen Portable devices (type 3) – hybrid tablets and embedded laptops** – These hybrid devices are now appearing on the market which form a tablet via a detachable screen from a laptop module. These devices have only been released on the market in 2013 and in terms of wireless capability will include both 3G/4G and Wi-Fi. Although these devices generate traffic predominantly on Wi-Fi today we have assumed that their impact on spectrum demand will be dependent on a mass market penetration by 2020 at which point laptop and tablet numbers will start to decline. The latest device on the market is the HP Envy x2 [21] which supports Wi-Fi up 802.11n and no cellular.
- **Feature phones** – We assume these handsets have some 3G data capabilities such as sending email and browsing the Internet but are not good for high resolution video and predominantly used for voice. The volume of traffic generated by these devices is expected to be more than 8-10x less than that generated by smartphones [19].
- **M2M**1 **(machine to machine) type 1** – These devices are basic modules embedded in another machine or device that consumes very little data at frequent intervals (early devices consume 10's of kbps). Types of devices include smart meters, asset tracking and telemetry devices.
- **M2M type 2** - These devices are in home or small office wireless peripherals, multimedia or AV devices. These are high data rate (100 Mbps+) devices which carry a lot of streamed and file transfer data. This include wireless multimedia devices such as Apple TV, wireless printers and other wireless office peripherals
- **Smart TV** – These devices are television sets which incorporate the capability to connect to the Internet. More specifically, the devices captured for this study are those which incorporate wireless connectivity, notably Wi-Fi. Note that we only include these devices in our LE demand estimates as they will not use licensed spectrum.
- **Portable gaming devices-** These devices are portable devices that are dedicated for playing video games in a small handheld form factor. These devices support both Wi-Fi and cellular connectivity which is growing in popularity so players can play against each other remotely. Example devices include Sony PlayStation PSVITA and Nintendo Wii U.

Note that in our very high demand forecasts for LE spectrum we also consider traffic from Wi-Fi only laptops, tablets and hybrid large screen portable devices and the higher traffic levels of smartphones with frequent access to a good Wi-Fi connection i.e. indicating the larger volumes of traffic generated by smartphone users when at home and not restricted by cost or network availability on the services that they use.

[1] M2M was considered a special case for demand and did not feature as part of the core modelled devices

The methodology derived to distribute the traffic from primary devices across locations is captured in Figure 12. The primary devices generate traffic in each of the three main locations; public area, office and home which are then all located in dense urban, suburban and rural teledensities. The communications pathway from the primary devices can be via a number of 'intermediary devices'. The intermediary devices consist of the following types:

- Direct (i.e. no intermediary used)
- Private/public Wi-Fi Access Point
- "Mi-Fi" and tethered link (using PLMN to support Wi-Fi provision)
- Window-ledge CPE
- Femtocell
- Intelligent repeaters (e.g. recent products from Nextivity)
- Conventional repeaters
- LTE relays

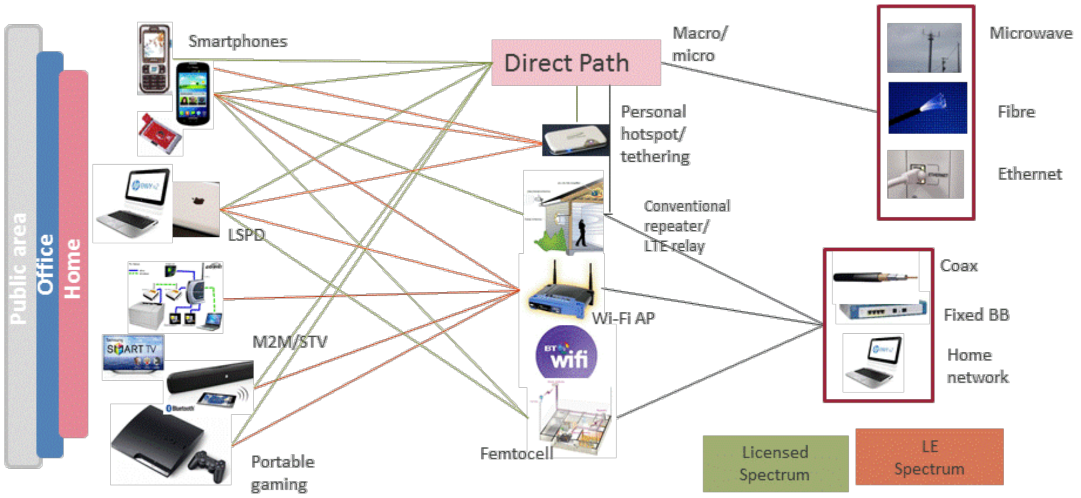


Figure 12: Distribution of mobile data traffic across locations and communications pathways

The intermediary devices provide all possible routes to the core network including:

- A direct path to an outdoor macro, micro or pico cell
- A connection via a private or public Wi-Fi access point
- A connection using a personal MiFi device or tethering to a smartphone etc.

These devices offer access using different spectrum bands in both licensed and licence exempt spectrum. In this way the study captures traffic across both types of spectrum. The diagram above illustrates the communications pathways that are possible from each of the primary user devices.

We have made the following key assumptions for the traffic demand model:

- The traffic generated by any **Primary User Device** varies by user device type – in general more capable devices generate more traffic.
- **Primary User Device** traffic is split between the different **User Environments** and the proportion of device traffic to different User Environments varies by the Primary Device.

- The probability of any **Primary User Device** using any **Intermediate Device** depends upon the **User Environment** (e.g. the probability of a Primary User Device using LTE instead of Wi-Fi will vary by User Environment)
- The communication links between the **Intermediate Device** en route to the **Core Network** does not depend upon the **Primary User Device** (e.g. a locally provided femtocell will use one Licensed Link before entering the fixed network but a window-ledge device may use one or two licensed and one LE link – irrespective of the Primary User Device – however the use of any intermediate will depend upon the environment)

3.2 LE demand approach and scenarios considered

Due to the small sector area of hotspots which tend to be used in LE spectrum, demand for LE spectrum needs to be considered on a highly localised basis. Requirements for licensed cellular spectrum are also driven by localised peak bottlenecks in demand and capacity and the ITU model accounts for this by estimating demand in different service environments and assessing the supply of network capacity in these specific service environments when determining spectrum requirements. However, we felt that today the range of devices, services and applications varies even more so by service environment for LE spectrum than for licensed spectrum and so have constructed licence exempt demand estimates around specific usage scenarios that we believe will drive requirements for LE spectrum. The usage scenarios considered and how these impact our demand estimates for LE spectrum are discussed in this section.

3.2.1 The LE spectrum scenarios considered indicate that home networking is likely to generate the biggest capacity bottlenecks for hotspots

We have examined four localised usage scenarios in which LE spectrum may be used with especially high density of demand as follows and as illustrated in Figure 13:

- Home: intense media distribution
- Transport hub: high offload density
- Sports venue: intense media consumption and creation
- Office: all-wireless networking

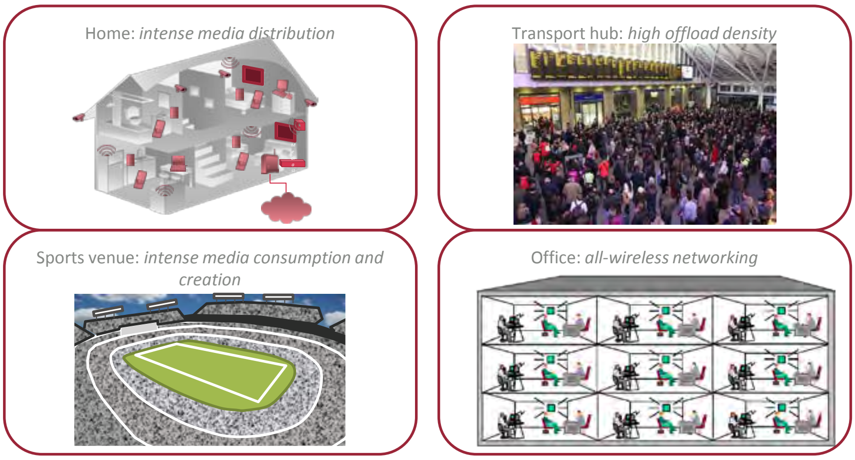


Figure 13: Scenarios for intensive LE spectrum usage

Home: intense media distribution
It is widely acknowledged that more than 80% of wireless data traffic takes place in the indoors with almost 60% in the home by 2013 [22]. This traffic is generated by a multitude of wireless capable devices that operate in both licensed and licence-exempt spectrum. The use of Wi-Fi in the home has created a variety of new products to stream video/audio traffic between devices either from a server or via the Internet using an online multimedia service such as Netflix or iPlayer.

The intensity of media distribution in the home can consist of several Wi-Fi devices used concurrently with each generating wireless traffic. These devices are not limited to Smart TVs, wireless multimedia devices or tablets and laptops but also include:

- Wireless speakers/stereos
- PC peripherals
- Gaming handsets/consoles
- Wireless printers
- Cameras

The main driver creating this traffic is video streaming as households start to consume what they want when they want it. Consumption of video traffic is acknowledged to be the key driver amongst the global vendors such as Cisco, Ericsson and Nokia Siemens Networks which will continue to grow as network efficiency increases and compression techniques improve.

Transport hub: high offload density
An example of high traffic demand at a transport hub is when hundreds and possibly thousands of users arrive at a large mainline train station or hub airport and log on to the available Wi-Fi networks. This intense scenario applies to the travelling public, both business and leisure, and across a multitude of devices including smartphone, tablets, laptops, gaming devices and children's portable consoles. The types of services that are used in this environment vary depending on the user and what they are doing for instance:

- A business user arriving at a mainline train station may use email, file transfer, or a VoIP/online meeting service for no longer than hour on their laptop/tablet.

- A leisure traveller arriving at an airport (two hours before departure) may use their laptop to watch a film or TV programme for at least an hour.

An additional consideration for this scenario is the number of concurrent users in the vicinity which in some cases such as a hub airport can be quite large. In 2011 there were 190,100 passengers passing (arriving/departing) through Heathrow airport in one day [23]. However, there will be a large variability in what users are doing as there may be a small proportion of users watching videos compared to those on email or simply browsing the Internet.

The transport hub scenario is not considered to be as intense compared to the home network scenario because of the time spent by users at these transport locations. These places are transitory and the main reason for being there is for travelling and therefore, there is a maximum amount of time a user can spend on their device compared to other facilities such as shopping, eating/drinking etc.

Sports venue: intense media consumption and creation
The traffic generated at a sports venue can be highly intensive because of the number of users which can be up to 100,000 (including workers) trying to use their devices in an area the size of Wembley stadium (approx. 79,000m^2). The demand density (kbps/m^2) increases dramatically as more users are packed into a small location. The capacity needs in such an environment also becomes challenging and therefore requires both sufficient bandwidth and technology capability to support events.

The type of usage that occurs at events in sports venues includes, social networking, video/image uploads and audio streaming. The traffic distribution is extremely high during an event which means operators must supply capacity in the most cost efficient way, which can include additional spectrum and the deployment of more sectors, or new technology (if it is available).

The quantity and distribution of traffic is considered to be an extended peak and sustained for a relatively short duration compared to the intense home scenario. In addition operators plan and are prepared for this intense usage and deploy the appropriate resources accordingly whereas this type of control is not available within a home environment. Users can add access points at home but in general this will create interference and reduce the quality of the overall experience.

Office: all-wireless networking
A wireless office is the closest environment to the home scenario due to:

- The mix of devices that are used
- The potential extended session duration
- Likelihood of intense video and audio streaming
- Potential for large quantities of data transfer

The traffic generated in a wireless office will be from devices such as smartphones, laptops, tablets and possibly Smart TVs. However, the overall consumption of traffic will depend on the quantity of data transferred in each case.

For example, using a medium size enterprise office building in a suburban environment which accommodates 200-300 people not all of them will be using wireless devices but a significant proportion (>50%) might be. The quantity of traffic over the network infrastructure in a single day could potentially be up to 1 TB (based on our own estimations) and possibly 50% of this is transmitted over the wireless network. In this scenario similar to all non-home scenarios the network is designed to support the traffic in the most efficient way so as not to impact performance for end users. This means there could be a professionally designed and installed Wi-Fi network whose spectrum requirements are sufficiently met using the currently available amount of spectrum.

Bottleneck use cases for LE spectrum

The graph in Figure 14 shows the average traffic per device for a smart TV, a M2M networking device and a tablet. This illustrates how the volume of traffic from devices used in a home environment is likely to be much more than a large density of tablets being used in a busy transport hub (i.e. same traffic from one Smart TV as approx. 44 tablets in 2015). When the lower session times of users in a transport hub due to them being in transit are also taken into account we conclude that the home networking scenario is likely to provide the most challenging LE spectrum requirements. Therefore we have concentrated on dimensioning hotspot spectrum on the home networking scenario.

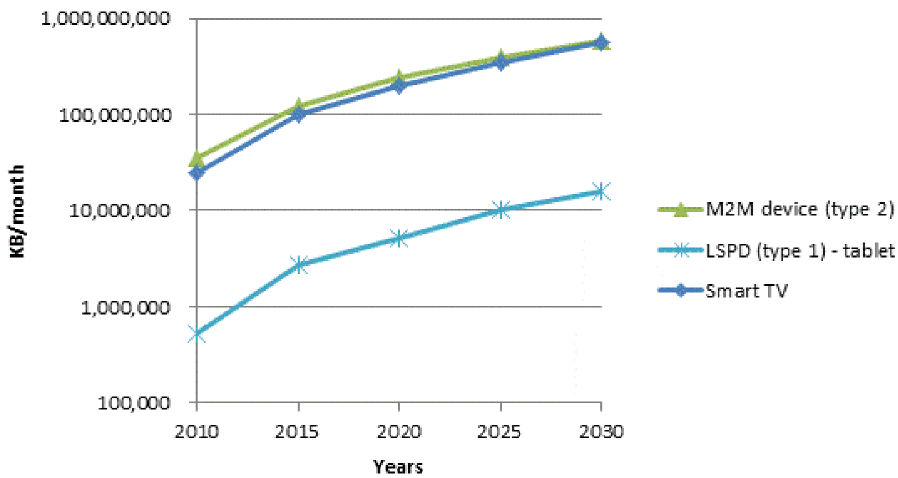


Figure 14: Comparison of traffic volume per device type for Smart TV, M2M type 2 and tablet devices

We also note that the outdoor use of LE picocells is a challenging scenario since it requires a higher coverage per access point than indoor LE usage and is not well supported by existing LE spectrum and its associated technical conditions (interface requirements). Therefore additional LE spectrum with different interface requirements might need to be identified for wider range LE picocells. To address this we also consider the spectrum requirements for LE picocells when being used to serve the outdoor users availing of mobile broadband services via LE networks on their portable devices such as smartphones, laptops and tablets. In estimating the demand density that these outdoor picocells might need to serve we assume that this demand will be concentrated along roads, paths and railways and dimension spectrum to meet these peaks in demand density for picocells.

Practical limitations on LE spectrum usage

Additional to considering the spectrum requirements that the demand density in a given area could generate, however, it is also necessary to consider the requirements on LE spectrum which may be imposed by the details of the technology used. In particular the spectrum may need to support efficient frequency reuse arrangements which implies multiple channels of the greatest bandwidth will be needed for concurrent use in a location. For example, if multiple access points are deployed in a block of flats then those in adjacent flats will select different channels to operate on to maximise performance.

In the case of spectrum requirements for LE hotspots we have estimated the spectrum requirement to support such channel reuse needs as are appropriate to Wi-Fi. We have also considered the fixed bandwidths supported by today's Wi-Fi access points and their future evolutions. This means that the LE spectrum requirements that we produce from the ITU model based on demand density are further interpreted to allow for the following assumptions:

- A minimum of three concurrent 20MHz channels per available LE frequency band is required in any given area to avoid interference and service degradation. We also examine the case for very dense deployments where up to six concurrent channels may be needed for frequency reuse.
- The following channel bandwidths must be observed per technology in keeping with our assumptions of Wi-Fi capability in any given year as shown on Table 16:
  - 802.11g 20MHz channels
  - 802.11n 20MHz or 40MHz channels
  - 802.11ac 40MHz or 80MHz
- LE spectrum requirements output by the ITU model are distributed across LE air interfaces in the same proportion as the split of access point capability over time shown in Table 16.

Year	802.11g in 20MHz / % APs	802.11 n in 20MHz / % APs	802.11 n in 40MHz / % APs	802.11ac in 20MHz / %APs	802.11ac in 40MHz / % APs	802.11ac in 80MHz / % APs
2010	0.6	0.35	0.05			
2015	0.25	0.25	0.25		0.25	
2020	0.03		0.2		0.385	0.385
2025	0.005		0.02		0.4875	0.4875
2030	0.005		0.02		0.4875	0.4875

Table 16: Assumptions on proportion of LE devices in a given band at each year (see section 5.5 for full details and assumptions behind these)

We present a worst case and best case view of LE spectrum once these practicalities of LE deployments are taken into account. In the best case shared view we assume that channels are shared across multiple Wi-Fi air interfaces. For example in this case the spectrum requirements of 802.11g and 802.11n devices at 2.4GHz are assumed to be time interleaved on the same channel rather than separate channels being required for each of these. In the worst case dedicated view of LE spectrum requirements we calculate the number of channels required per Wi-Fi air interface separately and then sum across these on the assumption that devices running different Wi-Fi air interfaces require different channels. In addition in the dedicated case if multiple air interfaces are being widely used in the same band we assume that a minimum of 3 channels per air interface are needed to minimise interference between access points as discussed earlier.

3.2.2 Our LE demand is a "bottom up" analysis considering both traffic offloaded from cellular networks and traffic native to LE networks

In this section we describe what traffic specifically we consider to be included as offloaded to licence exempt spectrum and also what traffic is native to licence exempt networks, i.e. traffic that is never carried across a public licensed wireless network or public fixed network.

We define the traffic carried by licence exempt spectrum for this study in the following way:

- "In the home" - LE specific demand from Smart TV and M2M home networking devices such as Apple TV or other wireless multimedia devices
- "Other LE traffic" - Traffic that could have been carried on licensed spectrum by our primary mobile devices but is offloaded to Wi-Fi through our set of intermediary devices.

We acknowledge that traffic generated by devices in the home is not limited to Smart TVs and wireless multimedia devices but we have assumed that these devices are the key drivers for intense usage of Wi-Fi in the home. In our range of LE demand scenarios, discussed later in more detail in section 3.5.2, we capture the use of Smartphone, tablets and laptops as devices that, if used with a frequent low cost Internet connection via Wi-Fi and concurrently with Smart TVs and wireless multimedia devices, can create significant quantities of spectrum.

Under the "Other LE traffic" category, Wi-Fi offload is the percentage of the total mobile demand that could potentially be carried on licensed spectrum but is actually carried or "offloaded" to Wi-Fi networks. Here the total mobile demand that could potentially be carried on licensed spectrum is the demand generated by mobile or portable devices (such as laptops and smartphones) that have a cellular capability and are availing of a service that could have been carried over licensed spectrum. This excludes traffic from devices with Wi-Fi only capability and applications such as Smart TV that are very unlikely to ever make use of cellular spectrum. We describe the methodology of how we treat the offload of cellular traffic to Wi-Fi in our demand model later in the report in section 3.3.6 when we consider how traffic is routed from end user devices via intermediary devices back into a fixed network for delivery its destination.

As discussed earlier due to the small cell nature of LE networks we felt that it was important to model demand for LE spectrum on as localised a basis as permitted by the ITU-R M.1768-1 model. The means that our LE demand estimate, unlike our licensed spectrum demand estimates, are not just based on demand per teledensity but also split between home, office and public area environments within these. As highlighted earlier we assume that the home environment will dominate hotspot requirements and so in our bottom up analysis of LE demand have focused on devices for a home networking scenario. However, we also consider and model demand in office areas to verify that home environments drive LE hotspot requirements over those of office users.

Also we consider what subset of devices from the home networking scenario might be used in public areas and build up a LE demand estimate for public areas which we assume will drive LE picocell spectrum requirements. For example, we consider the demand per device from laptops, tablet and smartphones but not Smart TV or M2M home networking devices for public area demand estimates. This demand per non-home networking device is then split between environments using the distributions shown in Table 17. These are in turn based on the distribution of mobile traffic between environments reported by sources such as [81], [82] and [83] and weighted by the opportunity to offload to Wi-Fi based on our assumed hotspot coverage levels discussed in appendix E. Finally we assume that this demand is focused on the paths, roads and railways to build up the LE demand density for public areas in each of the teledensities. The demand density in office areas is built up in a similar way by considering the subset of devices from the home networking scenarios that would be relevant to office environments, estimating the proportion of traffic on these based on Table 17 and then assigning this over the land area used for business purposes in each of the teledensities to estimate the LE demand density in office environments.

Dense urban					
	2010	2015	2020	2025	2030
Home	65%	70%	69%	68%	67%
Office	30%	27%	26%	26%	26%
Public areas	6%	4%	5%	6%	8%
Suburban					
	2010	**2015**	**2020**	**2025**	**2030**
Home	76%	82%	80%	78%	75%
Office	20%	16%	17%	18%	20%
Public areas	4%	2%	3%	4%	6%
Rural					
	2010	**2015**	**2020**	**2025**	**2030**
Home	76%	82%	80%	78%	75%
Office	20%	16%	17%	18%	20%
Public areas	4%	2%	3%	4%	6%

Table 17: Assumed split of LE traffic between environments for non-home networking devices based on split of mobile traffic between environments and opportunity to offload to Wi-Fi based on our assumed hotspot coverage levels

3.3 Step by step "bottom up" demand forecast development and sources

The following methodology presents a step by step process of how our mobile traffic demand forecasts have been derived according to the source data reviewed and our assumptions related to demand and mobile devices.

The methodology used was a bottom-up approach using the required set of distributions to calculate the average demand generated by devices according to the level of penetration of each device within the UK population. The process set out in the next sub section below illustrates the logical sequence of calculations undertaken to derive the average demand in Megabits per second (Mbps) per km^2 for the demand density across teledensities in the case of licensed demand and service environments in the case of LE demand in the model.

3.3.1 Process for deriving demand per study area

We adopted the following process to determine the average demand per demand type:

1. Evaluate penetration of each device type (devices per population) from 2010-2030 made up of an independent number for SE1 – 5 and SE6 (i.e. two numbers to produce per device)
2. Determine the population percentage across each service environment to calculate the population in each SE
3. Calculate the number of each device type in the service environment = penetration (step 1) x population in the Service Environment 1-6
4. Evaluate average demand (Bytes/month) per device type from 2010-2030
5. Split the distribution of traffic across intermediate devices to identify traffic carried across licensed or licence exempt spectrum and across service environments
6. Calculate total traffic (TBytes/month) in Service Environment 1-6 by device type = number of devices of each type (step 3) x traffic per device (step 4)
   a. Validate the total traffic in the study area (summed across all device types) against UK wide forecasts (e.g. PA Consulting [24]) scaled to Service environment
   b. Using the area of each teledensity in km^2 calculate the demand density in 2010-2030 in different teledensities in $TB/month/km^2$

In each step we present the data used to derive the growth assumptions and traffic values which, in some cases, used various analyst and vendor forecasts or reports. In other steps, basic calculations were conducted in order to divide or multiply the traffic according to that step in the process.

3.3.2 Step 1 - Evaluate penetration of each device type (devices per population) from 2010-2030

This first step evaluated the penetration of device types within the population. This metric establishes the proportion of devices of each type across each service environment population. The available source data provided a mix of population groups with some of the sources using penetration as a proportion of the country population or a proportion of the mobile user population or the proportion of the mobile broadband population and so on. Table 18 outlines how the different population groups impact the level of penetration per device type.

Device	2010 units UK millions	2010 total UK pop: millions	2015 total units million	Penetration % UK pop (2010)	Penetration % UK pop (2015)
Smartphone	19.4 [25] 12.8 [26]	62.3 [27]	38.5	31%	60%
LSPD - Tablet	1.5	62.3	11.5	3 %	18%
LSPD-Laptop	3.7	62.3	10	6%	16%
LSPD - Hybrid	0	62.3	0	0%	0%

Featurephone/ legacy	61.5 [20]	62.3	38.5	99%	60%
M2M type 1	3 [35]	62.3	12.8	4%	20%
M2M type 2	14.9	62.3	22.4	24%	35%
Smart TV	0.6	62.3	2.5	1%	4%
Portable gaming	0.35	62.3	6.2	0.3%	10%

Table 18: Penetration levels of different population groups by device type

It can be seen from the table that the penetration of devices as a percentage of UK population is generally used across sources. This avoids confusion over the installed base of devices across each device type which can arise due to some devices being mobile/portable and some being fixed in premises such as smart TVs and M2M. In addition this means that consistent penetration levels can be produced from a known set of authoritative statistics for the population growth over time. In addition, taking penetration of devices against the UK population also means that a more robust metric in determining the average quantity of traffic generated per person as individuals can represent individuals having more than one connection or device. In the table below we provide our chosen penetration level for 2010 across the devices for which we have sources.

Device	Penetration %	Supporting sources	Real Wireless Proposal (Penetration of device across the UK population)
Smartphone	50 (2012) 31 (2010)	Ofcom CMR 2012 [35] Mobile squared [25]	**31% in 2010** This value is based on the penetration of smartphones across the population from forecasts of rapid smartphone update in 2010. Ofcom also stated in 2011 that the UK were addicted to Smartphones in its Communication Market Report [28]
Tablet	7.5 (2011) 5 (pop) 2011 18.7 (Europe) 2011	Guardian [29] Mobile marketing[30] Morgan Stanley[31]	**3% in 2010** Sources suggest that tablets were not prevalent within the market out of the total installed global base in 2010. We assume that the penetration of tablets in 2010 was less than the source figures suggest which are given for 2011.
Laptop	2 (laptops) 15 (2009) 9	Disruptive [32] IDC [33] Cisco[19] (derived)	**6% in 2010** We have assumed there were double the number of laptops in 2010 than tablets
Feature phone/legacy	77 (2010) 99 64	Incentivated [34] Mobile squared [25] Analysys Mason [42]	**99% in 2010** This value is based on the number of expected early 3G type feature phones across the population in 2010. Sources suggest there is almost 1 3G phone per pop. These devices are starting to be replaced by more feature rich smartphones as new devices come on to the market

Table 19: Penetration of devices across the across various populations

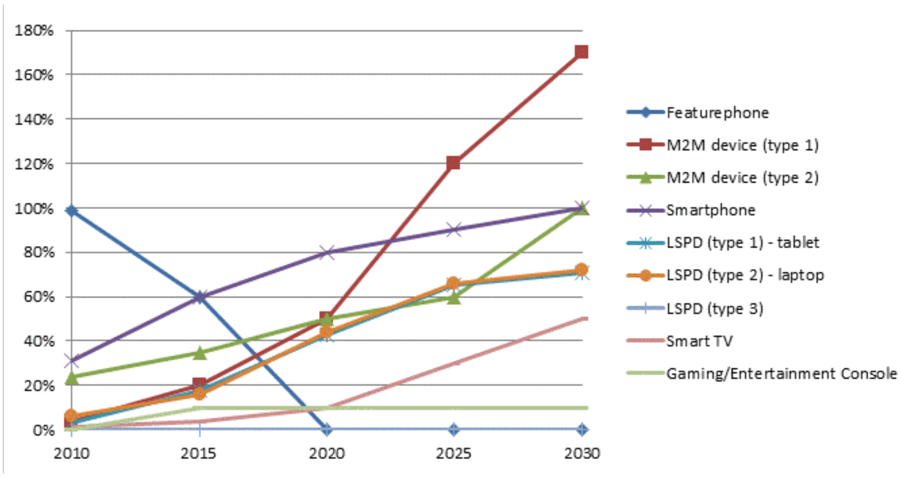


Figure 15: Penetration of primary devices across service environments 1-5

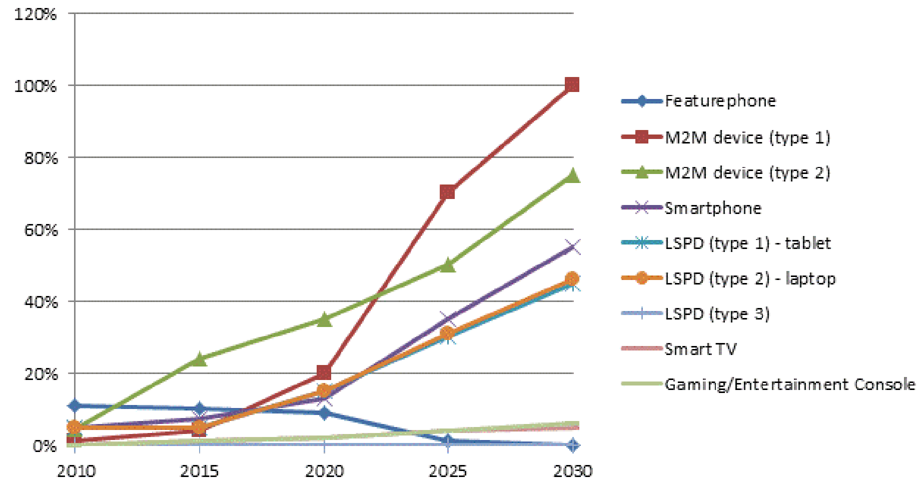


Figure 16: Penetration of primary devices across service environments 6

Figure 15 and Figure 16 present the penetration growth of the primary devices over time according to the sources we have reviewed for years 2010 and 2015 and Real Wireless estimates for the later years. The Real Wireless penetration levels for smartphones in the years 2010 and 2015 have been based on sources including Ofcom's CMR reports for 2010 [26] and 2012 [35] and Mobile Squared report [20]. These reports have been based on the previous year's sales numbers and growth forecasts for smartphones.

The following growth assumptions have been made in our device penetration forecasts:

- Generally our assumptions on the expected growth across device volumes have been based on the sources for each of the device types which closely align with public market data for 2011. These are used as the starting point for 2010 penetration levels and growth rates.
- Our initial growth in device volumes is extended over a longer period by keeping the growth rate for device penetration the same depending on the service environment.
- We assume that feature phone volumes are going to drop as users adopt smartphones and LSPDs.

- We assume that smartphone growth is going to continue up to around 2020 after which growth is going to slow down as the market matures/saturates and 100% device penetration rates are approached.
- For LSPD type 1-3 devices we assume growth in tablets and laptops will continue to 2015 but will then reduce as users adopt type 3 hybrid large screen portable devices which contain the functionality of both tablets and laptops
- We assume that Smart TV from a low base will continue to be taken up by consumers slowly but pick up pace in 2020 and see market saturation by 2030 which is every household (note penetration graphs are per head of population rather than household).
- We assume that gaming has a small user base with limited growth due to the increase in applications on mobile devices such as smartphones and tablets.
- We assume that M2M starts from a low initial deployment level and that its deployment is driven by premises rather than people. Type 1 M2M devices, which are low rate devices, we assume will start to increase in volume as smart meters are rolled out. Type 2 M2M devices, which are home networking and wireless multimedia devices, we assume have a lower initial penetration to type 1 as these are technology driven and initially taken up by early adopters with time needed before they will be rolled out on a mass adoption basis

3.3.3 Step 2- Determine the population percentage across each service environment to calculate the population in each SE

In this step we determine the population percentage across each service environment considered within the ITU-R M.1768-1 model. The population and in particular mobile users move around all the time between the different service environments at different times of the day. For example, in a working week, the working population will move from their homes to offices through public areas across urban, suburban and rural areas. This movement pattern across the day can impact how mobile traffic demand is captured. Below are some examples of how mobile traffic shifts throughout the day. Figure 17 shows the peaks and troughs of the traffic over a 24 hour period. It can be seen that in dense urban (city areas) the traffic has two peaks in the middle of the day. Additionally, the traffic starts to increase steeply from afternoon and peaks in the evening around 10-11pm.

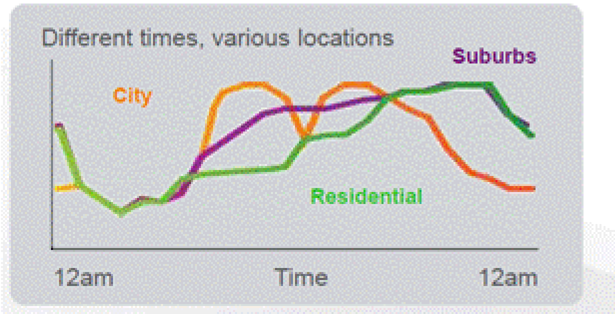


Figure 17: Illustration of how traffic is distributed by location over a whole day

Figure 18 provides a different perspective of traffic but with a similar pattern in terms of when peaks in traffic occur. It can be seen between the afternoon and evening hours the traffic steadily increases until around 11pm when it starts to decrease. Note that in the

ITU-R M.1768-1 model allowances for peak demand levels and network loading are made within the queuing theory block of the model and all demand inputs are expected to be average demand inputs rather than peak levels.

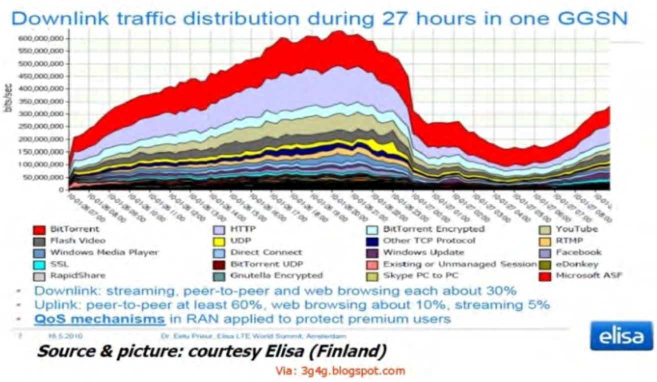


Figure 18: Distribution of traffic over a whole day by application type. Source: Elisa Finland [1]

The population percentage is calculated from the Office of National Statistics (ONS) latest statistics of UK population in 2010 and then divided into to the relevant service environments. However, this reflects the evening time population when census data is collected. The table below presents how we have assumed that the UK population is distributed across service environments during the day and at night. It can be seen that in terms of the location traffic for both day and night will be driven firstly by the suburban teledensity, followed by the dense urban locations in the day time. Traffic in rural locations at night time is expected to increase 5x over day time traffic and drop by more than half in dense urban from day time to night-time.

	SE 1-3	SE 4-5	SE 6
Daytime	35%	60%	5%
Night time	14%	60%	26%

Table 20: Distribution of the UK population during the daytime and night time. Source Greater London Authority [36]

3.3.4 Step 3- Calculate the number of each device type in the service environment = penetration (step 1) x population in the Service Environment (step 2)

In order to determine the total number of devices in each service environment we take the penetration of each device type and multiply this by the population in each Service environment. The resulting population in each service environment is shown in Figure 19.

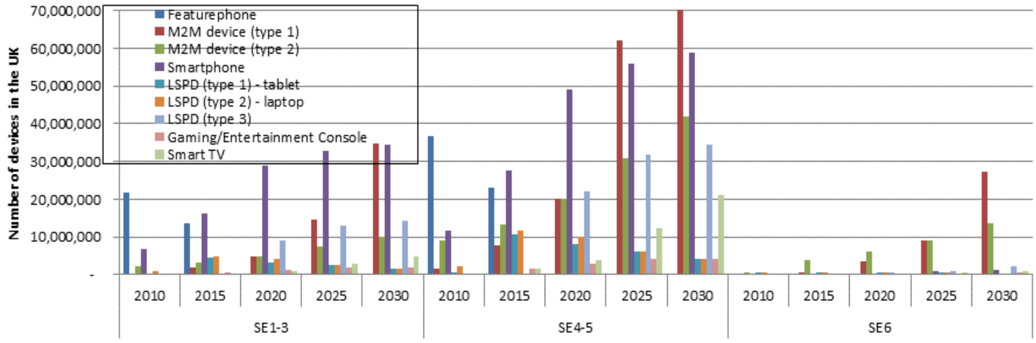


Figure 19: Total number of devices in the UK across service environment

The largest total number of devices is in the suburbs across daytime and night time with the fewest devices in rural areas. However, the largest penetration of devices will be low rate M2M devices such as smart meters, telemetry and other low rate type devices by 2030. This is driven by the rollout of smart meters to all premises in the UK by around 2025 and other domestic appliances becoming part of the wider Internet of Things such as networked fridges, washing machines etc. We assume there will be 3-4 M2M devices per capita in 2030.

We also assume smartphones reach 100% penetration on the basis that in 2013 there is more than 100% penetration in mobile connections in the UK [35]. This does not necessarily mean there are more handsets as a number of these subscribers may have SIM only tariffs implying that not everyone will have a unique handset per connection but could potentially have two SIMs. However, we note that there are a lot of users that carry two handsets nowadays such as business users who would typically have a smartphone for work use and another handset for personal use.

3.3.5 Step 4 - Evaluate average demand (Bytes/month) per device type from 2010-2030

At the beginning of this step we know the estimated total number of devices across each of the service environments as calculated in step 3. In this step we calculate the average volume of traffic generated by each of the primary user devices to give the total demand across each of the service environments and thus the whole of the UK. We have gathered a number of sources for average traffic across smartphones and tablets in a previous study for Ofcom [1]. Shown in Table 21 are the values for the volume of traffic in MB/month from these different sources for smartphone and tablet traffic. Note that smartphones and tablets are the two principal devices that are tracked by analysts for a number of reasons including:

- Being mass market consumer devices with a 18-24 month upgrade and evolution period (high churn)
- Having usage levels influenced by technology developments such as HD screens, larger screens and wireless performance.
- Demonstrating a continuing increase in traffic generation as well as increases in market penetration.

Device	2010 (MB/month)	2015 (MB/month)	2020 MB/month	Source	Date of source	Real Wireless view
Smartphone	85 79 375 500 max 400-500 1000 max 146 600 (max) 300 (2011)	776 1300 1500 N/A N/A 4000 450 N/A 800	N/A N/A 7000 N/A N/A N/A N/A N/A N/A	Informa [37] Cisco VNI 2011[19] IDATE[38] Ericsson[39] Sharma Cons[40] Rysavvy research[41] Analysys Mason[42] Gigaom[43] Ericsson[20]	2011 Feb 2011 May 2011 May 2011 2010 Feb 2010 July 2010 July 2011 Nov 2011	Majority of smartphone traffic is generated by video, browsing and social network media applications. Variations are wide in the data with majority of sources from 2011/2012. IDATE data taken from actual operators experiences. Research has shown industry generally perceives high growth (around 50-80% -YoY) over the period 2011-2014
Tablet	405 1000 800 800	2311 N/A N/A N/A	N/A N/A N/A N/A	Cisco VNI 2011[19] Sharma Cons[40] Gigaom [43] Ericsson[20]	Feb 2011 2010 July 2011 Nov 2011	Trends suggest tablets consume more traffic than smartphones, by four times which is in a range of around 800MB -1GB/. It was deemed reasonable when compared to smartphones as sessions last longer for tablets and more data can be generated due to increased form factor and screen size. Latest Ericsson data shows average tablet traffic at range of 250-800 MB/month, however the 800 value is similar to the other sources

Table 21: Smartphone and tablet volumes of traffic from different sources

We assume the traffic generated by these mobile devices is carried over licensed cellular spectrum but that some can be offloaded to fixed networks. In this study we assume a proportion of traffic from these mobile devices is offloaded from cellular networks to licence exempt Wi-Fi networks. The proportion of traffic offloaded to Wi-Fi is given in section 3.3.6 which discusses how traffic is routed from primary user devices via intermediary devices which may or may not make use of LE spectrum.

The traffic estimates given above for smartphones, tablets etc. are for traffic that would have originally targeted licensed spectrum but is increasingly being offloaded to LE spectrum. There is an argument that traffic from smartphones in Wi-Fi rich locations and traffic from Wi-Fi only tablets and laptops will be much greater than these traffic per device estimates. We explain in our LE very high demand scenario how smartphone traffic can be much higher than the traffic per device estimates above as this scenario takes into account intense Wi-Fi usage at home or in the office (see section 3.5.2).

In this section we propose the values for our mid case traffic scenario from which the very high and low market settings are derived and given in more detail in section 3.5.

Device	Traffic in 2010	Year	CAGR mid - market setting	CAGR high market setting
Smartphone	125 MB/month	2010-2020	59%	72%
		2021-2030	13%	17%
LSPD Type 1 Tablet	525 MB/month	2010-2020	47%	51%
		2021-2030	20%	30%
LSPD Type 2 – Laptop	1950 MB/month	2010-2020	29%	40%
		2021-2030	13%	31%
LSPD Type 3 – Hybrid	N/A	2010-2020	0%	0%
		2021-2030	16%	31%
M2M type 1 (Low rate)	0.1 MB/month	2010-2020	71%	71%
		2021-2030	10%	10%
M2M type 2 (high rate)	35000 MB/month	2010-2020	38%	58%
		2021-2030	16%	20%
Smart TVs	25000 MB/month	2010-2020	41%	51%
		2021-2030	19%	25%
Gaming consoles	310 MB/month	2010-2020	34%	34%
		2021-2030	17%	17%
Featurephone	15 MB/month	2010-2020	12%	12%
		2021-2030	0%	0%

Table 22: Primary user device CAGRs for 2010-2020 and 2021-2030

Table 22 shows the monthly average traffic generated across devices in 2010 as informed by our list of sources. The sources we have used to help define the traffic in the starting year in 2010 and the following year in 2015 are based on the data, where it was available, for previous traffic volumes per device for 2010 and other recent forecasts for traffic volumes per device as shown in Table 21.

As discussed earlier, smartphones and tablets are monitored closely by analysts and forecasters due to their significant mass market penetration and growth potential.

Average smartphone traffic volumes vary between sources ranging from 79 MB/month to 1000 MB/month as shown in Table 21. Traffic for smartphones above 400 MB/month we considered to be high and likely based on peak volumes. The smartphone traffic value used in our demand analysis is based on a slightly increased level from Cisco's global number (79 MB/month) for 2010 due to the penetration [25] of iOS and Android phones in the UK that typically generate more traffic than other smartphone operating systems. For example, Mobile Squared [25] forecast that Android will start to overtake iOS by 2012 thus increasing the average traffic consumed across smartphones. This is because Android phones generate additional traffic on the network when idle such as location based services, email updates, social networking updates etc. This all contributes a proportion of the total traffic generated by smartphones.

The other devices considered, although significant in generating traffic, are not tracked by analysts to the same extent. However, sources as shown in Table 23 do cover laptops, featurephones and gaming consoles. The M2M category has been divided into two categories, a low data rate (<100 kbps) and a high rate (>100 kbps) category which covers a number of different M2M devices including:

M2M type 1 devices:

- Smart meters
- Telemetry
- Location tracking
- Remote monitoring
- CCTV
- Digital signage

M2M type 2 devices:

- Wireless multi media
- Wireless printers
- Smart office peripherals

Table 23 shows the range of different values from the reference sources for laptops, feature phones and gaming consoles. Laptop traffic varied quite widely amongst the sources and we took a conservative view on the traffic volume based on the type of traffic carried on laptops typically which would be driven by video principally and the longer session durations compared to tablets (3-4x tablet traffic). The value we used for gaming consoles was taken from the Cisco source directly as this was the best source available. Analyst/vendor sources do not focus on gaming consoles as they do not create a significant impact on cellular networks. However, gaming blog sites [44] and forums in 2012 indicate that the value estimated by Cisco is within the range of real usage for 2010.

Device	2010 (MB/month)	2015 (MB/month)	2020 MB/month	Source	Date of source	Real Wireless view
Laptop	2500 5000 max 3500 1900	6522 N/A 11200 6500	N/A N/A N/A N/A	Cisco VNI 2011[19] Ericsson[20] Rysavy[41]	Feb 2011 May 2011 Feb 2010 Nov 2011	Laptops consume the largest volume of traffic out of all devices - this is due to longer sessions, larger and more advanced screens compared to smartphones and tablets. Reasonable traffic consumption between 2500 – 3000 MB/month for 2012. Expected to be at least double the traffic of tablets based on above rationale and sources such as Cisco suggesting laptop traffic is more than three times that of tablets.
Feature phone	3.3 50 (2012) 50 (2012)	54 N/A 500	N/A N/A 800	Cisco VNI 2011[19] Ericsson[20] IDATE[38]	Feb 2011 May 2011 May 2011	These devices are unlikely to consume large quantities of data more than 50MB/month. This is due to the small screen size, and amount of useful applications that can be used on these handsets. Traffic growth not likely to ever exceed 100 MB/month by which time most of these devices will have been replaced by smartphones
Gaming consoles	250	879	N/A	Cisco VNI 2011 [19]	Feb 2011	Gaming consoles generate similar quantities of traffic to smartphones based on interactivity with other users and downloading. However, we note that these devices are competing with game applications on smartphones but there is still a core user base of these devices which will grow at a steady rate

Table 23: Traffic volumes MB/month for Laptops, feature phones and gaming consoles against different sources

Increase in traffic capability per device type:

This section discusses the increase in traffic that a device can possibly support over time considering a number of factors, such as battery dependent devices and market saturation assumptions.

Smartphones:

- Smartphones are seen as the key driver for mobile traffic growth. We have assumed a penetration rate that reaches 100% of the population and that the services that are consumed will increase including the quality of those services. Therefore, we assume that traffic generated by smartphones will increase in line with the main sources of traffic growth such as those from Cisco [19], Ericsson

[20], Analysys Mason [42], Informa etc. This is in the order of a 70-80% CAGR over 5 years.

- We assume that this traffic growth rate per smartphone will start to decline as the market reaches saturation and service quality has reached its peak around 2020.

Tablets:

- In a similar way to smartphones, traffic generated by tablets will increase as the quality of services/content increases and general consumption increases. The actual traffic generated by tablets in our demand assessment is around 3-4 x more than smartphones. This aligns closely with Cisco's assertion [19] that tablets generate 2-3x more traffic than smartphones.
- There is still a lot of room for further growth of tablets in the UK in terms of market penetration and also for cellular capability. We assume that with the advent of LTE networks from 2015 onwards more traffic will be carried by cellular networks and that there is an increase in traffic per tablet growth of 51% over ten years from 2010 to 2020.

Laptops:

- The quantity of traffic generated by laptops is even greater than tablets. This is based on the more nomadic use of laptops and session durations typically lasting longer than tablets. In addition mains power provides for longer sessions without the concern of the battery running flat. Therefore, we assume laptops generate around 3-4x more traffic than tablets. This aligns with Cisco's [19] assertion that laptops generate around 3x more traffic than tablets.
- In a similar way to tablets there is still plenty of room for growth of laptops in the UK in terms of market penetration. The growth in traffic per laptop will not increase as much as tablets in the first five years as the traffic per laptop in 2010 is already quite high (1.95 GB/month compared to 0.525 GB/month for tablets). We assume a 40% CAGR over 10 years

Hybrid laptop/tablets:

- We have assumed these devices begin to start generating traffic that can impact cellular networks after 2015. Current generations of this device such as HP Envy x2 support the latest generations of Wi-Fi but do not support cellular connectivity. We would expect that the next generation of these devices will support cellular connectivity and thus move to mass adoption around 2015 and beyond.
- The assumption in the traffic generated by these devices is weighted between the traffic generated by laptops and tablets. We have assumed traffic generated by these hybrid devices is 75% of the sum of traffic from both tablets and laptops. We also reduce the penetration of tablets and laptops accordingly as penetration of the hybrid devices increases.

Gaming consoles:

- These devices are handheld gaming consoles such as the Nintendo 3DS and Wii-U, PSVita and others such as the latest children's tablets which now are Wi-Fi enabled. In Cisco's VNI published in 2010 their estimate of traffic per device for these types of devices was in the region of 259 MB/month. This correlates with posts amongst users on chat forums that have subscribed to their MNO networks to establish a data tariff that is suitable for their needs which is within the 200 – 300 MB/month range.

- The main issue with the future of gaming consoles is the growing trend of mobile applications and in particular games becoming readily available on other mobile devices such as smartphones. This is impacting the progress and growth of portable gaming consoles. However, we assume that traffic on these devices will continue to grow based on the increased quality and availability of new games releases and requirements for enhanced interactivity.

M2M type 1 (low rate):

- Machine to Machine communications is a key growth area of wireless communications. There is a wide variety of devices that are considered M2M and therefore we have categorised these into low rate (<100 kbps) and high rate (>100 kbps). The traffic consumed by low rate devices is considered to be around 0.1-4 MB/month. We assume the traffic capability of these devices will increase as the Internet of Things demands more data and possibly more interaction with these devices as M2M networks become more advanced.
- We assume that the traffic per M2M device grows at a relatively slow rate of a 12% CAGR over ten years. This is based on the needs of M2M traffic keeping pace with a wider technology market (than just communications) and infrastructure system upgrades such as smart meters and connected vending machines.

Smart TVs:

- The growth rate of traffic generated by Smart TVs will be consumer led and not necessarily restricted by technology although technology will enable the use of enhanced quality services such as HD and 3D video. We assume that only one Smart TV is used per household. While it could be argued that more than one Smart TV can be used within the home we consider it unlikely that there will be on average more than one Smart TV in a home.
- The capability and traffic generated by Smart TVs assumes two hours of video type traffic per night at an average of 3.3 GB x 30 days (a month) which equates to 100 GB/month traffic in addition to any wireless multimedia M2M type 2 device traffic potentially required alongside this for distribution. We assume this traffic doubles within five years but drops to a growth rate of 75% over the next five years and then drop further to a 60% growth in last five years of the time frame.

M2M type 2 (high rate):

- Wireless multimedia devices include things like Apple TV, wireless media players etc. These devices stream video and audio content to screens, speakers or adapters in the home so that users can stream cached content from their media servers to their multimedia device that is connected to a normal TV/speaker.
- We have made the following general assumptions in terms of average traffic generated by these devices which operate entirely across Wi-Fi or other LE spectrum and do not access a fixed access connection or the Internet. We assume printing using wireless printers such as 20 x 3MB docs and 20 x 5MB photos per month plus streaming of 1 film per night on average.
- Assuming the 720p video format is required for Smart TV of 720p, that users consume 1 film per night and that 4 GB is the average file streamed gives a traffic level of 120 GB/month (30 days) for today. This is reduced to around 35

GB/month for 2010 taking into account the capability of devices available at the time and that mainly early adopters were using the systems in 2010.

- We assume there is lots of room for growth in this sector as in 2013 consumers are still adopting this type of technology with 96.2% of homes [35] having a digital TV service which amounts to the potential growth in other delivery platforms. Therefore we assume a four-fold increase between 2010 and 2015, a doubling in traffic per device between 2015 and 2020, a 1.6 x increase between 2020 and 2025 and a 1.5x increase between 2025 and 2030.
- As a reference to the quantity of traffic we have used a source [45] which identifies the type of monthly data consumption by Netflix subscribers which was in the range of 200-300 GB/month. It should be noted however that there are instances when users exceed that limit but we assume most users keep within the cap.

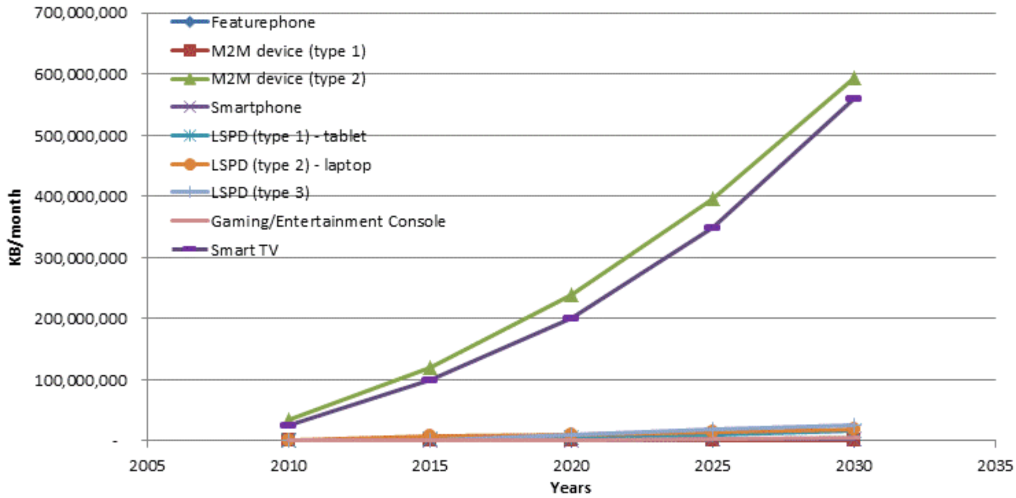


Figure 20: Data traffic per device type over time - All devices

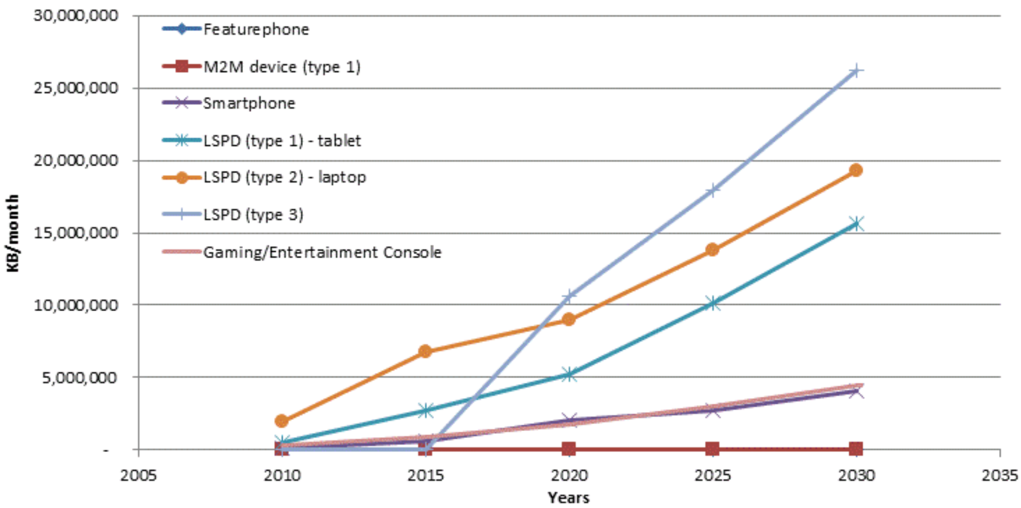


Figure 21: Data traffic per devices over time – Excluding M2M type 2 and Smart TVs

Figure 20 and Figure 21 shows the traffic growth per device assumed for our mid case market setting[2] over time. It shows clearly how licence exempt only devices such as the M2M type 2 and the Smart TV devices' traffic volumes are dominant compared to the other 'mobile/nomadic' devices which generate around 40x less traffic.

Traffic uplink to downlink split

Total traffic generated from devices includes both the uplink and downlink but is not usually explicitly presented in forecasts for traffic growth. However, we have used sources to help derive the traffic split across devices for UL and DL so that we can calculate total uplink and downlink traffic across each device and Service Environment and use this for calibration of user densities within the ITU-R M.1768-1 model.

Device	Downlink%	Uplink %	Rationale
Featurephone	90	10	In data terms traffic is predominantly in the downlink and assumed 90% of total traffic
M2M device type 1	50	50	We have assumed a balanced link based on findings within an AT&T research report [46]
M2M device type 2	95	5	Predominantly video streaming downlink with little uplink required
Smartphone	80	20	Based on broad variety of applications overall traffic is DL dominated [46]
LSPD – tablet	80	20	Similar type of use to a smartphone and therefore overall traffic is DL dominated
LSPD – laptop	70	30	We assume slightly more uplink than downlink due to more capability especially in P2P and file transfer
LSPD – hybrid	70	30	We assume this device is more similar in terms of UL/DL split to a laptop
Smart TV	95	5	We assume this is predominantly video streaming downlink with little uplink required
Gaming device	75	25	We assume more DL than uplink based on game/app downloading rather than interactivity

Table 24: Proportional split of total traffic for UL and DL

In Table 24 we present the proportional split in the UL and DL traffic across each of the devices considered in our demand analysis. We have used sources where available and made assumptions where not based on likely traffic usage in uplink and downlink for the specific devices.

As part of this study we analyse the spectrum demand in both the uplink and downlink which will be dictated by the proportional split given in Table 24.

[2] Note that our medium demand baseline market setting is actually a downward revision of our original bottom up estimates per device based on our findings when our bottom up estimate was compared against UK top down demand forecasts as discussed later in section 3.4.

3.3.6 Step 5 - Split the distribution of traffic across intermediate devices to identify traffic carried across Licensed or Licence exempt spectrum and across service environments

There are many ways primary user devices can get connectivity to the Internet or other IP networks. As illustrated in Figure 12 we have developed a framework which shows how traffic is distributed across licensed and licence exempt intermediate devices including portable and fixed infrastructure such as macro/micro base stations (fixed) and personal hot spots/tethering (portable). Also included in these types of devices are Wi-Fi access points/extenders, femtocells, conventional repeaters, LTE relays and window-ledge CPEs. Some of these devices will have a single link from the primary user device into the backhaul/core network and others might have two links to extend coverage such as repeaters or personal hot spots (or tethering your smartphone to a laptop) which uses both a licensed link and a licence exempt link which creates demand across both spectrum types simultaneously.

In developing the input demand model we made some assumptions about how traffic is distributed across these devices within each of the ITU Service Environments over the 2010 – 2030 timeframe. An extract of the detailed framework model can be seen in Figure 22 which presents our assumptions of the quantity of traffic distributed across devices in Service Environments 1-3 over time. The tables for SEs 4-6 are given in the Appendix F.

We outline the broad assumptions and description of the traffic distribution below from our mid offload case:

- We assume there are 7 intermediary devices that can carry traffic originated from primary user devices.
- In the dense urban SEs we assume limited use of repeaters and relays across all years as these tend to be used to extend coverage. However we do assume a growth in the proportion of Wi-Fi extenders based on increased use of 5GHz. In addition traffic is also distributed across repeaters and relays particularly in rural areas to help extend coverage.
- We assume there is growing use of femtocells over time. However, traffic across these intermediary devices is still a small proportion compared to direct mode via macro/micro sites.
- We assume fixed use of personal hot spots and tethering over time based on a continued limited use into the future across all service environments.
- We assume that the dominating traffic pathways are Wi-Fi access points, femtocells and direct mode in terms of the proportion of traffic carried across intermediate devices.
- The framework is designed to ensure the total traffic carried from primary devices across intermediary devices does not exceed 100%
- The demand model takes into account more than one link which, in the case of personal hot spots, has both a LE and licensed link
- The assumed split of traffic from devices such as smartphones, tablet, laptop and hybrid is based on reference sources for offload to fixed networks either to Wi-Fi (public/private/extenders) or femtocells.

Table 1

2010 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 1) - tablet	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 2) - laptop	0.4	0.1	0	0.01	0	0	0	0	0.49	1
LSPD (type 3)	0.4	0.05	0	0.01	0	0	0	0	0.54	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.4	0	0	0.01	0	0	0	0	0.59	1

Table 2

2015 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.39	0.02	0	0.01	0	0	0	0.01	0.57	1
LSPD (type 1) - tablet	0.49	0.02	0	0.01	0	0	0	0.01	0.47	1
LSPD (type 2) - laptop	0.49	0.1	0	0.01	0	0	0	0.01	0.39	1
LSPD (type 3)	0.49	0.05	0	0.01	0	0	0	0.01	0.44	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.6	0	0	0.01	0	0	0	0	0.39	1

Table 3

2020 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.34	0.02	0	0.1	0	0	0	0.03	0.51	1
LSPD (type 1) - tablet	0.39	0.02	0	0.05	0	0	0	0.03	0.51	1
LSPD (type 2) - laptop	0.36	0.1	0	0.05	0	0	0	0.03	0.46	1
LSPD (type 3)	0.41	0.05	0	0.05	0	0	0	0.03	0.46	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.6	0	0	0.05	0	0	0	0	0.35	1

Table 4

2025 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.34	0.02	0	0.1	0	0	0	0.03	0.51	1
LSPD (type 1) - tablet	0.34	0.02	0	0.1	0	0	0	0.03	0.51	1
LSPD (type 2) - laptop	0.31	0.1	0	0.1	0	0	0	0.03	0.46	1
LSPD (type 3)	0.36	0.05	0	0.1	0	0	0	0.03	0.46	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.6	0	0	0.1	0	0	0	0	0.3	1

Table 5

2030 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.29	0.02	0	0.15	0	0	0	0.03	0.51	1
LSPD (type 1) - tablet	0.29	0.02	0	0.15	0	0	0	0.03	0.51	1
LSPD (type 2) - laptop	0.26	0.1	0	0.15	0	0	0	0.03	0.46	1
LSPD (type 3)	0.31	0.05	0	0.15	0	0	0	0.03	0.46	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.6	0	0	0.01	0	0	0	0	0.39	1

Map environment type to Licensed or LE which assumes intermediary mapping not a function of environment

Table 16

	Public/Private WiFi	Personal HS/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-Fi extender	Direct
Licensed	0	1	1	1	2	2	2	0	1
Licensed Exempt	1	1	1	0	1	0	0	1	0
TOTAL	1	2	2	1	3	2	2	1	1

Figure 22: Traffic distribution across intermediary devices

Traffic offloading from mobile devices

It is important to note that from the list of devices it is the mobile devices which offload traffic from the cellular networks to fixed networks via Wi-Fi. We assumed the devices below can offload traffic when on the move or in nomadic situations such as in the office, restaurants, cafes, shopping centres etc.:

- Smartphones
- Tablets
- Laptops
- Hybrid
- Portable gaming consoles

For example, in the case of a Smartphone we assume the traffic is carried in the following way for dense urban in 2010:

- 57% traffic directly through the cellular network
- 40% [19] traffic 'offloaded' to Public/Private Wi-Fi
- 2% traffic carried over personal hotspot/tethering and
- 1% traffic carried over femtocells

The smartphone example is also used for large screen portable devices and portable gaming consoles. Again here traffic carried over Wi-Fi is considered to be offloaded to fixed networks. In this case the 40% offload level is taken from our UHF strategy study offload levels which in turn has been based on Cisco estimates of offload levels. We note that in the UHF strategy study offload combined small cell (covering enterprise and residential femtocells) and Wi-Fi offload levels whereas in the current study we examine Wi-Fi offload separate to small cell uptake. However, we assume that the offload from enterprise and residential femtocells would still have been at low levels in 2010 due to low deployment levels. Further details of Wi-Fi offload assumptions and how these vary over time are given in section 5.10.

Figure 23 shows the mid case Wi-Fi offload level when the distribution of traffic across intermediary devices for all cellular enabled devices and all environments over the study timeframe are considered. Initially in 2010 this gives a Wi-Fi offload of 43% in 2010 growing to 50% by 2015 but reducing to 33% by 2030.

This largely aligns with the Wi-Fi offload levels that were indicated to be realistic for today's UK cellular networks and in line with anticipated changes out to 2030 by one CFI response. Multiple CFI stakeholders also supported the view that Wi-Fi offload levels will reduce over time due to improved user experience from LTE surpassing user experience on Wi-Fi networks. In section 5.10 the RATG distribution graph for the ITU default values also supports Wi-Fi offload going down over time which supports our assumptions for medium Wi-Fi offload levels.

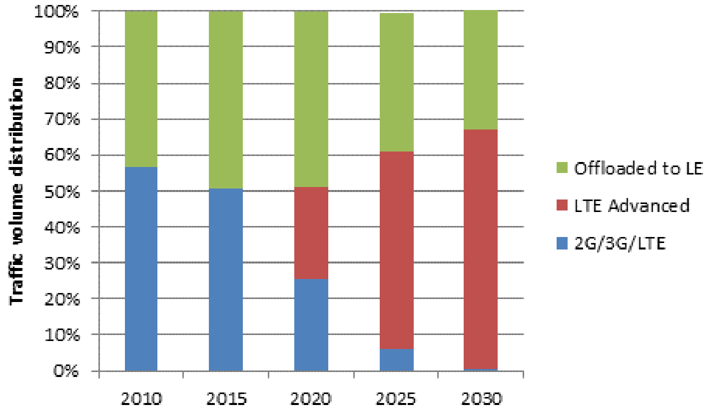


Figure 23: Mid case offload of licensed traffic to LE spectrum

To capture the traffic from other devices that cannot or do not offload or exclusively use LE spectrum we set the proportion of traffic from the primary device across the intermediary device to 1 or 100%. For example, traffic from Smart TVs is carried over licence exempt spectrum which can be via Public/Private Wi-Fi or Wi-Fi extenders. In our mid case we assume Smart TV traffic is carried by Public/Private Wi-Fi devices and not Wi-Fi extenders in the example in Figure 22.

3.3.7 Step 6 - Calculate total traffic (TBytes/month) in Service Environment 1-6 by device type = number of devices of each type (step 2) x traffic (split by licensed and licence exempt) per device

In this step we take the proportional split of traffic from step 5 across both licensed and licence exempt spectrum to calculate the total quantity of traffic from each device and within each service environment. The sum of traffic across devices and service environments provides the total traffic for the UK bottom-up approach.

The following graphs illustrate the total traffic across Service Environments for licensed and licence exempt separately and total traffic across both spectrum types in our mid demand case[3]. It can be seen from Figure 24 that total licensed traffic across SE's ranges within the region of 100,000 TB/month to 850,000 TB/month across SEs in 2030. In total this equates to 1,356 PB/month for all of the UK by 2030 which excludes offloaded traffic. In comparison to one response to Ofcom's call for inputs, this number is well below that of one CFI respondent's predicted traffic level for 2030 against our mid-case. However, another CFI response did align slightly better to ours using our assumed 33% offload in 2030.

In the licence exempt case the traffic across service environments is driven by devices within the home (see step 1 for description) and in the example shown in Figure 26 for the mid-case, the total traffic across all years is more than 40x greater than the licensed traffic by 2030. This correlates with sources [47] and [48] which suggest wireless traffic within the home is predominantly carried over licence exempt spectrum.

[3] Note that our medium demand baseline market setting is actually a downward revision of our original bottom up estimates per device based on our findings when our bottom up estimate was compared against UK top down demand forecasts as discussed later in section 3.4.

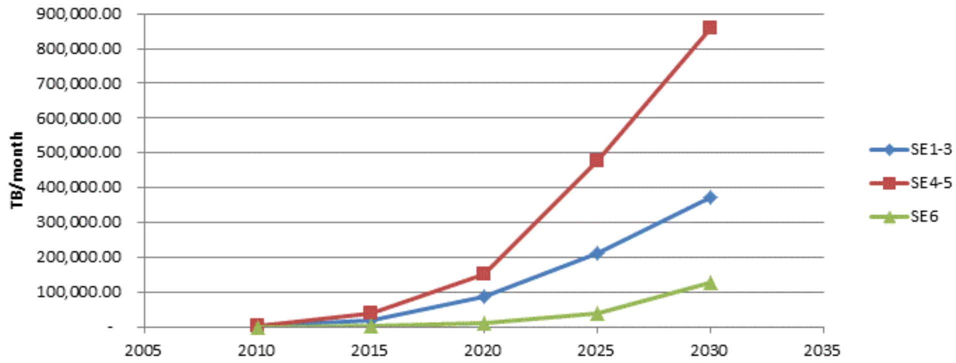


Figure 24: Total licensed traffic across all Service Environments mid case

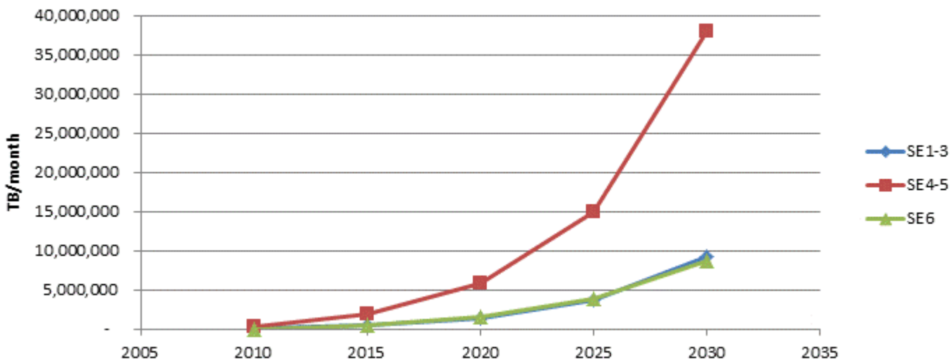


Figure 25: Total licence exempt traffic across all Service Environments mid case

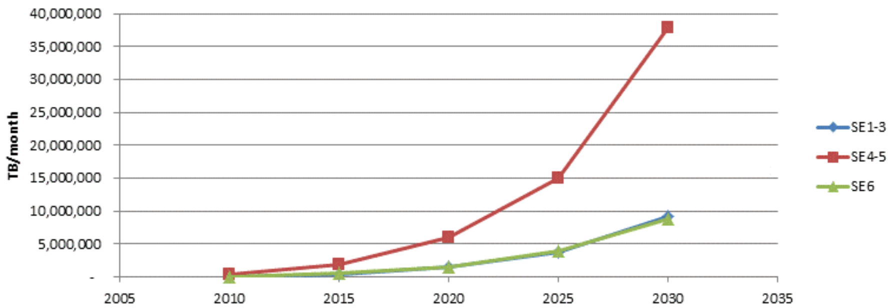


Figure 26: Total licensed and licence exempt traffic across all Service Environments mid case

The final step takes the total traffic for licensed and licence exempt and then divides this across the area that this traffic is distributed over in km2 using the values in Table 25 for each of the teledensities in the case of licensed demand and for each of the corresponding Service Environments in the case of LE demand. We use the uplink and downlink traffic density per teledensity as the input for traffic demand calibration in the licensed run of the ITU-R M.1768-1 model. Traffic density is sub-divided further into home, office and public area categories for our licence exempt run of the model due to the highly localised nature of LE spectrum requirements.

	Dense urban	Suburban	Rural	Water	Total
All environments	2,299	10,454	230,551	296	243,600
Home	565	3133	57218	N/A	N/A
Office	679	1853	37350	N/A	N/A
Public area	1055	5467	135984	N/A	N/A

Table 25: Area of each teledensity in the UK km^2

3.4 We have verified our "bottom up" demand forecasts against top down UK wide demand forecasts

The bottom up demand forecasts required research and analysis of traffic and penetration per device type. The sources for this are wide ranging and not necessarily aligned with what is developing within the UK. For example, traffic per device type from sources such as Ericsson, Cisco and Analysys Mason is normally the average value taken from a global perspective. Traffic generated per device is going to be different in the UK compared to the global average as we have indicated in section 3.3.5. This includes penetration of devices and the quantity of traffic generated per device type since in the UK we are an advanced nation technologically and in particular heavy users of our devices (see Ofcom CMR 2011 [28]).

We have verified our bottom up demand forecasts against top down UK demand forecasts and in some cases extrapolated for the UK forecasts to illustrate that the demand is within a sensible and credible range.

In Figure 27 we have plotted a number of top down mobile traffic growth forecasts including two from Cisco and Ericsson for different years and one from the UMTS forum. All of these forecasts have been down-converted for UK levels. We also include our UHF strategy study mid case scenario [1]. In the top plot it extends for a six year period with four sources forecasting for 2015 ranging from 106 PB/month to 183 PB/month. Ideally the starting point of this graph in 2012 would be based on real traffic levels reported by UK MNOs but we did not have access to this information for this study.

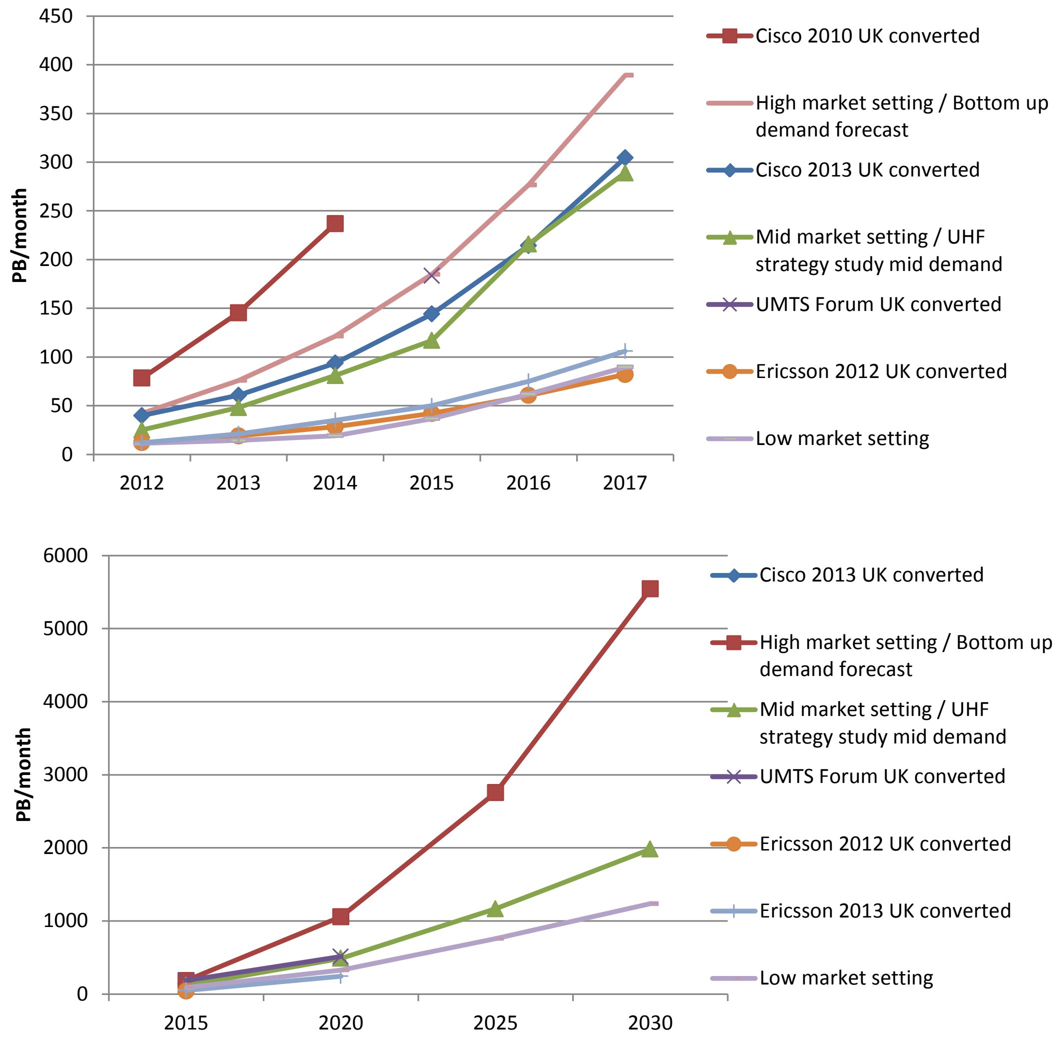


Figure 27: Comparison of top-down forecasts used for bottom-up verification

In the lower plot we compare our bottom-up traffic demand estimates using current assumptions and latest sources against top-down forecasts whose numbers have been plotted over some or all of the study time frame at five year intervals. It shows how the original bottom-up estimates are higher than the current top-down forecasts. This comparison against top-down forecasts suggested we should revert to the UHF strategy study mid case which shows good correlation with the UMTS Forum and Cisco 2013.

3.5 We have produced high, medium and low forecasts of our UK specific demand estimates to assess sensitivity of spectrum requirements to market conditions

To assess the sensitivity of spectrum estimates to varying market conditions and to meet the JTG 4567 requirement of assessing spectrum requirements in low and high market conditions we have used the results from our “bottom up” analysis of UK demand for mobile broadband services to produce high, medium and low demand forecasts for both licensed and licence exempt spectrum. A description of what these high, medium and low demand cases represent in both the licensed and licence exempt cases and the rationale behind the forecasts used for each of these is presented in this section.

3.5.1 High, medium and low market forecasts for licensed spectrum

The ITU-R model derives the higher and lower market setting based on different economies reaching a level of market development at different rates over time. For example, in developed parts of the world the market may become (technologically) advanced faster than some less developed markets due to comprehensive infrastructure deployments, adoption of leading edge technology and availability of technology neutral and globally harmonised spectrum.

This time shift approach is used in the ITU model to derive the lower and higher market settings for spectrum demand to provide two distinct cases for comparison so that a distinction between the different market assumptions can be made.

In this study we make some assumptions in a similar way which matches this concept but for the UK internal market i.e. a fast and slow internal market development. Figure 28 provides a conceptual view of lower and higher market setting increasing over time as presented by the WINNER study.

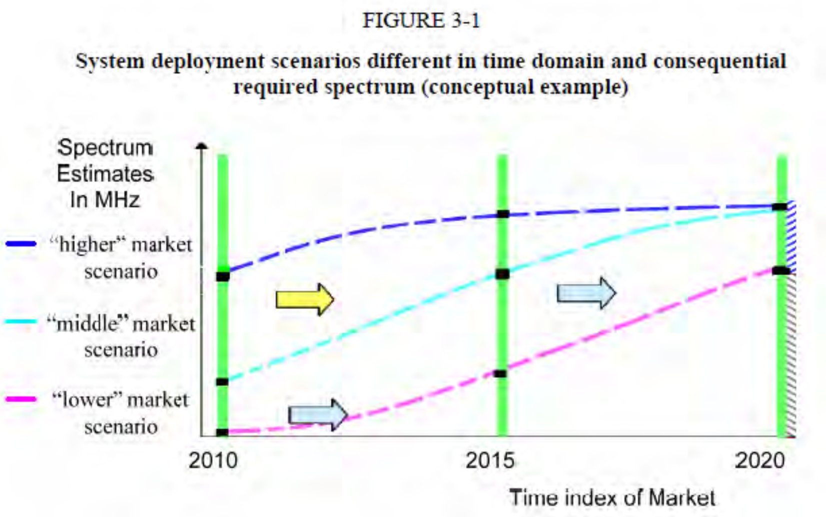


Figure 28: ITU interpretation of high, mid, low market settings increasing over time. Source (Winner [49])

In the UK we can refer to our sources used for forecasting traffic growth over time for low and high market settings. In particular in [1] we produced assumptions relating to the low, mid and high market growth scenarios which we have drawn upon to inform this study. Figure 29 shows the low, mid and high growth rates over time for UK traffic for devices whose traffic originated on licensed spectrum from that study.

In this study we model total UK traffic across devices that use licensed and licence exempt spectrum as shown in Figure 30. However, as can be seen this is totally dominated by home networking devices such as Smart TVs and wireless multimedia devices (high rate M2M type 2). In order to present a high and low market setting for total traffic in licensed and offloaded to LE spectrum we remove the home networking devices to reveal the traffic on licensed spectrum and that offloaded to LE spectrum which is shown in Figure 31.

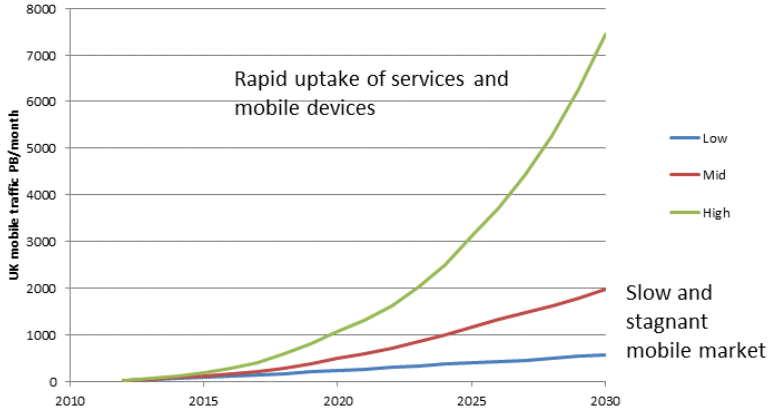


Figure 29: UK market setting assumptions used in [1]

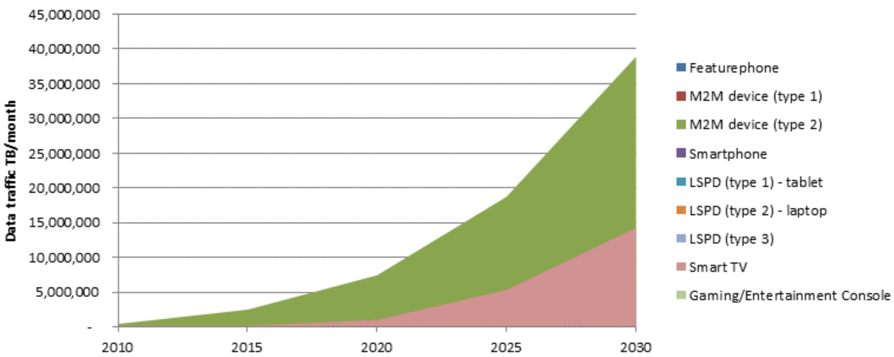


Figure 30: Total UK traffic across devices dominated by traffic over LE spectrum

In building our bottom-up approach of traffic demand forecasts we have used our previous study [1] as a benchmark and updated the numbers to reflect more recent global trends together with historic growth trends of mobile broadband uptake and some additional devices such as our hybrid laptop/tablet and gaming consoles.

Figure 31 shows a mix of traffic growth curves over the timeframe that cover a boundary range of high and low market settings. The traffic growth expressed in our bottom-up approach (green line) is based on fresh assumptions of device types and quantity of traffic modified from the numbers from [1] which now closely follows the high growth scenario from the same study. This is because we have considered more primary devices in this study compared to [1] and found from the latest sources that traffic generated by device type has increased since the previous study.

In the UHF strategy study it was found that the high demand level in later years was not economical for UK cellular network operators to serve and so we have recommended a reduction from the previous study high scenario for the current study. The bottom up demand analysis from the current study aligns well with this requirement and hence we use it as our high market setting.

However, our well verified traffic growth numbers are captured in the mid scenario of the UHF strategy study which we know are based on credible sources and a mix of device types. This also aligned better with UK top down forecasts of mobile demand as discussed in section 3.4. Therefore, we use the UHF strategy study mid case as a baseline demand scenario to determine our high and low market settings for this study.

In the UHF strategy study the low scenario was found not to be challenging enough for UK cellular networks and unlikely to occur in practice and so we suggest that the low demand scenario in the current study should be slightly higher than the previous low scenario. Therefore we have adjusted our mid-case scenario down to a level considered to be still a realistic case for traffic demand.

The three scenarios proposed are based on particular drivers and assumptions which we have drawn on from our previous UHF strategy study but refreshed and updated for this study with the demand forecasts against each of these scenarios shown in Figure 31**.** The plot also shows the relative increase in traffic from 2010 (e.g. 8x 2010 traffic in 2015 for the low market setting) across the low, mid and high market settings. This allows for comparison with the growth in traffic relative to 2010 against the ITU low and high market settings as shown in Figure 32.

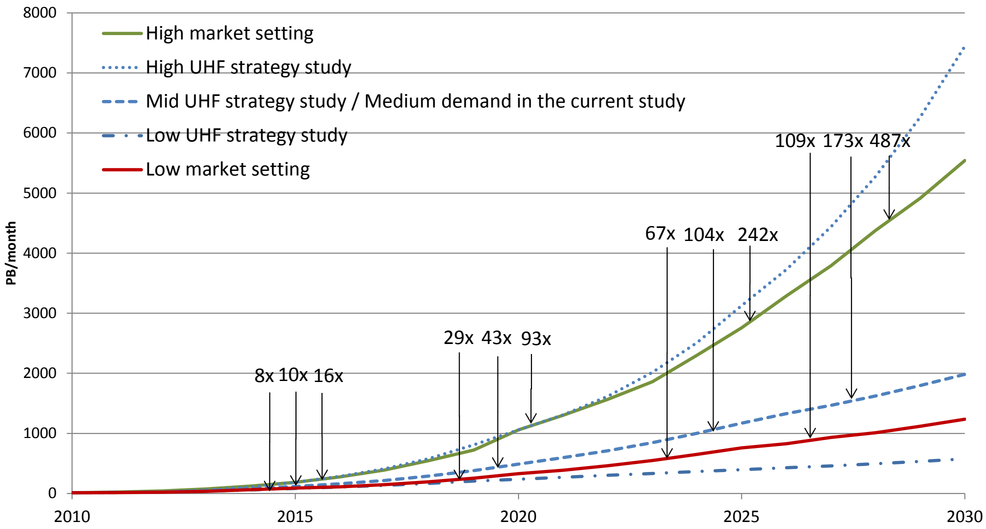


Figure 31: Higher and lower market settings of UK traffic over time used in this study and our previous UHF strategy study

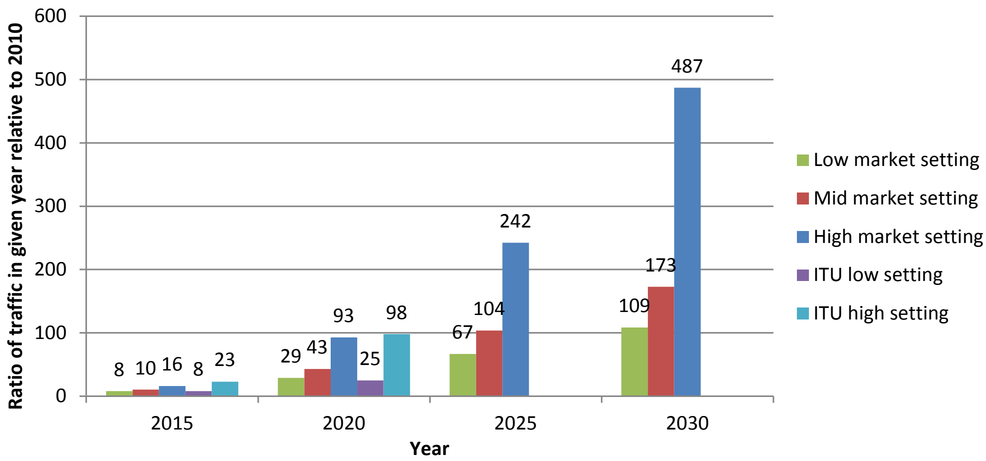


Figure 32: Comparison between Real Wireless and ITU low and high market settings value relative to 2010

We derived our market settings based on the following assumptions:

1. **High -** The higher market setting (green line) on the plot has used a bottom-up approach from traffic per device type and penetration of devices. The green line shows a 93x increase in traffic around 2020 for the high market setting. This aligns well with the ITU's [50] growth at 2020 relative to 2010 of around a 100x increase. This growth rate is based on assumptions of rapid uptake of services and technology by consumers and includes a market that has high end devices such as HD-smartphones (Samsung Galaxy S4) and LSPDs (HP Envy x2) and high performance networks that support very high multimedia services such as high definition video streaming, collaborative working and file transfer etc. The growth rate itself assumes that the higher market setting traffic is more than double the lower market setting traffic across all years in the timeframe. Much of this traffic will come from the introduction of LTE and LTE-A the established ecosystem of LTE enabled smartphones and other wireless devices
2. **Mid** – The mid case setting is the same as the mid case scenario from the UHF strategy study. This was based on traffic growth which tracks current trends and forecasts, as summarised from the UK top down demand sources for the next 5 years. This is based on continued growth in smartphones and tablets dominating the market and new media rich services emerging such as HD video gaming and other HD video applications"
3. **Low -** On the lower market setting (red solid line) this is effectively a time lagged version of the UHF strategy study mid scenario with reduced capability of devices over the years showing a steady and slower uptake in devices and usage of devices. The 29x increase in traffic compared with 2010 for the low market setting aligns well with the ITU 25x increase at 2020. The principal devices driving growth in traffic are smartphones, laptops and tablets and so in the low scenario we have lowered the capability of these in terms of quantity of traffic per device with respect to the UHF strategy study mid scenario. This is based on an assumed reduction in QoS to devices and operators delaying a roll out of improved services and thus users consuming less than they would if a higher QoS was available. Additionally, in the low scenario we suggest that the penetration of devices lags behind the UHF strategy study mid scenario in the low market setting and varies across devices with tablets and laptops being slower to penetrate compared to smartphones. This is caused by a slower than expected roll out of LTE and LTE-A networks, a lower variety of high quality handsets and a delay in release of high quality LSPDs and high end smartphones. Another assumption in the lower market setting is high tariff pricing of networks which do not perform much better than incumbent 3G technologies today.

3.5.2 Low, medium and very high LE demand scenarios

We have developed a set of low, medium and very high licence exempt demand scenarios in order to assess the range of demand in traffic across licence exempt spectrum. We define the traffic across licence exempt spectrum for this study as devices used within the home, office or public areas where there is the possibility of intensive LE spectrum usage.

Note that to distinguish from the high demand case developed for the demand for licensed spectrum, we class our LE higher demand scenario as a "very high" demand scenario. This very high LE demand scenario considers estimates of traffic per mobile device, such as laptops, which are far greater than those considered under our demand for licensed spectrum. These higher traffic estimates per device represent traffic from Wi-Fi only portable devices as well as those with cellular support and are representative of users with a frequent, free connection to Wi-Fi who are not limited in their data consumption. Therefore, the size of the demand is very high and predominantly driven by video streaming services which can consume tens of GB per day across multiple devices.

The table below illustrates the assumed traffic per device with a focus on the mobile/portable devices which when using 'Wi-Fi only' generate significantly more traffic than the same devices when using licensed spectrum. We assume these devices are located indoors at home or in offices connected to a reliable Wi-Fi connection with extended session durations (up to 1 hour per session) compared to that of cellular data traffic.

Device	2010 GB/month	2015 GB/month	2020 GB/month
Smartphone	1.2	4.8	16.8
LSPD 1 (Tablet)	2.4	12.3	23.7
LSPD 2 (Laptop)	8.9	31.1	41.2
LSPD 3 (Hybrid)			48.7
Gaming	0.9	1.8	3.1

Table 26: Licence exempt traffic per mobile device for LE demand estimates

The values in Table 26 at 2010 were drawn from a report by Informa Telecoms and Media and Mobidia [47] which examined the data usage trends on cellular and Wi-Fi networks. In particular, there is an extract re-presented in Figure 33 which shows a snapshot of Smartphone traffic between iOS and Android platforms for the UK. We took the average of the Wi-Fi traffic across both platforms and halved it to inform our 2010 starting point.

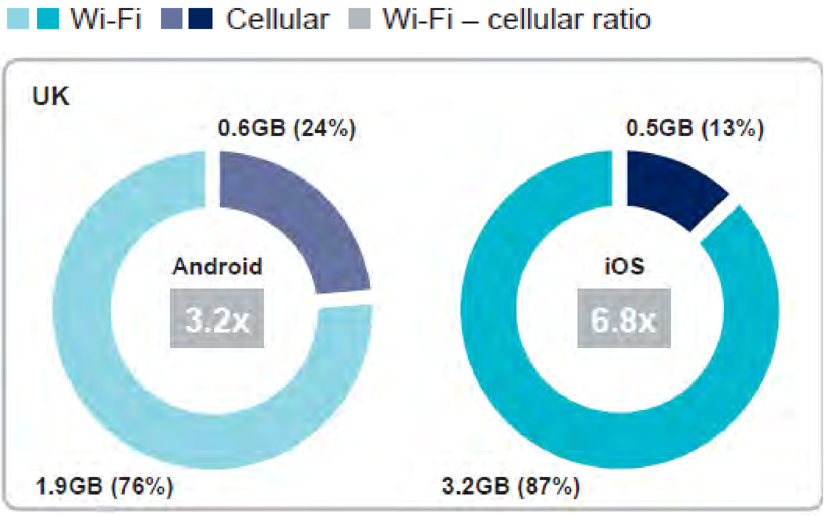


Figure 33: Comparison of Wi-Fi/cellular monthly traffic between Android and iOS platforms

We have also assumed a much higher penetration rate for Wi-Fi only devices such as laptops and tablets in particular for the very high LE demand scenario. In 2010 we assumed the following population penetration of Wi-Fi only laptops and tablets:

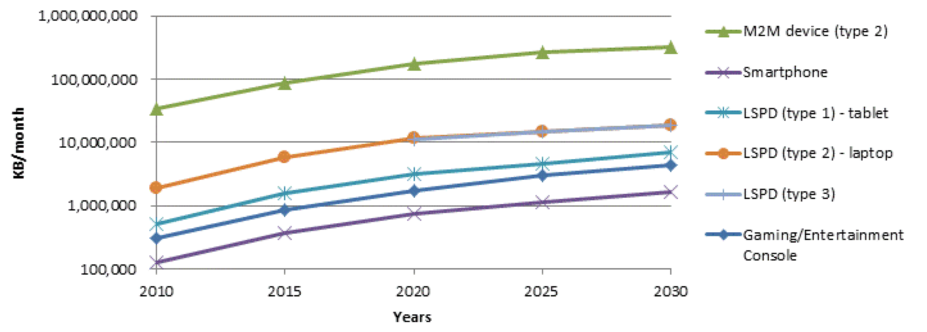
- 76% laptops
- 10% tablets

This was based on Ofcom CMR estimates [35] for households (61%) with laptops and (11%) tablets in 2012. We assumed businesses will increase the total population penetration further for laptops and for tablets.

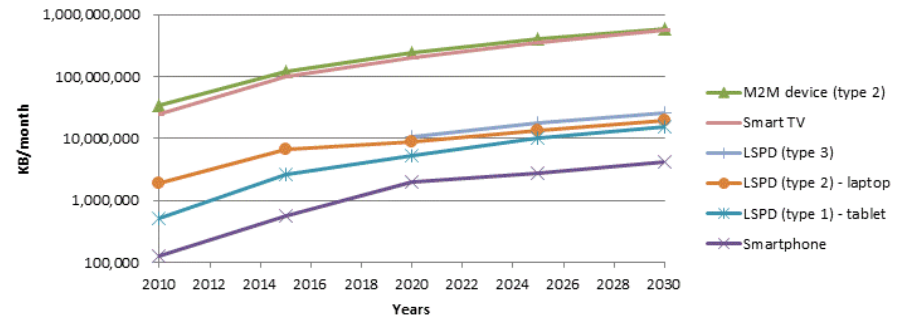
In our low, mid and very high LE demand cases we have developed the following scenarios:

1. **Very high-** An intensive home networking scenario with a family of users on different devices at once. This includes the smart TV and M2M home networking traffic per device estimates that were developed in 3.3 plus a laptop/tablet and smartphone all using the home access point concurrently.
2. **Mid** - A challenging but realistic peak demand on home Wi-Fi access points made up of smart TV and M2M home networking wireless device usage as per our current baseline LE estimates.
3. **Low** - A scenario where smart TV is not used in the average household but home networking M2M devices are still used along with a laptop/tablet i.e. Wi-Fi is used more for home IT than for home entertainment

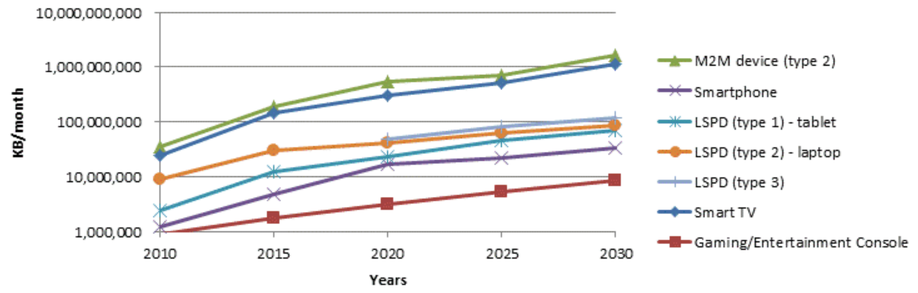
As discussed in section 3.2.2 we develop demand estimates under each of these scenarios specific to home, office and public area environments under each teledensity. We then use home and office spectrum requirements to estimate LE hotspot spectrum requirements and the spectrum requirements for public areas to estimate LE picocells requirements.



Low traffic growth

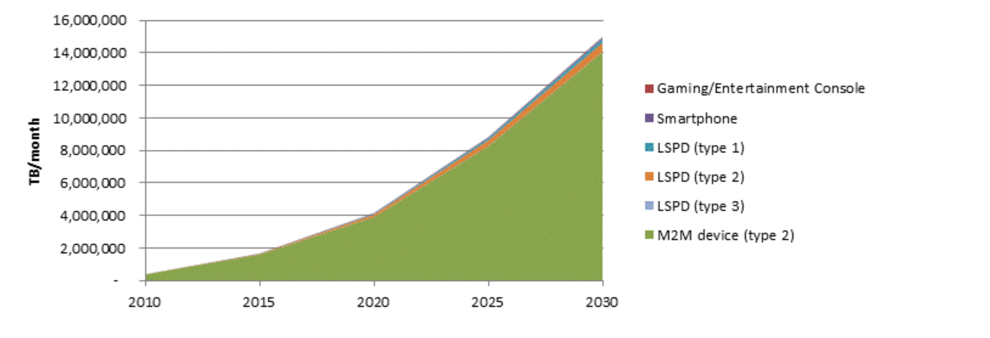


Mid traffic growth

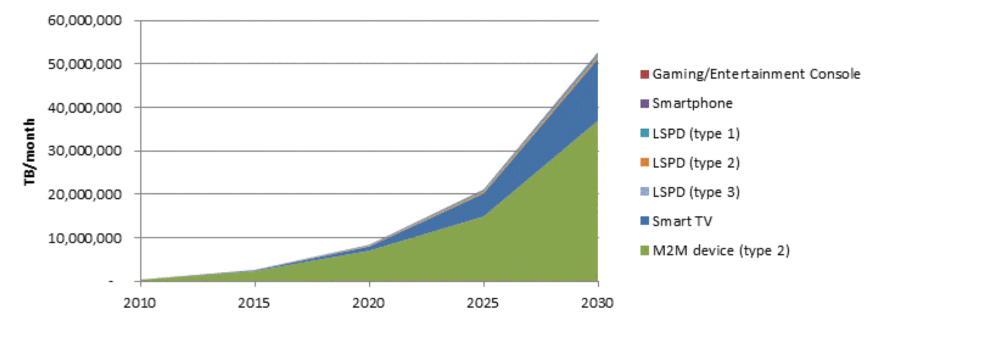


Very high traffic growth

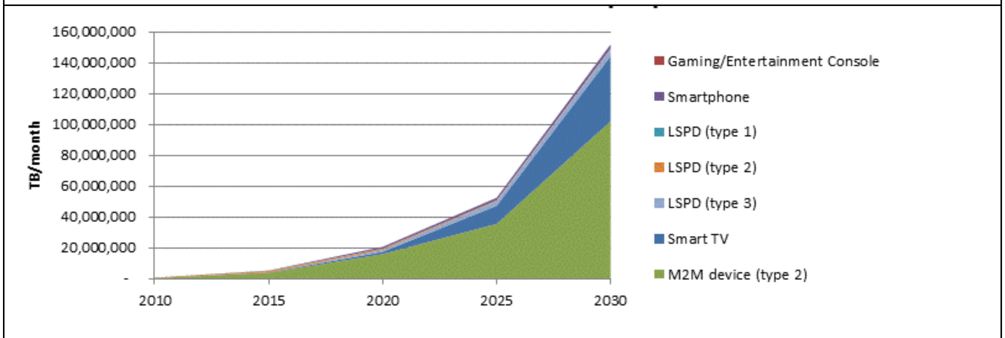
Figure 34: Low/Mid/Very High LE traffic growth across devices



Low traffic growth



Mid traffic growth



High traffic growth

Figure 35: Total Low/Mid/ Very High traffic growth across devices for LE spectrum

4. Appendix D - Critique of ITU default market and service related parameters

This appendix reviews the market and service related parameters for each of the service categories used by the ITU-R M.1768-1 spectrum demand model. We first identify service categories that are particularly demanding on spectrum and very much dominate the spectrum estimate if the recommended ITU values for service and market related parameters within the model are used. For key service categories we then review the recommended ITU values for market and service related parameters (see Figure 36 below) and suggest how these might be updated based on real services that have emerged since the original ITU-R market studies behind these recommended values were conducted in 2006.

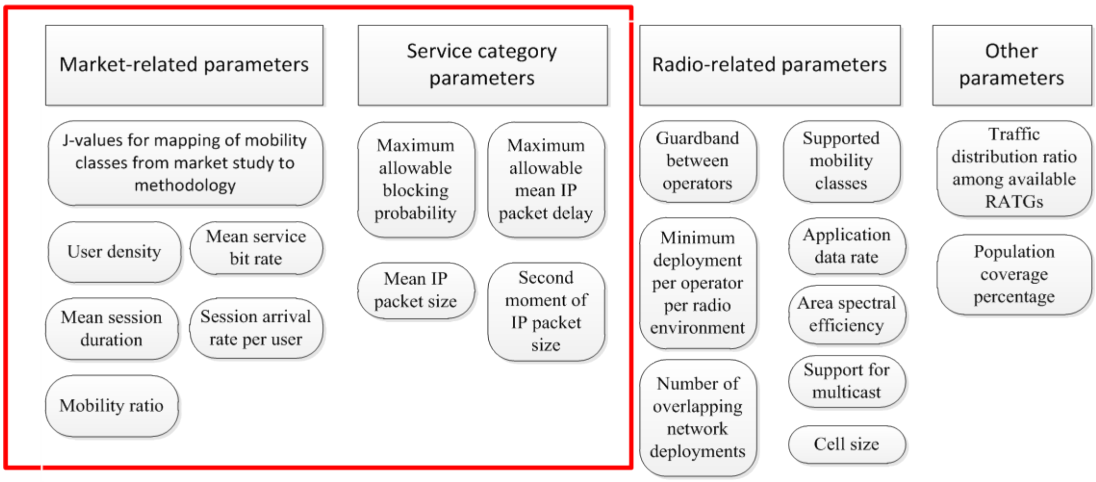


Figure 36: Input parameters required by the ITU-R M.1768-1 model with service and market related parameters as reviewed in this appendix highlighted

4.1 Recommended ITU market and service parameter settings produce “bottleneck” SCs with high spectrum requirements which make the ITU-R M.1768-1 model insensitive to demand

As discussed in section 3.2 of the main body of the final report for this study, we initially ran the ITU-R M.1768-1 model as per the ITU recommended model configuration and low demand levels outlined by working party 5D in their draft response to JTG 4-5-6-7 regarding agenda item 1.1 for WRC 2015 [50]. In this configuration the spectrum requirements produced:

- Matched those reported by working party 5D verifying the correct model set up and operation.
- Did not align well with actual broadband spectrum usage in the UK for 2010 and anticipated for 2015.

We next updated the distributed demand within the model to match our own UK specific medium demand forecast for mobile broadband services but kept all other model settings at the ITU recommended values. As discussed in section 3.2 of the main body of the final report for this study, spectrum requirement results for this case showed that despite large increases in the demand density between our UK specific medium demand forecast and the ITU low demand market setting for 2010 and 2015 that spectrum requirements in these years appeared relatively insensitive to these changes in demand levels.

To understand this insensitivity to demand when using the ITU recommended model settings we investigated which of the service categories within the model were driving spectrum requirements.

Service category number

	Traffic class / Service type	Conversational	Streaming	Interactive	Background
>30Mbps	Super high multimedia	SC 1	SC 6	SC 11	SC 16
>2Mbps	High multimedia	SC 2	SC 7	SC 12	SC 17
>144kbps	Medium multimedia	SC 3	SC 8	SC 13	SC 18
>16kbps	Low rate data and low multimedia	SC 4	SC 9	SC 14	SC 19
<16kbps	Very low rate data(1)	SC 5	SC 10	SC 15	SC 20

(1) This includes speech and SMS.

Figure 37: Overview of ITU service categories

Figure 37 provides a reminder of the Service Categories (SCs) that the traffic within the ITU-R M.1768-1 model is distributed across in varying amounts according to the particular service environment being considered. Each of the service categories represents a traffic class and service type combination. The minimum data rate for each service type is also shown to illustrate the range of data rates at which these SCs operate.

Upon reviewing the queuing theory element of the ITU-R M.1768-1 model we have found that while the model does take into account demand across all SCs, overall network capacity requirements are still heavily dominated by a few “bottleneck” service categories requiring large amounts of spectrum. The network capacity needed to fulfil the mean delay requirement for each service category is determined using a queuing model applicable for independent arrival times of packets and an arbitrary distribution of packet size as determined by the mean packet size model settings [51]. The “bottleneck” SCs appeared to be those configured with service requirements, defined via parameters such as packet size and mean packet delays, that created a vast capacity requirement on the network when considered in the queuing model.

Overall the spectrum requirements for the SC with the highest capacity requirements dominates the total required system capacity since, for the case that the Quality of Service (QoS) requirements of the most demanding SC are fulfilled, the requirements of the other SCs tend to be over-fulfilled. Therefore spectrum requirements within the model become driven by providing coverage for these demanding “bottleneck” SCs, which overwhelm spectrum requirements for other services. This resulted in changes in demand levels at the input to the model during 2010 and 2015 having little impact on overall spectrum estimates, as we observed when changing the demand input to the ITU configured model to a UK specific demand level. This was because in this configuration spectrum requirements across the network were already at the lower-limit to provide coverage to these demanding “bottleneck” SCs.

Figure 38 summarises the “bottleneck” SCs that we identified in the ITU-R M.1768-1 model when configured to ITU recommended parameter settings but using UK specific medium demand forecasts. In this analysis “bottleneck” services are identified based on those with spectrum requirements much higher than broadband spectrum known to be used in the UK in 2010 and anticipated to be available by 2015.

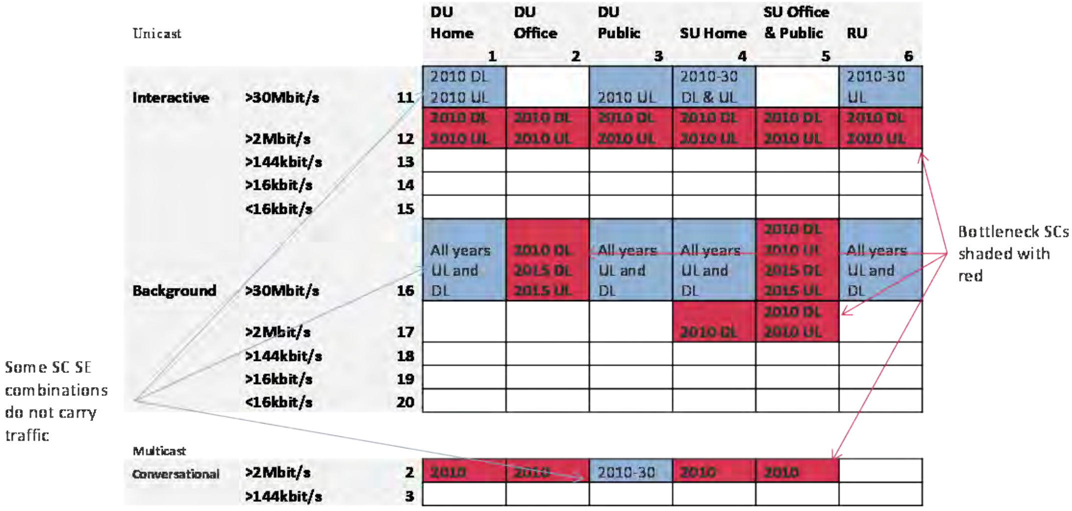


Figure 38: “Bottleneck” SCs identified when ITU default model settings but UK specific demand is used (Note all 20 ITU SCs were investigated but only those found to be bottleneck services are shown here)

Furthermore we conducted a brief analysis of the sensitivity of the model outputs in this configuration to changes in each of the input parameters. The results of this sensitivity analysis are shown in Figure 39 with the input parameters that impact spectrum requirements the most shown in red. Note that when the model is configured as per the ITU recommended settings that this causes some counterintuitive results such as a lack of sensitivity to demand as discussed earlier.

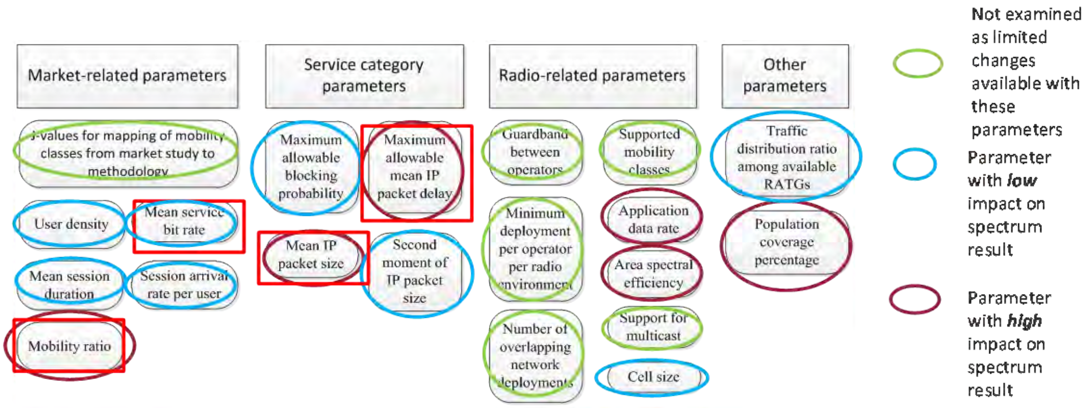


Figure 39: Sensitivity of ITU-R M.1768-1 model to input changes when configured to recommended ITU settings (with the service and market related parameters focused on for review highlighted by red boxes)

For the “bottleneck” services found in the model we have critiqued the service related parameters that influence the output most including:

- Mobility ratio

- Mean IP packet size
- Maximum allowable mean IP packet delay

In addition we have examined the applications and mean service bit rates included in the bottleneck service categories to check that the SCs represent realistic services at each year in the timeline.

Under this critique we have reviewed the recommended ITU values for market and service related parameters and suggested how these might be updated based on real services that have emerged since the original market studies behind the ITU recommended values. Note that the original ITU default values were essentially developed in 2006 when the first spectrum demand estimates were calculated for WRC 07.

The following sections capture our analysis and critique of the various service parameters identified above. The analysis presents the current ITU default parameters and a discussion of its validity based on comparison with sources researched that are considered more realistic.

4.2 Critique of mean service bit rate

The mean service bit rate sets the mean data rate that is expected to maintain the types of applications in each service category considered by the ITU-R M.1768-1 model. It is defined for each SC and SE combination and can vary over time.

Recommended mean service bit rates for each SC and SE combination have been proposed within ITU working party 5D in response to JTG 4-5-6-7 in preparation for agenda item 1.1 at WRC 2015 [50]. Earlier market studies such as those captured in the ITU-R M.2072 report [52] provides a list of applications that are considered within each SC and the range of mean service bit rates that have been proposed by member states against these. Below is an extract from M.2072 which provides a range of mean service bit rates for a variety of different applications for the various service categories considered within the ITU-R M.1768-1 model.

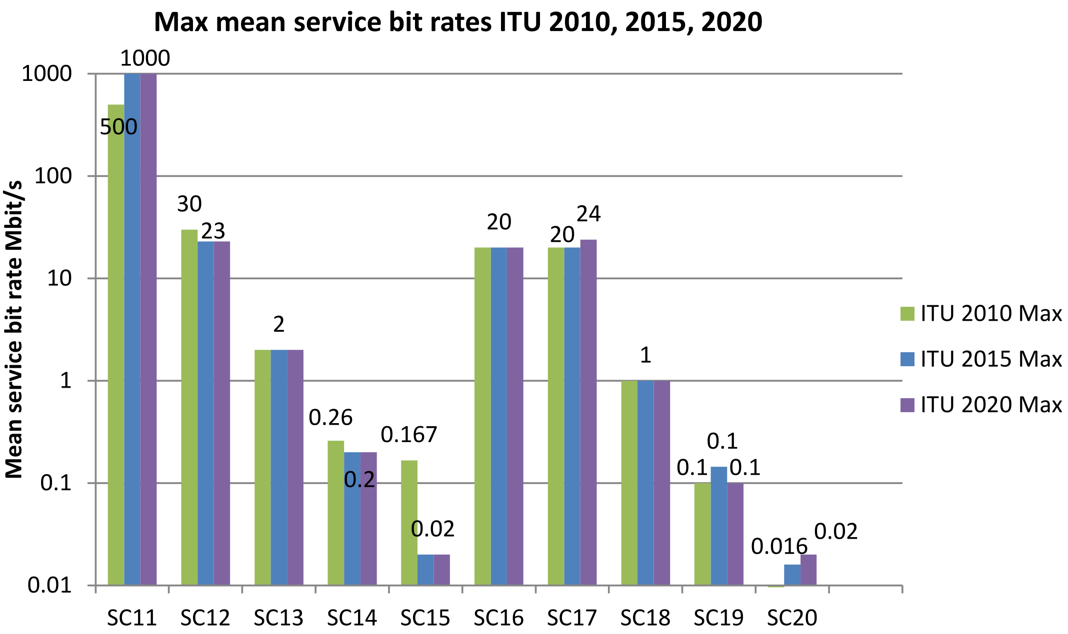
Sequence number of service	Sub sequence number in same service sequence number	SC of the service	Representative name of application/ service	Name of application/service	Doc. No. in Annex 2	SC *n*	Mean service bit rate	Average session duration
79	1	7	High volume business applications	High volume business applications	20, 32	7		
80	1	12	High volume business applications and collaborative working (application sharing) 4	Collaborative working (application sharing)	26			
80	2			High volume business applications	20			
81	1	11	Collaborative working (application	Collaborative working (application	26			

Sequence number of service	Sub sequence number in same service sequence number	SC of the service	Representative name of application/ service	Name of application/service	Doc. No. in Annex 2	SC *n*	Mean service bit rate	Average session duration
			sharing) 5	sharing)				
81	2			Collaborate working	22		30 to 100 Mbit/s/ 1 Gbit/s	
81	3			Virtual computer networks	12			
81	4			High volume business applications and file transfer	32	11		
82	1	16	High volume business applications, file transfer and collaborative working (application sharing) 6	Collaborative working (application sharing)	26			
82	2			High volume business applications and file transfer	20, 32		500 Mbit/s	7.17-133.31 s
82	3			Database service	9		< 50 Mbit/s	
82	4			File system service	9		< 50 Mbit/s	
82	5			File Transfer	22		30 to 100 Mbit/s/ 1 Gbit/s	
83	1	16	High rate data transfer (upload/ download)	Delivery large numbers of presentation while mobile	13			
83	2			High rate data transfer (upload/downloa d)	9		<50 Mbit/s	
84	1	17	Business applications 1	Business applications	20, 32	17		
85	1	16	Business applications 2	Business applications	20, 32	16		
85	2			Telematics with full multi-media in vehicle systems	23			
85	3			Remote office	12			
85	4			Collaborative work	9		10-50 Mbit/s	

Figure 40: Extract of application data rates per service category from [52]

It can be seen from this extract that in some cases for SC11 the mean service bit rate was anticipated in these ITU market studies to be as much as 1 Gbit/s for collaborative working applications. We conducted a critique of the maximum values as presented in [52] due to the very high mean service bit rates being considered. The model adjusts the minimum and maximum values based on the R% parameter input to derive the current mean service bit rate value. We present, by way of illustration, the max and min mean service bit rates from across the six service environments recommended by ITU default values [53].

These values are given in Figure 41 to illustrate the boundary range within which the mean service bit rate values recommended by the ITU can fall in order for the model to generate spectrum estimates. The current mean bit rate value for a given SC will vary across service environments depending on the applications from the SC used in this SE.



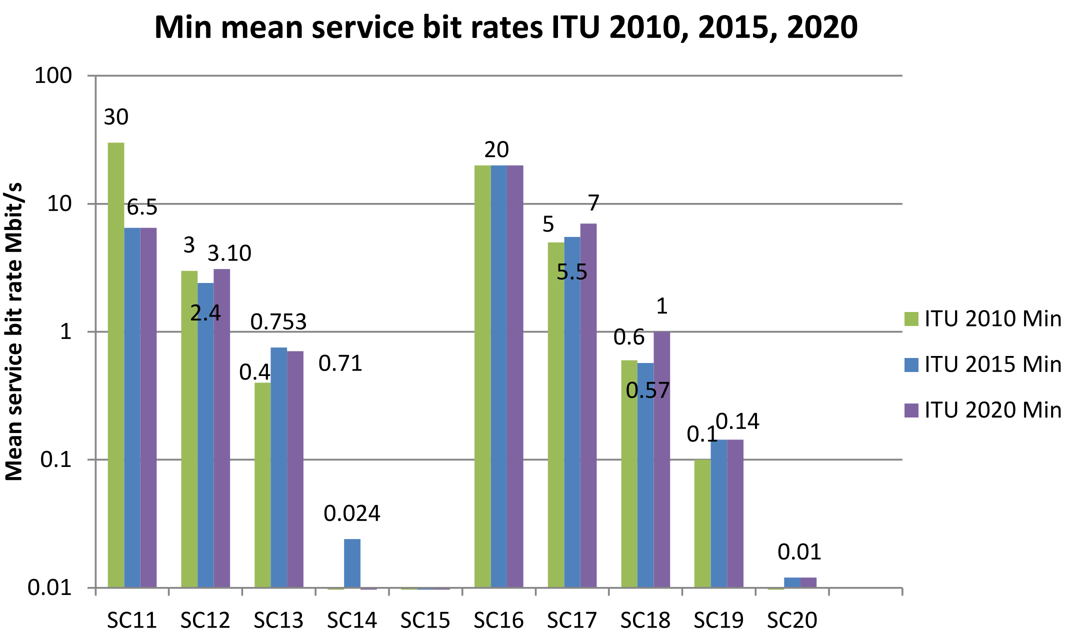


Figure 41: Maximum (top) and minimum (bottom) mean service bit rates recommended by ITU

Observations/recommendations

We reviewed the mean service bit rates across each of the service categories and service environments to pick out those we considered to be unrealistic for use in 2010. The service categories identified that we considered unrealistic for 2010 were SC11 (Super high multimedia Interactive) and SC16 (Super high multimedia Background). These service categories by their ITU definition should support applications of 30Mbps and above (although the actual ITU recommended minimum mean service bit rates for these SCs reflect lower levels in some cases in Figure 40).

We considered that these data rates would not have been feasible on networks using licensed spectrum in 2010 with licence exempt networks only just being able to provide these in limited locations where high broadband backhaul speeds were available. Generally we considered that the types of applications these referred to within SC 11 and SC 16 were highly unlikely to have been used across wireless networks at that time. Even in 2013 there are few applications that demand 30 Mbps to the end user that are not business or safety critical.

Our reality check points and their outcomes included:

1. Mean bit rates for any type of streaming or applications are nominally 8-12 Mbps in a contended environment. Therefore not one service should exceed this based on what we know exists in today's networks.
2. Removal of high volume business applications from our considerations because these applications did not really exist in 2010 and only in very business critical environments like banking where they would not typically rely on mobile/wireless networks for this.
3. As above for emergency/disaster applications as these rely on dedicated networks at the moment and anything related to emergency or critical communications is not normally carried on public mobile networks.
4. Peer to Peer (PTP) is a very popular application but not likely to be required at the ITU suggested rate of 15 Mbps. This application is more likely to require 6Mbps. We also note that in 2010 on congested networks 15 Mbps seems rather optimistic.

Within the model the distributed traffic which contributes to the overall spectrum requirements is determined by comparing the application rates of networks at the time to the mean service bit rates of the SCs. In the case of SC 11 we note that the high default ITU settings for mean service bit rate in this SC compared with application rates in our baseline model configuration (see section 5.5) will mean that this SC11 traffic is not distributed over wireless networks from 2010 to 2020 and only becomes feasible for RATG2 and RATG3 picocells and hotspots from 2025 onwards. This is in line with our observation that the high volume business applications represented by this service category generally would not be carried over cellular or Wi-Fi networks in the early years of our analysis at least and suggest that operators would not design/dimension their network to support such demanding applications

In the case of SC 16 we note that the ITU mean service bit rate for this SC at 20Mbps is actually below the 30Mbps threshold for this SC and again, in line with our thoughts regarding support for services above 30Mbps, this suggests that traffic would not be generated in this SC on wireless networks.

The other SCs have mean service bit rates that appear to be in the right range for the applications within these SCs.

Therefore the mean service bit rate settings in our recommended model baseline configuration for 2010 follow those of the ITU default settings noting that in practice this means that no SC16 traffic above 30Mbps is actually generated in the model and that SC 11 traffic is only distributed and contributing to spectrum requirements from 2025 onwards.

Recommendations over time

No authoritative evidence has been found that shows an increase in mean service bit rate over time but we do however assume technology evolution will drive bit rates particularly in high bandwidth applications. Therefore, the SC11 mean bit rate could potentially increase from our understanding of today's likely mean service bit rates for applications within this SC particularly as LE technology evolves to support higher bandwidth applications generally.

Figure 42 summarises our suggestions on how mean service bit rates might evolve across the packet switched SCs in the ITU model between 2010 and 2020 based on our review of the typical applications within these SCs.

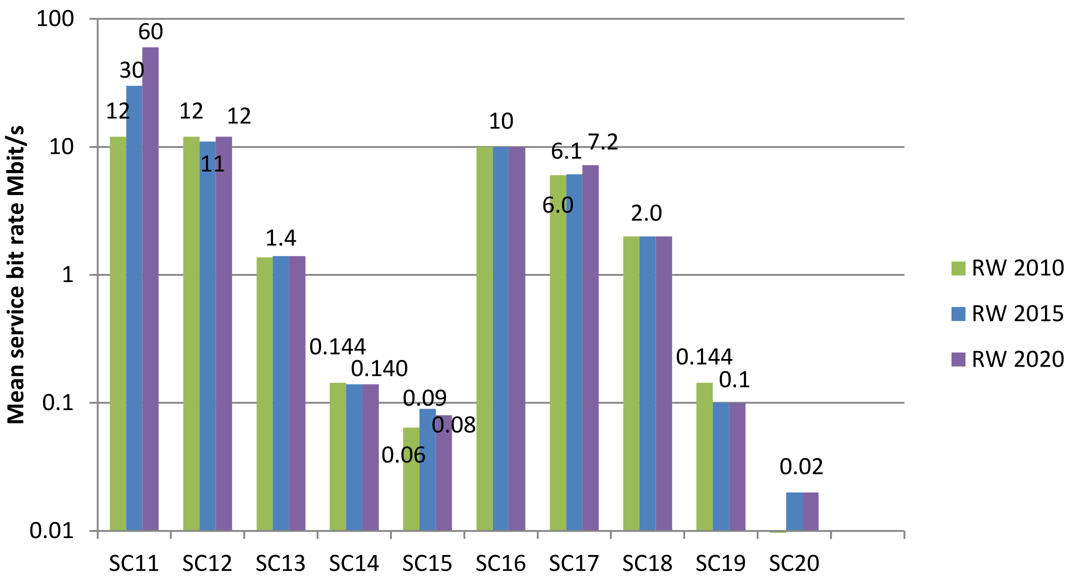


Figure 42 Mean service bit rates over time found from our review of typical applications in each of the packet switched SCs

It can be seen that for SC11 the mean service bit rate is expected to increase over time as would also be the case for SC17 (high multimedia, background). We suggest SC16 bit rates would remain constant over time as we assume that the applications in this category would not exceed a 10 Mbps mean service bit rate.

Our suggested values generally align with the ITU suggestions for mean service bit rates with the exception of SC 11. However, we note that our suggested SC 11 mean service bit rates for the applications within this SC, that we believe to be more realistic to be carried over wireless networks, remain below the 30Mbps threshold for the definition this SC for 2010 and 2015. This reflects our understanding that applications above 30Mbps would not target wireless networks in the near term at least and hence SC11 traffic should not be included in spectrum estimates in the early years of our timeline at least. As discussed earlier, the same desired effect of not including SC 11 traffic in spectrum requirements for earlier years is already achieved in the model by maintaining the ITU default mean service bit rate for this category and applying our recommended baseline settings for application rates.

Our recommended baseline configuration for the ITU-R M.1768-1 model therefore maintains the ITU default settings for mean service bit rate but the observations regarding support for SC 11 and SC 16 should be noted.

4.3 Critique of mobility ratio

Parameter description

Within the ITU-R M.1768-1 model there is a set of mobility class categories which traffic is distributed across within each SE. These include the following types of users:

- Stationary: 0 km/h
- Low speed: 0 < x < 4 km/h
- High speed: 4 < x < 100 km/h
- Super high speed: 100 < x < 250 km/h

The mobility ratio for each SC and SE combination defines the proportion of traffic in this SC SE combination that falls into the mobility categories above.

The mobility ratio is an important model parameter for determining spectrum estimates because the greater the mobility ratio towards higher velocity users the more challenging it will be to serve the user within a given coverage area. For example, only macrocells can support the higher mobility classes because of current handover limitations amongst small low cost cells and the lack of near contiguous coverage from smaller cells which limit support to lower velocity users. However, macrocells have a lower spectral efficiency density compared to small cells and hence forcing more traffic onto macrocells via mobility ratio settings will increase spectrum requirements.

Observations/recommendations

We have reviewed the ITU recommended parameters for mobility ratios and found that broadly we agree with these and hence our recommended baseline model setting follows ITU settings. However, it is worth noting that we did find instances of traffic in the super high mobility class in the home and/or office environments which ideally should be moved to the high mobility class or public area or rural service environments.

We believe that in 2010 there might be a lower proportion of traffic in the super high mobility class than assumed by the ITU values on the basis that any traffic from super high speed users are likely to be users of Wi-Fi on trains for example. For all of the service environments this would only make up a small proportion of total traffic with the majority of these users being in rural environments.

An example of potential updates to mobility ratio against ITU default settings are shown for SC 12 in Figure 43. However, these updates are relatively minor and so our recommended model baseline settings reflect the ITU default settings for this parameter. Note that our sensitivity analysis does, however, examine some of our observations on mobility ratio further.

Current ITU default parameters		Service category 12					
		DU Home	DU Office	DU Public	SU Home	SU Office & Public area	RU
	km/h	1	2	3	4	5	6
Stationary	0	67.5	67.5	46.231156	62.5	42.5	40.5
Low	>0 < 4	22.5	27.5	44.221106	25	20	15
High	>4<100	10	5	9.547739	12.5	32.5	37
Super higl	>100 < 250	0	0	0	0	5	7.5

Suggested parameters based on practical and real values		Service category 12					
		DU Home	DU Office	DU Public	SU Home	SU Office & Public area	RU
	km/h	1	2	3	4	5	6
Stationary	0	67.5	67.5	46.231156	62.5	30	40.5
Low	>0 < 4	27.5	22.5	44.221106	25	32.5	15
High	>4<100	5	10	9.547739	12.5	37.5	41.5
Super higl	>100 < 250	0	0	0	0	0	3

Figure 43: Mobility ratio example in service category 12

4.4 Critique of packet switched vs. circuit switched assumptions per SC

The ITU model makes assumptions on which services will be delivered by packet switched mechanisms and which will be delivered by circuit switched networks. This is informed by the table shown in Figure 37 at the beginning of this chapter which maps each service category to its respective traffic class (conversation, streaming, background, interactive) and service type (low rate data through to super high multimedia). These assumptions on whether a SC is delivered via packet or circuit switched mechanisms cannot be varied over time in the ITU-R M.1768-1 model.

The ITU recommended model settings assume that all conversational and streaming services (i.e. SC 1-10) will be delivered by circuit switched mechanisms. We have maintained these assumptions in our baseline model settings. However, we note that this may not be fully representative of current cellular networks and particularly the evolution of cellular networks over time. Therefore in our sensitivity analysis we include a case where all conversational and streaming services with the exception of SC5 (the lowest rate conversational service) are delivered via packet switched mechanisms. This assumption is supported by the delivery of many applications on cellular networks today via packet switched techniques.

To inform our sensitivity analysis in this area we have therefore also investigated suitable mean packet sizes, second moment of packet sizes and mean delay levels for SC1-4 and SC 6-10 even though these are not included as packet switched services by the ITU. Our findings on these are reported in the next three subsections of this appendix.

In our review of suitable settings for these parameters for each SC we have considered sources against the example applications indicated by ITU for each SC. The full list of applications against service categories 1-10 are given in ITU-R 2072 report [52] and broadly relate to applications like voice, video telephony, video with voice, videoconference, streaming and IP broadcast services. Table 27 below is an extract of some of the applications for these SCs by way of example.

Application	Service category
Video upload/download	SC1
High quality video conference	SC2
Mobile HDTV	SC2
IP broadcast	SC2, SC3
Video telephony	SC3, SC4
Video conference	SC3, SC4
VoIP	SC4
High volume streaming	SC6, SC8
Video/audio streaming	SC8
Interactive gaming	SC8
Internet radio	SC9
RFID	SC10

Table 27: Packet switched applications from SC1-10

We examined the above applications and their related parameters including mean service bit rate, mean IP packet size and tolerable IP packet delay. This was to determine whether these applications/service categories would create an increased requirement for spectrum when delivered via packet switched techniques as opposed to via circuit switched networks.

There are no ITU default packet switched values for these service categories, as they are treated as circuit switched in the ITU default model settings, but we have proposed some parameter values to use in our sensitivity analysis for SC1-10 (excluding SC5) so that some assessment of the impact on spectrum requirements can be made. However, we note that our review of these parameters has been limited in the timescales of this study and that a more detailed review of this area is needed. While the results of our sensitivity analysis give some indication of the size of the impact on spectrum requirements that changing assumptions on PS or CS mechanisms for SCs may have we note that it is not clear that the current overheads applied by the queuing theory block of the model are representative of the levels required for delivering guaranteed bit rate services via packet switched mechanisms such as used in Voice over LTE (VoLTE) approaches. Therefore we highlight this as an area for further investigation rather than a firm recommended change to the ITU-R M.1768-1 model baseline settings at this stage.

An example of the mean service bit rates which we have found based on reviewing sources for the applications within SC1-10 from the ITU-R M.2072 report is given in Figure 44. Here we assume that in 2010 service categories within super high multimedia and high multimedia service types would not have been available to users due the high bit rates required for these not being available over wireless networks at this time. For example, we assume that high quality video conferencing at 50 Mbps would not have been available on a wireless network in 2010 (in line with our earlier assumptions on wireless network capabilities highlighted when reviewing mean service bit rates for SC11-20 earlier). However, as in the cases of SC11-20 discussed earlier we maintain the ITU recommended values for mean service bit rate for SC1-4 and SC6-10 in our sensitivity analysis case which investigates packet switched assumptions but control which SCs would be available in any given year via our selected application rate (discussed in appendix E).

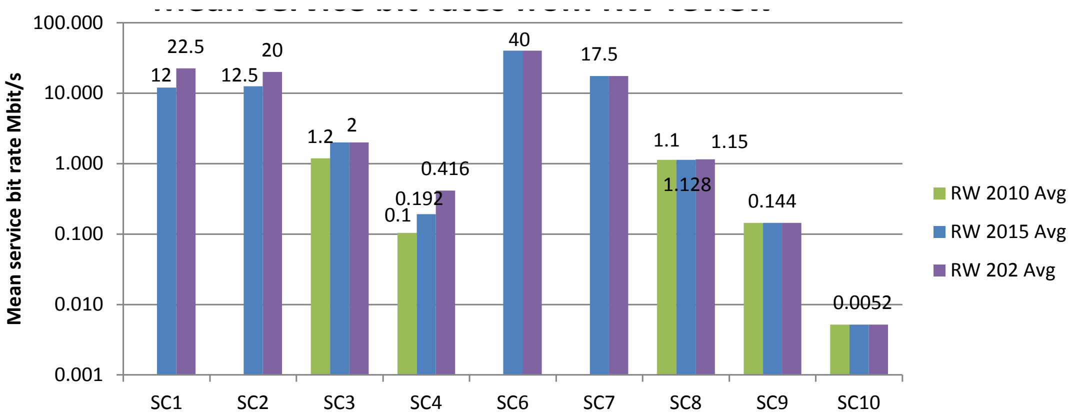


Figure 44: Average of mean service bit rates found across applications within the conversational and streaming classes for 2010, 2015 and 2020 from our review of applications in these SCs

In the next three sections we review suitable PS parameters for SC1-4 and SC6-20 which includes:

- Mean IP packet size
- Second moment of packet sizes
- Tolerable delays

4.5 Critique of mean packet size

Parameter description

Within the ITU-R M.1768-1 model the mean size of packets to be supported when delivering a particular service category is defined and can vary over time. The main impact of the mean packet size setting is seen in the queuing theory block in the ITU-R M.1768-1 model. The larger the packet size for a given service category the harder it is to schedule these larger packets which results in higher spectrum requirements to allow for this queuing overhead. In particular a combination of large mean packet sizes and challengingly short maximum allowable IP packet delays for some SCs in the model can make queuing packets for these SCs very difficult and lead to large overheads. This can lead to extremely high spectrum requirements and potential "bottleneck" SCs that overwhelmingly drive spectrum estimates from the model and may even make model outputs relatively insensitive to demand as discussed earlier.

The ITU-R M.2072 report lists the applications that can be considered for each service category with some service categories having as many as ten or more related applications listed. This is due to the variety of inputs from many different member states to the ITU market report ITU-R M.2072. In determining mean packet sizes across SCs we have used a number of sources, as explained further below, whose applications matched those from across the 20 service categories in the ITU report. The sources found corresponded to only a small number of the total applications given in the ITU report. However, one particular source from Stoke [55] covered most of the common applications found within the ITU report such as VoIP, file sharing, video streaming, real time gaming etc. In the cases where the Stoke paper either did not match the applications exactly or simply did not include it, which was mostly in SC 1-10, we found other sources from vendors such as Qualcomm and Cisco which we also used to obtain alternative values to the Stoke paper to generate an average IP packet size for that service category.

Observations/recommendations

In IP networks and particularly Ethernet the Maximum Transmission Unit (MTU) is typically around 1500 bytes [54] for a packet. This provided a general upper bound on mean packet sizes during our review of this parameter across SCs.

We researched a number of sources that provided a wide variety of different packet sizes. The range of sources we found targeted different applications and different network architecture set ups. The sources for service categories SC11-20 were predominantly from vendors, such as Stoke [55] and Cisco [56], and from research institutions, such as University of Hungary [57] and University of Waterloo [58]. The sources for service categories SC1-4 and SC6-10 in cases where there were some differences with SC11-20 were drawn from Qualcomm [59], Comcast [60] and KDDI/NHK Japan [61].

Across all of these sources we mainly drew from the vendor source Stoke for service categories SC1-4 and SC 6-20 (i.e. all packet switched SCs we considered) because it focused on the performance impact of networks from various packet sizes which aligned well with the ITU applications within the SCs. However, in some cases, the packet sizes for SC1-4 and SC6-10 had a number of variations for video focused applications and in these cases we were therefore informed by other sources such as those outlined above.

Figure 45 shows the initial research of mean packet sizes against the ITU default parameters for service categories 11-20. The values shown here are the low end values found in our research noting that there was a range of values found for a particular application such as file transfer or web browsing.

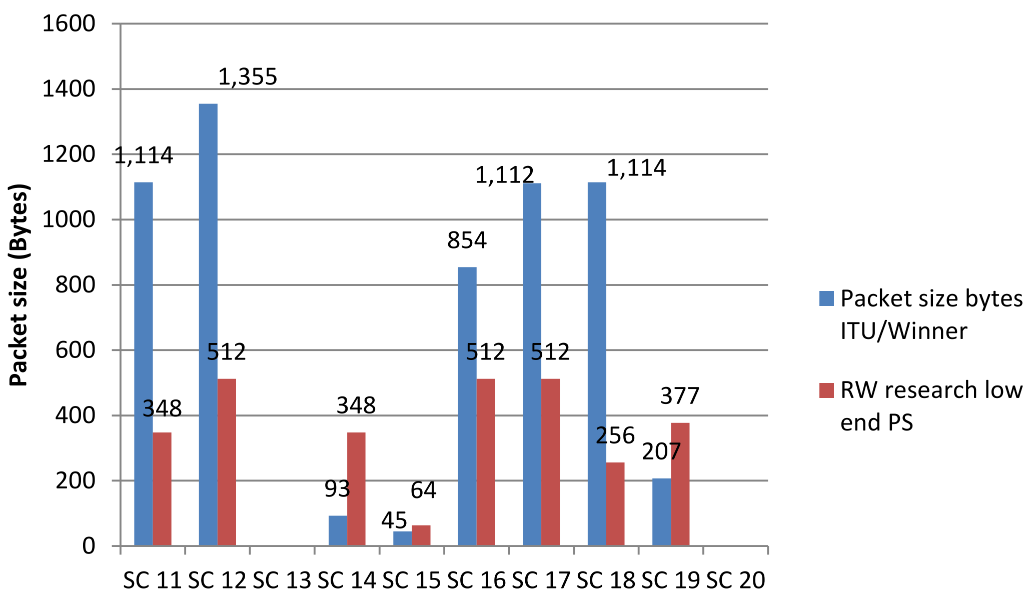


Figure 45: Real Wireless research of mean packet size vs. ITU default parameters in 2010

Our reviewed sources show that file transfer applications which are incorporated into SC12 which is the most significant application in terms of mean IP packet size could require as low as 512 bytes or as high as 1500 bytes. The ITU recommended parameter value for SC12 was 1354 bytes which although is within the range of byte sizes available may not necessarily be required by all applications in SC12 in reality. Some of the packet sizes found from the research were greater when compared to the ITU default values. Examples of these included gaming and browsing (SC 14) and email (SC19). In this case we used values from a paper by Stoke [55] which suggests a number of typical packet sizes based on its own analysis of IP traffic for LTE equipment evaluation. Figure 46 shows some mobile broadband applications and their typical packet sizes from this source.

Mobile Broadband Applications[4]	Typical Packet Sizes
VoIP / VoLTE	64B
Video Streaming (mobile)	256B
Web Browsing (HTTP)	384B
File Download/share	512-1,518B

Figure 6. Typical packet sizes for common applications.

Figure 46: Extract from Stoke paper for typical IP packet sizes. Source: Stoke [55]

Generally, the ITU packet sizes appeared to correlate with the mid to high levels of the packet size found in the Stoke paper for the SCs which require high bandwidths. Furthermore, we noticed that the mean IP packet sizes in the ITU default settings in some SCs rise and then fall over time (see Figure 47) which appears to have no further justification other than that this is an artefact of consolidating mean packet size levels from multiple contributions to the ITU from various countries/inputs.

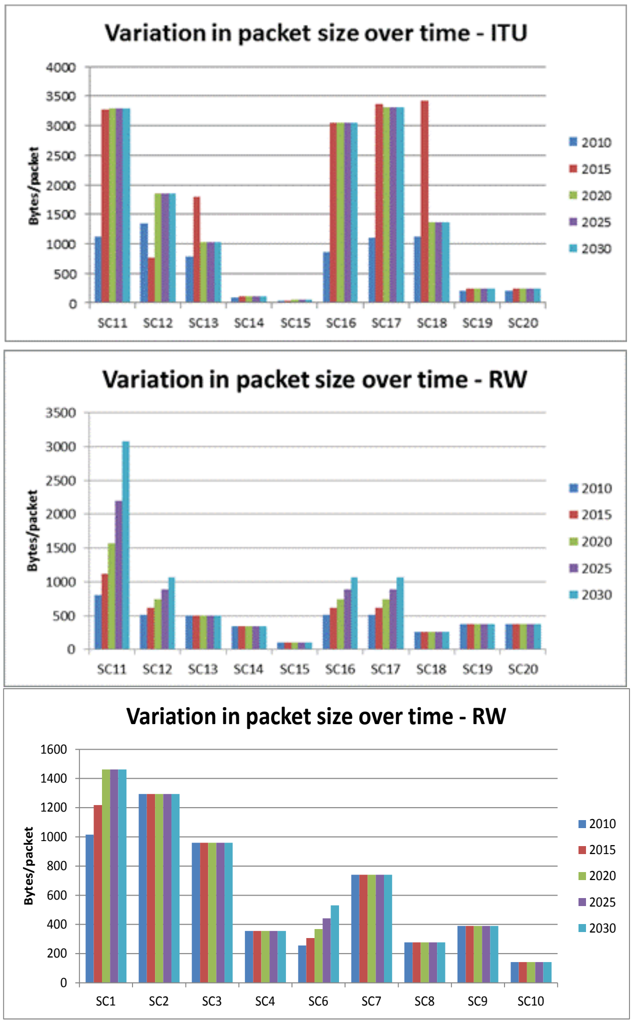


Figure 47: ITU default values and Real Wireless proposed values for mean packet size over time. Note there are no packet sizes for SC 1-10.

In ITU-R M 2072 report it suggests that "*packet size and total throughput will increase as high volume contents such as high quality video, 3D audio, hologram video contents are introduced*". This is driven by new advancements in technology such as fibre optics and high frequency radio technology. This correlates with our research of packet sizes which suggests that packet size is time sensitive to evolution of network technology and the ability to deliver better throughputs.

We have assumed that packet sizes will increase over time but we do not have sufficient evidence to explain why packet sizes fluctuate over time in the ITU recommended values for SC13, SC12, 17 and 18 other than that specific applications may require mean packet sizes in that way.

The Stoke paper suggests the following: "*The majority of LTE traffic today and in the future will consist of applications and services that use smaller packet transmissions – that is packet sizes less than 400 bytes, including VoLTE and streaming mobile video*". This suggests that packet sizes may actually reduce in size over time.

Overall we assume that for demanding applications such as those in SC11, 12, 16 and 17 there could be an increase packet sizes over time.

The following five tables provide our recommended updated packet size values for every 5 year period across service categories 1-4 and 6-20. Note that the numbers denoted with an asterisk under the conversational and streaming traffic classes in each of the tables are those we have updated to packet switched values for our sensitivity analysis but that these are maintained as circuit switched services in our baseline case. These are also shown alongside the original ITU recommended values in Figure 47.

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	1015*	256*	800	512
High multimedia	1293.5*	740*	512	512
Medium multimedia	959.5*	277*	500	256
Low rate data and low multimedia	356*	390*	348	377
Very low rate data	Treated as circuit switched	142.5*	100	377

Table 28 Packet size values in bytes/packet across service categories 1-20 in 2010

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	1218*	307.2*	1120	614.4
High multimedia	1293.5*	740*	614.4	614.4
Medium multimedia	959.5*	277*	500	256
Low rate data and low multimedia	356*	390*	348	377
Very low rate data	Treat as circuit switched	142.5*	100	377

Table 29 Packet size values in bytes/packet across service categories 1-20 in 2015

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	1461.6*	368.6*	1568	737.28
High multimedia	1293.5*	740*	737.28	737.28
Medium multimedia	959.5*	277*	500	256
Low rate data and low multimedia	356*	390*	348	377
Very low rate data	Treat as circuit switched	142.5*	100	377

Table 30 Packet size values in bytes/packet across service categories 1-20 in 2020

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	1461.6*	442.4*	2195.2	884.7
High multimedia	1293.5*	740*	884.7	884.7
Medium multimedia	959.5*	277*	500	256
Low rate data and low multimedia	356*	390*	348	377
Very low rate data	Treat as circuit switched	142.5*	100	377

Table 31 Packet size values in bytes/packet across service categories 1-20 in 2025

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	1461.6*	530.8*	3073.3	1061.7
High multimedia	1293.5*	740*	1061.7	1061.7
Medium multimedia	959.5*	277*	500	256
Low rate data and low multimedia	356*	390*	348	377
Very low rate data	Treat as circuit switched	142.5*	100	377

Table 32 Packet size values in bytes/packet across service categories 1-20 in 2030

One fundamental aspect with the default ITU parameters is that the number of bytes/packet from 2015 onwards exceeds the standard MTU (1500 bytes) [54] for Ethernet IP networks as shown in the top plot of Figure 47. This assumes the use of jumbo mode packets which enlarges the MTU to a size of 10,218 bytes. Most networks would, however, need to fragment this down to the standard MTU as most equipment is configured for an MTU of 1500 today. In addition, in the last 10-15 years the standard MTU size has been sufficient in most network equipment around the world.

However, in very high multimedia services such as (SC11) the MTU size may increase to a maximum of 9000 bytes so it is possible the mean packet sizes will grow to support high rate data transfer and high definition video streaming.

In translating the circuit switched service categories to packet switched in the conversational and streaming classes the byte sizes remain below the MTU size of 1500 bytes across all the service categories. Prior to the research for these service categories we expected that conversational and streaming services would have smaller packet sizes compared to applications within SC11-20. This was not the case and as shown in section 4.4 the applications for these conversational and streaming classes do indeed include applications such as video conferencing and video telephony which we found to require large packet sizes.

In addition, some of the byte sizes varied widely across the mix of applications within in each service category. Therefore, in order to derive a single number per service category we took the average packet size from the highest and lowest values from three different applications. For example, the applications chosen for SC4 included VoIP and video telephone which gave a range of packet sizes from 64 bytes to 648 bytes therefore the average packet size for SC4 was 400Bytes. This is compared to SC15 (which also included VoIP as an application) was around 100 bytes but did not have such a wide mix of different applications.

Recommendation

Overall, we disagree with the ITU recommended initial mean packet size values and suggested variations (increase/decrease) of packet sizes within a service category over time. However, we agree that there may be growth in packet sizes for those applications (SCs) that may benefit from having larger packet sizes e.g. large file data transfer and high definition video streaming. We also suggest changing the second moment of packet size or packet size variance, which is another parameter used by the model, by the same factor as our recommended changes to mean packet sizes but squared so that the mean standard error of packet size is maintained compared to the ITU values (see next section).

4.6 Critique of second moment of packet size

Parameter description

In the ITU model there is a parameter known as the second moment of the IP packet size which is the variance in the mean IP packet size i.e. $(\text{Standard deviation})^2$. Note that this determines the standard error of the packet size and the standard error reflects the ratio between the standard deviation of packet size and mean packet size.

Observations

In generating our recommended values for the second moment of packet size across SCs we have assumed that the ITU recommended values for the standard error of packet size are reasonable and have maintained these across SCs with similar applications where possible. This is due to, within the timescales of this study, a more detailed investigation of more suitable second moment of packet size values and the statistics of packet sizes across various applications not being feasible.

However, we note that in the cases of SC 11-20, which the ITU consider as PS services and hence define mean packet size and second moment of packet sizes for, that the standard error given by the recommended ITU values for mean packet size and second moment of packet size do in some cases imply negative packet sizes (see Figure 48). For example, a standard error of 1 leads to a 16% chance that the packet size is negative. A standard error of 574%, as in SC19 and SC20, leads to 43% chance that the packet size is negative. We also note that the standard error fluctuates over time for some SCs.

We recommend that more appropriate values for the second moment of packet size across SCs and the ITU assumptions on standard error levels are investigated further to develop standard error values that do not result in negative packet sizes.

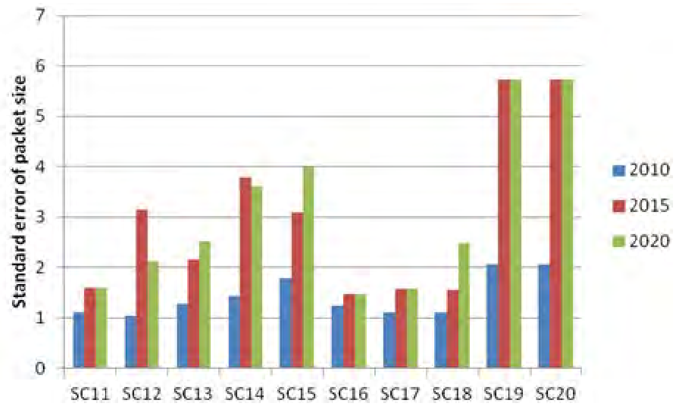


Figure 48: Standard error of packet size given by ITU recommended values for mean packet size and second moment of packet size for SC11-20

Recommendations

In the cases of SC 11-20, where ITU recommended values for mean packet size and second moment of packet size already existed, we have adjusted our recommended values for the second moment of packet size in line with our recommended changes to mean packet sizes for these SCs to ensure that the original standard error per SC resulting from the recommended ITU PS settings for each SC are still maintained.

In the cases of conversational and streaming services in SC1-4[4] and 6-10, whose PS settings we have investigated as part of our sensitivity analysis, these were originally CS services in the ITU recommended settings for the model and hence there were no ITU recommended standard error values for these SCs to maintain as in our approach for deriving second moment of packet sizes for SC 11-20. Therefore, we mapped the applications from these SCs to the applications in the SCs for the interactive and background classes and used the same standard error in those cases. However, in some cases there were no exact matches but we used the most appropriate standard error which we deemed were broadly in the same category.

The following five tables show for each five year period the second moment of the packet size for service categories 1-4 and 6-20 that we recommend. In the cases of SC 11-20 these are used in our baseline setting with those for SC 1-4 and 6-10 only investigated in our sensitivity analysis.

[4] Note in our sensitivity case we maintain SC 5 as a circuit switched service.

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	82.32	5.24	51.14	26.07
High multimedia	133.94	43.76	18.42	20.99
Medium multimedia	73.57	5.39	26.11	5.24
Low rate data and low multimedia	25.83	12.15	16.08	38.75
Very low rate data	Treat as circuit switched	5.54	2.04	38.75

Table 33 Second moment of the packet size values in bytes^2/packet^2 across service categories 1-20 in 2010

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	242.91	14.77	205.4	52.67
High multimedia	265.77	85.70	240.44	59.96
Medium multimedia	144.07	48.87	74.39	10.26
Low rate data and low multimedia	78.14	23.80	110.96	299.78
Very low rate data	Treat as circuit switched	42.83	6.17	299.78

Table 34 Second moment of the packet size values in bytes^2/packet^2 across service categories 1-20 in 2015

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	347.49	53.45	399.93	75.84
High multimedia	271.00	215.39	156.4	88.04
Medium multimedia	362.11	22.08	101.07	25.78
Low rate data and low multimedia	128.89	59.83	102.12	299.78
Very low rate data	Treat as circuit switched	42.83	10.17	299.78

Table 35 Second moment of the packet size values in bytes^2/packet^2 across service categories 1-20 in 2020

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	347.49	76.97	783.86	109.21
High multimedia	271.00	215.39	255.21	126.78
Medium multimedia	362.11	22.08	101.07	25.78
Low rate data and low multimedia	128.89	59.83	102.12	299.78
Very low rate data	Treat as circuit switched	42.83	10.17	299.78

Table 36 Second moment of the packet size values in bytes^2/packet^2 across service categories 1-20 in 2025

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super-high multimedia	347.49	110.84	1536.36	157.26
High multimedia	271.00	215.39	324.30	182.57
Medium multimedia	362.11	22.08	101.07	25.78
Low rate data and low multimedia	128.89	59.83	102.12	299.78
Very low rate data	Treat as circuit switched	42.83	10.17	299.78

Table 37 Second moment of the packet size values in bytes^2/packet^2 across service categories 1-20 in 2030

4.7 Critique of Maximum allowable mean IP packet delay

Parameter description

The maximum tolerable delay is the maximum delay in seconds that a given service category can tolerate in a packet switched context and still be delivered at an acceptable quality level. In other words this is the end to end delay a network can tolerate for an IP packet to be transmitted for a given service quality level. The parameter is defined per service category and can vary over time. The maximum allowable mean IP packet delay impacts spectrum requirements via the queuing theory block in the model.

As explained earlier in section 4.2 each service category has a number of different applications associated with it. In the ITU-R M.2072 market report [52] each application within each service category is listed and an associated mean service bit rate suggested. In order to derive the mean IP packet delay across SCs we used the particular application types which would likely drive the packet delay bottlenecks. For example, in SC12 real-time gaming is one application that would require low packet delay (less than 100 ms) as stated by 3GPP standardised tolerable delay values (see description below for more details). Outlined below are the applications which drive the IP packet delay for each SC.

Service category	Application driving IP packet delay	Greater/less than 100ms delay
SC 1	Download	>100
SC2	Live streaming	<100
SC3	Live streaming	<100
SC4	VoIP	<100
SC5	Circuit switched	N/A
SC6	File sharing	>100
SC7	Live streaming	<100
SC8	Interactive gaming (note there is also Real time gaming in SC12 which is different to interactive gaming)	<100
SC9	Live streaming	<100
SC10	File sharing	>100
SC 11	Browsing/download	> 100
SC12	Real time gaming	< 100
SC13	Browsing/M-payment	> 100
SC14	Browsing M-payment	> 100
SC15	VoIP	< 100
SC16	Mobile internet/file sharing	> 100
SC17	File transfer	< 100
SC18	Video streaming	< 100
SC19	Email	> 100
SC20	Telemetry	> 100

Table 38 Applications driving IP packet delay against each service categories

Observations/recommendations:

The ITU recommended model settings appear far too stringent in terms of setting very low tolerable delays and may be driving exceedingly high spectrum requirements in “bottleneck” SCs as discussed earlier in this appendix. We suggest revising down the tolerable delay levels specified by the ITU in line with real sources found from research but in particular from a paper published by NGMN [62].

The NGMN paper suggests tolerable delays of around 30ms are adequate for services such as real time gaming services which demand very fast response times for sufficient interactivity between users. We agree that file transfer, P2P, browsing and email are non-guaranteed bit rate services and therefore can tolerate higher delays than the values used by the ITU for those services.

Our recommended model baseline settings therefore update the mean packet delay values across service categories to those shown on the lower two graphs in Figure 49 which reflect NGMN/3GPP values. This is compared to the top plot which shows the ITU default packet delay levels which do not vary over time. Note that in our baseline model settings that SC1-4 and SC6-10 (conversational and streaming classes) are treated as circuit switched but the delay values for these that we found are used in our sensitivity analysis.

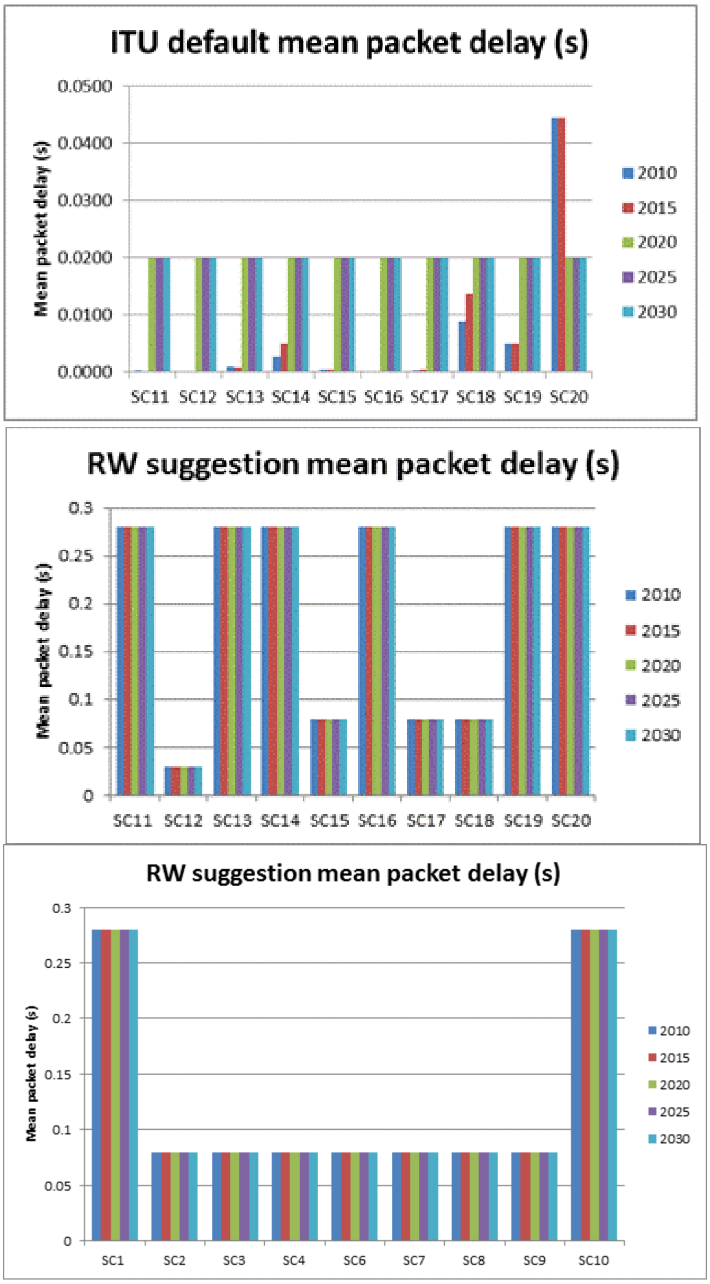


Figure 49: ITU default and RW suggested mean packet delay values

The following five tables show the IP packet delay for each 5 year period from 2010 to 2030 across service categories 1-4 and 6-20.

Service type \ Traffic class	Conversational	Streaming	Interactive	Background
Super-high multimedia	0.28*	0.08*	0.28	0.28
High multimedia	0.08*	0.08*	0.03	0.08
Medium multimedia	0.08*	0.08*	0.28	0.08
Low rate data and low multimedia	0.08*	0.08*	0.28	0.28
Very low rate data	Treated as circuit switched	0.28*	0.08	0.28

Table 39 Mean packet delay values in seconds across service categories 1-20 in 2010

Service type \ Traffic class	Conversational	Streaming	Interactive	Background
Super-high multimedia	0.28*	0.08*	0.28	0.28
High multimedia	0.08*	0.08*	0.03	0.08
Medium multimedia	0.08*	0.08*	0.28	0.08
Low rate data and low multimedia	0.08*	0.08*	0.28	0.28
Very low rate data	Treated as circuit switched	0.28*	0.08	0.28

Table 40 Mean packet delay values in seconds across service categories 1-20 in 2015

Service type \ Traffic class	Conversational	Streaming	Interactive	Background
Super-high multimedia	0.28*	0.08*	0.28	0.28
High multimedia	0.08*	0.08*	0.03	0.08
Medium multimedia	0.08*	0.08*	0.28	0.08
Low rate data and low multimedia	0.08*	0.08*	0.28	0.28
Very low rate data	Treated as circuit switched	0.28*	0.08	0.28

Table 41 Mean packet delay values in seconds across service categories 1-20 in 2020

Service type \ Traffic class	Conversational	Streaming	Interactive	Background
Super-high multimedia	0.28*	0.08*	0.28	0.28
High multimedia	0.08*	0.08*	0.03	0.08
Medium multimedia	0.08*	0.08*	0.28	0.08
Low rate data and low multimedia	0.08*	0.08*	0.28	0.28
Very low rate data	Treated as circuit switched	0.28*	0.08	0.28

Table 42 Mean packet delay values in seconds across service categories 1-20 in 2025

Service type \ Traffic class	Conversational	Streaming	Interactive	Background
Super-high multimedia	0.28*	0.08*	0.28	0.28
High multimedia	0.08*	0.08*	0.03	0.08
Medium multimedia	0.08*	0.08*	0.28	0.08
Low rate data and low multimedia	0.08*	0.08*	0.28	0.28
Very low rate data	Treated as circuit switched	0.28*	0.08	0.28

Table 43 Mean packet delay values in seconds across service categories 1-20 in 2030

The ITU recommended values show some increased delay tolerance over time in some of the not so demanding service categories such as file sharing and downloading. We have found no evidence in the course of our research which suggests mean packet delay will vary in future which correlates with the trend over time of most of the ITUs recommended values for delay across SCs.

We agree that the delay tolerance of any given SC is unlikely to change over time as this is determined by reaction times of users rather than technology enhancements and so have maintained delay levels at the same level for each service category over the study timeframe.

Translating the conversational and streaming traffic classes to packet switched for our sensitivity analysis reveals a number of interesting issues. For example, in SC8 which includes interactive gaming we found that this type of application has a higher tolerable delay than for real time gaming as found under SC 12. There is a distinction given in the ITU-R M.2072 report between these two applications within each service category which maps across exactly to the respective 3GPP QCI classes for real time and interactive gaming.

Additionally, we expected SC1-10, which cover the conversational and streaming classes and the ITU sets as circuit switched, to require low delay tolerances. However, we found the opposite in some cases which showed some SCs did not require such low delays. These were applications such as download (SC1) and RFID/low data rate (SC10).

Packet delay budgets are driven by the types of applications within SCs and the tolerable delay for each of these based on various QoS classes as identified by 3GPP TS 23.401 [63]. We have reproduced the table from the NGMN paper below to identify how the packet delay budgets vary across QoS classes in Figure 50. We recommend using the minimum allowable mean packet delay from all of the applications in any SC so that the requirements of all applications are captured for any given service category.

QCI	RESOURCE TYPE	PRIORITY	PACKET DELAY BUDGET (ms) (Note 1)	PACKET ERROR LOSS RATE (Note 2)	EXAMPLE SERVICES
1 (Note 3)	GBR	2	100	10^{-2}	Conversational Voice
2 (Note 3)		4	150	10^{-3}	Conversational Video (live streaming)
3 (Note 3)		3	50	10^{-3}	Real-Time Gaming
4 (Note 3)		5	300	10^{-6}	Non-Conversational Video (buffered streaming)
5 (Note 3)	Non-GBR	1	100	10^{-6}	IMS Signalling
6 (Note 4)		6	300	10^{-6}	Video (buffered streaming) TCP-based (www, email, chat, ftp, ptp file sharing, progressive video, etc.)
7 (Note 3)		7	100	10^{-3}	Voice, Video (live streaming), Interactive Gaming
8 (Note 5)		8	300	10^{-6}	Video (buffered streaming) TCP-based (www, email, chat, ftp, ptp file sharing, progressive video, etc.)
9 (Note 6)		9	300	10^{-6}	Video (buffered streaming) TCP-based (www, email, chat, ftp, ptp file sharing, progressive video, etc.)

NOTES	
(1)	A delay of 20 ms for the delay between a PCEF and a radio base station should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface. This delay is the average between the case where the PCEF is located "close" to the radio base station (roughly 10 ms) and the case where the PCEF is located "far" from the radio base station, e.g. in case of roaming with home routed traffic (the one-way packet delay between Europe and the US west coast is roughly 50 ms). The average takes into account that roaming is a less typical scenario. It is expected that subtracting this average delay of 20 ms from a given PDB will lead to desired end-to-end performance in most typical cases. Also, note that the PDB defines an upper bound. Actual packet delays - in particular for GBR traffic - should typically be lower than the PDB specified for a QCI as long as the UE has sufficient radio channel quality.

Figure 50: Packet delay budget values from NGMN paper [62]

4.8 Market attribute percentages

A series of market attribute percentages are set within the ITU-R M.1768-1 model to further vary the service parameters used from their baseline settings:

- U%: User density
- Q%: Session arrival rate per user
- R%: Mean service bit rate
- µ%: Average session duration

We have briefly reviewed these percentages and noticed that the ITU default settings for these percentages have some inconsistencies over time i.e. they increase, then decrease and then increase again in some cases. We are not aware of any reason why these percentages would fluctuate over time and so in our baseline settings of the ITU model we have instead reverted to market attribute percentages as recommended by the WINNER study which, while still close to the ITU default settings, are more consistent over time.

The WINNER suggested values that we have adopted in all but the U% case suggest the following trends in the market attribute percentages over time:

- U% kept constant over time at 20%
- Q% kept constant over time at 25%
- R% a constant increase with time of 5% per year
- µ% a constant decrease with time of 10% per year

Note that WINNER values are only provided to 2020. For our 2025 and 2030 estimates we assume that the Q%, R% and µ% remain constant from 2020 onwards. This is because to continue the trend of decreasing the µ% over time would reduce the average session duration for some SCs to zero by 2030 which is not realistic.

We have not adopted the U% values from the WINNER study which control user density as we instead calibrate this so that the distributed demand density being served by the ITU model meets our UK specific demand estimates as discussed under model calibration in appendix A.

4.9 Critique of mean session duration

We have briefly reviewed the ITU default settings for mean session duration and noticed that the ITU default values contain inconsistencies such as the mean session duration fluctuating over time. In our analysis we have therefore reverted to the mean session duration settings as suggested by the WINNER study as these are close to the ITU default settings but give a consistent 10% reduction per year.

Note in our demand research we did find sources indicating that as mean service levels improve mean session durations may increase as users will be encouraged to spend longer using a service if the user experience is more reliable and the service overall less frustrating to use. This suggests a trend of increasing mean session durations potentially which is counter to the assumption in the WINNER study that mean session durations will decrease over time as the performance of mobile services improves and users therefore can access the same amount of data in less time.

Overall the mean session duration does not appear to impact the spectrum estimate greatly and so we have not examined the impact of mean session duration increasing rather than decreasing over time in our sensitivity analysis in the time limits of this study.

4.10 Summary of changes to service and market related parameters

Figure 51 provides a summary of the changes to ITU recommended values for the service and market related ITU-R M.1768-1 model parameters in our recommended model baseline settings.

Parameter	Recommended updates	Comments	Impact on spectrum requirements of input revision
User density	Calibrate to match UK specific demand	The user density for each service category and service environment is calibrated so that the distributed demand per teledensity matches Real Wireless UK specific demand forecasts for each teledensity.	Generally our baseline UK user densities are slightly higher than the ITU low market setting which would drive spectrum requirements up. Note that the impact is mixed across SEs and demand scenarios though.
Mean service bit rate	ITU default values	We maintain mean service bit rates as per ITU default settings but note that in combination with our application rate settings that this means little or no traffic in SC 11 and SC 16 representing services above 30Mbps (which are unlikely to target wireless networks in the near term at least).	No impact.
Mean session duration	Use WINNER values	WINNER values are close to ITU default mean session duration settings but have a consistent 10% reduction per year whereas ITU default settings fluctuate over time.	Minor as very close to ITU default setting.
Session arrival rate	ITU default setting	We have not reviewed session arrival rates in detail and have used the ITU default settings for this in our analysis.	No impact
Mobility ratio	ITU default settings	Our baseline follows the ITU default settings on the basis that suggested updates were relatively minor. We also investigate changes in mobility ratio further in our sensitivity analysis.	No impact
Maximum allowable blocking probability	ITU default setting	We have not reviewed the maximum allowable blocking probability in detail and have used the ITU default settings for this in our analysis.	No impact
Maximum allowable mean IP packet delay	Update to use NGMN and 3GPP values	The tolerable packet delays in the ITU default settings are much lower than those recommended by 3GPP and NGMN. This has a big impact on spectrum requirements in the queuing theory element of the model and so we have reverted to NGMN and 3GPP values in our analysis.	Increasing the tolerable packet delays in our baseline compared with ITU settings will decrease overheads in the queuing theory block and decrease spectrum requirements.

Parameter	Recommended updates	Comments	Impact on spectrum requirements of input revision
Mean IP packet size	Update to Real Wireless recommended values	Real Wireless values draw on mean packet sizes from recent industry papers. These assume that fragmentation of packets for mobile networks would occur so as not to exceed the MTU for Ethernet in IP networks today of 1500 bytes even with jumbo mode IP packets. Real Wireless recommended values also do not fluctuate over time as was the case in the ITU default settings.	Decreasing the mean packet size relative to the ITU default settings will decrease overheads required in the queuing theory block and decrease spectrum estimates.
Second moment of IP packet size	Update to reflect Real Wireless recommended values for mean IP packet size	Our analysis also uses updated packet size variance in line with changes to the mean packet size squared. Note that our recommended values for the second moment of packet size maintain the ITU standard error in packet size across SCs but require further review as we observed that the ITU standard error levels can result in negative packet sizes in some cases.	As above.
Market attribute percentages	Update to WINNER suggested values with 2020 values kept constant out to 2030.	Our analysis uses the suggested market attribute percentages from the WINNER study as while these are close to the ITU default settings they have a more consistent trend over time than the ITU default settings. Note that the WINNER study has no suggested values for 2025 and 2030 so we use the 2020 suggestions for both of these as to follow the WINNER trend would result in zero values for average session duration of some SCs by 2030.	Minor as close to ITU default setting.

Figure 51: Summary of changes to service and market related parameters (Green: ITU default setting, amber: minor changes close to ITU default setting, red: major changes against ITU default settings)

5. Appendix E - Technology and network assumptions

This chapter reviews the input parameters to the ITU-R M.1768-1 model that describe the radio access technologies and networks within each service environment that are assumed to be available to carry the demand density input to the model. Figure 52 highlights the input parameters that we have reviewed in this appendix to ensure that they:

- Reflect typical site numbers in the UK's cellular networks.
- Reflect the expected capabilities of the UK's cellular networks over time.
- Reflect the UK's appetite for offloading traffic from wider area macrocellular networks via small cellular cells in licensed spectrum and Wi-Fi integration into cellular networks.

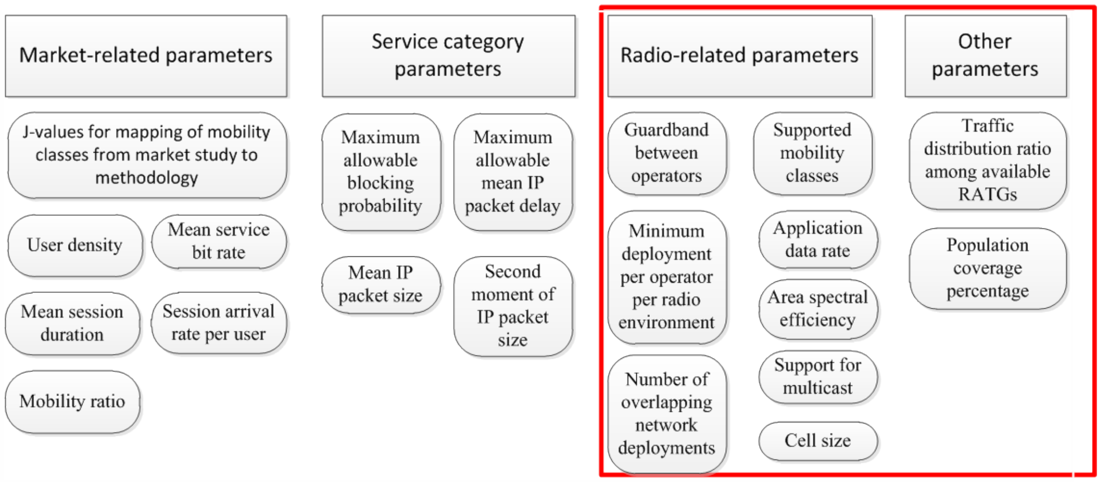


Figure 52: Input parameters for ITU-R M.1768-1 model with the technology and network related parameters discussed in this appendix highlighted

5.1 Review of guard bands between operators

5.1.1 Parameter description

The ITU-R M.1768-1 model permits additional spectrum to be allowed for in the spectrum requirements estimate that it generates to account for a guard band between operators. Once a spectrum estimate per operator has been determined by the model based on serving the required demand levels input to the model this parameter adds additional spectrum to account for a guard band between the spectrum allocations of different operators. This parameter can be set differently per RATG but cannot be varied over time in the model.

5.1.2 Recommended values

In the recommended model settings that are set out by ITU-R working party 5D in their work in progress response to JTG 4-5-6-7 [50], the guard band between operators is set to 0MHz for both RATG1 and RATG2. Note that there is no guard band setting for RATG3.

Setting the guard band between operators to 0MHz assumes that FDD spectrum will dominate the way that the spectrum requirements for the model will be allocated in practice. This preference for FDD spectrum reflects UK spectrum usage currently and for the foreseeable future with the vast majority of wireless broadband systems in the UK being FDD based. We therefore maintain the ITU recommended setting of 0MHz for the guard band between operators for both RATG1 and RATG2 but note that this guard band level may need to be reconsidered if particular assumptions on TDD spectrum availability are to be investigated at any stage.

	ITU recommended value	RW baseline setting
RATG1	0 MHz	0 MHz
RATG2	0 MHz	0 MHz
RATG3	No guard band setting required in model inputs	No guard band setting required in model inputs

Table 44: ITU recommended values and Real Wireless baseline settings for guard band between operators

5.2 Review of minimum deployment per operator per radio environment

5.2.1 Parameter description

The minimum deployment per operator per radio environment parameter sets the minimum spectrum allocation that an operator can have when deploying a network of a particular radio access technology. This parameter varies with RATG and cell type in the model but is fixed over time.

5.2.2 Recommended values

The ITU recommended value for this parameter is 20MHz in all cell types for both RATG1 and RATG2. This aligns with the maximum supported bandwidth for LTE networks but note that LTE can also be deployed at 5MHz and 10MHz. In the case of LTE-A bandwidths could reach much higher levels via carrier aggregation. The EU WINNER project [49] that developed the Excel implementation of the ITU-R M.1768-1 model, that is now being used by working party 5D and this study, recommended minimum deployment bandwidths of 10MHz across RATG1 and RATG2 which is more aligned with the typical baseline spectrum deployment that operators are expected to roll out LTE networks at. This parameter is not required for RATG3.

Our recommended baseline setting for the model is to use 5MHz as the minimum deployment per operator for both RATG 1 and 2 and across all cell types. This is based on:

- Being the minimum supported bandwidth for UMTS, LTE, and LTE-A networks.
- Being the setting that will give the highest resolution spectrum estimate from the model which can then be interpreted based on different scenarios for how operators would deploy this spectrum requirement in practice. Note that this will likely include a mixture of supported bandwidths with some operators having acquired spectrum licences for wider bandwidths at particular frequencies than others.
- Results of the recent auction of spectrum at 2.6GHz and 800MHz in the UK, which will likely be used to deploy LTE and future networks, which show some

operators acquiring only 2x5MHz of FDD spectrum in some bands and hence indicating that 5MHz is still considered a useful deployment bandwidth by Mobile Network Operators (MNOs) [64].

The ITU default settings, WINNER recommended values and our recommended baseline settings for the minimum deployment per operator are compared on Table 45.

	Macrocell	Microcell	Picocell	Hotspot
ITU default setting	20 MHz	20 MHz	20 MHz	20 MHz
WINNER suggested values	10MHz	10MHz	10MHz	10MHz
Real Wireless baseline setting	5MHz	5MHz	5MHz	5MHz

Table 45: ITU recommended values and Real Wireless baseline settings for minimum deployment per operator per radio environment for RATG 1 and RATG2 (not required for RATG3)

We note that the ITU-R M.1768-1 model assumes that three spectrum layers are needed for RATG1 i.e. a spectrum layer for macrocells, one for microcells and one for picocells and hotspots combined. In the case of RATG2 the working party 5D draft response to JTG 4-5-6-7 suggests that the spectrum calculation algorithm in ITU-R M.1768-1 assumes that macrocells and microcells share a large cell spectrum layer and picocells and hotspots are operated on a separate small cell carrier. However, the current Excel implementation of the ITU-R M.1768-1 model appears to maintain the three spectrum layer assumption for RATG2 in the same way as for RATG1. Either approach may arguably give a pessimistic spectrum estimate as they are slightly different to how carriers are arranged in current UK cellular networks in practice.

In the case of GSM services UK operators tend to have separate carriers for macrocells and microcells as reflected by the ITU-R M.1768-1 assumptions. In UMTS deployments UK operators tend to reserve a first carrier for macrocell wide area coverage and a second carrier for capacity that can be used by either macrocells or microcells. In the case of Vodafone a third capacity carrier exists which has been used for femtocell deployments. Other UK operators without the availability of a third carrier for femtocells have deployed femtocells so that they use bandwidth from both the first coverage carrier and second capacity carrier and hence effectively share spectrum with higher network layers.

This needs to be kept in mind when interpreting spectrum results from the model. Also, there will be requirements for minimum amounts of spectrum to remain available to operators to support backwards compatibility with older GSM and UMTS legacy handsets in the existing device population for some years to come.

To avoid confusion our spectrum estimates are reported for:

- A best case “shared” spectrum estimate based on spectrum sharing between all network layers
- A worst case “dedicated” spectrum estimate based on separate carriers being required for each network layer

In practice the actual amount of spectrum required will be between these two scenarios with a more detailed interpretation of results for various operator approaches possible based on the detailed spectrum estimates from the model which split spectrum requirements by teledensity and cell type.

5.3 Review of number of overlapping network deployments

5.3.1 Parameter description

Within the ITU-R M.1768-1 model the number of overlapping deployments for each RATG can be set which describes the number of operators typically expected to be deploying networks to support the spectrum requirements output by the model. This parameter is set per RATG but cannot vary over time or cell type in the model.

5.3.2 Recommended values

This setting has the impact of rounding up the spectrum requirement reported by the model to allow for multiple operators each needing to deploy carriers using at least the bandwidth set by the minimum deployment per operator parameter discussed in section 5.2 i.e. 5MHz in our baseline setting. For example if the number of overlapping networks was 3 and the minimum deployment size was set to 5MHz the model would round up spectrum estimates to the nearest 15MHz.

The ITU suggest setting the number of overlapping networks for both RATG1 and RATG2 to 1. Our recommended baseline setting also reflects this despite there being more than 1 wireless broadband operator in the UK today. This is because, in the same rationale as for recommending setting the minimum operator deployment to the minimum 5MHz level, maintaining this parameter at 1 will give the highest resolution spectrum estimate from the model which can later be interpreted for varying scenarios of operators supported over time. This also allows for interpretation of the results for more complex situations such as localised providers of wireless broadband services emerging offering access to small cells in towns and cities that could be used by multiple wide area operators. For example, the recently acquired mobile broadband spectrum in the UK by Niche Ventures [64], who do not have an existing nationwide cellular network in the UK, could be used to provide wireless broadband access via small cells in capacity constrained busy city areas as a wholesale service to multiple nationwide cellular operators. Developments like this make the best setting for the number of overlapping network deployments less clear and favour an approach which gives the highest resolution spectrum estimate from the model which can later be interpreted for different operator scenarios.

5.4 Review of supported mobility classes

5.4.1 Parameter description

The supported mobility class settings in the ITU-R M.1768-1 model set the maximum user velocity supported by each combination of RATG and cell type.

When demand is input to the model it is distributed across SEs. Within each SE this demand is then distributed across users with different mobile requirements depending on the assumed proportion of users in the various mobility classes for each SE. The mobile requirements of users can vary from pedestrians to those in vehicles and to those on high speed trains. This demand is then distributed across available RATGs (that can support the mean service bit rate of the services making up the demand) before being distributed across cell types or network layers for each RATG. The distribution of demand across cell types is affected by the supported mobility class of a particular cell type. For example, hotpots will likely only support traffic from stationary or pedestrian users whereas macrocells should support users travelling at high speeds as seen on trains.

5.4.2 Recommended values

Table 46 summarises the ITU recommended mobility class settings across the supported combinations of cell types and RATGs. For RATG1 and RATG2 this implies that:

- Macrocells can address all users including those travelling at the highest speeds on trains
- Microcells address mobile users including those in vehicles but travelling at speeds seen in built up areas rather than motorways
- Picocells and hotspots are used by pedestrians and stationary users only

The WINNER study did not suggest any updates to these values.

	Macrocell	Microcell	Picocell	Hotspot
RATG1	250 km/hr	50 km/hr	4 km/hr	4km/hr
RATG2	250 km/hr	50 km/hr	4 km/hr	4 km/hr
RATG3	0 km/hr	0 km/hr	4 km/hr	4 km/hr

Table 46: ITU recommended supported mobility class settings across RATGs (as supported by WINNER and maintained in our baseline model settings)

We support these mobility class settings and reflect them in our recommended baseline model settings. However, we note that in the case of hotspots using Wi-Fi and to a lesser extent cellular picocells and femtocells today that there are some issues with handover between cells and so arguably support for pedestrians over areas greater in size than the average house requiring multiple access points may be limited. However, with the introduction of standards such as Hotspot 2.0 the integration of Wi-Fi into cellular networks is fast improving and we assume that these issues of handover will be resolved by 2015 and hence the ITU assumption is valid for the majority of the timescale this study considers.

5.5 Review of application rates

5.5.1 Parameter description

Within the ITU-R M.1768-1 model an application rate is set for each combination of cell type and RATG. This limits the services that can make use of each of the network layers of each RATG by comparing the service bit rate of each service category against this application rate.

Note that there is some debate on whether this parameter should be the minimum cell edge application rate (i.e. the service that all users in a cell can receive although most will be above this) or if it should be the average data rate in a cell (representing the service level that a user can on average expect to receive but not be guaranteed to receive at all times particularly at the cell edge).

It is also noted that the supported application rate will vary by teledensity with macrocells in dense urban deployments with small sector areas likely to support much higher application rates than those in rural areas with larger sector areas (although the ITU model does not facilitate changing the application rate by teledensity).

5.5.2 Recommended values – RATG1

A comparison of the ITU recommended application rates for RATG1 against those given by the WINNER study and our own recommended baseline settings is shown in Table 47.

Year	Macrocell / Mbps			Microcell / Mbps			Picocell / Mbps			Hotspot / Mbps		
	ITU	WINNER	RW	ITU	WINNER	RW	ITU	WINNER	RW	ITU	WINNER	RW
2010	20	1	1	40	1	1	40	2.5	2.5	-	-	-
2015	20	1	2	40	1	17	40	2.5	20	-	-	-
2020	20	1	2	40	1	17	40	2.5	20	-	-	-
2025	-	-	2	-	-	17	-	-	20	-	-	-
2030	-	-	2	-	-	17	-	-	20	-	-	-

Table 47: Comparison of RATG1 application rates from ITU and WINNER against Real Wireless recommended baseline setting

In our baseline setting we assume that RATG1 macrocells will be deployed to target coverage and hence base macrocell application rates over time on cell edge rates of the leading air interface within RATG1 for a given year.

In line with the WINNER study we felt that the ITU recommended RATG1 application rates for 2010 were too high particularly given that for the UK at least the main RATG1 networks deployed would have been GSM and HSPA+. In our recommended baseline we adopt the WINNER suggested values for RATG1 application rates over the ITU values for 2010 based on:

- The assumption that UMTS/HSPA+ networks would have delivered the majority of the data traffic in the UK compared to GSM in 2010
- WINNER values appear more in line with expected performances on HSPA+ networks than ITU values
- The WINNER values largely align with our average RATG1 spectral efficiency values (see section 5.6) in a 5MHz bandwidth (as would be used for HSPA+) with some allowance made for practical inefficiencies in real networks due to loading and mixed traffic[5].

From 2015 onwards we increase data rates in line with the roll out of LTE networks whereby we calculate data rates based on:

[5] In [66] a 85% correction for loading and a 65% correction for mixed traffic is recommended for these practical inefficiencies for LTE networks. However, this may be different for HSPA+ networks due to different network architectures and use of dedicated bearers between HSPA+ and LTE.

- Macrocells being deployed to provide coverage and targeting cell edge rates of 2Mbps (in line with coverage obligation levels imposed on some lower frequency LTE bands in the UK [65])
- Microcells and picocells being deployed with performance in mind and hence suggest data rates within expected average spectrum efficiency values (see section 5.6) adjusted for loading (85% correction) and mixed traffic (65% correction) as per [66] in the maximum LTE bandwidth of 20MHz. We then limit suggested values to a maximum of 20Mbps as per practical target cell edge data rates being suggested for LTE outdoor small cells [67].
- Higher frequency, low range hotpot cells not being deployed for RATG1 in line with the ITU and WINNER recommendations.

5.5.3 Recommended values – RATG2

A comparison of ITU recommended values for RATG2 application rates against those in our recommended baseline setting across the different cell types is shown in Table 48. Note that the WINNER study did not suggest any updates to the ITU recommended settings for RATG2 application rates.

Year	Macrocell / Mbps		Microcell / Mbps		Picocell / Mbps		Hotspot / Mbps	
	ITU/ WINNER	RW	ITU/ WINNER	RW	ITU/ WINNER	RW	ITU/ WINNER	RW
2010	50	0	100	0	1000	0	1000	0
2015	50	0	100	0	1000	0	1000	0
2020	50	34	100	38	1000	50	1000	80
2025	-	50	-	100	-	1000	-	1000
2030	-	50	-	100	-	1000	-	1000

Table 48: Comparison of RATG2 application rates from ITU and WINNER against Real Wireless recommended baseline setting

We felt that the ITU recommended values are ambitious for target data rates on initial LTE-A deployments given that these initially will be upgrades to existing LTE networks to support wider bandwidths and higher orders of MIMO and, in line with our recommended setting for traffic distribution across RATGs see section 5.10, will not start to be deployed in the UK until 2020.

Our recommended baseline setting for RATG2 application rates is therefore lower than the ITU recommended values initially but then does converge on the ITU values by 2025 based on the following assumptions:

- LTE-A only gets deployed in the UK from 2020 onwards as LTE networks are only starting to emerge in the UK as at 2013.
- LTE-A networks are deployed alongside LTE targeting performance rather than coverage and so base application rates for RATG2 on average achievable data rates rather than cell edge rates as was the case for RATG1.

- Suggested application rates for 2020 are based on average spectral efficiencies for LTE-A (see section 5.6) in a 20MHz adjusted for loading (85% correction) and mixed traffic (65% correction) based on [66].
- From 2025 onwards we suggest that the ITU recommended application rates would become feasible in LTE-A networks based on:
  - An increase in expected spectrum efficiencies in LTE-A between 2020 and 2025 of a 1.6 times.
  - Increases in bandwidth via carrier aggregation techniques becoming available at this time.
- In line with ITU recommended values we include application rates for LTE-A hotspots on the assumption that these will be very short range, high capacity small cells operating at high frequencies where wider bandwidths are available and be similar in range to today's Wi-Fi access points.

5.5.4 Recommended values – RATG3

A comparison of ITU recommended values for RATG3 application rates against those in our recommended baseline settings across the different cell types is shown in Table 49. Note that the WINNER study did not suggest any updates to the ITU recommended settings for RATG3 application rates. Also note that the Excel implementation of the ITU-R M.1768-1 model as received from ITU working party 5D did not include the ability to vary RATG3 application rates over time but we have set up the model to be run on a year by year basis for our LE spectrum estimates as we felt it was important to reflect a variation of RATG3 application rates over time in our analysis.

Year	Macrocell / Mbps		Microcell / Mbps		Picocell / Mbps		Hotspot / Mbps	
	ITU/ WINNER	RW	ITU/ WINNER	RW	ITU/ WINNER	RW	ITU/ WINNER	RW
2010	-	-	-	-	50	0	500	35.8
2015	-	-	-	-	50	17.3	500	113.2
2020	-	-	-	-	50	40.2	500	240.3
2025	-	-	-	-	-	50	-	526.3
2030	-	-	-	-	-	50	-	1052.6

Table 49: Comparison of RATG3 application rates from ITU and WINNER against the Real Wireless recommended baseline setting

More specifically running the model to allow the RATG3 application rate to vary over time allowed us to:

- Introduce "Super Wi-Fi" picocells at a particular year in our analysis rather than assuming they are available from 2010 as in the ITU recommended values.
- Set a RATG3 application rate that increases over time in line with support for various evolutions of the IEEE 802.11 standards and 2.4GHz and 5GHz bands over time and developments beyond these into non Wi-Fi focused LE technologies and bands over time.

- Gain finer control on the service categories that RATG3 will be able to support at particular points in time.

Generally the ITU recommended settings for RATG3 application rates appear ambitious against Wi-Fi devices available on the market today. For example, the ITU default setting for RATG3 hotspots is 500Mbps which would only be achieved as a maximum data rate by 802.11 ac with bandwidths at or above 40MHz and support for four spatial streams.

In the case of picocells we consider that there are no RATG3 access points with extended range beyond Wi-Fi hotspots available in the UK market today. However, "Super Wi-Fi devices" are being developed in TVWS spectrum at 800MHz and will eventually become available (from 2015 at the earliest) with larger than hotspot ranges. We consider these types of devices in this RATG3 picocell category but only introduce them from 2015 onwards.

Our suggested revisions to the RATG3 application rates against the ITU recommended values are based on:

- Generating blended maximum anticipated RATG3 throughputs over time which are based on the anticipated mix of support for 802.11 standards and for bandwidths beyond 20MHz using the 5GHz spectrum band in Wi-Fi devices in the UK which is in turn based on Wi-Fi device forecasts from a recent report by Plum Consulting [17] for Cisco on Wi-Fi future proofing (see Figure 53).
- Reducing maximum throughputs by 45% to get the average expected throughput on real networks based on simulation results in [68] and [69] which showed an average of 6Mbps to a maximum of 11Mbps for 802.11b. This also largely aligns with the recommendation in the Plum Consulting report of a 60% conversion for maximum to average data rates [17]. Although this reduction (to 55% of the maximum throughput) is based on a home environment we note that there may be corner points in dense outdoor environments where congestion is at higher levels and this reduction may indeed need to be greater.

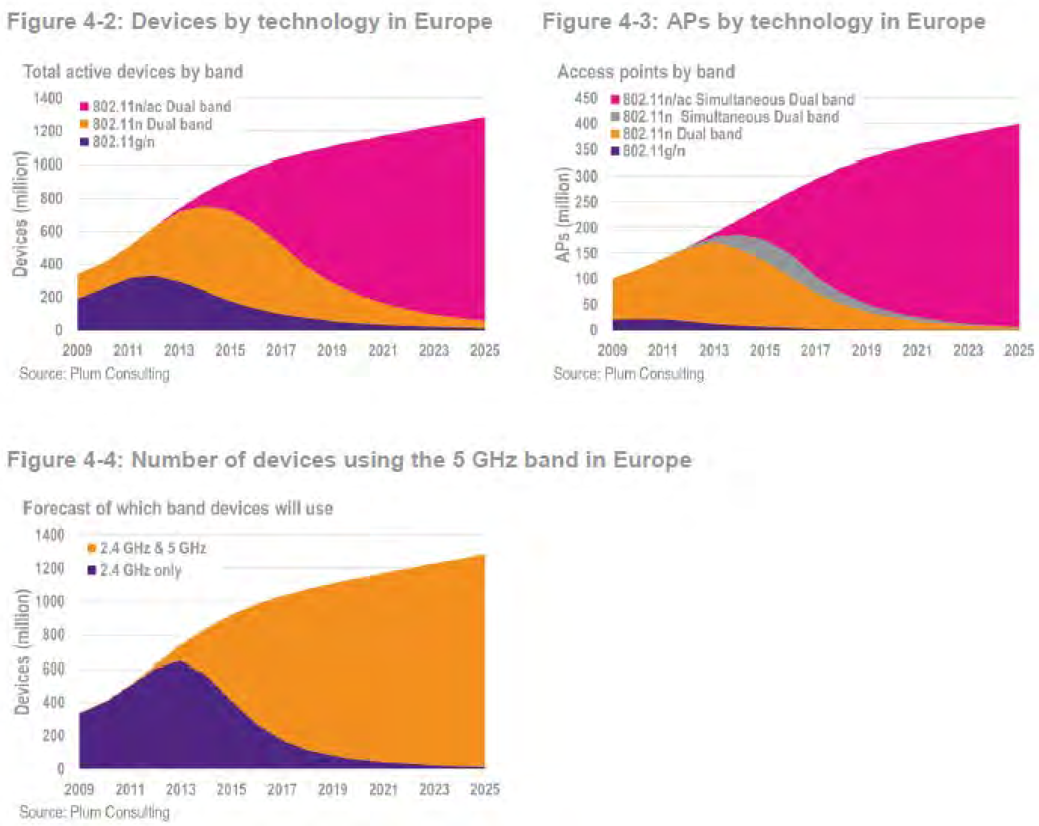


Figure 53: Extract from Plum Consulting report [17] with forecasts on support for various 802.11 generations of technology in devices and access points and support for higher bandwidths via 5GHz spectrum (note we assume application rates are limited by the device rather than access point capability)

Table 50 shows our assumed proportion of access points (APs) within RATG3 with support for the various 802.11 standards and bandwidths over time. As mentioned earlier these are largely based on forecasts from Plum Consulting (see Figure 53) but with the following updates applied:

- While the Plum report shows very limited support for 5GHz during 2010 (sub 1%) there were 802.11n devices available on the UK market in 2010 that could support 40MHz at 2.4GHz. We therefore assume 5% of devices could support 40MHz bandwidths in 2010 as these were relatively new on the market with 802.11n only ratified in 2009.
- We assume in 2015 that the 25% of devices forecast by Plum to support 802.11ac will use the wider 40MHz bandwidth. This is in line with the forecast that 50% of devices overall will have support for the 5GHz band by then and hence wider bandwidths beyond 20MHz as is the limitation at 2.4GHz. The remaining 25% of devices supporting 5GHz we assume to be 40MHz 802.11n devices.
- We start to introduce a 50:50 split between support for 40 MHz and 80 MHz in 802.11ac from 2020 onwards to show an evolution towards wider bandwidths.
- The Plum Consulting report claims that the majority of portable devices today only support 1 stream. However, by 2015 we assume 2 streams will be supported in line portable devices for 2x2 LTE baseline deployments becoming available at this time.

- The Plum Consulting report indicates that it is unlikely that 4 spatial streams would be reached within their forecast period which goes out to 2025 but we disagree and include 4 streams from 2025 in line with LTE-A devices supporting higher orders of MIMO becoming available in these timescales. We also introduce 8 streams in 2030 to represent an evolution of 802.11ac to 802.11ad by then and support for bandwidths beyond 80MHz with higher data rates. We note that 3x3 MIMO access points will likely be available before 2025 but in our analysis aim to represent MIMO support in the majority of RATG3 devices.

Year	802.11g in 20MHz / % APs	802.11 n in 20MHz / % APs	802.11 n in 40MHz / % APs	802.11ac in 20MHz / %APs	802.11ac in 40MHz / % APs	802.11ac in 80MHz / % APs	Max no. of streams	Blended max data rate/ Mbps	Blended average data rate/ Mbps
2010	0.6	0.35	0.05				1	65.2	35.8
2015	0.25	0.25	0.25		0.25		2	205.9	113.2
2020	0.03		0.2		0.385	0.385	2	437.0	240.3
2025	0.005		0.02		0.4875	0.4875	4	956.9	526.3
2030	0.005		0.02		0.4875	0.4875	8	1913.8	1052.6

Table 50: Proportion of RATG3 devices with support for each air interface and bandwidth over time based largely on forecasts from Plum Consulting from Figure 53 and assuming 802.11ac and 802.11n uses wider bandwidths in proportion to support for the 5GHz band

We acknowledge that 802.11ac will be capable of supporting wider bandwidths than we have considered here of up to 160MHz. However, we assume that this 160MHz bandwidth will only be used in a very small proportion of the device population. This is based on:

- The split of the current LE allocation at 5GHz meaning that it is only possible to form two contiguous 160MHz channels which are only available in particular locations where this band is not already being used by Radar. With such limited availability it is unlikely these 160MHz channels would be used in busy locations in practice where multiple access points would need to be accommodated.
- The proposed extension of the 5GHz band would make four contiguous 160MHz channels available which makes using these wider bandwidths more feasible but this is still limited to areas where radar is not already in operation and more than four access points at this higher bandwidth are not contending for service.

Based on the assumed capability of Wi-Fi devices over time, as given in Table 50, and the maximum supported data rates across these, see Table 51, we calculate the blended maximum supported RATG3 throughputs over time and then convert this to average supported throughputs based on a 45% reduction as mentioned earlier (see Table 50). The resulting blended average RATG3 throughputs are then used for our recommended baseline setting for RATG3 hotspot application rates.

	802.11g in 20MHz	802.11 n in 20MHz	802.11 n in 40MHz	802.11ac in 20MHz	802.11ac in 40MHz	802.11ac in 80MHz	802.11ac in 160MHz
Maximum feasible data rate per stream	54	72.2	150	81.25	162.5	325	866
Maximum no. of streams	1	2	2	4	4	4	4

Table 51: Data rate per stream and maximum number of streams supported by each 802.11 air interface based on Plum report [17]

Our recommended baseline settings for picocell RATG3 application rates over time are calculated based on our recommended spectrum efficiencies for RATG3 picocells (see section 5.6) and the following assumptions:

- That the dense urban environment will be the most congested for LE picocells and hence be the limiting case for LE picocells spectrum requirements. We therefore use average spectral efficiencies from the dense urban case in calculating supported RATG3 picocell application rates.
- That 8MHz of bandwidth will be available in 2010 and 2015 for RATG3 picocells in line with potential TVWS availability in the UK and that this will increase to 16MHz of bandwidth being available from 2020 onwards.
- That practical application rates for picocells are limited to 50Mbps in future years in line with ITU recommended settings. Note that in the case of hotspots we did not limit application rates at the suggested ITU setting as higher rates may be available by 2030 via standards such as 802.11ad.

5.5.5 Application rates investigated in sensitivity analysis

It is not clear whether the application rate setting for the ITU-R M.1768-1 model should be set to:

- Cell edge throughputs
- Average cell throughputs
- Maximum throughputs achievable in the cell

The Real Wireless recommended baseline settings discussed in the previous sections assume that RATG1 is used for coverage and so the application rate for RATG1 macrocells is limited to cell edge rates. For RATG2 and RATG3 we assume that these are used for performance and so the application rates in these cases are in line with average cell rates that users could expect from these technologies in the different cell sizes.

In our sensitivity analysis described in section 4.8 of the final report we have investigated the sensitivity of results to application rate assumptions via examining spectrum requirements for the following three cases:

- Real Wireless medium demand and baseline model settings which assume average data rates for RATG2 and 3 but cell edge rates for RATG1.

- Real Wireless medium demand and baseline model settings but with ITU application rates (which are more in line with maximum achievable data rates for each RATG).
- Real Wireless medium demand and baseline model settings but with average cell edge rates used for the application rate in all RATGs (which is an increase over our baseline but less than the ITU values). This case might be more representative of performance in cells in dense urban and suburban areas which are capacity rather than coverage limited. This only impacts the RATG1 application rates by increasing them above our baseline setting as RATG2 and RATG3 are already set in the baseline scenario to average data rates based on the average achievable spectral efficiency.

In this third case we update our RATG1 application rates to be in line with average achievable data rates over RATG1 air interfaces based on our assumed average spectral efficiency values given in section 5.6 and adjustments for inefficiencies encountered in practice on real networks.

For 2010 RATG1 application rates we maintain the same values in this third sensitivity case as we had in our recommended baseline model settings which are taken from WINNER and as discussed in 5.5.2 already largely align with expected average HSPA+ throughputs.

For 2015 onwards in this third case we apply average achievable RATG1 data rates based on:

- The average spectral efficiency values for RATG1 in our baseline model settings given in section 5.6
- Allowing a 10MHz bandwidth for macrocells (i.e. a typical baseline LTE deployment) and 20MHz bandwidth for microcells and picocells (i.e. a wider bandwidth reflecting these smaller cells being deployed targeting performance enhancements)
- Allowing 85% and 65% adjustments for the loading and mixed traffic effects of real networks respectively [66].

This leads to the RATG1 application rates shown in Table 52 being applied in this third sensitivity analysis case.

Year	Macrocells	Microcells	Picocells	Hotspots
2010	1 Mbps	1 Mbps	2.5 Mbps	-
2015	8 Mbps	17 Mbps	29 Mbps	-
2020	8 Mbps	17 Mbps	29 Mbps	-
2025	8 Mbps	17 Mbps	29 Mbps	-
2030	8 Mbps	17 Mbps	29 Mbps	-

Table 52: Application rates assumed for the average application rate case for RATG1 for our sensitivity analysis

5.6 Review of area spectral efficiency

5.6.1 Parameter description

The ITU-R M.1768-1 model allows the user to specify the area spectral efficiency assumed per combination of RATG and cell type in the model. This can be set to vary over time also and is defined in bps/Hz/cell (where a cellular site may support more than one cell or sector).

We note that there is a relationship between spectral efficiency and cell size. This is due to the area spectral efficiency being defined as being calculated from the mean data throughput achieved over all users, which are homogenously distributed in the area of the radio environment, on the IP layer for packet switched services and on the application layer for circuit switched services [49].

We also note that a completely accurate estimation of the area spectral efficiency of a radio system is inherently difficult to achieve since issues such as the deployment type, interference, scheduling, cell load and protocol effects (e.g. TCP slow start) all come into play and interact in a complicated manner to impact average data rates achieved in a cell and hence spectral efficiency. The results are also heavily dependent on a number of assumptions such as site density, the number of sectors per site, the number of transmit and receive antennas and the complexity of the signal processing in the receiver (which is related to terminal price) [49].

5.6.2 Recommended values – RATG1 and RATG2

The ITU recommended values for the spectral efficiency levels of RATG1 and RATG2 are a combination of contributions from several administrations and companies. However, it is likely that results across these contributions will be varied due to different assumptions on, for example, propagation models and multi-antenna capabilities. The WINNER study has reflected on some of these differences and suggested spectral efficiency values that are largely lower than the ITU recommended values. In particular the WINNER study noted that ITU recommended values reflect 3GPP target LTE characteristics which will be high compared to real network performance levels [49]. We also note that ITU and WINNER spectral efficiency estimates were derived at 5GHz which is not representative of cellular frequency bands typically used in the UK today [70].

In recommending spectral efficiency values for RATG1 and RATG2 in our baseline model setting we have considered:

- Values recommended by ITU and currently used within working party 5D which are based on [70]:
    - Target 90% satisfied users (typically 98% is assumed)
    - Full buffer traffic model
    - Pedestrian 3 km/h
    - Perfect synchronization, channel estimation, and link adaptation
    - Ideal estimation for and synchronization for inter-cell interference suppression
    - Ideal control feedback without errors and delay
    - No consideration of outdoor-to-indoor coverage

    - No consideration of point-to-multipoint or broadcasting services
    - No consideration of overhead
- Values recommended by the WINNER study which considered additional effects beyond the ITU values including [49]:
    - Scheduling
    - Cell load
    - Protocol effects
    - Complexity of signal processing in the receiver
- Findings from an article in ETRI journal regarding the use of the ITU-R M.1768-1 model for spectrum estimates for the Korean mobile broadband market which includes an overhead allowance in spectral efficiencies [71].
- Values extracted from our simulation model to assess techniques for increasing network capacity in our UHF strategy study for Ofcom. This made assumptions on the spectral efficiency of cellular networks out to 2030 in different bands, cell types and clutter types and included an allowance for loading and mixed traffic as found on real networks [1]. The spectrum efficiency values used in this study are in turn largely based on findings from our 4G capacity gains study for Ofcom [66] which reviewed spectral efficiency values from system level simulations for the assessment of technologies against ITU IMT-Advanced in a FDD, urban deployment at 2GHz using a 2x10MHz bandwidth. The overall spectral efficiency levels reported at any point in time in this 4G capacity gains study were based on the blend of device and network capabilities available at that time and presented both with and without adjustments for loading and mixed traffic (as opposed to full buffer traffic) to represent some of the inefficiencies of real networks.

Comparing spectral efficiency values across these sources consistently showed the ITU recommended values for spectral efficiency to be optimistic. For example, in Figure 54 we compare the spectral efficiency values given across these sources for RATG1 in 2010 which shows the ITU recommended values to be high compared to others. We have therefore revised spectral efficiency values from the ITU recommended values in our recommended baseline settings for the ITU-R M.1768-1 model.

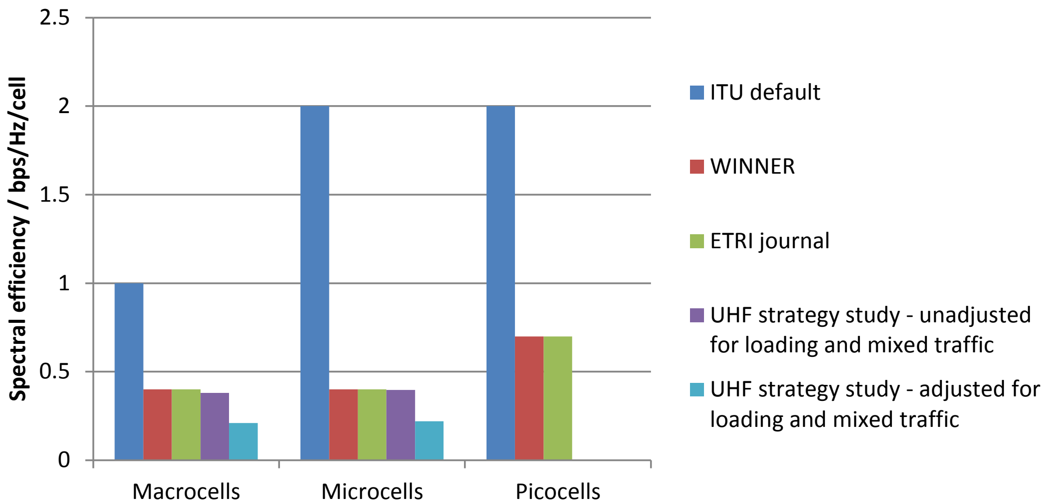


Figure 54: Example comparison of spectral efficiency values for RATG1 in 2010 extracted from reviewed sources

To determine which spectral efficiency source gives the most realistic spectrum estimate we have compared spectrum estimates for 2010 and 2015 generated by the ITU-R M.1768-1 model for our medium UK specific demand levels and our recommended baseline model settings (at the time of this investigation) against our estimate of mobile broadband spectrum levels that were used in the UK in practice in 2010 and will be used by 2015 (see appendix B) for the following cases of spectral efficiency:

- ITU recommended settings
- WINNER study recommendations
- Real Wireless values from our UHF strategy study for Ofcom when unadjusted for network loading and mixed traffic
- Real Wireless values from our UHF strategy study for Ofcom when adjusted for network loading and mixed traffic

The resulting spectrum estimates for our medium demand baseline case are compared across these spectral efficiency assumptions in Figure 55. Note that these spectrum results are slightly different to those given in our report main body as they were carried out based on our recommended baseline model settings at the time of this investigation which has since been refined slightly before being finalised for this report. However, the findings of this analysis still hold true.

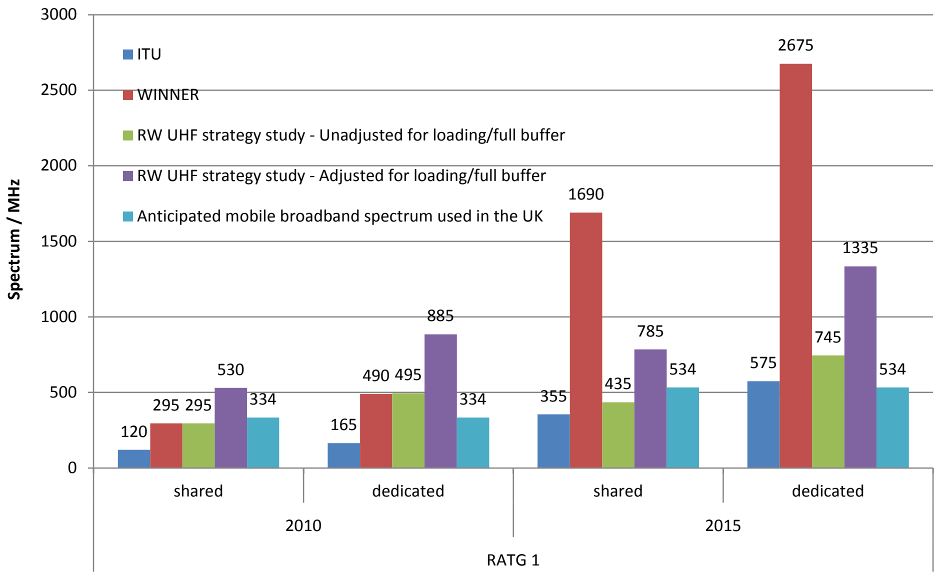


Figure 55: Resulting spectrum estimates for ITU vs. WINNER vs. RW recommended RATG1 spectral efficiency values

The key findings from this comparison were that:

- The ITU default settings give an optimistic spectrum estimate when compared against the amount of UK broadband spectrum thought to be in use in practice in 2010 and 2015.
- Spectrum estimates based on the WINNER suggested spectral efficiency values show good alignment with our estimate of the amount of UK broadband spectrum thought to be in use in practice in 2010. However, this source suggests no improvement in spectral efficiency by 2015 which leads to apparently high spectrum needs in 2015 when compared against the other sources for spectral

efficiency and our anticipated volume of UK broadband spectrum that will be used by 2015.

- Spectrum estimates based on the Real Wireless spectral efficiency values from our UHF strategy study for Ofcom when unadjusted for the inefficiencies of real networks (i.e. loading and usage by mixed traffic types) show good alignment with the amount of UK broadband spectrum thought to be in use in practice in 2010 and 2015. Note that that the actual spectrum required in practice will be a mix between the shared and dedicated results as discussed when presenting spectrum estimates in our final report (see section 2.2 of our final report).
- Spectrum estimates based on the Real Wireless spectral efficiency values from our UHF strategy study when adjusted for loading and mixed traffic levels give a pessimistic spectrum estimates compared to the amount of UK broadband spectrum thought to be in use in practice in 2010 and 2015. This is likely due to the queuing block in the ITU model already allowing for inefficiencies such as the impact of mixed traffic types on networks. Therefore adjusting spectral efficiency values to allow for these inefficiencies in practical networks is effectively double counting these effects.

Based on these results our recommended baseline settings for spectral efficiency for RATG1 macrocells, microcells and picocells make use of:

- 2010 spectral efficiency values from WINNER/ETRI journal which align with our macrocell and microcell spectral efficiency values from our UHF strategy study when unadjusted for mixed traffic and loading.
- Growing these spectral efficiency values between 2010 and 2015 in line with our unadjusted spectral efficiency values in our UHF strategy study to reflect the evolution from UMTS to LTE networks in this time.
- RATG1 values becoming constant after 2015, as LTE Release 8's spectral efficiency does not improve after this time, similar to the approach taken by WINNER and ETRI journal, due to future enhancements coming under LTE-A i.e. RATG2.

In the case of LTE hotspots we do not foresee the roll out of LTE small cells in line with the sector areas of ITU hotspots and so do not include spectral efficiency values for hotspots for LTE. We assume that any very small area, high frequency small cells in licensed spectrum will be a development under LTE-A rather than LTE. This is in line with our application rate settings for RATG1 discussed earlier.

For RATG2 our recommended macrocell and microcell spectral efficiency values are based on the average spectral efficiency value between low and high frequencies in dense urban environments found in our UHF strategy study unadjusted for loading (85% correction) and mixed traffic (65% correction) [66]. For 2020, which is when we assume LTE-A will be rolled out in the UK, these spectral efficiency values from our UHF strategy study largely align with the spectral efficiency values given by WINNER and ETRI journal.

Again, based on the WINNER study and ETRI journal we then apply the following ratios to convert from our recommended baseline spectral efficiency values for macrocells and microcells to picocell and hotspot spectral efficiency values for RATG2:

- Picocell spectral efficiency = 1.3 x microcell spectral efficiency
- Hotspot spectral efficiency = 1.6 x picocells spectral efficiency

The spectral efficiencies discussed so far are for unicast networks. Both ITU and WINNER recommended values for spectral efficiency follow a trend of setting multicast spectral efficiencies to be half those of unicast spectral efficiencies. We maintain this approach in our recommended baseline multicast spectral efficiencies also.

Our recommended baseline settings for RATG1 and RATG2 spectral efficiency are given in Table 53, Table 54, Figure 56 and Figure 57.

2010- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	0.4	0.4	0.7	-
Suburban	0.4	0.4	0.7	-
Rural	0.4	0.4	0.7	-

2010- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	0.2	0.2	0.35	-
Suburban	0.2	0.2	0.35	-
Rural	0.2	0.2	0.35	-

2015- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	1.48	1.56	2.66	-
Suburban	1.48	1.56	2.66	-
Rural	1.48	1.56	2.66	-

2015- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	0.74	0.78	1.33	-
Suburban	0.74	0.78	1.33	-
Rural	0.74	0.78	1.33	-

2020- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	1.48	1.56	2.66	-
Suburban	1.48	1.56	2.66	-
Rural	1.48	1.56	2.66	-

2020- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	0.74	0.78	1.33	-
Suburban	0.74	0.78	1.33	-
Rural	0.74	0.78	1.33	-

2025- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	1.48	1.56	2.66	-
Suburban	1.48	1.56	2.66	-
Rural	1.48	1.56	2.66	-

2025- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	0.74	0.78	1.33	-
Suburban	0.74	0.78	1.33	-
Rural	0.74	0.78	1.33	-

2030- Unicast area spectral efficiency (bits/s/Hz/cell)				
Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	1.48	1.56	2.66	-
Suburban	1.48	1.56	2.66	-
Rural	1.48	1.56	2.66	-

2030- Multicast area spectral efficiency (bits/s/Hz/cell)				
Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	0.74	0.78	1.33	-
Suburban	0.74	0.78	1.33	-
Rural	0.74	0.78	1.33	-

Table 53: Real Wireless recommended baseline setting for spectral efficiency values for RATG 1

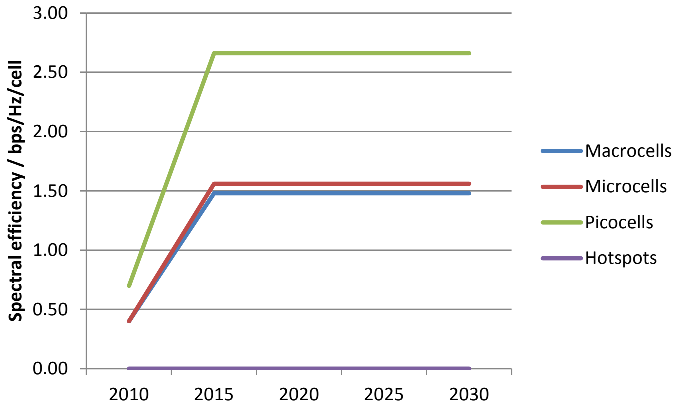


Figure 56: Real Wireless recommended baseline unicast spectral efficiencies for RATG1 over time

2020- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	3.15	3.49	4.54	7.28
Suburban	3.15	3.49	4.54	7.28
Rural	3.15	3.49	4.54	7.28

2020- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	1.58	1.75	2.27	3.64
Suburban	1.58	1.75	2.27	3.64
Rural	1.58	1.75	2.27	3.64

2025- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	5.01	6.3	8.18	13.09
Suburban	5.01	6.3	8.18	13.09
Rural	5.01	6.3	8.18	13.09

2025- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	2.5	3.15	4.09	6.55
Suburban	2.5	3.15	4.09	6.55
Rural	2.5	3.15	4.09	6.55

2030- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	7.1	12.69	16.49	26.39
Suburban	7.1	12.69	16.49	26.39
Rural	7.1	12.69	16.49	26.39

2030- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	3.55	6.345	8.245	13.195
Suburban	3.55	6.345	8.245	13.195
Rural	3.55	6.345	8.245	13.195

Table 54: Real Wireless recommended baseline setting for spectral efficiency values for RATG 2

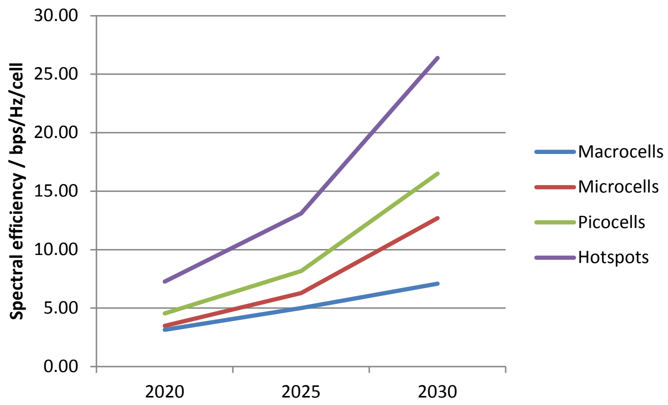


Figure 57: Real Wireless recommended baseline unicast spectral efficiencies for RATG2 over time

5.6.3 Recommended values – RATG3

In the case of RATG3 no recommended values for spectral efficiency are given by WINNER or ITU-R. This is because the analysis of spectrum requirements by these groups, so far, does not include a RATG3 spectrum estimate. However, within our current study Ofcom has requested a LE spectrum estimate and so we have added to the Excel implementation of the ITU-R M.1768-1 model from ITU-R working party 5D to include a RATG3 spectrum estimate (see appendix A). This updated model now includes inputs for the spectral efficiency values of RATG3 across all cell type but we provide values for picocells and hotspots only (in line with assumptions on the availability of RATG3 hotspots and picocells discussed already under application rates in section 5.5). Our recommended baseline settings for these are shown in Table 55.

As per our RATG1 and 2 spectral efficiencies we maintain multicast spectral efficiencies at half those of unicast services as per the approach followed by the ITU and WINNER for RATG1 and 2 spectral efficiency values.

2010- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	1.0	1.6
Suburban	N/A	N/A	1.2	1.8
Rural	N/A	N/A	1.3	2.1

2010- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	0.5	0.8
Suburban	N/A	N/A	0.6	0.9
Rural	N/A	N/A	0.65	1.05

2015- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	2.2	3.5
Suburban	N/A	N/A	2.5	4.1
Rural	N/A	N/A	2.9	4.7

2015- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	1.1	1.75
Suburban	N/A	N/A	1.25	2.05
Rural	N/A	N/A	1.45	2.35

2020- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	2.5	4.0
Suburban	N/A	N/A	3.0	4.7
Rural	N/A	N/A	3.4	5.5

2020- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	1.25	2.0
Suburban	N/A	N/A	1.5	2.35
Rural	N/A	N/A	1.7	2.75

2025- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	5.1	8.1
Suburban	N/A	N/A	6.0	9.6
Rural	N/A	N/A	6.9	11.1

2025- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	2.55	4.05
Suburban	N/A	N/A	3.0	4.8
Rural	N/A	N/A	3.45	5.55

2030- Unicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	10.2	16.2
Suburban	N/A	N/A	12.0	19.1
Rural	N/A	N/A	13.8	22.2

2030- Multicast area spectral efficiency (bits/s/Hz/cell)

Tele-density	Radio Environments			
	Macro cell	Micro cell	Pico cell	Hot spot
Dense Urban	N/A	N/A	5.1	8.1
Suburban	N/A	N/A	6.0	9.55
Rural	N/A	N/A	6.9	11.1

Table 55: RW recommended baseline settings for RATG3 spectral efficiencies

In the case of spectral efficiencies for RATG3 hotspots our recommended baseline settings are calculated based on:

- The average throughputs expected for RATG3 over time as discussed under application rates in section 5.5.
- The assumed average bandwidth used by RATG3 devices over time in generating these throughput levels.
- Using the above two results to generate a baseline spectral efficiency estimate per year.
- Adjusting this baseline spectral efficiency estimate by -8.33%, +8.33% and +25% to represent the difference in performance in dense urban, suburban and rural environments respectively based on simulation results in [69]. This adjustment allows for differences in the deployment density, interference conditions and number of collisions between teledensities.

These values at each of these steps are outlined in Table 56.

Year	Average Bandwidth supported / MHz	Average application rate / Mbps	Baseline spectral efficiency estimate bps/Hz/cell	Dense urban spectral efficiency bps/Hz/cell	Suburban spectral efficiency bps/Hz/cell	Rural spectral efficiency bps/Hz/cell
2010	21	35.8	1.7	1.6	1.8	2.1
2015	30	113.2	3.8	3.5	4.1	4.7
2020	54.8	240.3	4.4	4.0	4.7	5.5
2025	59.4	526.3	8.9	8.1	9.6	11.1
2030	59.4	1052.6	17.7	16.2	19.1	22.2

Table 56: Calculation of RATG3 spectral efficiencies for hotspots based on recommended application rates discussed in section 5.5

In the case of RATG3 picocells we assume that the spectral efficiency of these is the RATG3 hotspot spectral efficiency value reduced by a factor of 1.6 as outlined for RATG 1 and 2 earlier. Note that these RATG3 picocell spectral efficiencies are then used to estimate the application rates for RATG3 picocells over time reported earlier in section 5.5. However, we note that interference may become an increasing factor in wider range LE systems over time due to increased usage of these bands without the protection to users offered in licensed bands. These increased interference levels may become a factor in driving the type of spectrum to be utilised and restrictions on access to spectrum for future LE picocell bands. This in turn may impact the spectral efficiency and application rates assumed for RATG3 picocells.

5.7 Review of support for multicast

5.7.1 Parameter description

The ITU-R M.1768-1 model allows the user to specify whether multicast services should be supported by a particular RATG. This impacts the service types and hence demand that can be distributed across a particular RATG in the model. This parameter can be set by RATG but not by year or cell type in the model.

5.7.2 Recommended values

The ITU recommended settings for multicast support are to assume that RATG1, RATG2 and RATG3 all support multicast services. This is in line with capabilities of LTE, LTE-A and Wi-Fi today and so we maintain the ITU recommended settings in our recommended model baseline settings also.

5.8 Review of cell area

5.8.1 Parameter description

The ITU-R M.1768-1 allows the user to define the assumed cell area for each cell type (i.e. macrocell, microcell, picocells and hotspot) in each of the teledensities (i.e. dense urban, suburban and rural). Note that a site may consist of multiple cells or sectors. The cell area is combined with the spectral efficiency values in the model to determine the spectral efficiency density for each combination of RATG and cell type in a given teledensity. This is then compared against the demand density distributed across each combination of RATG and cell type in each of the model SEs to determine the spectrum requirements.

5.8.2 Recommended values

The ITU default recommended values for cell sizes are compared against our recommended baseline values in Table 57.

	Dense Urban / km^2		Suburban / km^2		Rural / km^2	
	ITU	Real Wireless	ITU	Real Wireless	ITU	Real Wireless
Macrocell	0.1	0.07	0.15	0.25	0.87	11.57
Microcell	0.07	0.05	0.1	0.1	0.15	0.15
Picocell	1.60E-03	1.60E-03	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Hotspot	6.50E-05	6.50E-05	6.50E-05	6.50E-05	6.50E-05	6.50E-05

Table 57: Comparison of ITU recommended cell areas against Real Wireless suggested baseline settings

As highlighted by the WINNER study, the ITU recommended values for cell area are the result of long discussions (including debate on propagation models, how to build in coverage to indoor environments, using smaller cells or other techniques like relays etc.) and several input documents to the ITU–R working party 8F [49]. When ITU cell areas without penetration loss were reviewed by the WINNER study no updates were suggested to the ITU recommended values for cell areas at the time except for the case of the rural macrocell cell area which was suggested to be updated to from 0.65 km^2 to 1.5 km^2. However, we notice that the latest ITU recommended cell areas as given on Table 57 include a larger rural macrocell cell size than the ITU values either with or without penetration loss reviewed by the WINNER study. This revised ITU recommended value for the rural macrocell cell area is now more in line with the indoor equivalent of the WINNER suggested value of 1.5 km^2.

Within the WINNER study macrocell and microcell ranges and cell areas are calculated based on link budgets at a 5GHz operating frequency and a challenging 25Mbps target data rate. These are pessimistic assumptions for UK networks where we would expect in coverage limited scenarios that operators would have access to lower frequencies and would target lower cell edge data rates in the region of 1Mbps for 2010 via HSPA networks and 2Mbps from 2015 onwards via LTE networks. Our recommended baseline setting for cell area therefore updates the ITU suggested cell area values (which are indoor equivalents of the WINNER suggested values) to reflect use of lower frequencies in UK cellular deployments and to reflect real UK deployments and site numbers. Note that while the cell sizes that we recommend are based on current UK site numbers and deployments in each teledensity and largely reflect the mix of spectrum available in the UK today that this does not completely address limitations in the ITU-R M.1768-1 model regarding providing frequency specific results. In rural environments the number of sites deployed will mostly reflect a coverage limited situation and be based on the average site ranges at the lower frequency bands available to operators in the UK today. However, this is an average site range and is limited by the lowest frequency bands available to operators today. To determine spectrum requirements at individual frequency bands a more detailed planning exercise allowing for local terrain would still need to be undertaken.

In determining our baseline settings for cell areas in dense urban and suburban areas we note that in these teledensities the cell area will be driven by capacity rather than coverage. This suggests that there will be significant overlap between the coverage areas of sites and that the average cell area is related to the total area covered and number of sites deployed in that area to serve a given demand level. This is in contrast to rural areas where deployments will be coverage rather than capacity focused and hence the ITU and WINNER link budget approach becomes more applicable.

Table 58 calculates the sector areas from our previous Ofcom UHF strategy project [1] based on:

- The percentage of land area covered in each study region considered
- The number of sites in each study region

	Dense urban	Suburban	Rural
Total area in study region (km^2)	37.6	321.5	6,102.6
Area covered by macrocells (%)	100%	100%	89%
Number of macrocells	95	227	157
Number of sectors	570	1305	471
Average macrocell sector area (km^2)	0.07	0.25	11.57

Table 58: Macrocell sector areas from our UHF strategy study for Ofcom [1]

In the dense urban case the value from our study region is about 30% less than the ITU default setting. In the suburban case the results from our study indicate a 1.7 times increase compared against the ITU default setting.

The biggest difference is in the macrocell rural sector area with more than an increase of 13 times over the ITU default value suggested by our study. Unlike the dense urban and suburban environments, these rural environments will be coverage rather than capacity limited. The result from our UHF strategy study includes access to lower frequencies and a target data rate of 2Mbps and is therefore much larger than the ITU sector size which was calculated at 5GHz and a 25Mbps target rate. Note that the rural sector area from our UHF spectrum strategy study also aligns with the average sector size seen in our study from July 2012 to assess the cost of the coverage obligation at 800MHz [72] which was calibrated against real RSSI levels provided by UK operators.

As the resulting sector areas from our UHF strategy study were based on real site locations and deployments from UK operators we have adopted these in our recommended baseline settings for macrocell sector areas instead of the ITU recommended values. Additionally comparing the number sites required to provide coverage across the three teledensities at the levels predicted by our UHF strategy study based on the assumed sector areas given across the sources reviewed shows that the sector areas in our recommended baseline give an estimate of sites required for the UK most aligned with current deployments.

Real Wireless

	DU	SU	RU	Total
Sector area (km2)	0.07	0.25	11.57	
Area coverage (%)	100%	100%	89%	
Number of sectors	32,843	41,816	17,757	
Sectors per site	6	5.75	3	
Number of sites	5,474	7,272	5,919	18,665

ITU values in spreadsheet

	DU	SU	RU	Total
Sector area (km2)	0.1	0.15	0.87	
Area coverage (%)	100%	100%	89%	
Number of sectors	22,990	69,693	236,154	
Sectors per site	6	5.75	3	
Number of sites	3,832	12,121	78,718	94,670

ITU values in WINNER document - Indoor

	DU	SU	RU	Total
Sector area (km2)	0.1	0.15	0.22	
Area coverage (%)	100%	100%	89%	
Number of sectors	22,990	69,693	933,881	
Sectors per site	6	5.75	3	
Number of sites	3,832	12,121	311,294	327,246

ITU values in WINNER document - Outdoor

	DU	SU	RU	Total
Sector area (km2)	0.65	0.65	0.65	
Area coverage (%)	100%	100%	89%	
Number of sectors	3,537	16,083	316,083	
Sectors per site	6	5.75	3	
Number of sites	589	2,797	105,361	108,747

WINNER document

	DU	SU	RU	Total
Sector area (km2)	0.65	0.65	1.5	
Area coverage (%)	100%	100%	89%	
Number of sectors	3,537	16,083	136,969	
Sectors per site	6	5.75	3	
Number of sites	589	2,797	45,656	49,043

Table 59: Comparison of estimating cellular sites required per operator across all of the UK based on different sources for sector area

In the case of microcell sector areas we have performed a similar analysis to that shown in Table 58. In the case of dense urban microcells we estimate a sector area of 0.05 km^2 compared with the ITU recommended value of 0.07 km^2. Our recommended baseline setting adopts the 0.05 km^2 value as this is based on real microcell deployments in the study areas examined and also aligns with being slightly smaller than our recommended dense urban macrocell sector area.

In the case of suburban and rural microcells there were not enough microcell sites in the study areas examined in our UHF strategy study to get an accurate estimate of sector area. We have therefore instead examined the cell ranges implied by the ITU default values (see Table 60) and compared these with site ranges achieved in recent outdoor small cell trials in the UK.

	Dense urban / m	Suburban /m	Rural /m
Macrocell	437.0	524.0	911.5
Microcell	149.3	178.4	218.5
Picocell	22.6	22.6	22.6
Hotspot	4.5	4.5	4.5

Table 60: Cell ranges implied by ITU recommended cell areas

For the conversion of sector area to range we assume circular coverage and the following sector assumptions based on real site data from our UHF strategy study:

- Macrocells in dense urban environments have 6 sectors
- Macrocells in suburban environments have 5.75 sectors
- Macrocells in rural environments have 3 sectors
- Microcells, picocells and hotspots have a single sector

In recent trials by Virgin Media outdoor ranges of approximately 390m (for a 20Mbps target service) were achieved for a single LTE outdoor small cell in a built up environment with no interference and LOS conditions [67]. 60Mbps data rates were also measured in buildings 250m from the access point with a good LOS. The ITU default microcell sector area for a suburban environment assumes a range of 178m. However, this is targeting indoor locations and so largely aligns with the 390m outdoor range from the Virgin Media trials. The ITU suggested microcell range of 218m in rural areas fits with being slightly higher than the range for suburban areas due to fewer obstructions from buildings in rural areas. Our recommended baseline settings for microcell sector areas in suburban and rural environments therefore maintain the ITU recommended values.

In the case of hotspot cell areas we compare the ITU recommended value of 65m^2 against the average size of a UK home. This is based on the assumption that hotspots represent short range access points similar to Wi-Fi access points today which typically provide coverage to a home with a single access point. Given that the average new build house in the UK has an area of 76 m^2 or 7.6e-5 km^2 we support the ITU recommended value for hotspot sector area in our recommended baseline settings [73].

Arguably residential cellular femtocells should also come under this "hotspot" category as they target covering a home with a single femtocell. However, in our study for Ofcom of a low power shared access channel at 2.6GHz it was shown that the coverage area of commercially available femtocell products with an EIRP of 7dBm would be in the range of 1400 m^2 for a 10Mbps single user cell edge throughput target or 0.0014 km^2 assuming LTE with a 10MHz bandwidth (see Figure 58) [73]. This aligns with the ITU "Picocell" sector area and so we assume that cellular residential femtocells are included in this "Picocell" category.

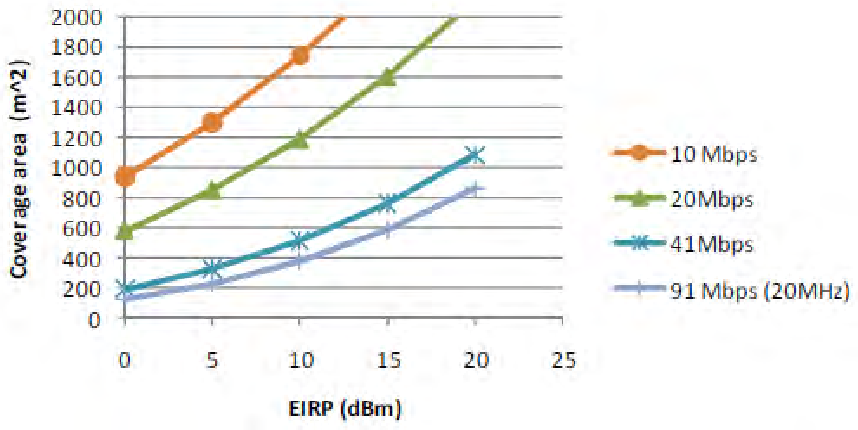


Figure 58: Residential downstairs coverage area in an old style house for an LTE access point at 2.6GHz [73]

Note that our study of a low power shared access channel at 2.6GHz examined coverage at 2.6GHz which assumes that small cells will use higher frequencies. This is based on the assumption that lower frequency bands are more valuable for outdoor macrocells targeting coverage rather than capacity. However, changes in frequency are unlikely to change sector areas indoors greatly due to the propagation being limited by walls and other obstructions.

In the case of cellular picocells or enterprise femtocells higher maximum EIRPs than residential femtocells would be expected in the region of 20dBm [74]. As illustrated by Figure 58 this higher EIRP could be used to achieve a larger coverage area or higher data rates to support more users in a similar coverage area to a femtocell. However, given that an average UK office size is around 840 m^2 (see [73]) and larger offices and public buildings tend to require more than one picocell to be deployed it is unlikely that cellular picocells would target a coverage area much higher than the default ITU picocell coverage area.

Overall we support the ITU recommended cell areas for picocells and hotspots in our recommended baseline settings. In summary this is based on the following observations:

- Suggested hotpot cell areas are in line with Wi-Fi access point coverage areas.
- Suggested picocells cell areas are in line with enterprise and residential femtocell products today.
- As picocells and hot spots are deployed in indoor environments their coverage area will not change with being deployed in dense urban vs. suburban vs. rural environments as indicated by the ITU default settings.
- The ITU spectrum requirements model does not allow sector area to vary with frequency but we would anticipate small changes in picocell and hotspot sector areas with frequency due to indoor coverage being limited more by walls and other obstructions than free space propagation.
- We also note that the WINNER study did not challenge the ITU default sector sizes for picocells and hot spots.

5.9 Review of population coverage

5.9.1 Parameter description

The population coverage percentage is the percentage of the population which, based on site deployments at the time, would be within the coverage areas of the different ITU cell types in the different service environments considered in the model. This parameter determines the maximum percentage of the total demand for a given service environment that a given network layer or cell type can carry. This parameter can be set to vary over time but not by RATG.

We interpret this coverage percentage to be the coverage achieved based on:

- All sites in a given year supporting the dominant air interface used for coverage at that time for that cell type i.e. in the case of macrocells HSPA in 2010, LTE in 2015 onwards.
- Targeting a minimum service level in line with the application rate as set for the dominant air interface providing coverage at the time i.e. in the case of macrocells 1Mbps HSPA coverage in 2010, 2Mbps LTE in 2015 onwards.

Note that increases in site numbers over time will not necessarily increase coverage levels as some sites are added for capacity rather than coverage enhancements. For example outdoor small cells or metrocell deployments over time in dense urban environments will impact capacity but not coverage levels as existing microcell coverage levels in dense urban environments are already high.

Ideally the coverage percentage within the ITU-R M.1768-1 model should vary by RATG to facilitate not all existing LTE sites being immediately upgraded to support LTE-A in 2020 for example. However, to a certain extent this deficiency is handled by the RATG distribution percentage (see next section).

5.9.2 Recommended values - baseline

Our baseline recommended values for coverage percentages are given in Table 61 to Table 65. Note that these baseline values reflect the medium small cell uptake cell used in our sensitivity analysis (with low and high settings discussed later in 5.9.3).

Service environment	Macro cell	Micro cell	Pico cell	Hot spot
SE1	100	90	0	70
SE2	100	90	10	70
SE3	100	95	10	10
SE4	100	15	0	70
SE5	100	40	20	20
SE6	90	0	10	45

Table 61: Real Wireless recommended baseline coverage levels for 2010

Service environment	Macro cell	Micro cell	Pico cell	Hot spot
SE1	100	90	10	75
SE2	100	90	20	75
SE3	100	95	20	25
SE4	100	30	10	75
SE5	100	80	35	30
SE6	90	5	30	50

Table 62: Real Wireless recommended baseline coverage levels for 2015

Service environment	Macro cell	Micro cell	Pico cell	Hot spot
SE1	100	90	20	85
SE2	100	90	40	85
SE3	100	95	40	40
SE4	100	60	20	85
SE5	100	90	70	40
SE6	90	10	35	55

Table 63: Real Wireless recommended baseline coverage levels for 2020

Service environment	Macro cell	Micro cell	Pico cell	Hot spot
SE1	100	90	30	95
SE2	100	90	45	95
SE3	100	95	45	55
SE4	100	80	30	95
SE5	100	90	75	50
SE6	90	10	40	60

Table 64: Real Wireless recommended baseline coverage levels for 2025

Service environment	Macro cell	Micro cell	Pico cell	Hot spot
SE1	100	90	40	95
SE2	100	90	50	95
SE3	100	95	50	70
SE4	100	80	40	95
SE5	100	90	75	60
SE6	90	10	45	65

Table 65: Real Wireless recommended baseline coverage levels for 2030

Macrocell and microcell coverage levels

In the case of macrocell coverage levels our recommended baseline setting aligns with the ITU recommended values (which assume 100% coverage in all SEs constant over time) for all SEs except for SE6 which we revise down to 90% for all years. This is based on 2010 coverage percentages found in similar environments in our UHF strategy study for Ofcom [1] based on real UK site locations.

Next Figure 59 compares ITU recommended microcell coverage levels against our recommended baseline setting.

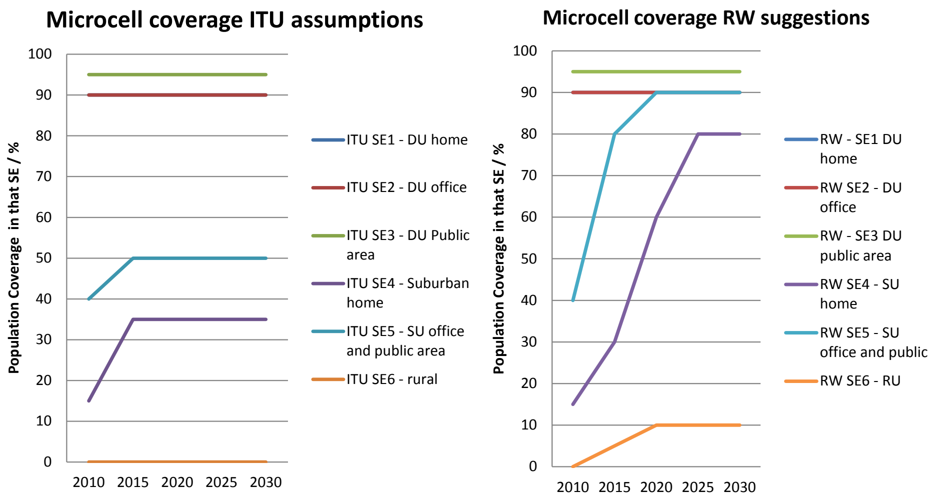


Figure 59: Comparison of microcell coverage levels recommended by ITU and those in our recommended baseline settings (Note that on both graphs the SE1 and SE2 coverage values are the same)

In the case of microcell coverage levels in SE1, SE2 and SE3 in 2010, the ITU default coverage levels are in a similar range as results for the dense urban study area in our UHF strategy study for Ofcom where 85% of the population was covered by the micro layer. We therefore maintain the recommended ITU default microcell coverage levels for SE1, SE2 and SE3 in 2010.

In the case of microcell coverage levels in SE4 in 2010 we compare this with our suburban result from the UHF strategy study, in which 15% of the population was covered by the microcell layer. This aligns with the ITU recommended value and so this is maintained in our baseline setting.

In the case of microcell coverage levels in SE6 in 2010 we compare this with our rural result from the UHF strategy study, in which 0% of the population was covered by the microcell layer. This aligns with the ITU recommended value and so this is maintained in our baseline setting.

Finally in the case of SE5 microcell coverage levels in 2010, our UHF strategy study does not provide a comparable study region, however we recommend maintaining the ITU SE5 microcell coverage level for 2010 since all of the rest of the ITU default microcell coverage entries are similar to what we have found in the UHF strategy project.

We next consider changes in coverage levels over time. In the case of macrocells our baseline setting assumes that as macrocell coverage levels are already close to 100% these are not likely to change over time and so are kept fixed at their 2010 value out to 2030.

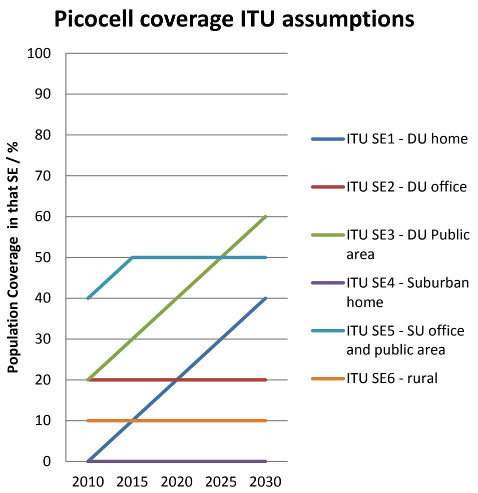
In the case of changes in microcell coverage levels over time our baseline recommended values track the following trends:

- In rural areas we assume that outdoor small cells known as “meadowcells” are used to fill the 10% coverage gap from the macrocell layer (although these are reasonable immature as yet). We therefore include a SE6 microcell coverage percentage for 2015 of 5% increasing to 10% by 2020 and then remaining fixed to 2030.

- In suburban areas where microcell volumes are reasonably low our recommended baseline setting suggests a doubling in coverage for microcells between 2010 and 2015 and then growing at a slower rate as 90% coverage levels are approached. This is based on an Informa report on the small cell market status for Q1 2013 which forecasts a 2.6 times growth in the revenue from "public area" small cells between 2011 and 2016 [75]. This is also largely supported by one of the stakeholder responses to the CFI on this topic.
- In dense urban environments where microcell coverage levels are already quite high we assume that coverage remains at the 2010 level out to 2030. Note this does not mean that metrocells will not be rolled out in dense urban environments. Indeed the most metrocells are likely to appear in cities but will add capacity rather than coverage and so do not impact the dense urban microcell coverage percentages to be modelled.

Picocell coverage levels
Figure 60 compares ITU recommended picocell coverage levels against our recommended baseline setting for picocell coverage levels.

We assume that picocells cover residential femtocells and picocells / enterprise femtocells in line with our findings under cell area. Considering first residential femtocell coverage levels we assume that residential femtocells will dominate picocells coverage in the home environments of SE1 and SE4 where enterprise femtocells are unlikely to be deployed. We also assume that SE6 rural coverage is dominated by residential femtocells due to the limited volume of medium sized businesses in these areas requiring enterprise femtocells.



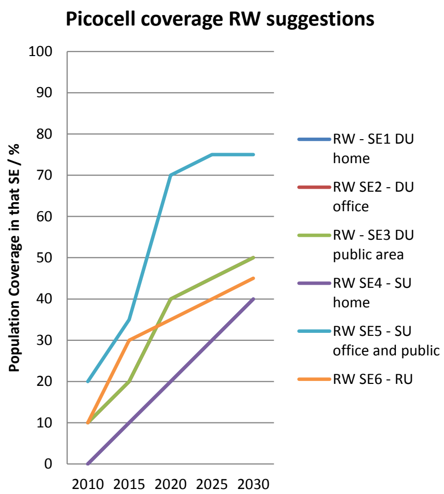


Figure 60: Comparison of picocell coverage levels recommended by ITU and those in our recommended baseline settings (Note that the Real Wireless coverage values for SE1 and SE4 and SE2 and SE3 are the same)

Our recommended baseline settings for picocell coverage levels at 2010 in rural areas are based on:

- The number of homes in the UK at 2012 being 26.4m [76]
- The Ofcom Communications Infrastructure Report update for 2012 [77] estimating 200,000 femtocells in the UK with three times as many femtocells in

rural areas compared with more built up areas (i.e. 150,000 femtocells in rural areas compared with more built up areas).

- Rural areas in the UK having a population of approximately 5% of the UK population.
- The above three points giving an 11% population coverage of femtocells in rural areas at 2012.
- Future growth of small cell revenues forecast to be at a CAGR of 73% or nearly quadrupling over 5 years in the Small Cell Forum's Q1 2013 market status update [75]. Applying this to the 2012 estimate of rural femtocell coverage levels of 11% gives an estimate for 2010 of 8%.

In the case of suburban and dense urban picocell coverage levels in home environments in 2010 the remaining 50,000 femtocells in suburban and dense urban areas out of the total of 200,000 estimated to be deployed in the UK gives a percentage coverage much less than 1%. We therefore maintain the ITU recommended coverage level for picocells of 0% for SE1 and SE4 in 2010.

In terms of growth in picocells coverage levels in SE1, SE4 and SE 6 based on residential femtocell uptake our baseline recommended values reflect:

- A 400% increase in femtocell coverage in SE6 between 2010 and 2015 which is then slowed after this as the majority of those with poor existing coverage are already reached [75]. Based on our study of improving in-building coverage levels for Ofcom [76], by 2016 35% of rural users may need a dedicated in-building solution to achieve a reliable 2Mbps mobile service data rate so we assume that femtocell coverage levels will not exceed this level by much over time.
- Take up in suburban and dense urban environments being to a lesser extent than in rural areas due to residential femtocells being deployed to target user experience improvements rather than coverage. The ITU default settings for picocell uptake in SE1 show a 10% increase every 5 years and we maintain this in our recommended baseline setting to represent a significant uptake of femtocells in dense urban areas but to a lesser extent than in rural areas. In SE4 the ITU assume no growth in picocells over time whereas we suggest that this should be matched to the growth seen in dense urban areas in SE1 so apply the SE1 ITU default picocell coverage over time to SE4 also.

In the case of picocells coverage levels in SE2, SE3 and SE5 we assume that these will be dominated by the uptake of enterprise femtocells over residential femtocells due to being office and public area environments. Our suggested 2010 coverage levels for these environments are based on:

- 39% of UK businesses with over 250 employees being reported to suffer from poor mobile coverage levels today with 28% of these having deployed a dedicated in-building solution themselves to improve service levels [76]. Therefore we suggest picocell coverage levels in dense urban business environments (i.e. SE2) where these larger businesses are likely to be located at 10% for 2010.
- Assuming that public areas are likely to suffer similar problems with coverage from macrocells and microcells to office environments in dense urban areas and so will require a similar level of picocells dedicated solutions. This is in line with

the ITU default settings and gives an assumed 10% picocells coverage level for SE3 at 2010.

- Assuming that picocell coverage levels in suburban business and public area environments (i.e. SE 5) will be a similar proportion of the SE2 and SE 3 coverage levels as in the ITU default settings and so adjusting SE5 coverage levels to maintain this proportion in our baseline settings also.

In terms of the uptake of enterprise femtocells and hence increased picocells coverage levels over time in SE2, SE3 and SE5 where enterprise small cells are relevant we assume a doubling in picocell coverage every 5 years for 2015 and 2020 and then reduce this rate out to 2030 once the main coverage challenged businesses have deployed a picocell solution. This is based on the Informa small cell market report for Q1 2013 which shows enterprise small cells growth at approximately half the rate of femtocells every 5 years [75]. This is a more aggressive uptake of picocells in these environments than that suggested by the ITU default parameters but we recommend this more aggressive uptake based on the Informa small cell market report.

Hotspot coverage levels

Figure 61 compares ITU recommended hotspot coverage levels against our recommended baseline setting.

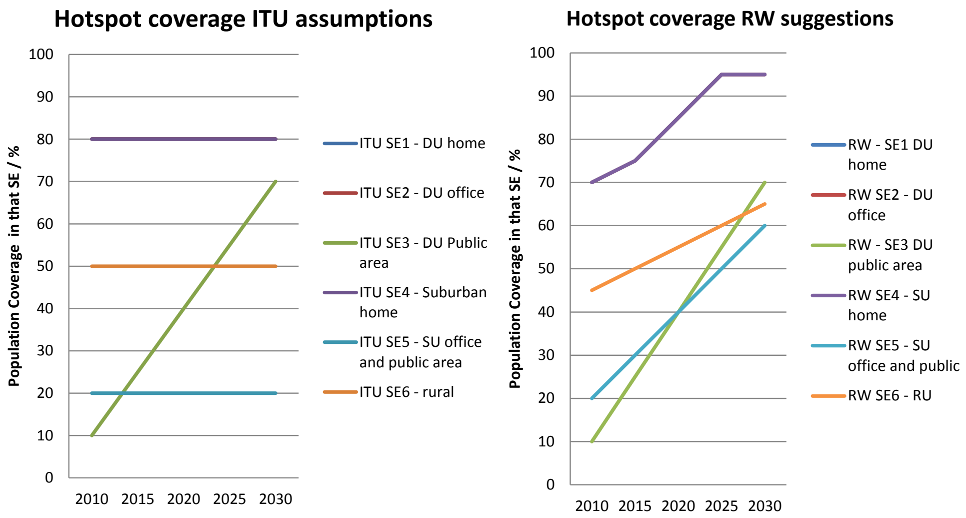


Figure 61: Comparison of hotspot coverage levels recommended by ITU and those in our recommended baseline settings (Note that in both the ITU and Real Wireless graphs that the coverage values for SE1, SE2 and SE4 are at the same level)

Our recommended baseline coverage levels for hotspots in 2010 are based on:

- A study from U switch which found that 73% of UK homes today make use of Wi-Fi [78]. Therefore we assume 2010 coverage levels in home environments (SE1 and SE4) at a slightly reduced level of 70% compared to this estimate for 2012.
- The assumption that businesses will have similar Wi-Fi coverage levels to homes as reflected by the ITU default values for hotspot coverage levels. Therefore we assume 2010 coverage levels in SE2 of 70% also.
- Reducing the hotspot coverage levels of SE3, SE6 and SE5 in line with adjustments to SE1 and SE4 against the ITU recommended coverage levels for

these environments. Note that in the case of SE3 and SE5 this adjustment is so minor that we maintain the ITU recommended values.
- Ofcom's Communications Infrastructure report [77] 2012 update indicating that there is very limited use made of public access Wi-Fi access points by users when they are out and about with users preferring to use their mobile connection in these situations. This supports the lower coverage levels in the ITU default settings suggested for SE3, SE5 and SE6.

In terms of hotspot coverage improvements over time our recommended baseline settings assume:

- A 2% per year growth rate from 2010 onwards to hotspot coverage levels in SE1, SE2 and SE4 based on Plum Consulting's estimate of growth in [17] of Wi-Fi access point volumes per year for markets with high existing Wi-Fi penetration levels.
- More rapid growth in the case of public access Wi-Fi coverage which follows the ITU default suggestion of increasing coverage by 15% every 5 years in SE 3.
- An improvement in coverage in SE 5 every 5 years at a significant but reduced rate compared to SE3 of 10% noting that SE5 includes offices as well as public areas (and that the office element in SE5 will already be at a high Wi-Fi coverage level and so growing less quickly than SE3). In this environment the ITU suggest no growth over time but we would expect public access Wi-Fi uptake to grow in suburban as well as urban areas (which matches our assumption that outdoor small cells or microcells will increase over time in suburban areas).

5.9.3 Recommended values – low and high small cell uptake scenarios

In our sensitivity analysis in this study we have investigated varying our assumptions on the uptake of small cells to a low and high setting relative to the baseline settings already discussed in the previous section.

We assume that licensed small cells within the ITU-R M.1768-1 model cell type categories fall under:

- Microcells which include microcells and outdoor small cells such as metrocells and meadowcells
- Picocells which included enterprise and residential femtocells

The hotspot category of cell type is largely used for RATG3 or LE hotspots in the model (although LTE-A hotspots are also included in later years) so we do not vary the coverage levels of hotspots in our sensitivity analysis of the uptake of small cells. The increase in LE hotspots on licensed spectrum requirements is instead covered by the low, medium and high Wi-Fi offload percentages (discussed under section 5.10).

Differences across our assumed low and high small cell uptake settings can be summarised as follows:

1. A low small cell uptake assumes that small cells are only deployed where essential. This is represented by:

- o Microcell coverage levels based on the number of outdoor small cells found to be necessary to be built to meet the medium demand scenario in our UHF strategy study for Ofcom [1]. In this study outdoor small cells were only deployed if all other options for macrocell upgrades were exhausted or too costly or time consuming.
- o Picocell coverage levels in line with the ITU recommended picocell coverage level settings which are less aggressive than the baseline picocell coverage assumptions in our medium scenario. The exception to this is SE 1 where our recommended baseline coverage level for picocells already tracks the ITU default setting so we instead halve coverage levels in the low scenario.

2. A high small cell uptake which assumes revising microcell and picocell coverage levels to the upper end of small cell growth levels given by Informa's latest forecast on the small cell market from Q1 2013 [75] and with higher ceilings on coverage percentages in later years to represent small cells being used to enhance user experience rather than just coverage.

The coverage levels in each of the SEs for microcells and picocells that correspond to these small cell uptake scenarios are shown in Figure 62 and Figure 63. Note that in SE 1-3 we keep microcell coverage levels at the same level in both the high and low cases of small cell uptake as was originally suggested in our baseline case as these coverage levels are already at 90% in dense urban areas and so there is not much scope to vary coverage out to 2030 around this. The rationale behind the coverage levels used for microcells for other SEs and picocells is given in the next two sub sections.

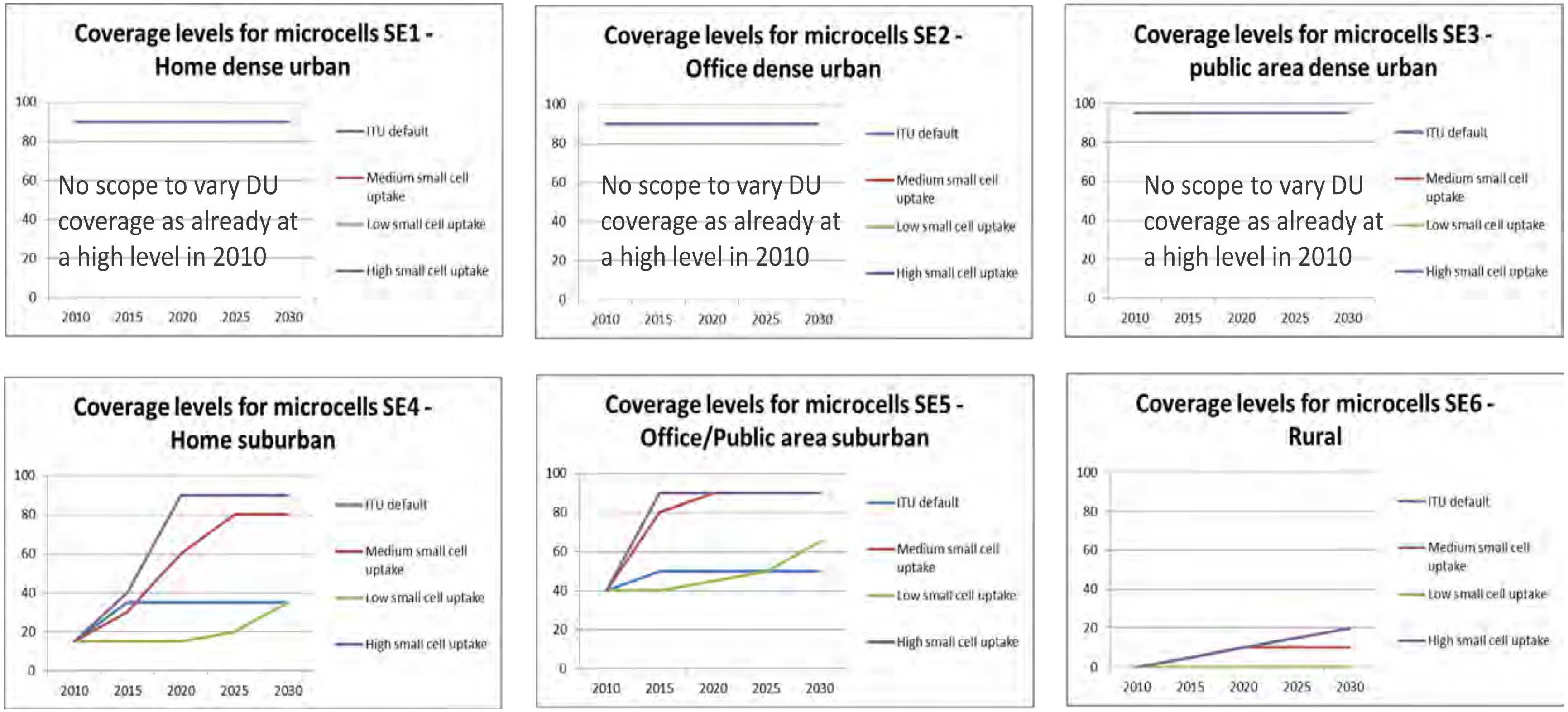


Figure 62: Low, medium and high microcell uptake levels investigated

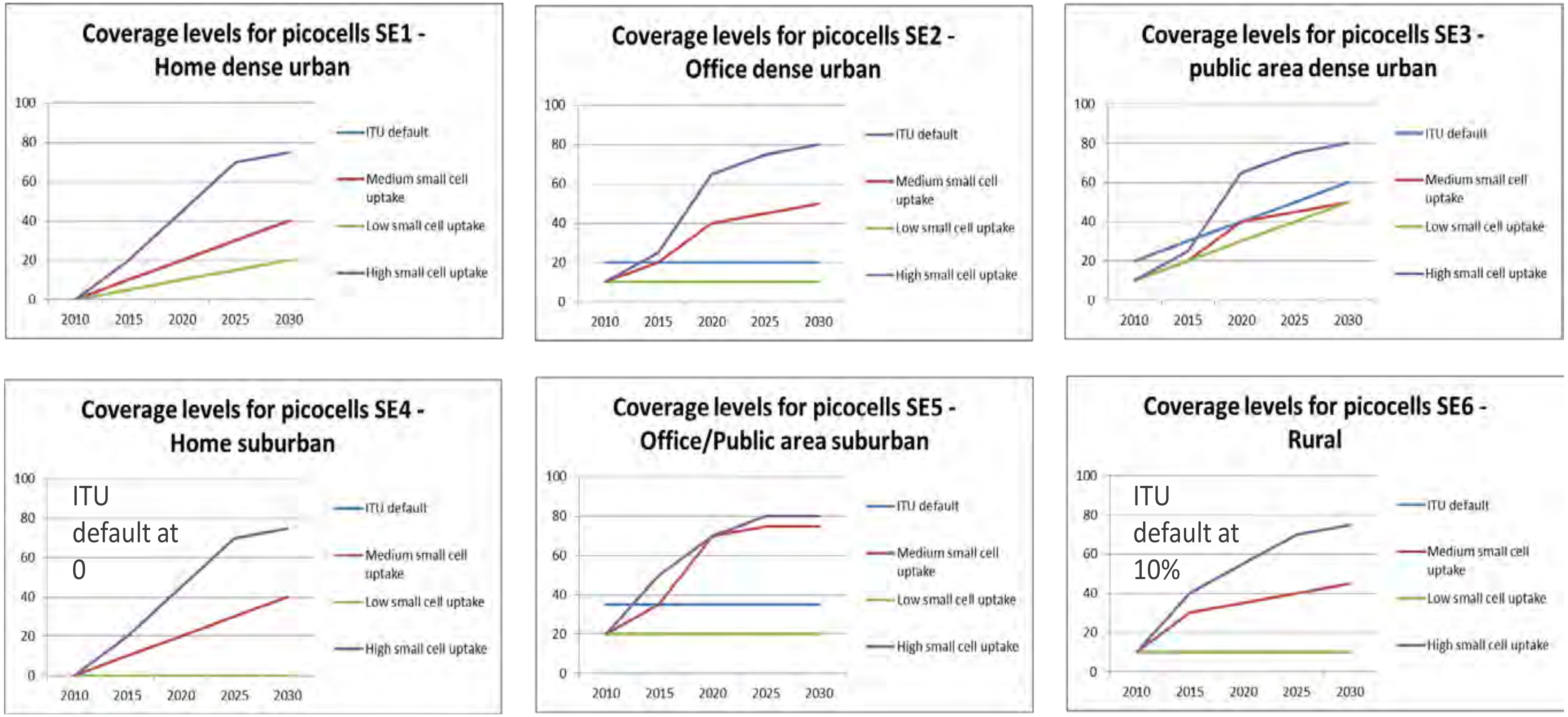


Figure 63: Low medium and high picocells uptake levels investigated

Low small cell uptake values used

In the low uptake of small cells scenario we aim to use microcell and picocell coverage levels that are representative of small cells only being deployed where essential. In the case of microcell coverage levels we have based these low uptake coverage levels on the number of outdoor small cells found to be necessary to be built to meet the medium demand scenario in our UHF strategy study for Ofcom [1]. In the UHF strategy study outdoor small cells were only deployed if all other options for macrocell upgrades were exhausted or too costly or time consuming. This approach aligns with the view of one CFI respondent who indicated that small cells would only be deployed once all other capacity improvement options had been exhausted.

Figure 64 compares the coverage levels that would be achieved by microcells given the number of new outdoor small cells built in our UHF strategy study to meet a medium demand baseline scenario in that study (which matches the medium demand for licensed spectrum used in the current study) with the recommended baseline coverage level for microcells in the current study. On the figure the outline bars are the recommended baseline microcell coverage levels from the current study whereas the coloured bars show the estimated coverage levels from the number of outdoor small cells forecast in our UHF strategy study. For SE 4-6 our low small cell uptake scenario in the current study uses the microcell coverage levels as per the coverage levels shown here based on outdoor small cell site builds from our UHF strategy study

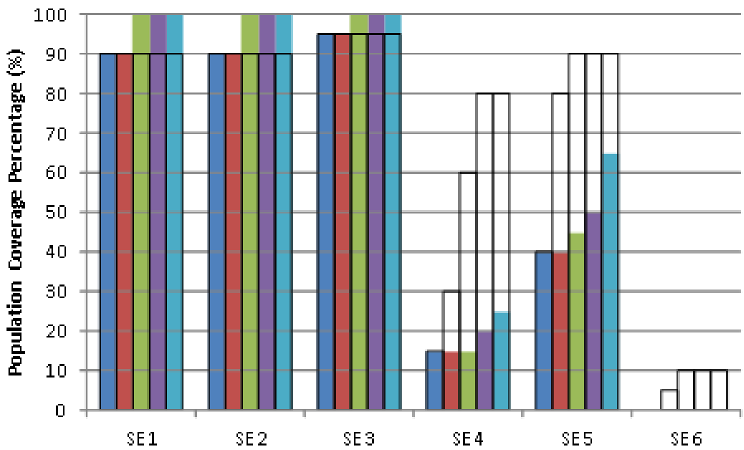


Figure 64: Comparison of population coverage from microcells from our UHF strategy study medium demand baseline case compared against our recommended baseline coverage levels in this current study

Note that the small cell site build estimates from our UHF strategy study represent an overall network upgrade plan that was found to be economical to operators in terms of enhancing user experience to a sufficient level that the willingness to pay by consumers for improved service levels balanced out the overall network cost for a given spectrum availability. However, by suggesting small cells levels could be higher than the site numbers from this UHF strategy study in the medium and high small cell uptake scenarios of the current study we are not suggesting that operators roll out small cells at an uneconomical level but that some of the network investment seen in the UHF strategy study is redirected towards small cells more readily, that the small cells improve user experience and hence willingness to pay, that more spectrum is made available than assumed in UHF strategy study or a combination of these.

In the case of picocells we found no definitive sources suggesting lower uptake levels relative to our baseline coverage levels and so have reverted to using the ITU recommended values for picocells coverage levels which are lower than our baseline settings (see Figure 63) with the exception of SE 1 where the baseline coverage already tracks the ITU default setting. Instead in this case we halve coverage levels in the low scenario.

High small cell uptake values used
For the high small cell uptake scenario we update microcell coverage levels as follows:

- Use the same 2010 starting coverage for microcells in all SEs in the high setting as in our recommended base case setting.
- In the case of SE 1-3 the high uptake case follows the baseline case as there is little scope to vary coverage around the 90% 2010 microcell coverage levels in dense urban environments.
- In the case of SE 4-5 we grow the 2010 coverage level at 2.6 times every five (rather than the doubling in coverage every 5 years that we have in the baseline case) in line with forecasts on public area small cell uptake from Informa's latest forecast on the small cell market from Q1 2013 [75].
- In the case of SE6 we assume meadowcells are deployed beyond purely coverage solutions, which limits SE6 microcell coverage to 10% in the baseline case. Instead we assume that meadowcells are used to improve user experience as well as coverage and use more aggressive SE6 picocell coverage levels that reach 20% rather than the 10% limit of the baseline case.

In the case of picocells (made up of residential and enterprise femtocells) for the high small cell uptake scenario we update coverage levels based on the following rationale:

- An Informa small cell market status report from Q4 2012 shows femtocell volumes deployed worldwide increasing from 2m in 2011 to above 80m in 2016 or a 40 fold increase in femtocells in this 5 year period [79].
- Given that there were 200k femtocells in the UK in 2012 [77] this would imply 8m femtocells potentially in the UK by 2017 or a femtocell in 30% of households.
- Reducing this coverage level for 2015 rather than 2017 and allowing for more femtocells in rural than dense urban and suburban areas we assume 2015 coverage levels in SE1 and SE4 of 20% rather than the baseline level of 10% and 40% in SE6 rather than the baseline level of 30%. [7775]
- In our high uptake of small cells we assume that residential femtocells grow in popularity to the extent of Wi-Fi access points today and so reach penetration level of around 70% of homes [78] by 2025 and grow more slowly after this.
- In the case of SE2, SE3 and SE5 which would focus on enterprise femtocells rather than residential femtocells we increase growth rates in the high scenario from the doubling every five years assumed in the baseline case to the higher 2.6 times increase based on Informa's latest forecast on the small cell market from Q1 2013 [75] which shows a 2.6 times growth in public area access point revenue between 2011 and 2016. We reduce this growth in later years as high coverage levels are reached.

5.10 Review of traffic distribution ratio amongst available RATGS

5.10.1 Parameter description

The distribution ratio amongst RATGs settings in the ITU-R M.1768-1 model determines the proportion of total traffic input to the model that should be routed over the various RATGs.

5.10.2 Recommended values

Our recommended baseline setting for the traffic distribution ratios across the RATGs from 2010 to 2030 are shown in Figure 65. Here the total traffic volume being distributed is the total traffic that could potentially have been carried on licensed spectrum. The total traffic here therefore includes traffic that could be offloaded to Wi-Fi but does not include LE specific traffic like Smart TV that would not use licensed spectrum. The green RATG3 bars represent the percentage of traffic offloaded from cellular networks to LE spectrum. The red bars represent the proportion of traffic on RATG2 technologies which we assume will mainly be LTE-A for the foreseeable future. The blue bars show the proportion of traffic on RATG1 which for the UK includes GSM, UMTS and LTE.

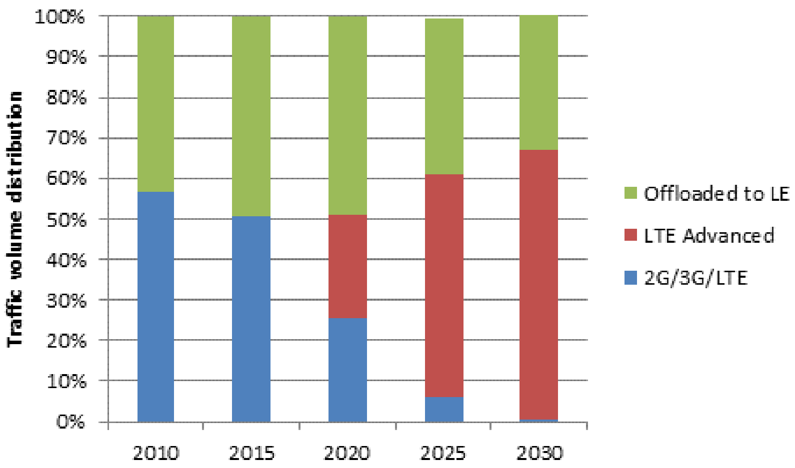


Figure 65: Real Wireless recommended baseline setting for traffic distribution across RATGs

RATG1 and RATG2

Figure 66 illustrates the ITU recommended settings for the traffic distribution ratios amongst the RATGs from 2010 to 2020 with the 2025 and 2030 values shown extrapolated from these earlier years. Examining this for licensed spectrum technologies, it shows an equal split in traffic between RATG1 and RATG2 from the assumed introduction of LTE-A in 2015 with RATG2 quickly growing by 2020 to carry the majority of the traffic between RATG1 and RATG2 and 50% of the overall mobile broadband traffic that could potentially be carried over licensed spectrum.

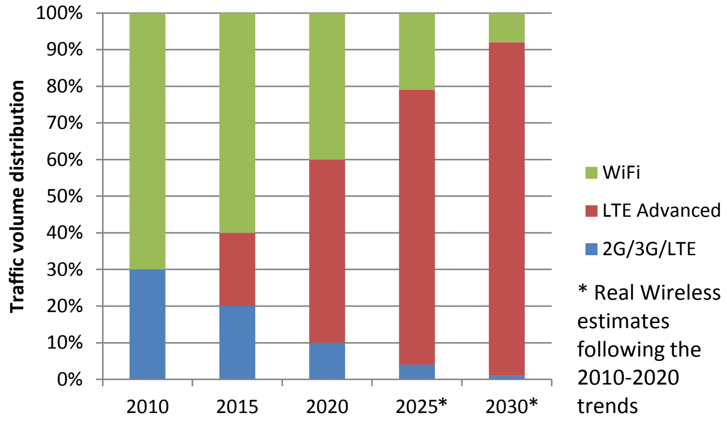


Figure 66: ITU recommended values for traffic distribution across RATGs (note values provided up to 2020 with 2025 and 2030 figures extrapolated from earlier years)

The split of traffic between RATG1 and RATG2 in our recommended baseline setting follows the ITU default settings for the ratio of traffic between these two RATGs but with the introduction of RATG 2 delayed by 5 years to 2020. This is based on LTE networks only emerging in the UK in 2013 and so LTE-A networks are likely to be some time off yet.

RATG3 – Wi-Fi offload

As discussed earlier the percentage of traffic distributed on RATG3 within the RATG ratio settings we interpret as the Wi-Fi offload level. As the RATG distribution ratio settings only vary by year within the ITU-R M.1768-1 model and not by SE we interpret this as the average Wi-Fi offload level across all SEs but note that the Wi-Fi offload level will vary between indoor and outdoor users and between stationary, pedestrian and mobile users.

As our LE spectrum estimates include spectrum requirements for services that would not target licensed spectrum such as Smart TV we have developed two separate runs of the ITU-R M.1768-1 model; one focused on licensed spectrum estimates from RATG1 and RATG2 and one focused on LE spectrum estimates which considers the traffic offloaded from licensed spectrum to LE spectrum and LE specific traffic. In practice this means that the Wi-Fi offload levels or RATG3 distribution percentage from the RATG distribution ratios within the ITU-R M.1768-1 model are applied to our estimates of the total demand that could potentially be carried on licensed spectrum to determine our separate estimates of demand for licensed and LE spectrum. These are in turn used to calibrate the distributed demand densities within our licensed and LE focused runs of the model.

Our baseline Wi-Fi offload levels (or RATG3 distribution percentages) are obtained by comparing the offloaded traffic element of our LE demand estimates against our estimates of demand for licensed spectrum. As discussed in appendix C these have been developed via a bottom up analysis of demand per device which takes into account how traffic is routed from the end user to fixed networks via either a direct cellular connection or some intermediary device such as a Wi-Fi access point or femtocell and the usage of licensed and LE spectrum across these. This means that our baseline Wi-Fi offload levels take into consideration varying offload levels across different device types and environments. Further details of the exact distribution of traffic across intermediary devices per user device type can be seen by examining the devices that can offload cellular traffic in Figure 22 and appendix F which include:

- Smartphones
- Tablets
- Laptops
- Hybrid
- Portable gaming consoles

As discussed in appendix C, the Wi-Fi offload settings per device for 2010 used in our baseline settings to determine the traffic distribution across these intermediary devices are based on the medium offload levels from our UHF strategy study for Ofcom [1] which were in turn sourced from Cisco estimates. We note that in the UHF strategy study that the offload values quoted combined small cell offload (covering enterprise and residential femtocells) and Wi-Fi offload levels. In the current study we examine Wi-Fi offload separate to small cell uptake. However, we assume that the offload from enterprise and residential femtocells would still have been at low levels in 2010 due to low deployment levels.

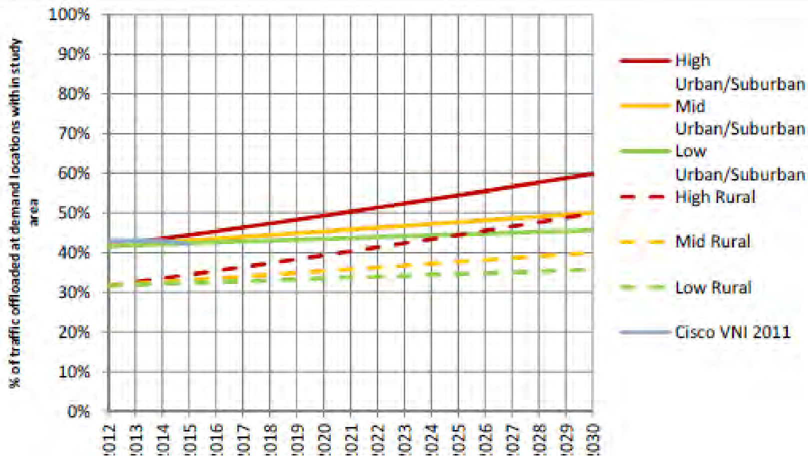


Figure 67: Assumed growth in offload of indoor traffic (proportion of total demand) for urban, suburban and rural areas from our UHF strategy study [1]

We assume that initially until 2015 there is growth in Wi-Fi offload levels but then Wi-Fi offload levels decline from 2015 onwards in line with the following trends:

- The significant (4x) growth in small cell numbers, with Informa forecasting a quadrupling in femtocell levels between 2011 and 2016 [79], to which wide area cellular traffic can be offloaded rather than Wi-Fi.
- Small cells being deployed in towns and cities across the UK for wireless provision initially supporting Wi-Fi but likely to soon be upgraded to support 3G and 4G technologies as traffic hot spots appear in these areas.
- Cellular small cells potentially becoming the preferred offload option over Wi-Fi as they can provide a more reliable service in congested areas compared to Wi-Fi due to being in uncontended spectrum and also having larger ranges as higher maximum EIRP levels are supported for licensed femtocells compared to Wi-Fi access points operating in licence exempt spectrum.
- Improvements in cellular technologies such as the migration to LTE and LTE-A bringing an enhanced user experience across key applications (video, VoLTE, etc.) which will make offload to Wi-Fi less essential for some applications than it has been in the past (as reflected by stakeholder responses to the CFI).

Overall this gives us a Wi-Fi offload level across all cellular enabled devices of 43% in 2010 growing to 50% by 2015 but reducing to 33% by 2030. In support of our recommended baseline setting for Wi-Fi offload or the split between licensed RATGs (i.e. RATG1 and RATG2) and LE RATGs (i.e. RATG3) this largely aligns with Wi-Fi offload levels indicated as realistic for UK cellular networks today and for trends out to 2030 indicated by one of the CFI responses. Additionally multiple CFI responses supported the view that Wi-Fi offload levels will reduce over time due to improved user experience from LTE surpassing user experience on Wi-Fi networks (see appendix G). This reduction in Wi-Fi offload over time in our baseline setting is also in line with the ITU default settings for the traffic distribution across RATGs but at a less aggressive rate.

In our sensitivity analysis we have made assumptions about high offload and low offload levels. Figure 68 shows the assumed Wi-Fi offload levels in each of these cases with a description of these scenarios given on Table 66.

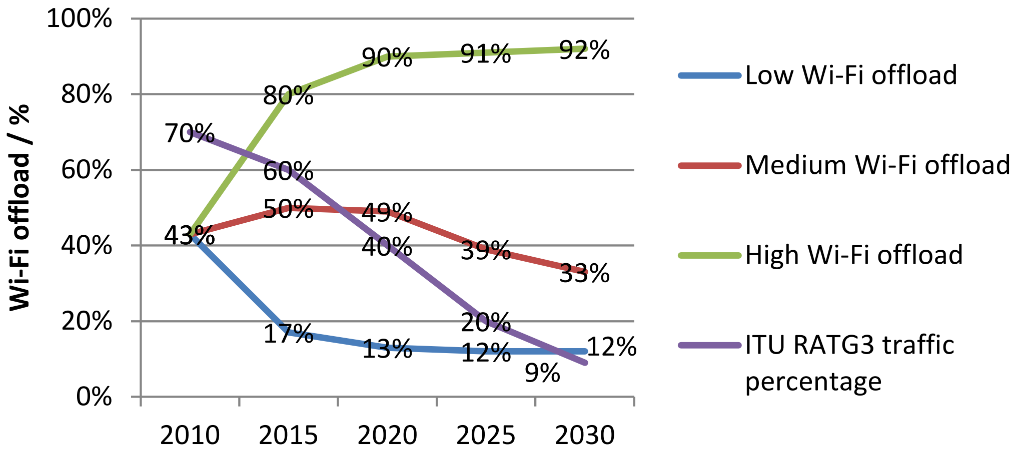


Figure 68: Low, medium and high Wi-Fi offload levels investigated

Market Setting	Outline assumption	Rationale
Low offload	In this case offloading traffic to Wi-Fi reduces over time and is picked up by the extensive roll out of femtocells within the indoor environment.	We have based our assumptions in this case on poor quality Wi-Fi equipment/devices suffering excessive interference in residential environments resulting in poor QoE for the end user. This continues over time and consumers deploy femtocells as a replacement to ensure a more satisfactory user experience. Initial offload levels for 2010 match our baseline medium offload case but reduce down to 12% by 2030 in line with worst case responses to the CFI.
High offload	In this case offloading traffic to Wi-Fi increases over time with more and more mobile device traffic carried over Wi-Fi indoors and outdoors due to better integration of Wi-Fi into cellular networks and the success of standards such as Hotspot 2.0. Generally Wi-Fi dominates over cellular small cells in this case.	We have based our assumptions in this case on very high quality equipment/devices with improved interference cancellation which offers a much enhanced user experience compared to cellular platforms. Wi-Fi becomes well integrated into cellular networks due to standards such as Hotspot 2.0 and dominates over cellular small cells. Initial offload levels for 2010 match our baseline medium offload case but this rapidly increases to higher end estimates of offload today of 80% by 2015 with further increases to 95% by 2030.

Table 66: High and low offload assumptions for sensitivity analysis

For the high Wi-Fi offload case we use a 2010 starting Wi-Fi offload level of 43% in line with our medium offload case and then grow this to 80% by 2015 in line with the following sources:

- A report from Mobidia [47] which suggests that almost 70% of smartphone-originated data traffic is carried over Wi-Fi today.
- Ofcom's report of demand for LE spectrum [48] which suggests that "80% of UK mobile phone data traffic is already carried by Wi-Fi".
- A Wireless Broadband Alliance survey which found that smartphones are starting to overtake laptops as a comparison between devices connecting to Wi-Fi [80].
- Cisco estimates that "of all traffic associated with mobile and portable devices in 2012, 97% was Wi-Fi and 3% was cellular.". However, we believe this is not specific to cellular enabled mobile devices but includes all mobile devices.
- The BEIRG response to the CFI which suggests exponential growth in Wi-Fi usage and that more users over time will go for the cheaper option of Wi-Fi over cellular.

We then anticipate further growth to 95% by 2030 to represent the integration of Wi-Fi into cellular networks and it becoming the dominant offload technology for cellular networks in most indoor environments. In this 95% we acknowledge that the offload opportunity for Wi-Fi, due to small cell sizes and handover issues, will remain confined to mostly indoor and pedestrian outdoor users. Based on sources for the proportion of mobile traffic consumed indoors such as shown in Figure 69 and also [81] and [82] this is likely to limit Wi-Fi offload levels to 95%.

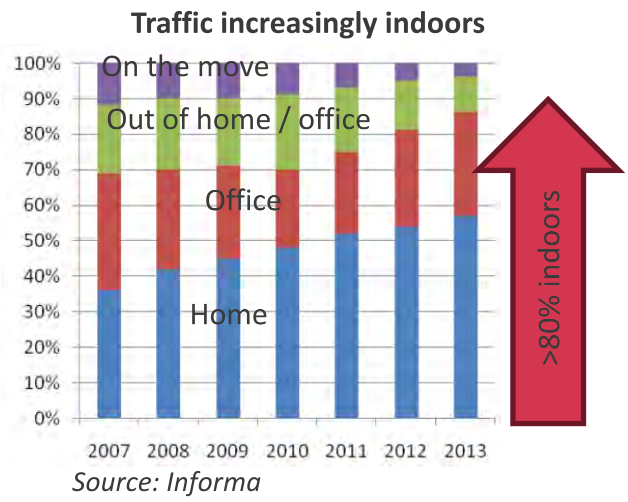


Figure 69: Traffic generated indoors [83]

We have based our low Wi-Fi offload case on a selection of worst case Wi-Fi offload levels given by respondents to the CFI. These lead us to assume the following for our low Wi-Fi offload scenario:

- A 2010 starting offload level of 43% in line with our medium offload case
- A Wi-Fi offload level of 17% by 2015 based on worst case Wi-Fi offload levels quoted by CFI responses for this time adjusted to produce an average Wi-Fi offload level which is representative of a higher opportunity to offload traffic in some of the ITU model SEs than others.
- A Wi-Fi offload level of 12% by 2030 on a similar basis to the rationale for the 2015 Wi-Fi offload value.

5.11 Summary of changes to technology and network input parameters

Table 67 provides a summary of the changes to the recommended ITU values for the technology and network related ITU-R M.1768-1 model parameters proposed in our recommended model baseline settings.

Parameter	Recommended updates	Comments	Impact on spectrum requirements of input revision
Guard band between operators	Maintain ITU default values	A 0MHz setting as per ITU recommendations assumes that FDD spectrum is dominant which reflects the UK usage of mobile	No impact

Parameter	Recommended updates	Comments	Impact on spectrum requirements of input revision
		broadband spectrum. Therefore we maintain this at the ITU default value.	
Minimum deployment per operator per radio environment	Update from 20MHz to 5MHz for RATG1 and 2.	We recommend changing this to 5MHz in line with minimum LTE, UMTS and LTE-A deployment bandwidths and the outcome of the UK 4G auction.	Spectrum requirements appear slightly reduced due to being produced at a finer resolution under the updated setting.
Number of overlapping network deployments	Maintain ITU default values	Maintain at 1 for RATG1 and 2 (not needed for RATG3) to obtain the highest resolution spectrum estimate from the model.	No impact
Supported mobility classes	Maintain ITU default values	Support ITU assumptions that macrocells address highest speed users, microcells address mobile users and picocells and hotspots are used by pedestrians only.	No impact
Application data rate	Update to use: - Cell edge rates for RATG1 - Average data rates for RATG2 adjusted for real networks - Average data rates for RATG3 that reflect Wi-Fi standards support over time	Generally ITU recommended application rates appear high and introduce technologies too early (i.e. LTE-A prior to 2020 and RATG3 picocells prior to 2015). Our revised application rates assume RATG1 networks will provide coverage and hence suggest cell edge rates whereas RATG2 and 3 will provide performance and so are based on average supported data rates (adjusted for average performance on real networks).	Reducing application rates in our baseline base relative to the ITU settings reduces support for more demanding SCs and generally should **reduce spectrum requirements**. Although note our sensitivity analysis later shows that this is not always the case.
Area spectral efficiency	Update to reduced spectral efficiencies compared with ITU default settings that are more aligned with the WINNER study. New spectral efficiencies added for RATG3.	ITU default settings are generally very high compared against other sources. Our recommended baseline setting reduces the ITU spectral efficiencies to largely align with WINNER suggested values at the assumed year of the RATG's deployment. This spectral efficiency is then grown at a rate in line with our UHF strategy study for Ofcom. New spectral efficiency values are	Our suggested lower spectral efficiencies relative to the ITU default levels will **increase spectrum requirements**.

Parameter	Recommended updates	Comments	Impact on spectrum requirements of input revision
		introduced for RATG3 in line with suggested application rates and assumed average supported bandwidth in LE devices over time.	
Support for multicast	Maintain ITU default values	Support ITU suggestion of multicast support across all RATGs.	No impact
Cell size	Maintain ITU recommended values for picocells and hotspots in all environments and microcells in suburban and rural areas. Macrocell sector areas in all environments and microcell sector areas in dense urban environments to be updated in line with UK site deployments.	Support the ITU recommended values for picocells and hotspots in all environments and microcells in suburban and rural areas. Suggest an adjustment to the macrocell sector areas in all environments and microcell dense urban sector areas in line with UK microcell deployments. Note this is a reasonably minor adjustment in all cases except rural macrocells where the sector area is increased by 13 times. This is likely due to differences in assumed frequencies and target data rates between our analysis and the ITU's.	Our suggested large increase in rural cell sizes will decrease the spectral efficiency density in this teledensity and **increase rural spectrum requirements.** In suburban areas we suggest an increase in macrocell size which would **increase suburban spectrum requirements.** In dense urban areas we suggest a decrease in macrocell and microcell cell sizes which would **decrease spectrum estimates in dense urban areas.**
Traffic distribution ratio among available RATGs	Maintain ITU traffic distribution between RATG1 and RATG2 but delayed by 5 years. Update the RATG3 to (RATG1 + RATG2) distribution to reflect our Wi-Fi offload analysis i.e. 43% at 2010 and 33% at 2030.	We assume that LTE-A in the UK is not deployed until 2020 which is 5 years later than the ITU default setting. We agree with the ITU assumption of Wi-Fi offload reducing over time but suggest a lower 2010 Wi-Fi offload starting point of 43% compared with 70% in the ITU default.	Our suggested baseline updates to the ITU default settings will have a **mixed impact on spectrum requirements**. Delaying the roll out of LTE-A by 5 years will increase spectrum requirements from 2015 onwards. Our suggested lower Wi-Fi offload level will increase spectrum requirements in early years. However, we do not reduce Wi-Fi offload as aggressively as ITU in our baseline setting so by 2030 the ITU Wi-Fi offload level is much less than our baseline leading to lower spectrum requirements for our baseline settings.
Population coverage	Minor updates to 2010 coverage	Our recommended baseline coverage levels largely align	Our suggested more aggressive uptake of small

Parameter	Recommended updates	Comments	Impact on spectrum requirements of input revision
percentage	levels suggested against ITU recommended values but more much aggressive uptake of small cells anticipated over time.	with the ITU default settings for macrocells. However, in the case of smaller cells we suggest mostly minor adjustments to the assumed 2010 coverage levels but then assume more aggressive small cell uptakes compared to the ITU recommendations based on forecasts for the small cell market.	cells relative to the ITU default settings will offload more macrocell traffic to more spectrally efficient small cells (if non mobile traffic) and **decrease spectrum requirements.**

Table 67: Summary of changes to technology and network related parameters (Green: ITU default setting, amber: minor changes close to ITU default setting, red: major changes against ITU default settings)

6. Appendix F – Assumed traffic distribution across intermediary devices

This appendix presents our assumptions for distributing traffic across intermediary devices for our demand estimates. In particular the tables show how traffic from our primary user devices are split across our intermediary devices so that all traffic is captured across the various possible/available networks that a given wireless device is capable of using.

We have produced an offload table for the low, baseline and high cases for each of the service environments because the traffic distribution varies across each one.

The overall offload percentage is calculated once all licensed and licence exempt traffic has been quantified across all devices and service environments for each year. This leads to the distribution of traffic across RATGs as shown for example earlier in Figure 65 for our baseline mid offload case which results in a 43% Wi-Fi offload for 2010, 50% Wi-Fi offload for 2015, 49% Wi-Fi offload in 2020, 39% Wi-Fi offload in 2025 and 33% Wi-Fi offload in 2030.

Baseline offload SE 4, 5 and 6

Table 6

2010 SE4-5	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 1) - tablet	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 2) - laptop	0.4	0.1	0	0.01	0	0	0	0	0.49	1
LSPD (type 3)	0.4	0.05	0	0.01	0	0	0	0	0.54	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.4	0	0	0.01	0	0	0	0	0.59	1

Table 7

2015 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.38	0.02	0	0.01	0	0	0	0.02	0.57	1
LSPD (type 1) - tablet	0.48	0.02	0	0.01	0	0	0	0.02	0.47	1
LSPD (type 2) - laptop	0.48	0.1	0	0.01	0	0	0	0.02	0.39	1
LSPD (type 3)	0.48	0.05	0	0.01	0	0	0	0.02	0.44	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.6	0	0	0.01	0	0	0	0	0.39	1

Table 8

2020 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.35	0.02	0	0.1	0	0	0	0.03	0.5	1
LSPD (type 1) - tablet	0.49	0.02	0	0.05	0	0	0	0.03	0.41	1
LSPD (type 2) - laptop	0.57	0.1	0	0.05	0	0	0	0.03	0.25	1
LSPD (type 3)	0.51	0.05	0	0.05	0	0	0	0.03	0.36	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.6	0	0	0.05	0	0	0	0	0.35	1

Table 9

2025 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.33	0.02	0	0.1	0	0	0	0.04	0.51	1
LSPD (type 1) - tablet	0.38	0.02	0	0.1	0	0	0	0.04	0.46	1
LSPD (type 2) - laptop	0.3	0.1	0	0.1	0	0	0	0.04	0.46	1
LSPD (type 3)	0.35	0.05	0	0.1	0	0	0	0.04	0.46	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.6	0	0	0.1	0	0	0	0	0.3	1

Table 10

2030 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.3	0.02	0	0.15	0	0	0	0.02	0.51	1
LSPD (type 1) - tablet	0.3	0.02	0	0.15	0	0	0	0.02	0.51	1
LSPD (type 2) - laptop	0.27	0.1	0	0.15	0	0	0	0.02	0.46	1
LSPD (type 3)	0.32	0.05	0	0.15	0	0	0	0.02	0.46	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.6	0	0	0.01	0	0	0	0	0.39	1

Table 68 Baseline offload Service environments 4 and 5

	2010 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.01	0.001	0.001	0.001	0	0.987	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.4	0.02	0	0.01	0.001	0.001	0.001	0	0.567	1
Table 11	LSPD (type 1) - tablet	0.68	0.02	0	0.01	0.001	0.001	0.001	0	0.287	1
	LSPD (type 2) - laptop	0.7	0.1	0	0.01	0.001	0.001	0.001	0	0.187	1
	LSPD (type 3)	0.65	0.05	0	0.01	0.001	0.001	0.001	0	0.287	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.6	0	0	0.01	0	0	0	0	0.39	1

	2015 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.01	0.001	0.001	0.001	0	0.987	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.38	0.02	0	0.01	0.001	0.001	0.001	0.02	0.567	1
Table 12	LSPD (type 1) - tablet	0.66	0.02	0	0.01	0.001	0.001	0.001	0.02	0.287	1
	LSPD (type 2) - laptop	0.68	0.1	0	0.01	0.001	0.001	0.001	0.02	0.187	1
	LSPD (type 3)	0.63	0.05	0	0.01	0.001	0.001	0.001	0.02	0.287	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.6	0	0	0.01	0	0	0	0	0.39	1

	2020 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.05	0.001	0.001	0.001	0	0.947	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.37	0.02	0	0.05	0.001	0.001	0.001	0.03	0.527	1
Table 13	LSPD (type 1) - tablet	0.57	0.02	0	0.05	0.001	0.001	0.001	0.03	0.327	1
	LSPD (type 2) - laptop	0.57	0.1	0	0.05	0.001	0.001	0.001	0.03	0.247	1
	LSPD (type 3)	0.57	0.05	0	0.05	0.001	0.001	0.001	0.03	0.297	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.6	0	0	0.05	0	0	0	0	0.35	1

	2025 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.15	0.001	0.001	0.001	0	0.847	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.36	0.02	0	0.15	0.001	0.001	0.001	0.04	0.427	1
Table 14	LSPD (type 1) - tablet	0.46	0.02	0	0.15	0.001	0.001	0.001	0.04	0.327	1
	LSPD (type 2) - laptop	0.46	0.1	0	0.15	0.001	0.001	0.001	0.04	0.247	1
	LSPD (type 3)	0.46	0.05	0	0.15	0.001	0.001	0.001	0.04	0.297	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.5	0	0	0.15	0	0	0	0	0.35	1

	2030 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.25	0.001	0.001	0.001	0	0.747	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.3	0.02	0	0.25	0.001	0.001	0.001	0.02	0.407	1
Table 15	LSPD (type 1) - tablet	0.3	0.02	0	0.25	0.001	0.001	0.001	0.02	0.407	1
	LSPD (type 2) - laptop	0.27	0.1	0	0.25	0.001	0.001	0.001	0.02	0.357	1
	LSPD (type 3)	0.32	0.05	0	0.25	0.001	0.001	0.001	0.02	0.357	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.35	0	0	0.25	0	0	0	0	0.4	1

Table 69 Baseline offload Service environment 6

Low offload for all service environments

	2010 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.4	0.02	0	0.01	0	0	0	0	0.57	1
Table 1	LSPD (type 1) - tablet	0.4	0.02	0	0.01	0	0	0	0	0.57	1
	LSPD (type 2) - laptop	0.4	0.1	0	0.01	0	0	0	0	0.49	1
	LSPD (type 3)	0.4	0.05	0	0.01	0	0	0	0	0.54	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.4	0	0	0.01	0	0	0	0	0.59	1

	2015 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.16	0.02	0	0.05	0	0	0	0.01	0.76	1
Table 2	LSPD (type 1) - tablet	0.16	0.02	0	0.05	0	0	0	0.01	0.76	1
	LSPD (type 2) - laptop	0.16	0.1	0	0.05	0	0	0	0.01	0.68	1
	LSPD (type 3)	0.16	0.05	0	0.05	0	0	0	0.01	0.73	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.16	0	0	0.01	0	0	0	0	0.83	1

	2020 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.12	0.02	0	0.15	0	0	0	0.01	0.7	1
Table 3	LSPD (type 1) - tablet	0.12	0.02	0	0.15	0	0	0	0.01	0.7	1
	LSPD (type 2) - laptop	0.12	0.05	0	0.15	0	0	0	0.01	0.67	1
	LSPD (type 3)	0.12	0.05	0	0.15	0	0	0	0.01	0.67	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.12	0	0	0.05	0	0	0	0	0.83	1

	2025 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.11	0.02	0	0.3	0	0	0	0.01	0.56	1
Table 4	LSPD (type 1) - tablet	0.11	0.02	0	0.3	0	0	0	0.01	0.56	1
	LSPD (type 2) - laptop	0.11	0.05	0	0.3	0	0	0	0.01	0.53	1
	LSPD (type 3)	0.11	0.05	0	0.3	0	0	0	0.01	0.53	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.11	0	0	0.2	0	0	0	0	0.69	1

	2030 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.11	0.02	0	0.35	0	0	0	0.01	0.51	1
Table 5	LSPD (type 1) - tablet	0.11	0.02	0	0.35	0	0	0	0.01	0.51	1
	LSPD (type 2) - laptop	0.11	0.05	0	0.35	0	0	0	0.01	0.48	1
	LSPD (type 3)	0.11	0.05	0	0.35	0	0	0	0.01	0.48	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.11	0	0	0.35	0	0	0	0	0.54	1

Table 70 Low offload for service environments 1 - 3

Table 6

2010 SE4-5	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 1) - tablet	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 2) - laptop	0.4	0.1	0	0.01	0	0	0	0	0.49	1
LSPD (type 3)	0.4	0.05	0	0.01	0	0	0	0	0.54	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.4	0	0	0.01	0	0	0	0	0.59	1

Table 7

2015 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.16	0.02	0	0.05	0	0	0	0.01	0.76	1
LSPD (type 1) - tablet	0.16	0.02	0	0.05	0	0	0	0.01	0.76	1
LSPD (type 2) - laptop	0.16	0.1	0	0.05	0	0	0	0.01	0.68	1
LSPD (type 3)	0.16	0.05	0	0.05	0	0	0	0.01	0.73	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.16	0	0	0.01	0	0	0	0	0.83	1

Table 8

2020 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.12	0.02	0	0.15	0	0	0	0.01	0.7	1
LSPD (type 1) - tablet	0.12	0.02	0	0.15	0	0	0	0.01	0.7	1
LSPD (type 2) - laptop	0.12	0.05	0	0.15	0	0	0	0.01	0.67	1
LSPD (type 3)	0.12	0.05	0	0.15	0	0	0	0.01	0.67	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.12	0	0	0.05	0	0	0	0	0.83	1

Table 9

2025 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.11	0.02	0	0.3	0	0	0	0.01	0.56	1
LSPD (type 1) - tablet	0.11	0.02	0	0.3	0	0	0	0.01	0.56	1
LSPD (type 2) - laptop	0.11	0.05	0	0.3	0	0	0	0.01	0.53	1
LSPD (type 3)	0.11	0.05	0	0.3	0	0	0	0.01	0.53	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.11	0	0	0.2	0	0	0	0	0.69	1

Table 10

2030 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.11	0.02	0	0.35	0	0	0	0.01	0.51	1
LSPD (type 1) - tablet	0.11	0.02	0	0.35	0	0	0	0.01	0.51	1
LSPD (type 2) - laptop	0.11	0.05	0	0.35	0	0	0	0.01	0.48	1
LSPD (type 3)	0.11	0.05	0	0.35	0	0	0	0.01	0.48	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainmer	0.11	0	0	0.35	0	0	0	0	0.54	1

Table 71 Low offload for service environments 4 and 5

	2010 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.01	0.001	0.001	0.001	0	0.987	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.4	0.02	0	0.01	0.001	0.001	0.001	0	0.567	1
Table 11	LSPD (type 1) - tablet	0.68	0.02	0	0.01	0.001	0.001	0.001	0	0.287	1
	LSPD (type 2) - laptop	0.7	0.1	0	0.01	0.001	0.001	0.001	0	0.187	1
	LSPD (type 3)	0.65	0.05	0	0.01	0.001	0.001	0.001	0	0.287	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.6	0	0	0.01	0	0	0	0	0.39	1

	2015 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.01	0.001	0.001	0.001	0	0.987	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.21	0.02	0	0.07	0.001	0.001	0.001	0.01	0.687	1
Table 12	LSPD (type 1) - tablet	0.21	0.02	0	0.07	0.001	0.001	0.001	0.01	0.687	1
	LSPD (type 2) - laptop	0.21	0.1	0	0.07	0.001	0.001	0.001	0.01	0.607	1
	LSPD (type 3)	0.21	0.05	0	0.07	0.001	0.001	0.001	0.01	0.657	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.21	0	0	0.01	0	0	0	0	0.78	1

	2020 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.05	0.001	0.001	0.001	0	0.947	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.17	0.02	0	0.2	0.001	0.001	0.001	0.01	0.597	1
Table 13	LSPD (type 1) - tablet	0.17	0.02	0	0.2	0.001	0.001	0.001	0.01	0.597	1
	LSPD (type 2) - laptop	0.17	0.1	0	0.2	0.001	0.001	0.001	0.01	0.517	1
	LSPD (type 3)	0.17	0.05	0	0.2	0.001	0.001	0.001	0.01	0.567	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.17	0	0	0.05	0	0	0	0	0.78	1

	2025 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.15	0.001	0.001	0.001	0	0.847	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.16	0.02	0	0.25	0.001	0.001	0.001	0.01	0.557	1
Table 14	LSPD (type 1) - tablet	0.16	0.02	0	0.25	0.001	0.001	0.001	0.01	0.557	1
	LSPD (type 2) - laptop	0.16	0.1	0	0.25	0.001	0.001	0.001	0.01	0.477	1
	LSPD (type 3)	0.16	0.05	0	0.25	0.001	0.001	0.001	0.01	0.527	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.16	0	0	0.15	0	0	0	0	0.69	1

	2030 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.25	0.001	0.001	0.001	0	0.747	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.16	0.02	0	0.3	0.001	0.001	0.001	0.01	0.507	1
Table 15	LSPD (type 1) - tablet	0.16	0.02	0	0.3	0.001	0.001	0.001	0.01	0.507	1
	LSPD (type 2) - laptop	0.16	0.1	0	0.3	0.001	0.001	0.001	0.01	0.427	1
	LSPD (type 3)	0.16	0.05	0	0.3	0.001	0.001	0.001	0.01	0.477	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.16	0	0	0.25	0	0	0	0	0.59	1

Table 72 Low offload for service environment 6

High offload

Table 1

2010 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 1) - tablet	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 2) - laptop	0.4	0.1	0	0.01	0	0	0	0	0.49	1
LSPD (type 3)	0.4	0.05	0	0.01	0	0	0	0	0.54	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.4	0	0	0.01	0	0	0	0	0.59	1

Table 2

2015 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.79	0.02	0	0.01	0	0	0	0.01	0.17	1
LSPD (type 1) - tablet	0.79	0.02	0	0.01	0	0	0	0.01	0.17	1
LSPD (type 2) - laptop	0.79	0.06	0	0.01	0	0	0	0.01	0.13	1
LSPD (type 3)	0.79	0.05	0	0.01	0	0	0	0.01	0.14	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.79	0	0	0.01	0	0	0	0.01	0.19	1

Table 3

2020 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.87	0.02	0	0	0	0	0	0.03	0.08	1
LSPD (type 1) - tablet	0.87	0.02	0	0	0	0	0	0.03	0.08	1
LSPD (type 2) - laptop	0.87	0.06	0	0	0	0	0	0.03	0.04	1
LSPD (type 3)	0.87	0.05	0	0	0	0	0	0.03	0.05	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.87	0	0	0.05	0	0	0	0	0.08	1

Table 4

2025 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.87	0.01	0	0	0	0	0	0.04	0.08	1
LSPD (type 1) - tablet	0.87	0.02	0	0	0	0	0	0.04	0.07	1
LSPD (type 2) - laptop	0.87	0.06	0	0	0	0	0	0.04	0.03	1
LSPD (type 3)	0.87	0.05	0	0	0	0	0	0.04	0.04	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.87	0	0	0.1	0	0	0	0	0.03	1

Table 5

2030 SE1-3	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.87	0.02	0	0	0	0	0	0.05	0.06	1
LSPD (type 1) - tablet	0.87	0.02	0	0	0	0	0	0.05	0.06	1
LSPD (type 2) - laptop	0.87	0.06	0	0	0	0	0	0.05	0.02	1
LSPD (type 3)	0.87	0.05	0	0	0	0	0	0.05	0.03	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.87	0	0	0.01	0	0	0	0	0.12	1

Table 73 High offload for service environment 1 - 3

Table 6

2010 SE4-5	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 1) - tablet	0.4	0.02	0	0.01	0	0	0	0	0.57	1
LSPD (type 2) - laptop	0.4	0.1	0	0.01	0	0	0	0	0.49	1
LSPD (type 3)	0.4	0.05	0	0.01	0	0	0	0	0.54	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.4	0	0	0.01	0	0	0	0	0.59	1

Table 7

2015 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.79	0.02	0	0.01	0	0	0	0.01	0.17	1
LSPD (type 1) - tablet	0.79	0.02	0	0.01	0	0	0	0.01	0.17	1
LSPD (type 2) - laptop	0.79	0.06	0	0.01	0	0	0	0.01	0.13	1
LSPD (type 3)	0.79	0.05	0	0.01	0	0	0	0.01	0.14	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.79	0	0	0.01	0	0	0	0.01	0.19	1

Table 8

2020 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.01	0	0	0	0	0.99	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.87	0.02	0	0	0	0	0	0.03	0.08	1
LSPD (type 1) - tablet	0.87	0.02	0	0	0	0	0	0.03	0.08	1
LSPD (type 2) - laptop	0.87	0.06	0	0	0	0	0	0.03	0.04	1
LSPD (type 3)	0.87	0.05	0	0	0	0	0	0.03	0.05	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.87	0	0	0.05	0	0	0	0	0.08	1

Table 9

2025 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.87	0.01	0	0	0	0	0	0.04	0.08	1
LSPD (type 1) - tablet	0.87	0.02	0	0	0	0	0	0.04	0.07	1
LSPD (type 2) - laptop	0.87	0.06	0	0	0	0	0	0.04	0.03	1
LSPD (type 3)	0.87	0.05	0	0	0	0	0	0.04	0.04	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.87	0	0	0.1	0	0	0	0	0.03	1

Table 10

2030 SE4-5	Public/Private WiFi	"Personal HS"/tether	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
Featurephone	0	0	0	0.1	0	0	0	0	0.9	1
M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
Smartphone	0.87	0.02	0	0	0	0	0	0.05	0.06	1
LSPD (type 1) - tablet	0.87	0.02	0	0	0	0	0	0.05	0.06	1
LSPD (type 2) - laptop	0.87	0.06	0	0	0	0	0	0.05	0.02	1
LSPD (type 3)	0.87	0.05	0	0	0	0	0	0.05	0.03	1
Smart TV	1	0	0	0	0	0	0	0	0	1
Gaming/Entertainment Console	0.87	0	0	0.01	0	0	0	0	0.12	1

Table 74 High offload for service environment 4 and 5

	2010 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.01	0.001	0.001	0.001	0	0.987	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.4	0.02	0	0.01	0.001	0.001	0.001	0	0.567	1
Table 11	LSPD (type 1) - tablet	0.68	0.02	0	0.01	0.001	0.001	0.001	0	0.287	1
	LSPD (type 2) - laptop	0.7	0.1	0	0.01	0.001	0.001	0.001	0	0.187	1
	LSPD (type 3)	0.65	0.05	0	0.01	0.001	0.001	0.001	0	0.287	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.6	0	0	0.01	0	0	0	0	0.39	1

	2015 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.01	0.001	0.001	0.001	0	0.987	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.79	0.02	0	0.01	0.001	0.001	0.001	0.01	0.167	1
Table 12	LSPD (type 1) - tablet	0.79	0.02	0	0.01	0.001	0.001	0.001	0.01	0.167	1
	LSPD (type 2) - laptop	0.79	0.06	0	0.01	0.001	0.001	0.001	0.01	0.127	1
	LSPD (type 3)	0.79	0.05	0	0.01	0.001	0.001	0.001	0.01	0.137	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.79	0	0	0.01	0	0	0	0.01	0.19	1

	2020 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.05	0.001	0.001	0.001	0	0.947	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.87	0.02	0	0	0.001	0.001	0.001	0.03	0.077	1
Table 13	LSPD (type 1) - tablet	0.87	0.02	0	0	0.001	0.001	0.001	0.03	0.077	1
	LSPD (type 2) - laptop	0.87	0.06	0	0	0.001	0.001	0.001	0.03	0.037	1
	LSPD (type 3)	0.87	0.05	0	0	0.001	0.001	0.001	0.03	0.047	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.87	0	0	0.05	0	0	0	0	0.08	1

	2025 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.15	0.001	0.001	0.001	0	0.847	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.87	0.01	0	0	0.001	0.001	0.001	0.04	0.077	1
Table 14	LSPD (type 1) - tablet	0.87	0.02	0	0	0.001	0.001	0.001	0.04	0.067	1
	LSPD (type 2) - laptop	0.87	0.06	0	0	0.001	0.001	0.001	0.04	0.027	1
	LSPD (type 3)	0.87	0.05	0	0	0.001	0.001	0.001	0.04	0.037	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.87	0	0	0.1	0	0	0	0	0.03	1

	2030 SE6	Public/Private WiFi	"Personal HS"/tethered	WindowLedge CPE	Femto Cell	Intel. Repeaters	Conv.Repeaters	LTE Relays	Wi-fi extender	Direct	TOTAL
	Featurephone	0	0	0	0.25	0.001	0.001	0.001	0	0.747	1
	M2M device (type 1)	0	0	0	0	0	0	0	0	1	1
	M2M device (type 2)	1	0	0	0	0	0	0	0	0	1
	Smartphone	0.87	0.02	0	0	0.001	0.001	0.001	0.05	0.057	1
Table 15	LSPD (type 1) - tablet	0.87	0.02	0	0	0.001	0.001	0.001	0.05	0.057	1
	LSPD (type 2) - laptop	0.87	0.06	0	0	0.001	0.001	0.001	0.05	0.017	1
	LSPD (type 3)	0.87	0.05	0	0	0.001	0.001	0.001	0.05	0.027	1
	Smart TV	1	0	0	0	0	0	0	0	0	1
	Gaming/Entertainment Console	0.87	0	0	0.01	0	0	0	0	0.12	1

Table 75 High offload for service environment 6

7. Appendix G – Responses to Call for Input and how we have addressed these in our modelling

7.1 Introduction

Ofcom issued a Call For Input (CFI) on several issues related to the computation of spectrum demand for this project [84]. We have reviewed the responses to the CFI and have taken account of them in our modelling work. This appendix summarises key points of those responses and explains our views on the relevant issues and how we have taken our views and those of stakeholders into account in our work.

We have grouped the relevant parts of the responses into the following issues:

- General issues relating to spectrum demand estimation
- The change of UK mobile data demand over the period 2015-2030
- The offload of data from existing mobile networks to Wi-Fi and other licence-exempt technology
- The spectral efficiency of mobile technologies
- Mobile application data rates
- The proportion of traffic to be carried on small cells in licensed spectrum
- The change in the ratio of uplink to downlink capacity required

7.2 General issues of spectrum demand estimation

7.2.1 Summary of stakeholder responses

Several stakeholders (including BT, Vodafone, Scottish Government, Inmarsat, BEIRG and confidential responses) noted that the long period under consideration (2015-2030) leads to significant uncertainties concerning both changes in mobile demand and in the technology performance and architectures to be used to support that demand, and this makes the estimation of spectrum requirements intrinsically prone to uncertainty.

Vodafone questioned the validity of the ITU-R methodology for the purpose, in that it does not consider market, economic and societal factors. They recommended use of a more economically-focused approach such as that used by Real Wireless for Ofcom in previous projects such as [1].

BT similarly noted that availability of more spectrum will generally lead to lower network costs or improved quality and reliability and that as a result spectrum estimates which do not take into account the influence of network costs on the architecture used for service delivery are limited in their usefulness. Nevertheless their assessment is that existing mobile spectrum bands together with other bands that are already identified internationally for IMT but not yet assigned in the UK (e.g. MoD bands at 2.3/3.4GHz), plus the foreseen longer term availability of the 700MHz band and other public sector spectrum releases should together be able to support foreseeable future demand.

BEIRG took the view that adequate mobile broadband coverage should be possible using the current level of spectrum and that more efficient use could be made of existing spectrum.

Other responses indicated that, while current mobile spectrum was sufficient to accommodate demand for the next few years, additional spectrum was likely to be required in the period beyond 2020.

7.2.2 Our view and treatment of responses

We agree that the long-term nature of this exercise and the associated uncertainty of both demand and supply parameters create uncertainty in the resulting estimates of spectrum requirements. We have sought to accommodate a wide but plausible range of views on all these parameters via distinct market settings and via a series of sensitivity analyses.

We note however that the majority of these settings leads to a situation in which additional mobile spectrum is required beyond currently planned releases for the UK, although the quantity and timing of such additional spectrum varies significantly with the model inputs.

We also agree that the ITU-R methodology is subject to a number of limitations, especially those concerning a lack of consideration of costs and their impact on the most efficient network architecture. These limitations are listed in section 2.1 of the main body of the final report. However use of the ITU-R methodology was required by Ofcom for this project to support their discussions within ITU-R and other international bodies. We have used our best endeavours to adapt the model to limit the impact of these limitations where feasible and have informed our choice of inputs from the current UK reality and the results of our other studies for Ofcom. Nevertheless, we recommend that the resulting spectrum estimates are considered in the light of these limitations.

7.3 Change of UK mobile data demand from 2015 to 2030

Stakeholders provided feedback on this issue in response to the following question in the CFI:

Question 1: How much do you expect UK mobile data demand to change in the period 2015-2030? Please provide evidence for the trend and, where possible,

please indicate how demand might vary across the device categories listed in paragraph 4.7. How should we account for factors (including pricing) that would constrain demand?

7.3.1 Summary of stakeholder responses

All stakeholders agree that mobile data demand has risen substantially in recent years and that further growth is expected in the future. However the extent of the expected future growth varies substantially.

In the near term, stakeholders expect growth of several tens of percent annually. For example, BT cite Cisco's forecasts for a 50% CAGR over the period to 2017, but point out that growth rates reduce towards the end of that period. The DTT multiplex operators challenge the view that data consumption will continue exponentially and cite figures by Analysys-Mason and changes to Cisco forecasts over time to show that both the rate of demand growth is expected to slow and that forecasts for demand are generally reducing over time. Sony Europe state that data traffic is growing currently at 50-100% in mobile networks and expect global traffic to continue to grow at approximately70% CAGR until at least 2020. Other stakeholders agree that while growth rates are expected to slow over time relative to the levels over the last few years (which were over 200%), future growth rates of 50-100% are still very high.

Few published forecasts address periods beyond the next five years. However some CFI responses indicated that they expected to see an increase of between approximately 15 and 20 times in peak throughput requirements in the period from now to over the next 20 years.. Several stakeholders point to video services as a key driver of long-term future demand growth, but this leads to significant variance in forecasts depending on the uptake of these services over mobile networks and the video resolution of such services. Given this uncertainty, Vodafone state that Ofcom's study should consider forecasts nearer the higher end of Real Wireless's previous scenarios for Ofcom given the potential high value from mobile services while ensuring that decisions made do not lead to unnecessary disruption to other users if growth is lower than this. BEIRG provide a view that demand will be limited by prices, citing experience of 4G in South Korea. RSGB suggest that growth in devices will flatten and that based on poor take-up of DV-H and internet radio, high end streaming data forecasts should be treated with caution.

The particular devices which will contribute to future demand are also uncertain. Vodafone say that new device types will emerge over the period under study and some of those in the list in paragraph 4.7 of the CFI will have faded away. They suggest it would be more reliable to consider the ways in which consumers may use mobile data rather than the categories of device. Inmarsat suggest that some assumptions concerning video consumption made in ITU-R Report M.2072 are unrealistically high. One case has users viewing mobile HDTV at a consumption level of 37 GByte in 4 hours, compared to a high definition file size currently at around 4 GByte. Intel note that device-to-device applications (which exchange content without an intermediate access point or base station) are missing from Ofcom's list and that these often require high data rates.

Several stakeholders expect that machine-to-machine (M2M) traffic will grow rapidly in future, and will be carried mainly over wide area cellular networks. Sony for example state that although M2M traffic will be relatively much smaller in scale than personal mobile device data consumption driven by video, it will be proportionally much more important in licensed spectrum. However RSGB expect such traffic to be in quote separate frequency bands to those allocated for IMT. UKSA expect M2M to be driven by a large growth in device numbers (while personal mobile devices will approach saturation).

7.3.2 Our view and treatment of responses

Given the wide range of views on demand amongst stakeholders, we have created demand scenarios which span a wide range of possible future scenarios. These are described in section 3 of these appendices. These scenarios have been used to derive low and high market settings and several sensitivity studies which span the range of stakeholder views. We believe that these scenarios are all plausible outcomes, but given the long time period involved and the many uncertainties they span a very wide range. Ofcom should take these uncertainties into account in considering the allocation and assignment of spectrum in the future.

We would note that the demand for services and the spectrum available to provide those services are not independent, since greater supply of spectrum will allow services to be delivered more cost-effectively, so a full assessment requires consideration of relative costs of varying scenarios which is beyond the scope of the ITU-R model. This and other limitations of the modelling process are described in in section 2.1 of the main body of the final report.

7.4 Offload to Wi-Fi and other licence-exempt technology

Stakeholders provided feedback on this issue in response to the following question in the CFI:

Question 3: What proportion of mobile data traffic do you expect to be carried over (a) Wi-Fi and similar systems in licence-exempt spectrum and (b) mobile networks in licensed spectrum? How do you expect this to change over the period 2015-2030 and how do you expect total data demand for Wi-Fi and similar systems in licence-exempt spectrum to change over the same period? How might this vary by location, environment etc.?

7.4.1 Summary of stakeholder responses

This question elicits a particularly wide range of views amongst stakeholders.

Some stakeholders take the view that Wi-Fi allows such a large and increasing volume of mobile traffic to be carried that this allows future demand to be accommodated with little or no need for incremental spectrum. BEIRG for example expect that LTE will give a poorer data quality and cost than Wi-Fi which will lead to most consumers offloading services to Wi-Fi in preference to mobile broadband. As a consequence they expect Wi-Fi usage to increase by 1000-200% between 2015 and 2030, especially in office and public areas. The DTT Multiplex operators consider that offloading, especially to Wi-Fi, has been substantially underplayed by previous forecasts, especially in view of the potential availability of additional 5 GHz spectrum. They also advocate action from Ofcom to enable sharing of such small cell and Wi-Fi networks by mobile operators. Inmarsat point to developments in Wi-Fi such as Passpoint which will enable easier use and roaming of Wi-Fi access points in the future and also state that perceived limitations in Wi-Fi's ability to support a guaranteed quality of service is not a practical drawback in most cases. As a result they suggest that the degree of offloading indicated in Figure A5.2 of the CFI underestimates the future potential of Wi-Fi offload. BT also suggest that mobile data capacity will increasingly be delivered using small cells in buildings connected to fixed broadband networks, although those small cells will includes both licensed and licence-exempt spectrum with proportions depending on market developments. They cited their own measurements and those of others to suggest that this trend is already apparent. David Hall also expects an increase in the proportion of mobile data carried in licence-exempt spectrum but that the technology, policy and economic developments make forecasts of the proportions difficult. Sony also see most data traffic will be carried over Wi-Fi and cite sources expecting 60% of data over Wi-Fi in the period 2017-20. BSkyB state that Wi-Fi is already an essential component of mobile data and that Wi-Fi traffic growth is around 4-6 times that of cellular data growth. They state that around 70% of UK smartphone data traffic is on Wi-Fi today and that around 80% of data on connected mid-screen devices makes use of Wi-Fi. They see a need for an increase in licence-exempt spectrum enabled via geo-located white space technology.

Other stakeholders, however, take the view that traffic carried on Wi-Fi is incremental to mobile demand in licensed spectrum and that the increasing capabilities of LTE and other technologies reduce the incentive for users to seek service via Wi-Fi. A confidential respondent indicated that while Wi-Fi traffic is substantially greater than that on the surrounding cellular network, cellular network traffic has not decreased. This suggests that Wi-Fi is creating additional demand rather than providing a means of offload. A confidential respondent also expects that, while the absolute volume of mobile traffic on Wi-Fi will continue to increase in absolute terms from 2015 to 2030, it will decrease as a proportion of the total. The reduction will be caused by increases in cellular coverage and an improved customer experience from LTE compared with Wi-Fi. They quote a study which suggests substantial variation in Wi-Fi offload amongst UK mobile networks. Another stakeholder response takes a similar view: they cite evidence that Wi-Fi usage is significantly smaller for LTE-capable handsets than for those with only 3G. Samsung is also cautious about the role of licence exempt services in future especially if greater security and quality of service are required. In 2020 and beyond they believe there is a case for a greater proportion of mobile data remaining within the licensed spectrum as current mobile network coverage and capacity limitations which are currently addressed by Wi-Fi are dealt with.

7.4.2 Our view and treatment of responses

It is difficult to span the wide range of views expressed by stakeholders on this issue. On the one hand, it may be that licence-exempt technologies, notably Wi-Fi, increasingly offer the features of a mobile service and thereby act as a complete substitute. On the other hand, and notwithstanding this possibility, licensed spectrum systems via small cells may offer a similarly low delivery cost for services. In practice we believe that neither approach is a complete substitute for the other since they have somewhat complementary characteristics and will be used in combination in different proportions according to local circumstances. Several industry initiatives in current progress bear this out and essentially lead to the ability for demand to make best use of whatever spectrum is available.

We would note that, whatever view is taken regarding the future evolution of mobile offload, such traffic remains a small proportion of the total traffic carried over Wi-Fi and is therefore a rather minor driver for licence-exempt spectrum. Our demand scenarios span a wide range of potential offload levels, but particularly span a wide range of scenarios for ‘native’ licence-exempt traffic.

We also note that forecasts of traffic generated by mobile devices over Wi-Fi often mix traffic over Wi-Fi which would never have been carried over licensed spectrum with that which constitutes true ‘offload’, making it difficult to compare forecasts directly and acting as a source of apparent disparity between the views of some stakeholders and industry commentators. We have attempted to avoid this confusion wherever possible.

7.5 Spectral efficiency of mobile technologies

Stakeholders provided feedback on this issue in response to the following question in the CFI:

Question 4: What factors will act to change the spectral efficiency of mobile technologies in the future? What spectral efficiency values are appropriate for consideration in our study for the period 2015-2030?

7.5.1 Summary of stakeholder responses

Stakeholder responses on this issue were fairly consistent. Several expressed the view that, while spectrum efficiency of mobile technologies will continue to increase in the future, both technical and practical limitations will cause the rate of increase to reduce progressively and will occur at a lower rate than the growth of demand. Telefónica expressed this view and concluded that additional spectrum would therefore be required in the coming years. Vodafone also noted that LTE already exhibits performance close to the Shannon limit. A confidential stakeholder expressed a similar view and noted that some technical advances such as eMBMS could only help in special local circumstances (such as sporting venues) and so contribute very little to overall capacity. A number of responses indicated that they expect available capacity to increase by between in the approximate region of 1.5 and 2 times over the next 10 years depending on technical advances. Sony indicate that spectral efficiency improvements are now limited to spectrum aggregation and adding MIMO antennas. Multiple responses noted that, while antenna technology such as MIMO and CoMP could in principle increase spectrum efficiency beyond these levels, practical and technical restrictions on the deployment of extra antenna at both base stations and handsets limit their likely deployment. BT stated it has no firm view on the question given the long time period involved but stated that Real Wireless' previous reports for Ofcom on this may provide a reasonable prediction. The DTT Multiplex operators also indicated that LTE is approaching theoretical limits for spectral efficiency, but nevertheless indicated that they expect that increases of at least 3 fold on current LTE rates can be expected. Inmarsat cite the Real Wireless work on this which shows approximately a five-fold increase in bit/s/Hz/cell between now and 2020. CAA suggest the use of a spectral efficiency value "in the top 5% of those currently available".

7.5.2 Our view and treatment of responses

There is good consistency in the views expressed by stakeholders on this point. We would advocate caution in expressing spectrum efficiency in relative terms, such as "1.5 times" since the baseline for comparison is often ill-defined. For example, "3G" systems vary enormously in their spectral efficiency, with later variants exhibiting very similar spectral efficiency to early deployments of LTE. Similarly, while we expect LTE spectral efficiency to increase rapidly over initial deployments, we expect the rate of progress beyond that to reduce significantly as practical limitations on the deployment of multiple antennas increase.

We considered these factors in detail in the UK context in our previous studies [1,66] and have compared the absolute spectral efficiencies from these studies with those embodied in the ITU default values and other studies, notably the WINNER project. Details of this comparison are provided in section 5.6 in these appendices. The results are in line with our previous work when the structure of the ITU model is taken into account.

7.6 Mobile application data rates

Stakeholders provided feedback on this issue in response to the following question in the CFI:

Question 5: What service bit rate values are appropriate for consideration in our study for the period 2015-2030? What evidence do you have of changing needs for service bit rates?

7.6.1 Summary of stakeholder responses

Relatively few stakeholders provided specific data on this issue and views were widely separated

BT noted that for indoor small cell solutions and Wi-Fi backhauled by fibre based superfast broadband peak download speeds of up to 80 Mbps may be experienced depending on the content type, with video to individual mobile devices and tablets being much less than 10 Mbps. Samsung was concerned that the ITU-R spectrum estimates focus on average requirements over the cell area and they should seek a target of 1 Gbps for all users, even at the cell edge. Sony stated that video traffic would be the main driver for high bitrates, implying typical bit rates of order tens of Mbps depending on the streaming quality (720p/1080p) and the choice of video codec. A confidential respondent suggested that some studies have suggested the human body can only accept data at around 10 Mbps per eye.

7.6.2 Our view and treatment of responses

The required data rates in the future are a significant source of uncertainty. We do take the view that the minimum required data rate to constitute a viable mobile broadband service has increased significantly to date and is likely to increase further in the future. However even modest increases in such data rates can very significantly decrease cell sizes and here the role of a sufficient quantity of low frequency spectrum to deliver service to a large number of users with a realistic number of cells is important.

The mean service bit rates, which shape the requirements of services considered in the ITU-R M.1768-1 model, have been maintained at the ITU recommended values in our baseline settings. This assumes some growth in required service rates in high end service categories that already require rates beyond 30Mbps. In our settings of application rates which determine the service levels that wireless networks will be capable of providing over time we assume (see appendix E):

- RATG1 macrocells provide coverage at a cell edge target rate of 2Mbps from 2015 onwards
- RATG 1 non macrocell cell types and RATG2 and RATG3 provide the performance layer of the network and target service levels in line with the average achievable spectral efficiency levels on the air interfaces considered within these RATGs.

For RATG1 this gives small cell data rates around 20Mbps across the study timeframe which is in keeping the small cell limitations outlined by BT. In the case of RATG2 small cells we assume application rates from 38 to 80Mbps in 2020 which are again in line with the BT limitations but note that by 2025 an improvement in backhaul will be needed to support up to 1Gbps in RATG2 hotspots. We note that our assumed RATG 3 application rate of over 100Mbps may be optimistic compared to the limitations outline by BT of 80Mbps at peak levels but is nonetheless in the right region. We also note that the BT limitation of 10Mbps of video streaming to individual devices supports our assumptions in our critique of the ITU service categories that SCs above 30Mbps would not have been supported in practice in

2010 (see appendix D). The application rates suggested by Sony of 1Gbps are included in our assumptions of application rates for RATG2 and RATG3 hotspots but only towards the end of our study timeframe.

We note in passing that the maximum bit rate which the human visual system can accept has been estimated in some sources to be as high as 1.36×10^{12} bps [85].

7.7 Proportion of traffic on small cells

Stakeholders provided feedback on this issue in response to the following question in the CFI:

> *Question 6: What proportion of traffic do you consider should be assumed to be carried on each cell types for the period 2015-2030? How will this vary with service environment i.e. between home, office, public areas, rural, suburban and urban? What evidence do you have of the factors affecting the uptake of small cells in licensed spectrum in the future?*

7.7.1 Summary of stakeholder responses

Stakeholders generally agree that small cells operating in licensed spectrum will play an increasingly important role in future, but disagree on the extent to which this reduces the future demand for spectrum.

One confidential respondent sees small cells growing rapidly, but expects them only to be deployed as a last resort once the capacity of a macrocell network is exhausted. They cite several constraints on the volume of small cells including the availability of suitable sites, the cost of power and backhaul. These factors may constrain the deployment of small cells deployed for capacity purposes (although they view these separately to femtocells deployed to enhance coverage). They also state that small cells need harmonised spectrum below around 6 GHz for backhaul purposes. BT expect mobile capacity to be increasingly delivered using small cells in buildings connected to fixed broadband networks.

The DTT multiplex operators believe that a combination of small cells and Wi-Fi will allow sufficient additional capacity to avoid any additional allocation of spectrum and cite studies which indicate an increase in throughput of over 5 times by deploying ten small cells per macrocell in high traffic areas. They advocate action from Ofcom to enable such small cells to be shared by mobile operators. UKSA also expect greater use of pico/femto cells along with Wi-Fi to allow existing IMT spectrum to be used more densely, so that there is already sufficient spectrum allocated to mobile broadband.

As to the specific distribution of traffic amongst cell layers, a confidential respondent supported use of the data included in ITU-R M.1768-1.

7.7.2 Our view and treatment of responses

It is clear that small cells will play an increasingly important role in mobile networks, but the extent of their deployment is dependent on practical and cost factors which are out of the scope of the ITU model. The model takes the distribution of traffic across cell layers as an input rather than an output. We have informed our choice of distribution of traffic from our previous work for Ofcom, from the stakeholder comments and from the ITU recommendations.

We consider that our dedicated spectrum estimates from the ITU model which assumes use of distinct spectrum for each cell layer to be overly pessimistic and have therefore included additional estimates where the small cells share spectrum with the macrocell network to give an indication of the range of potential spectrum requirements. However we note the potential for small cells to deliver a greater benefit for a given cost when they are deployed in dedicated spectrum, so we expect the most realistic spectrum level to lie between the fully dedicated and fully shared extremes.

We note that small cells may be deployed to enhance user experience (including typical data rates) as well as capacity. We also note the potential need for spectrum suitable for small cell backhaul, which is not part of the estimates produced by the ITU model.

7.8 Uplink/downlink ratio

Stakeholders provided feedback on this issue in response to the following question in the CFI:

Question 7: Given the current mix of services on cellular networks what is the ratio of downlink to uplink capacity currently dimensioned for and how would you expect this to change over time by 2015, 2020, 2025 and 2030? How do you expect the ratio of downlink to uplink demand to vary for the service categories given in Table A5.4 of Annex 5, and what factors might affect this? How does this ratio of downlink to uplink capacity change (if at all) with network radio access technology and offload to licence-exempt systems?

7.8.1 Summary of stakeholder responses

Stakeholders generally expect downlink traffic to continue to dominate over uplink traffic and to remain the critical factor in dimensioning networks in future, although the balance was likely to shift somewhat towards the uplink.

One respondent indicated that current data traffic in the uplink in their network is much smaller in volume than downlink traffic, with similar figures for other European operators, and do not see this changing materially in the medium term. Vodafone also see the downlink as the limiting factor currently and expect this to continue although the downlink to uplink traffic ratio is likely to reduce over time. BT’s current consumer products typically have a 4:1 ratio of peak downlink to uplink speeds.

David Hall expects that the growth of cloud computing and user generated content could cause uplink traffic to nearly equal the downlink traffic. Sony expect the downlink to uplink ratio to change from currently around 10:1 to 3:1 or lower. In particular they see the potential for M2M traffic to be uplink dominated and that this low data rate traffic may constitute a considerable portion of traffic in sub 1 GHz spectrum macrocells. Telefónica note that while downlink traffic is likely to be higher than uplink traffic, since the spectrum efficiency in the downlink will remain much higher than in the uplink this will help to mitigate against traffic asymmetry.

7.8.2 Our view and treatment of responses

Consistent with stakeholder views and our previous work for Ofcom, we regard downlink traffic as the major limiting factor on capacity, although the balance may vary significantly according to location and service type.

Table 24 reflects our assumptions and sources for the uplink to downlink split assumed in our demand analysis. Generally we agree with CFI stakeholders that downlink traffic will continue to dominate over uplink levels but that this varies across devices with M2M smart metering type devices having the potential to have a 1:1 ratio of downlink to uplink traffic (the lowest level assumed in our analysis). In feature phones we assume a higher 9:1 ratio as given by the Sony response but in more modern wireless devices such as tablets and smartphones assume lower ratios of 4:1 in line with how stakeholders thought overall ratios would change over time.

Abbreviations

CFI	Call for Inputs
CoMP	Co-ordinated Multi-Point
CPE	Consumer Premise Equipment
CS	Circuit Switched
DL	Downlink
DTT	Digital Terrestrial Television
eMBMS	Evolved Multimedia Broadcast Multicast Service
ITU-R	International Telecommunications Union Radiocommunications
LE	Licence exempt
LOS	Line of Sight
LSPD	Large Screen Portable Devices
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
PLMN	Public Land Mobile Network
PS	Packet Switched
PTP	Peer to Peer
RATG	Radio Access Technology Group
SC	Service Category
SE	Service Environment
UE	User Equipment
UL	Uplink
UMTS	Universally Mobile Telecommunications System
VoLTE	Voice over LTE

References

1 *"Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030"*, Real Wireless for Ofcom, March 2012
2 "*Revised 700 MHz Band Plan for Commercial Services*", FCC, 2007 http://wireless.fcc.gov/auctions/data/bandplans/700MHzBandPlan.pdf
3 "*Commission Decision 2010/267/EU*" European Commission, 2010 http://www.erodocdb.dk/docs/doc98/official/pdf/2010267EU.pdf

4 "*UK Interface Requirement 2014 Public Wireless Networks*", Ofcom, Aug 2005, http://stakeholders.ofcom.org.uk/binaries/spectrum/spectrum-policy-area/spectrum-management/research-guidelines-tech-info/interface-requirements/ir2014.pdf
5 "*UK Interface Requirement 2019 Third Generation Mobile*", Ofcom, Aug 2005, http://stakeholders.ofcom.org.uk/binaries/spectrum/spectrum-policy-area/spectrum-management/research-guidelines-tech-info/interface-requirements/3gm.pdf
6 "*ECC Decision of 18 March 2005 on harmonised utilisation of spectrum for IMT-2000/UMTS systems operating within the band 2500 – 2690 MHz*", ECC Decision (05)05, March 2005, http://www.erodocdb.dk/docs/doc98/official/pdf/ECCDec0505.pdf
7 "*UK Interface Requirements 2015.1 to IR 2015.3 Spectrum Access in the 3400 to 4009 MHz band*", Ofcom, 2011, http://stakeholders.ofcom.org.uk/binaries/spectrum/spectrum-policy-area/spectrum-management/research-guidelines-tech-info/interface-requirements/IR_2015_3_4GHz.pdf
8 "*Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (Release 9)*," 3rd Generation Partnership Project, 3GPP TS 36.101 v10.1.0, September 2011, http://www.3gpp.org/specifications
9 "*Enabling UK growth – Releasing public spectrum Making 500 MHz of spectrum available by 2020*", Department for Culture Media, March 2011, http://www.culture.gov.uk/publications/7994.aspx
10 "*E-UTRA Physical Channels and Modulation*", 3GPP TS 26.211 V10.3.0 (2011-09), http://www.3gpp.org/ftp/Specs/html-info/36211.htm
11 ECC DEC 03(02) ECC Decision of 17 October 2003 on the designation of the frequency band 1479.5 – 1492 MHz for use by Satellite Digital Audio Broadcasting systems, European Commission, 2003, http://www.erodocdb.dk/docs/doc98/official/pdf/ECCDec0302.pdf
12 *"Economic study of the benefits from use of 1452-1492 MHz for a supplemental mobile downlink for enhanced multimedia and broadband services"*, Plum consulting, June 2011, http://www.plumconsulting.co.uk/pdfs/Plum_June2011_Benefits_of_1.4GHz_spectrum_for_multimedia_services.pdf
13 "*Consultation on assessment of future mobile competition and proposals for the award of 800 MHz and 2.6 GHz spectrum and related issues*", Ofcom, March 2011, http://stakeholders.ofcom.org.uk/binaries/consultations/combined-award/summary/combined-award.pdf
14 "*White Paper LTE TDD Operator Business Case and Adoption Forecast*", Berge Ayvazian, Heavy Reading, March 2011,
15 UK Broadband, Our 4G network, UK Broadband website, http://www.ukbroadband.com/4g-networks/our-4g-network

16 *“IR 2030 - UK Interface Requirements 2030 Licence Exempt Short Range Devices”,* Ofcom Dec 2011
17 *“Future proofing Wi-Fi – the case for more spectrum – a report for Cisco”*, Plum Consulting, January 2013.
18 “TV white spaces – A consultation on white space device requirements”, Ofcom Nov 2012,
http://stakeholders.ofcom.org.uk/binaries/consultations/whitespaces/summary/condoc.pdf
19 “*Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010–2015*”, February 2011, Cisco,
http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html
20 *“Traffic and Market data report ON THE PULSE OF THE NETWORKED SOCIETY”,* Ericsson, November 2011, http://hugin.info/1061/R/1561267/483187.pdf
21 HP web site for HP Envy x2 http://www8.hp.com/uk/en/ad/envy-x2/specs.html
22 *Mobile data moves indoors*”, SenzaFili Consulting, September 2011
http://www.senzafiliconsulting.com/Blog/tabid/64/articleType/ArticleView/articleId/59/Mobile-data-move-indoors.aspx
23 Facts and Figures from Heathrow Airport http://www.heathrowairport.com/about-us/company-news-and-information/company-information/facts-and-figures
24 *“Predicting areas of spectrum shortage”*, PA Consulting report for Ofcom, April 2009
25 *“Mobile Market Trends UK: Data to engage with consumers 2010-2012”*, Mobile Squared, 2012
26 *“Communications Market Report”,* Ofcom 2010
27 *“Annual Mid-year Population Estimates, 2010”,* June 2011,
http://www.statistics.gov.uk/hub/population/population-change/population-estimates/index.html
28 “Communications Market Report”, Ofcom 2011
29 “*Apple's 73% UK tablet market share 'set to fall*”, September 2011
http://www.guardian.co.uk/technology/2011/sep/12/apple-tablet-market-share-set-to-fall
30 “*Tablets To Surpass Laptop Sales In 2015, One Third Of US Consumers Will Own One*”, Jan 2011 http://www.mobilemarketingwatch.com/tablets-to-surpass-laptop-sales-in-2015-one-third-of-us-consumers-will-own-one-12356
31 “*Tablet Demand and Disruption Mobile Users Come of Age*”, Morgan Stanley, Feb 2011,
http://www.morganstanley.com/views/perspectives/tablets_demand.pdf
32 www.laptopsdirect.co.uk
33 *“Mobile Broadband: The shift from Detachable to Embedded Solutions*”, IDC, Bakhshi, Shiv K, David Daoud, July 2007
http://www.dell.com/downloads/global/products/latit/en/IDC_EmbeddedWhitepaper.pdf
34 “*UK Mobile Market Overview*”, Incentivated, March 2010
http://www.slideshare.net/Incentivated/uk-mobile-market-overview-0310
35 *“Communications Market Report 2012”,* Ofcom, July 2012.
36 *“Land Area and Population Density, Borough, GLA”,*
http://data.london.gov.uk/datastore/package/land-area-and-population-density-borough
37 “*Smartphones generate 65 per cent of all mobile traffic - congestion remedies urgently needed”*, Informa Telecoms and Media, Alan Weissberger, March 2011
http://community.comsoc.org/blogs/ajwdct/informa-smartphones-generate-65-cent-all-mobile-traffic-congestion-remedies-urgently-ne

38 “*Mobile traffic forecasts 2010-2020 and offloading solutions”,* IDATE, Frederic Pujol, May 2011, http://www.ict-befemto.eu/fileadmin/documents/publications/workshop_2011/F._PUJOL_IDATE_15_05_2011.pdf
39 “*LTE and emerging technologies”,* Ericsson presentation, May 2011
40 “*Managing growth and profits in the yottabyte era – 2nd edition*” Chetan Sharma Consulting, June 2010 http://www.chetansharma.com/Managing_Growth_and_Profits_in_the_Yottabyte_Era_Second_Edition.pdf
41 “*Mobile Broadband Capacity Constraints And the Need for Optimization*”, Rysavy Research, Feb 2010, http://www.rysavy.com/Articles/2010_02_Rysavy_Mobile_Broadband_Capacity_Constraints.pdf
42 “*Worldwide mobile broadband connections to hit 445 million by 2015”*, Analysys Mason , July 2010
43 “*Smartphones, iPads & the state of the mobile Internet*”, Om Malik, July 2011 http://gigaom.com/broadband/smartphones-ipads-the-state-of-the-mobile-internet
44 Extract from PlayStation Forum discussion “So, bought myself a PSVita 3G/Wifi... this is my experience”, June 2012, http://community.eu.playstation.com/t5/PS-Vita-General-Discussion/So-bought-myself-a-PSVita-3G-Wifi-this-is-my-experience/td-p/16438453
45 http://www.iphoneincanada.ca/news/netflix-ceo-i-dont-quite-understand-why-canada-has-very-low-internet-caps/
46 *“A First Look at Cellular Machine-to Machine Traffic – Large Scale Measurement and Characterisation”*, M. Zubair Shafiq, Alex X. Liu, Jeffrey Pang, Jia Wang, Department of Computer Science and Engineering, Michigan State University, East Lansing, MI, USA
47 “*Understanding today’s smartphone user Demystifying data usage trends on cellular and Wi-Fi networks Part 2: An expanded view by data plan size, OS, device type and LTE*”, Informa telecoms and media and Mobidia, 2012
48 *“Technologies and approaches for meeting the demand for wireless data using licence exempt spectrum to 2022”,* Quotient Associates, Jan 2013
49 *“Spectrum requirements for systems beyond IMT-2000”*, Ojala et al., IST-4-027756 WINNER II D5.10.2 v1.0, March 2007.
50 *“Working Document To Liaise Information To Joint Task Group 4-5-6-7 On Spectrum Requirements As Set Out In Resolution 233”*, ITU Working Party 5D, Document 5D/TEMP/185-E, February 2013.
51 *“Draft revision of recommendation ITU-R M.1768”,* ITU-R working party 5D, Revision 1 to document 5/14-E, November 2012.
52 *“World mobile telecommunications market forecast”,* ITU-R M 2072, 2005, ITU-R
53 ITU-R M 1768 model Excel implementation provided by WP 5D, http://www.itu.int/ITU-R/index.asp?category=study-groups&rlink=rwp5d&lang=en
54 Maximum transmission Unit definition Wikipedia http://en.wikipedia.org/wiki/Maximum_transmission_unit
55 *“LTE Equipment Evaluation: Considerations and Selection Criteria”,* Stoke, 2012 http://www.google.co.uk/url?sa=t&rct=j&q=lte%20equipment%20evaluation%3A%20considerations%20and%20selection%20criteria&source=web&cd=1&ved=0CDEQFjAA&url=http%3A%2F%2Fwww.stoke.com%2FGetFile.asp%3Ff%3Dbb1bc4037bc0a4bd437db7601ee73bf4&ei=fV6LUfrRK4mm0wXEu4HADQ&usg=AFQjCNGeV_v9bK96GSrooFbCPsppBseKVg
56 “*Not all packets are equal, Part I Streaming Video Coding and SLA Requirements*”, Jason Greengrass, John Evans and Ali C Began, Cisco, 2009

57 "*Identification and Analysis of Peer-to-Peer Traffic*", Marcell Perenyi, Trang Dinh Dang, Andra Gefferth, Sandor Molnar, Budapest University of Technology and Economics Hungary
58 "*Anatomy of WiFi Access Traffic of Smartphones and Implications for Energy Saving Techniques*", Rajesh Palit, Kshirasagar Naik, Ajit Singh, Department of Electrical and Computer Engineering University of Waterloo
59 "Rate Adaptation for Video Telephony in 3G Networks", Harinath Garudadri, Hyukjune Chung, Naveen Srinivasamurthy, Phoom Sagetong, Qualcomm, 2007
60 "Video Calling Over Wireless Networks", David Urban, Comcast
61 "IP-based HDTV Broadcasting System Architecture with Non-Stop Service Availability", Teruyuki Hasegawa, Kauhiro Kamimura, Haruo Hoshino, Shigehiro Anoand Toru Hasegawa, KDDI R&D Laboratories and NHK Japan Broadcasting Corporation 2005
62 "*Integrated QoS Management*", Paper by the NGMN Alliance, Dec 2012, http://www.ngmn.org/uploads/media/NGMN_Backhaul_Evolution_-_Integrated_QoS_Management_Part_One_v1.3.pdf
63 *"3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access (Release 8)",* 3GPP TS 23.401
64 *"Ofcom announces winners of the 4G mobile auction",* Ofcom, Press release, February 2013, http://media.ofcom.org.uk/2013/02/20/ofcom-announces-winners-of-the-4g-mobile-auction/
65 "4G Coverage obligation notice of compliance verification methodology: LTE", Ofcom, November 2012, http://stakeholders.ofcom.org.uk/binaries/consultations/award-800mhz/statement/4GCov-verification.pdf
66 *"4G Capacity Gains",* Real Wireless, Report for Ofcom, January 2011, http://www.realwireless.biz/4g-long-term-capacity-gains-report/
67 *"An assessment of the value of small cell services to operators based on Virgin Media trials",* Real Wireless, October 2012
68 *"Impact of EIRP Limit Changes on the Performance of 2.4 GHz WiFi Systems",* S. Kawade et al., IEEE VTC Spring, 2791-5, 2007.
69 *"Performance Analysis: Co-existence of IEEE 802.11g with Bluetooth",* K. Shuaib et al. IEEE WOCN, 2005.
70 *"Area spectral efficiency values of RAT group 2 for the IMT estimate"*, ITU-R study group contribution from Germany, Sweden and Finland, Document 8F/822-E, April 2006.
71 *"Calculation of spectral efficiency for estimating spectrum requirements of IMT-advanced in Korean mobile communications environments",* Chung W. et al, ETRI journal, Volume 29, Number 2, April 2007.
72 *"Methodologies used for the analysis of costs relating to a coverage obligation at 800MHz - For existing sites and using MIP sites"* , Real Wireless, July 2012
73 *"Low-power shared access to spectrum for mobile broadband",* Real Wireless, March 2011.
74 Ubiquisys, http://ubiquisys.com/small-cells-blog/what-is-an-enterprise-femtocell-2
75 *"Small Cell market status Q1 2013"*, Informa, SCF050, February 2013.
76 *"Options for Improving in-building mobile coverage"*, Real Wireless, April 2013
77 *"Infrastructure report – 2012 update",* Ofcom, December 2012.
78 U-Switch, http://www.uswitch.com/broadband/news/2012/04/73_of_uk_homes_have_wi_fi_study_reveals/.
79 *"Small Cell Market Status",* Informa, December 2012

80 *“Global Trends in Public Wi-Fi Next-Generation Hotspot: Moving from Standardization to Commercialization”*, WBA Wi-Fi Industry Report (November 2012)
81 *“Wireless network traffic 2010–2015: forecasts and analysis”,* Analysys Mason, July 2010.
82 *“Mobile data moves indoors”,* Paolini M. , September 2011.
83 *“ Release one: Home – overview”,* Small Cell Forum, February 2013, http://www.scf.io/en/documents/101_Release_One_Home_overview.php
84 *“Future demand for mobile broadband spectrum and consideration of potential candidate bands”*, Ofcom Call for Input, 18th March 2013. Available at: http://stakeholders.ofcom.org.uk/consultations/cfi-mobile-bb/summary
85 *“The bit rate of reality”*, T. Holman, pp. 398-99, International Conference on Consumer Electronics, 2000.

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