# MOBILE SPECTRUM REQUIREMENT ESTIMATES: GETTING THE INPUTS RIGHT

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# Executive Summary

LS telcom provides spectrum management services to regulators, operators and spectrum users around the world. In addition to software and hardware solutions, LS provides consultancy services in spectrum management. A common request amongst regulators is to provide an evaluation of the amount of spectrum required for commercial terrestrial mobile broadband (IMT) services. In trying to assess the demand for spectrum for IMT services, we have examined the model used by many regulators around the world to produce the forecasts which will eventually be used to inform decisions at World Radiocommunication Conferences (WRC). Using this model, developed by the International Telecommunications Union (ITU), we have identified a number of issues which mean that the model, as it stands, does not provide useable nor useful results.

We are not alone in our findings. Several parties (including the Russian spectrum regulator and the European Broadcasting Union) have questioned the values produced for IMT spectrum demand generated by the ITU model. Telecommunications analyst and consultant Tim Farrar of TMF Associates had also identified flaws in the model. In order to try and inform a discussion of how the model can be modified, so that it is useable for predicting IMT spectrum demand, LS telcom and TMF Associates have jointly produced this report to share our findings.

ITU-R Report M.2290-0[1] present forecasts for growth in the total amount of mobile traffic in the world to 2020 and then models spectrum demand based on traffic density in across a variety of service environments (SE) which include urban, suburban and rural areas. It concludes that the demand for spectrum in 2020 is between 1340 MHz and 1960 MHz (in low and high demand situations respectively).

The ITU model purports to have used, amongst others, the UMTS Forum traffic forecasts as a basis for developing the spectrum demands. However, the traffic forecasts in the ITU model appear to be built-up from different sets of assumptions, which are at odds with the UMTS Forum forecasts. A comparison of the traffic density figures actually used in the ITU model with figures based on the UMTS Forum forecasts for urban and suburban areas show that the traffic density figures in the ITU model are at least two orders of magnitude too high.

We have identified that there is a fundamental problem with the ITU model in that the **traffic density does not appear to have been benchmarked** against total predicted traffic in any particular country. Having undertaken such an analysis, our conclusion is that **the traffic densities** which drive the ITU's spectrum demand forecasts **are *at least two orders of magnitude* (i.e. a factor of 100 times) too high** when compared with those which would be expected in any developed or developing country in a 2020 timeframe.

The figure below graphically illustrates this problem. The ITU's forecasts for traffic density (measured in Petabytes per month per square kilometre) in 2020 far exceed the values that industry forecasts provide, to the extent that even the ITU's rural traffic density figures exceed forecasts for urban areas in some of the World's most developed countries.[2]

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[1] "Future spectrum requirements estimate for terrestrial IMT", 13 January 2014

[2] Figure 1 compares the ITU model traffic density in the "low growth" case with benchmarks derived from UMTS Forum Report 44 (published in 2011), which also represents a low end growth forecast for data traffic in 2020.

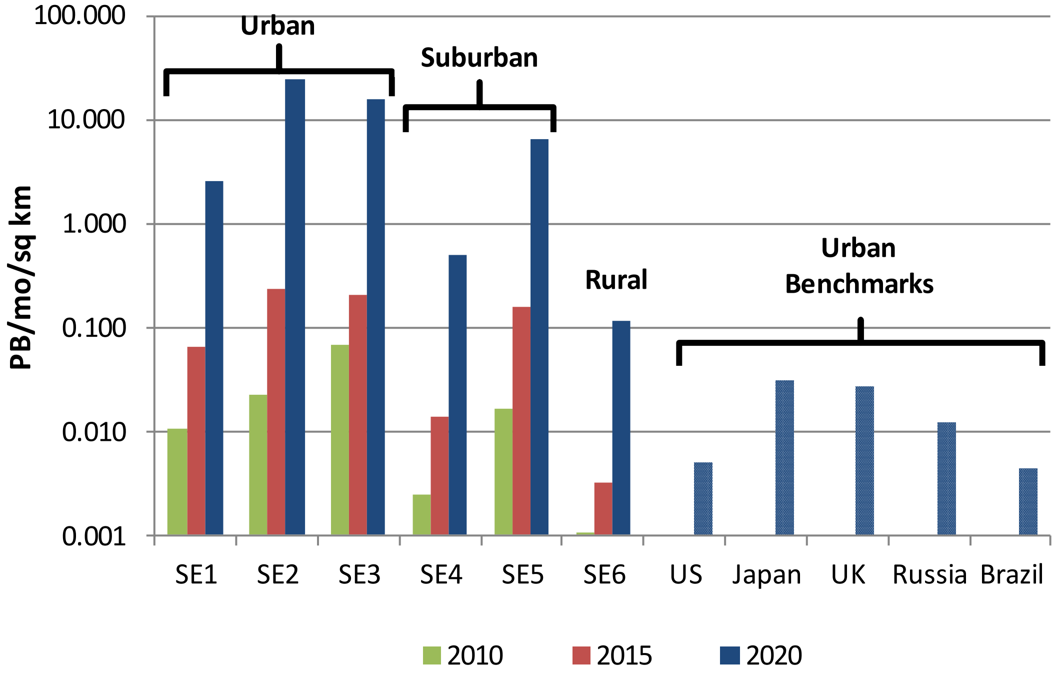

**Figure 1: Monthly data traffic per square km; the figures from the ITU model ("low growth" case) for the six different service environments are compared with benchmark figures (from UMTS Forum Report 44) for urban area traffic in five example countries. (Note the logarithmic scale)**

The source of the overestimate results from a combination of an **unrealistic user density** (i.e. number of people using each application) *and* **excessive traffic per user** (i.e. data consumption per person using each application), as illustrated in the figures below. We have identified the total usage per sq km and divided by this user density in the ITU model, then compared this to the average usage per head of urban population according UMTS Forum forecasts. It can be seen that even in SE 5 (suburban), the density of 30,400 users per sq km forecast by the ITU is between 5 times (Brazil) and 32 times (US) the typical urban population density (let alone the suburban population density), while the traffic of 212 GB per month per user is between 27 times (Japan) and 285 times (Brazil) the estimated usage per head of population in the UMTS Forum forecasts.

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Comparisons of the ITU model "high growth" case against benchmarks derived from extrapolating the February 2014 Cisco VNI mobile data forecast give similar results, as discussed in Section 2 below.

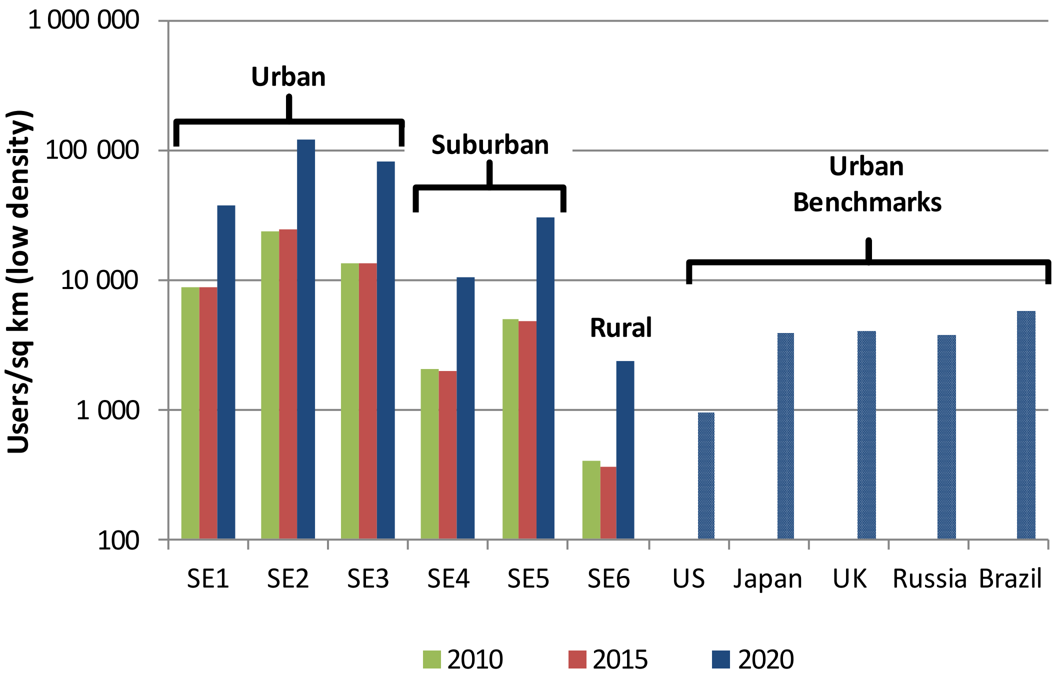

Figure 2: User population density; the figures from the ITU model ("low growth" case) for the six different service environments are compared with benchmark figures (from UMTS Forum Report 44) for five example countries in urban areas. (Note the logarithmic scale)

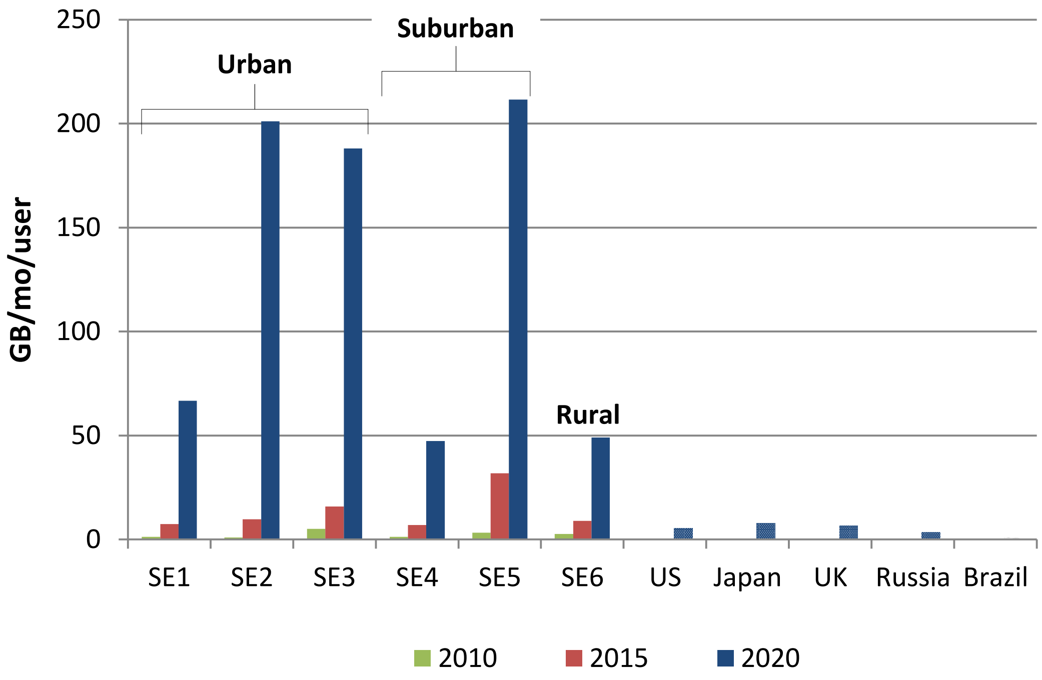

Figure 3: Average monthly data consumption; the figures from the ITU model ("low growth" case) for the six different service environments are compared with benchmark figures (from UMTS Forum Report 44) for five example countries in urban areas.

Thus it is clear that the ITU spectrum demand model not only has an **excessively high user density**, but also has **far too much usage** of certain applications.

There are further inputs to the model (such as spectrum efficiency) which appear to be at significant variance to any realistic projections and these may be serving to counterbalance the high traffic values and thereby yielding a believable output, albeit from an unrealistic set of inputs.

The extent of the differences in the input values from real-world values means that **the model cannot currently be used to give any reliable predictions of spectrum demand** until the inputs are fully reviewed, revised and calibrated to more realistic levels.

We have examined a number of (simplified) alternative methodologies which typically divide expected traffic growth by an average increase in spectrum efficiency (bits per Hz) and spectrum re-use (number of cells or cell radius). We have found that these are also highly vulnerable to input data inaccuracies. This was clearly demonstrated by the FCC's forecast in October 2010 that 275 MHz of additional spectrum would be required for US mobile networks to meet expected demand by 2014. In reality, US wireless operators have been able to **accommodate all of the traffic growth** projected, **without deploying even the spectrum that was already allocated** for wireless services in the US by 2010, despite the fact that both traffic growth and the number of cell sites deployed have been largely in line with the FCC's projections.

An error of a factor of 2 would be significant if using the results to take decisions on spectrum allocation, but an error of the magnitude identified in this analysis means the current results of the ITU model are simply not valid. However, **the ITU spectrum demand model uses a logical methodology** which is more reliable than many of the alternatives, because it considers the different network architectures used in different service environments, rather than simply taking an unrepresentative average figure for an entire country. We therefore suggest that before it is used to estimate the spectrum demand for terrestrial IMT, **the inputs to the ITU spectrum demand model should be revised** to match projected levels of traffic for individual countries in 2020, and benchmarked against best practice network build-out expectations (e.g. number of cell sites of different types, use of offload in different environments). A good example of effective benchmarking is the recently published ACMA mobile network capacity forecasting model for Australia,[3] which explicitly projects total countrywide traffic and allocates it to different service environments. In this way, future spectrum estimates can be based on a realistic set of demand and supply projections in specific service environments and detailed modelling of how demand can be accommodated will yield robust and acceptable results.

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[3] See http://www.acma.gov.au/theACMA/Consultations/Consultations/Current/acma-mobile-network-capacity-forecasting-model

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# 1 Introduction

## 1.1 General

LS telcom provides spectrum management services to regulators, operators and spectrum users around the world. In addition to software and hardware solutions, LS provides consultancy services in spectrum management. A common request amongst regulators is to provide an evaluation of the amount of spectrum required for commercial terrestrial mobile broadband (IMT) services. In examining the demand for spectrum for IMT services using the model developed by WP 5D of the ITU, as used by regulators around the world, we have identified that a number input values to the model are wholly unrealistic.

Tim Farrar of TMF Associates reached a similar set of conclusions and in order to try and enable a discussion of how the model can be adjusted, so that it more realistically reflects likely data traffic in 2020, we have jointly produced this report to share our findings. Without such adjustments, the outputs that the model currently produces cannot be relied upon.

## 1.2 The ITU spectrum allocation process

The allocation of radio spectrum at an international level is conducted at conferences held by the ITU every 3 to 4 years. At these World Radiocommunication Conferences (WRC), national administrations try to reach agreement on how radio spectrum should be shared between different services. Each conference also sets a series of Agenda Items for a future conference, the preparation of which are addressed by various Working Parties (WP) in the period between conferences. For changes in radio frequency allocations to be made, consensus between the members of the ITU (which comprise national spectrum administrations) must be achieved and this consensus is driven by options reflected in the CPM (Conference Preparatory Meeting) report. The inputs for texts in the CPM report are prepared by the Working Parties.

One of the items on the agenda (agenda item 1.1) for the next WRC in 2015 is the amount of spectrum that should be allocated to wireless broadband services . Most emphasis within this item is on the identification of bands for IMT (technologies such as LTE Advanced) but allocations for RLAN (i.e. WiFi) are also under study.

The ITU established a special group to be responsible for the preparations of this agenda item, JTG (Joint Task Group) 4-5-6-7. One important input that this group is considering is a report on the IMT spectrum requirements, which was developed in ITU WP 5D. Underlying the spectrum requirement work in WP 5D is a model that was originally defined in Recommendation ITU-R M.1768 in 2006 and was updated in 2013. The model divides spectrum demand between a number of radio access technology groups (RATG). RATG 1 represents 2G, 3G and pre-4G technologies such as GSM, CDMA, UMTS and LTE. RATG 2 represents 4G services, in particular LTE-Advanced. The model currently indicates that the amount of spectrum needed for IMT services by 2020 is up to 1960 MHz as shown in Table 1-1.

| | Total spectrum requirements for RATG 1 | Total spectrum requirements for RATG 2 | Total spectrum requirements RATGs 1 and 2 |
|---|---|---|---|
| Lower user density settings | 440 MHz | 900 MHz | 1 340 MHz |
| Higher user density settings | 540 MHz | 1 420 MHz | 1 960 MHz |

**Table 1-1: ITU predictions of IMT spectrum demand by 2020**

An earlier version of this model was used to inform decisions being taken at WRC 2007. At the time, the model indicated that the amount of spectrum which would be needed for IMT services would be between 760 and 840 MHz by 2010. The reality of the situation in 2010, however, was much different: the typical amount of spectrum allocated to mobile networks was only around 360 to 400 MHz as illustrated in Table 1-2 and not all of this spectrum had even been licensed or deployed.

| Band | Spectrum | Region 1 (Europe, Middle East, Africa) | Region 2 (The Americas and Caribbean) | Region 3 (Asia and Australasia) |
|---|---|---|---|---|
| 850 MHz (Band 5)<br>824 – 849 // 869 – 894 | 50 MHz<br>(2 x 25 MHz) | 20 MHz[4] | 50 MHz | 20 MHz[5] |
| 900 MHz (Band 8)<br>880 – 915 // 925 – 960 MHz | 70 MHz<br>(2 x 35 MHz) | 70 MHz | 40 MHz[6] | 70 MHz |
| 1700 MHz (Band 4)<br>1710 – 1755 // 2110 – 2155 MHz | 90 MHz<br>(2 x 45 MHz) | Not used | 90 MHz | Not used |
| 1800 MHz (Band 3)<br>1710 – 1785 // 1805 – 1880 MHz | 150 MHz<br>(2 x 75 MHz) | 150 MHz | Some South American Countries | 150 MHz |
| 1900 MHz (Band 2)<br>1850 – 1910 // 1930 – 1990 MHz | 120 MHz<br>(2 x 60 MHz) | Rarely used | 120 MHz | 40 MHz[7] |
| 2100 MHz (Band 1)<br>1920 – 1980 // 2110 – 2170 MHz | 120 MHz<br>(2 x 60 MHz) | 120 MHz | Not used | 120 MHz |
| **Best Case Assignment** | | **~360 MHz** | **~360 MHz** | **~400 MHz** |

**Table 1-2: Principal spectrum bands available for IMT services in different ITU regions in 2010**

Thus the amount of spectrum actually licensed and in use was typically only half of that which the model predicted would be needed, while at the same time far more mobile data was consumed than predicted. It is therefore clear that either:

1. The model predicting the amount of spectrum needed for IMT services is in some way flawed; or

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[4] Not all of the band is available in Region 1 due to overlap with the 900 MHz band

[5] Not all of the band is available in Region 3 due to overlap with the 900 MHz band

[6] Only the portion of the 900 MHz band that does not overlap with the 800 MHz band can be used

[7] Only the portion of the 1900 MHz band that does not overlap with the 1800 MHz band can be used.

2. Mobile operators have found ways of handling data traffic that were not factored into the model.

We believe that both of these are possibly true, however any improvement in ways to handle mobile traffic should also be factored into the model. We therefore posit that the model needs to be reviewed, and its inputs revised, so that it can provide validated and calibrated results.

## 1.3 Purpose of this document

Forecasting demand for IMT spectrum is critically important, both at a national level, but also to inform decisions at the ITU WRC. It is therefore important that the model used to make these demand forecasts are reliable and robust. Having tried to use the model to predict spectrum demand, and having found several inconsistent and unrealistic inputs, we felt it important to share these findings with the wider community so as to inform discussions both on adjustments to the model inputs, and to the wider question of IMT spectrum demand forecasts.

This document is structured as follows:

- Section 2 discusses the model used by the ITU in particular looking at the market forecasts used as inputs and the resulting traffic and density predictions;
- Section 3 examines spectrum demand forecasts and related studies produced by other organisations;
- Section 4 considers some of the economic and technological issues surrounding the forecast growth in data traffic;
- Section 5 draws conclusions on the forecast demand for IMT spectrum in a 2020 timeframe; and
- Annex A considers in detail the technical issues driving the ITU model and the resulting demand forecasts.

# 2 Analysing the ITU model

## 2.1 Introduction

In this section, we analyse the inputs to the ITU spectrum demand model to assess whether or not its forecasts are based on realistic assumptions.

We have discovered that there is a major flaw with the inputs to the model, in that the traffic density it uses does not appear to have been benchmarked against total predicted traffic in any particular country. This simple analysis would determine whether the demand density (which is estimated bottom-up based on usage of various applications or service characteristics) is in line with typical traffic densities. The analysis undertaken below compares the traffic density per sq km assumed in the model to be served by IMT technologies using licensed spectrum in 2020, against the average traffic density in urban areas, based on regional forecasts of total annual traffic in 2020 produced by the UMTS Forum (low traffic growth) and Cisco’s VNI (high traffic growth). The results of this analysis lead us to the conclusion that the traffic densities used in the model, which drive the spectrum demand forecasts, are at least two orders of magnitude (i.e. a factor of 100) too high when compared with those which would be expected in urban and suburban areas of any developed or developing country in 2020.

Furthermore, if extrapolated to overall demand for a given country, the assumed demand would be far higher than any realistic projection of data consumption per person in the 2020 timescale. Traffic levels may only come close to the levels assumed in the model in a few isolated locations, such as major train stations, skyscrapers or sports stadiums, however special measures would be expected to be utilised to address excessive demand via offloading, either to WiFi or to small cells operating in licensed spectrum. Even in those locations the levels of demand are likely excessive, since the model predicts that traffic per sq km in a dense urban public area in 2020 (Service Environment 3), even in the “low growth” case, that would equate to about 100 times the levels experienced during in the busiest hour at the 2014 Superbowl in New York. There are further inputs to the model (such as spectrum efficiency) which are at significant variance to the equivalent parameters used in alternative analyses and these may be serving to counterbalance the high traffic values and yield a believable output.

The level of incoherence seen in the inputs to the model means that the model cannot be used in its current form to give any reliable predictions of spectrum demand requirements and should not be relied upon until the input values are fully reviewed and the projected traffic density and other inputs are adjusted to realistic, traceable values.

## 2.2 Background to ITU spectrum projections

In Report ITU-R M.2072, originally published in 2005, the ITU summarised the results of surveys of member countries and other contributors such as the UMTS Forum on demand for different wireless services over the period to 2020. This data was used to estimate specific “market attribute values” and construct a spectrum demand model based on the methodology described in Recommendation ITU-R M.1768. The model that was developed (by an industry-led project called WINNER[8]), referred

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[8] See: http://www.ist-winner.org/Spectrum_Calculation.html

to as the “Speculator”, forecasts demand by application in different service environments (i.e. dense urban, urban, suburban and rural areas). In addition, some overall forecasts of worldwide and European traffic growth were provided, from sources including the UMTS Forum and France Telecom. However, it is critically important to recognise that, despite these numbers being cited in the same document, there is no evidence of a direct link or cross-checking between the bottom-up “market attribute” values used in the spectrum demand model and the overall forecasts of total world-wide or country-wide mobile traffic.

As used at WRC-07, the ITU-R projection of spectrum requirements was set out in Report ITU-R M.2078 and called for between 1280 MHz and 1720 MHz of spectrum to be made available for licensed cellular services by 2020, as shown in Table 2-1 below. Demand was split between two Radio Access Technology Groups (RATGs) corresponding to current technologies, up to and including LTE, in RATG 1 and LTE-Advanced in RATG 2.

**Predicted spectrum requirements for both RATG 1 and RATG 2 (MHz) at WRC-07**

| Market setting | Spectrum requirement for RATG 1 | | | Spectrum requirement for RATG 2 | | | Total spectrum requirement | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2015 | 2020 | 2010 | 2015 | 2020 | 2010 | 2015 | 2020 |
| Higher market setting | 840 | 880 | 880 | 0 | 420 | 840 | 840 | 1 300 | 1 720 |
| Lower market setting | 760 | 800 | 800 | 0 | 500 | 480 | 760 | 1 300 | 1 280 |

**Table 2-1: ITU spectrum demand estimates in 2010, 2015 and 2020 [Source: Report ITU-R M.2078 Table 25]**

In 2011, the ITU published Report ITU-R M.2243, which reviewed recent market developments and attempted to update spectrum demand forecasts for new IMT-Advanced services. This document also included both forecasts of overall mobile data traffic growth and more detailed data by application and service environment which was used to update the Speculator model inputs. Clearly, growth in mobile data traffic between 2005 and 2011 was higher than expected, and so as Report ITU-R M.2243 notes, and as shown in Figure 2-1 below, worldwide mobile traffic exceeded the forecasts of Report ITU-R M.2072. The “Actual Traffic” and “New Forecast” shown in this figure are based on data from the February 2011 version of Cisco’s Visual Networking Index (VNI), which projected total global mobile data traffic would grow to 6.2 EB/month by the end of 2015. However, it should be noted that the February 2014 Cisco VNI report has reduced this forecast by 30% to only 4.35 EB/month at the end of 2015. Nevertheless Cisco only measures mobile *data* traffic, not voice and data traffic combined, and thus actual worldwide voice and data traffic in 2010 exceeded the forecast in Report ITU-R M.2072 even more significantly than is indicated in Figure 2-1.

We also consider that Cisco’s most recent VNI report remains representative of high growth forecasts for mobile data traffic and in Figure 2-5 below we have extrapolated Cisco’s figures from the February 2014 VNI report to give an alternative “high case” benchmark for our traffic density analysis.

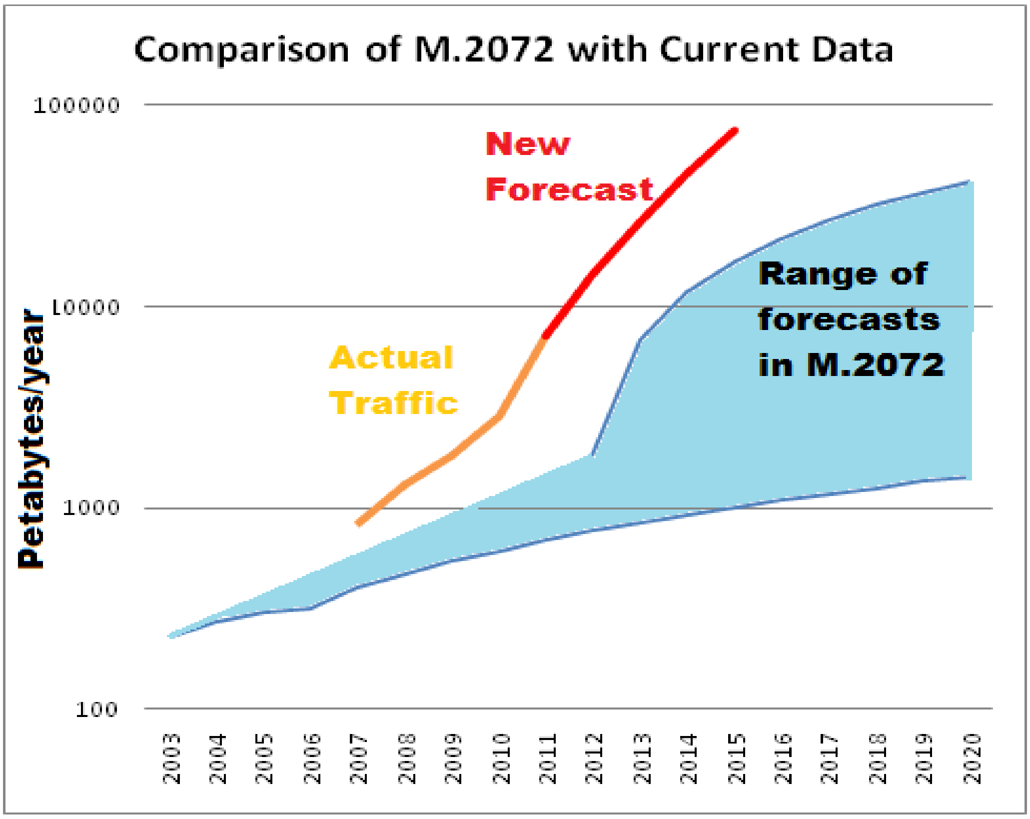
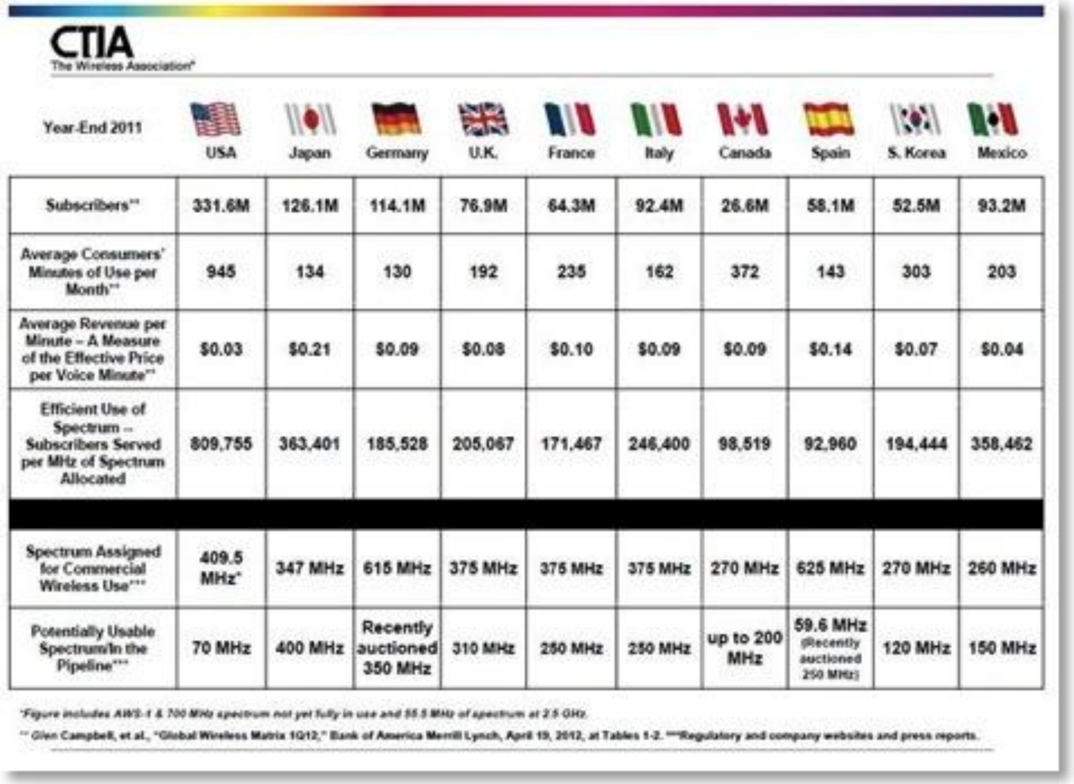


**Figure 2-1: ITU traffic estimates in 2011 vs 2005 [Source: Report ITU-R M.2243 Figure 7]**

Whereas growth in data traffic has sometimes exceeded expectations, especially in forecasts published prior to 2010, the amount of spectrum made available and deployed for licensed mobile services in most countries fell far below that projected by the ITU spectrum demand model, which suggested that between 760 MHz and 840 MHz of spectrum would be needed by 2010. At the end of 2011, as shown in Figure 2-2 below, CTIA-The Wireless Association stated that none of the major countries it had surveyed had assigned more than 625 MHz of spectrum for commercial use (not all of which was fully deployed) and several countries had less than 300 MHz of spectrum assigned for commercial use. Thus it seems clear that the Speculator model drastically overestimated the amount of spectrum required for wireless networks in 2010, despite the fact that far more data was consumed than expected. This suggests that the ITU has overestimated spectrum needs in the past, and of course therefore raises questions about whether the spectrum requirements currently being projected for 2020 are similarly overstated.



CTIA
The Wireless Association®

| Year-End 2011 | USA | Japan | Germany | U.K. | France | Italy | Canada | Spain | S. Korea | Mexico |
|---|---|---|---|---|---|---|---|---|---|---|
| Subscribers** | 331.6M | 126.1M | 114.1M | 76.9M | 64.3M | 92.4M | 26.6M | 58.1M | 52.5M | 93.2M |
| Average Consumers' Minutes of Use per Month** | 945 | 134 | 130 | 192 | 235 | 162 | 372 | 143 | 303 | 203 |
| Average Revenue per Minute – A Measure of the Effective Price per Voice Minute** | $0.03 | $0.21 | $0.09 | $0.08 | $0.10 | $0.09 | $0.09 | $0.14 | $0.07 | $0.04 |
| Efficient Use of Spectrum – Subscribers Served per MHz of Spectrum Allocated | 809,755 | 363,401 | 185,528 | 205,067 | 171,467 | 246,400 | 98,519 | 92,960 | 194,444 | 358,462 |
| Spectrum Assigned for Commercial Wireless Use*** | 409.5 MHz* | 347 MHz | 615 MHz | 375 MHz | 375 MHz | 375 MHz | 270 MHz | 625 MHz | 270 MHz | 260 MHz |
| Potentially Usable Spectrum/In the Pipeline*** | 70 MHz | 400 MHz | Recently auctioned 350 MHz | 310 MHz | 250 MHz | 250 MHz | up to 200 MHz | 59.6 MHz (Recently auctioned 250 MHz) | 120 MHz | 150 MHz |

*Figure includes AWS-1 & 700 MHz spectrum not yet fully in use and 55.5 MHz of spectrum at 2.5 GHz.

** Glen Campbell, et al., "Global Wireless Matrix 1Q12," Bank of America Merrill Lynch, April 19, 2012, at Tables 1-2. ***Regulatory and company websites and press reports.

**Figure 2-2: Licensed spectrum for wireless services, end of 2011 [Source: CTIA ex parte filing to FCC, April 2012[9]]**

It is also worth noting that despite forecasting a need for up to 500 MHz of spectrum for RATG 2 (LTE-Advanced) services by 2015, there is likely to be little to no deployment of RATG 2 technologies in this timeframe, suggesting that not only have operators been able to cope with greater than forecast data, in less than forecast spectrum, but they have been able to do this without the improved spectrum efficiency that RATG 2 technologies would deliver.

## 2.3 Summary of Speculator model structure and inputs

The algorithm used by the Speculator spectrum demand model is shown in Figure 2-3 below. The model takes as its input the traffic demand for each application (service category) in each of six service environments (3 dense urban environments representing home, office and public area locations respectively, 2 suburban environments representing home and a combined office/public area location, and 1 rural environment representing all location types). There are 20 service categories, representing five different data rates and four types of application (conversational, streaming, interactive and background). The service environments and service categories defined by in Report ITU-R M.2072 are summarised in Figure 2-4.

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[9] See http://files.ctia.org/pdf/filings/120430_-_FINAL_Wireless_Competition_PN_Reply_Comments_wExhibits.pdf

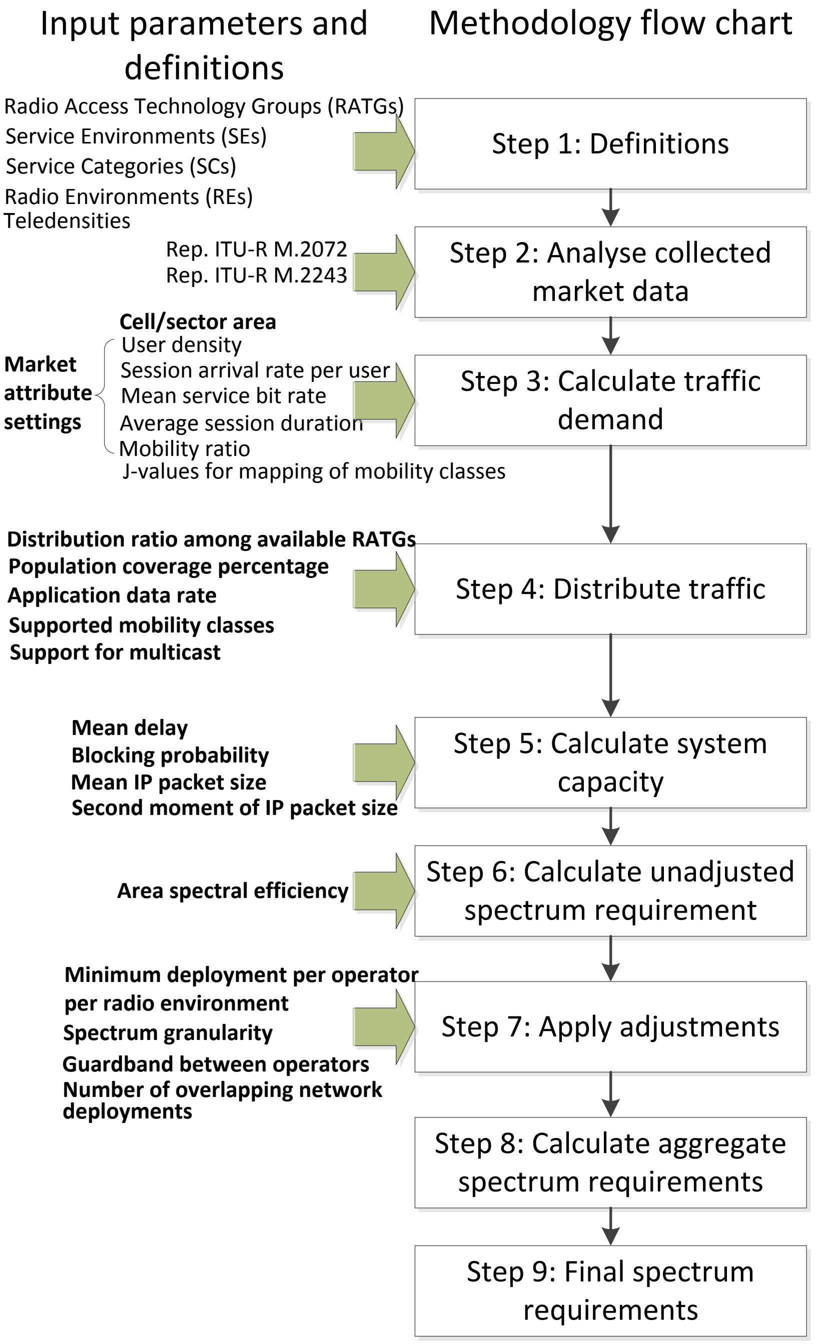
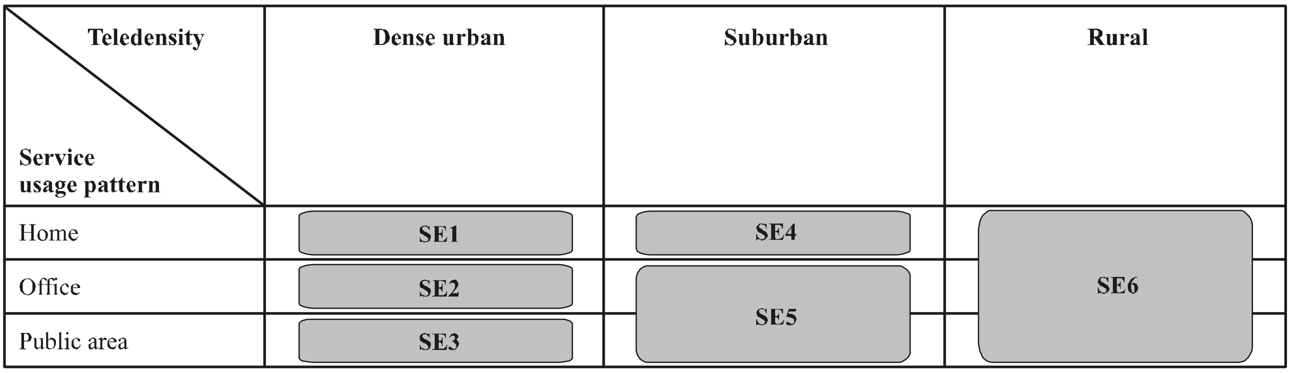


**Figure 2-3: Speculator model algorithm and input parameters [Source: Report ITU-R M.2290 Figure 3]**



| Service usage pattern \ Teledensity | Dense urban | Suburban | Rural |
|---|---|---|---|
| Home | SE1 | SE4 | SE6 |
| Office | SE2 | SE5 | |
| Public area | SE3 | | |

Rap 2072-tab53

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

(1) This includes speech and SMS.

**Figure 2-4: Service environments and service categories [Source: Report ITU-R M.2072 Tables 53 and 52]**

In order to compare the Speculator model inputs to the forecasts of traffic produced by the likes of the UMTS Forum, we need to convert the traffic density values in the model to an equivalent value measured in Gbytes per sq km per month[10]. From the series of inputs shown in Figure 2-3 above, the traffic density can be converted to a total monthly demand in Gbytes per sq km, based simply on an assumption about how much of the traffic occurs in the busy hour.

Some estimates of busy hour traffic are provided in the various ITU-R reports, with 6.4% of daily data traffic in China forecast to occur in the busy hour in 2020 (M.2072 at Tables 32 and 33) and 6.5% of daily data traffic in Japan measured to occur in the busy hour in 2010 (M.2243 at Table A2.8, total uplink plus downlink traffic, weekly average). In the comparison below, we have chosen to adopt a more conservative assumption that 10% of traffic occurs in the busy hour, and so the daily traffic is equal to 10 times the hourly traffic volume estimated in the Speculator model inputs (in other words total monthly traffic is lower than it would be if only 6.4% of the traffic was in the busy hour which would make daily traffic more like 15 times busy hour traffic).

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[10] Figures given in this report are stated in Gigabytes, Terabytes, Petabytes or Exabytes. One Gigabyte (Gbyte or GB) is equal to $10^9$ bytes or 1000 Megabytes, while 1 Terabyte (Tbyte or TB) equals $10^{12}$ bytes or 1000 Gigabytes, 1 Petabyte (Pbyte or PB) equals $10^{15}$ bytes or 1000 Terabytes and 1 Exabyte (Ebyte or EB) equals $10^{18}$ bytes or 1000 Petabytes,

The calculation is as follows:

> *Speculator Traffic in kbits/hour/sq km = User density in users/sq km * session arrival rate in arrivals/hour/user * mean service bit rate in kbps * average session duration in secs*
>
> *Monthly traffic in Gbytes/sq km = Speculator Traffic in kbits/hour/sq km / 10% of traffic in busy hour / 1,000,000 kbps/Gbps / 8 bits/byte * 30 days/month*

Or simplified:

> *Monthly traffic (Gbytes/sq km) = Speculator Traffic in kbits/hour/sq km * 0.0000375*

Secondly the Speculator model also uses estimates of how data traffic is assigned to different technologies (RATGs). RATG 3 represents unlicensed spectrum and therefore the ratio of traffic in each service environment that is assigned to RATG 3 to the total volume of traffic in the service environment is equal to the share of offloaded traffic. This can be benchmarked against alternative estimates of offloading, such as those produced by Cisco and other analysts.

Although it is not possible to derive total wireless network traffic for a country as a whole directly from the Speculator model (because the proportion of the land area of a country allocated to each service environment is undefined), a comparison can be made with the average expected traffic density based on the forecasts for total traffic in a particular country. As discussed in Section 2.4 below, the fact that the traffic density for each service environment cannot be reconciled with benchmarks based on total traffic indicates that the market attributes used in the Speculator model appear to dramatically overestimate the level of traffic density in 2020.

## 2.4 Benchmarking with forecasts of wireless traffic through 2020

### 2.4.1 Global traffic levels

In Report ITU-R M.2243, a number of forecasts for mobile data traffic over the coming years are cited, although only that from the UMTS Forum (Report 44, published in January 2011) extends until 2020. The UMTS Forum report projected that total worldwide voice and data traffic would increase by 33 times from 2010 to 2020, reaching 127.8 EB, compared to 3.86 EB in 2010, as shown in Table 2-2 below.

| Region | Total mobile traffic (EB/year) | | |
|---|---|---|---|
| | 2010 | 2015 | 2020 |
| Europe | 1.03 | 10.88 | 28.15 |
| Americas | 0.78 | 9.84 | 27.33 |
| Asia | 1.65 | 16.31 | 43.85 |
| Rest of the World | 0.41 | 8.22 | 28.48 |
| **Total** | **3.86** | **45.25** | **127.82** |

**Table 2-2: Estimated total mobile traffic (EB/year), 2010-2020 [Source: Table 23, UMTS Forum Report 44, January 2011/iDATE]**

However, in Report ITU-R M.2290, a polynomial extrapolation of traffic forecasts from 2011 to 2015 was performed "*in order to have a more reliable estimate in 2020*" and as a result the report estimated that "*traffic in 2020 exhibits a 25 to 100-fold growth ratio compared to 2010.*" The report then concludes that "*traffic growth ratios of 44- and 80-fold*" should be used, corresponding to the 25% and 75% values of this estimated growth range. Since the traffic growth forecasts from which this "growth ratio" is derived are forecasts for cellular data traffic (i.e. excluding WiFi), this growth ratio should only be applied to the RATG 1 and RATG 2 traffic. If this growth ratio is applied to total traffic (and it is unclear whether this is in fact the case, since the ratio of total traffic in 2020 to total traffic in 2010 within the Speculator model does not appear to increase by 44 or 80 times for any Service Environment in either the low or high growth scenarios) then the growth in cellular traffic will be different. In fact, since the model assumes a decline from an average of 80% of traffic offloaded in 2010 to only around 40% offloaded in 2020[11] for several Service Environments, an increase of 44 to 80 times in total traffic would therefore correspond to an increase of 132 to 240 times in cellular traffic for these environments, which clearly does not reflect the appropriate growth ratio for cellular traffic.

In addition, the fact that many of the forecasts only include data traffic (and not voice traffic) is ignored in this analysis[12], as is the fact that some analysts (such as Cisco) have since scaled down their estimates significantly (from 6.2 EB/mo in 2015 in Report ITU-R M.2243 Figure 8 to 4.35 EB/mo in Cisco's February 2014 market forecast). Because the Speculator model forecasts both voice *and* data traffic, it is inappropriate to use forecasts of data-only traffic growth as a benchmark for overall traffic growth ratios between 2010 and 2020. It is also inappropriate to use forecasts of cellular traffic growth as a benchmark for growth in total traffic, especially if (as in the Speculator model, but not in most other forecasts) the amount of offload is assumed to decline significantly over this period.

The absolute value of the UMTS forecast for cellular traffic in 2020 (127.8 EB in the year as a whole) is relatively close to that produced by several other analysts, including AnalysysMason, who estimate cellular traffic in 2017 at 54 EB[13]. Applying growth of 33% p.a. between 2017 and 2020 to the AnalysysMason forecast (broadly consistent with the growth trend seen in AnalysysMason's projections between 2013 and 2017) would lead to total traffic of 128EB in 2020, equal to the level projected by the UMTS Forum. Forecasts produced by Cisco and Ericsson, which estimate cellular traffic of approximately 100EB in 2017 as a whole[14] would give higher results for cellular data traffic in 2020, and are more appropriately compared with the ITU high case growth ratio. Notably, one major factor in Cisco's higher estimate (compared to AnalysysMason) is that Cisco estimates that considerably less traffic will be offloaded to WiFi: AnalysysMason projects that over 60% of traffic will be offloaded to WiFi in 2017 compared to 51% for Cisco. Thus, while the UMTS Forum's 2011

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[11] The assumption of a decline in traffic offloading between 2010 and 2020 is of course is drastically different to many other forecasts, including Cisco

[12] Cisco's February 2011 report estimated that worldwide mobile data traffic (i.e. excluding voice) in December 2010 was 237 TB/mo, compared to 91 TB/mo estimated for December 2009 (in Cisco's February 2010 report). If we accept (as document M.2243 states at page 61) that "Voice traffic was overtaken by data traffic in the mobile networks at the end of 2009 when the global amount of traffic was around 280 Terabytes (TB)/month according to telecom industry players," then it is reasonable to estimate worldwide mobile voice traffic at between 90 TB/mo and 140 TB/mo in 2009. It is also clear that the UMTS Forum estimate of 2010 traffic is much higher than Cisco's estimate largely because it includes both voice *and* data traffic.

[13] See http://www.analysysmason.com/About-Us/News/Insight/Mobile-data-Oct2013/

[14] Cisco and Ericsson's forecasts estimate monthly traffic at the end of the year and do not give a specific annual total

forecast may be seen as a lower growth projection, it is also well within the range of plausible outcomes for total cellular traffic in 2020, as seen in Figure 2-5.

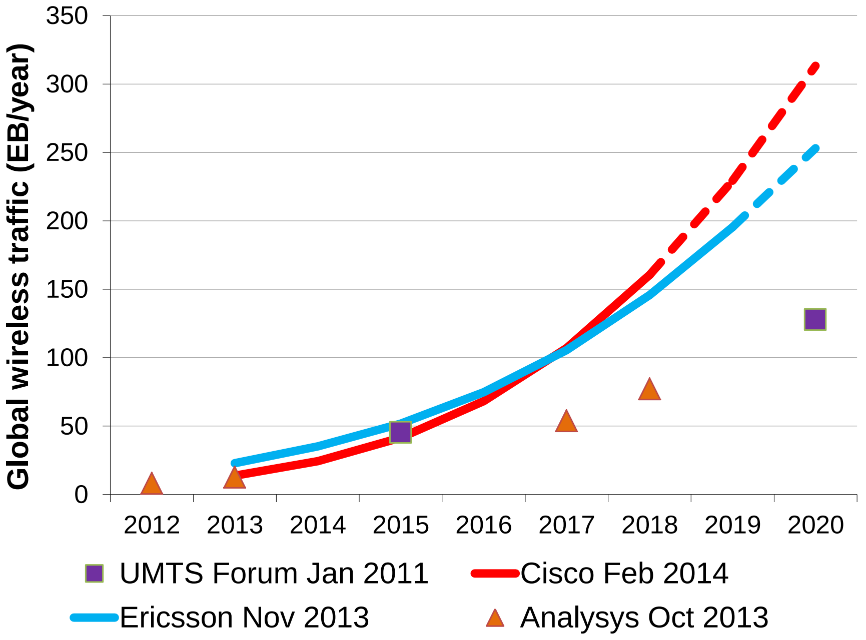

**Figure 2-5: Growth in global wireless traffic over the period from 2012 to 2020 [Source: TMF/LS analysis of Cisco, Ericsson, AnalysysMason and UMTS Forum data[15]]**

We therefore accept the UMTS Forum Report 44 as a baseline traffic forecast for 2020, under *lower growth* assumptions. In line with Report ITU-R M.2290, we adopt an extrapolated version of Cisco's forecasts as our *higher growth* assumption. From these forecasts benchmarks for typical traffic density levels are established and compared with the market attributes used for different service environments within the ITU spectrum demand model for the low and high case growth forecasts respectively.

### 2.4.2 Urban population and traffic density

The total urban population and the average population density for different countries are documented in a Demographia publication[16], which indicates that the average population density in urban areas (including their connected suburbs) ranges from 900 people per sq km in the United States to 3,900 people per sq km in Japan and 4,000 people per sq km in the United Kingdom. Some individual cities are more densely populated, such as Hong Kong at 26,600 people per sq km and Dhaka at 44,500 people per sq km, and there are certain individual locations, such as downtown business districts, where there is an even higher population density, especially during the working day. However, it should be noted that according to Demographia, the average urban population density in mainland China is 7,000 people per sq km and the population density in Beijing is only 5,200 people per sq km.

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[15] Note that the UMTS Forum and Ericsson projections are for total wireless voice and data traffic, whereas Cisco and Analysys Mason only forecast growth in data traffic

[16] See http://www.demographia.com/db-worldua.pdf (March 2013)

Although there may be some definitional differences regarding whether suburbs are included in the overall “urban” area[17], it is hard to understand the statement in Report ITU-R M.2072 (Table 15) that the *suburban* population density in China in 2010 was 21,000 people per sq km, which is three to four times the density of Beijing as a whole.

As a benchmark, we can derive the traffic density forecast in urban and suburban areas from the UMTS Forum report by estimating the proportion of overall wireless traffic generated in these areas and dividing by the total urban area within the country in square kilometres. Urban dwellers are likely to consume somewhat more traffic than people living in rural areas: A May 2013 Pew Research survey of mobile phone users in the US[18] found that 66% of urban cell phone owners and only 50% of rural cell phone owners use their phone to access the Internet. It is possible that this gap will close over time, but based on this Pew data, we can assume that data usage per head of population in urban areas is one third higher than in the rest of the country.

We also take into account expected total population growth and increasing urbanisation over the period to 2020, based on data published by the US Department of Agriculture and the UN Population Fund, which shows the increase in the percentage of the total population who live in urban areas[19]. We further assume that the total urban area of each country increases at half the rate by which the urban population grows, so that urban areas become somewhat more densely populated over time[20]. Tables 2-3 and 2-4 below shows the resulting derivation of average urban traffic density in Gigabytes per month per sq km in the United States, Japan, the United Kingdom, Russia and Brazil, based on the UMTS Forum and Cisco VNI estimates respectively for total annual traffic in 2020.

| | United States | Japan | UK | Russia | Brazil |
|---|---|---|---|---|---|
| Regional traffic (EB) (UMTS Forum 2020) | 27.33 (Americas) | 43.85 (Asia) | 28.35 (Europe) | 28.48 (RoW) | 27.33 (Americas) |
| % of regional GDP | 73% | 25% | 16% | 17% | 6% |
| Annual traffic 2020 (EB) | 20.0 | 11.1 | 4.5 | 4.8 | 1.8 |
| Population 2020 (M) | 334 | 126 | 66 | 142 | 223 |
| Urban sq km 2020 | 244,525 | 23,084 | 8,233 | 14,447 | 17,304 |
| Urban % of population | 69% | 72% | 51% | 38% | 44% |
| Urban % of total traffic | 74% | 77% | 58% | 45% | 51% |
| Urban traffic 2020 (GB/sq km/mo) | 5,100 | 31,000 | 26,500 | 12,300 | 4,400 |
| Urban traffic 2020 (GB/person/mo) | 5.4 | 7.9 | 6.5 | 3.3 | 0.8 |

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[17] See http://www.demographia.com/db-define.pdf

[18] See http://www.pewinternet.org/~/media//Files/Reports/2013/PIP_CellInternetUse2013.pdf

[19] See http://www.ers.usda.gov/data-products/international-macroeconomic-data-set.aspx and http://www.unfpa.org/swp/2007/english/notes/indicators/e_indicator2.pdf

[20] Urban areas will increase in size as a result of increasing urbanization, and thus urban population density will increase more slowly than urban population

**Table 2-3: Urban traffic in different countries based on UMTS Forum projections for 2020 [Source: TMF/LS analysis]**

| | United States | Japan | UK | Russia | Brazil |
|---|---|---|---|---|---|
| Annual traffic 2020 (EB) | 51.5 | 33.9 | 9.5 | 8.6 | 8.5 |
| Population 2020 (M) | 334 | 126 | 66 | 142 | 223 |
| Urban sq km 2020 | 244,525 | 23,084 | 8,233 | 14,447 | 17,304 |
| Urban % of population | 69% | 72% | 51% | 38% | 44% |
| Urban % of total traffic | 74% | 77% | 58% | 45% | 51% |
| Urban traffic 2020 (GB/sq km/mo) | 13,100 | 94,900 | 56,300 | 22,300 | 21,100 |
| Urban traffic 2020 (GB/person/mo) | 13.9 | 24.2 | 13.8 | 6.0 | 3.7 |

**Table 2-4: Urban traffic in different countries based on extrapolation of February 2014 Cisco VNI projections to 2020 [Source: TMF/LS analysis]**

Though some downtown urban areas such as Manhattan, central Tokyo or central London may have much higher levels of traffic, the traffic density for the *urban* area as a whole should certainly exceed that assumed for *suburban* areas in the Speculator model (as documented in Report ITU-R M.2290). However, this is not the case.

We can derive total traffic per sq km per month in the Speculator model for the low growth and high growth cases by adding up all of the downlink and uplink traffic per hour for each application (excluding multicast) in each service environment, using the model calculations of what proportion of traffic is offloaded to RATG 3 (unlicensed spectrum) in each service environment and multiplying by the busy hour factor and number of days in a month to derive a comparable traffic density figure.

Figure 2-6 below shows the assumptions of the proportion of traffic offloaded to RATG 3 in each service environment.  Figures 2-7 and 2-8 then show the comparison of cellular traffic density (i.e. allocated to RATG 1 and RATG 2) assumed by the Speculator model, with our benchmarks given above for the US, Japan, the UK, Russia and Brazil, measured in Petabytes per sq km per month, for the low and high traffic growth cases respectively.

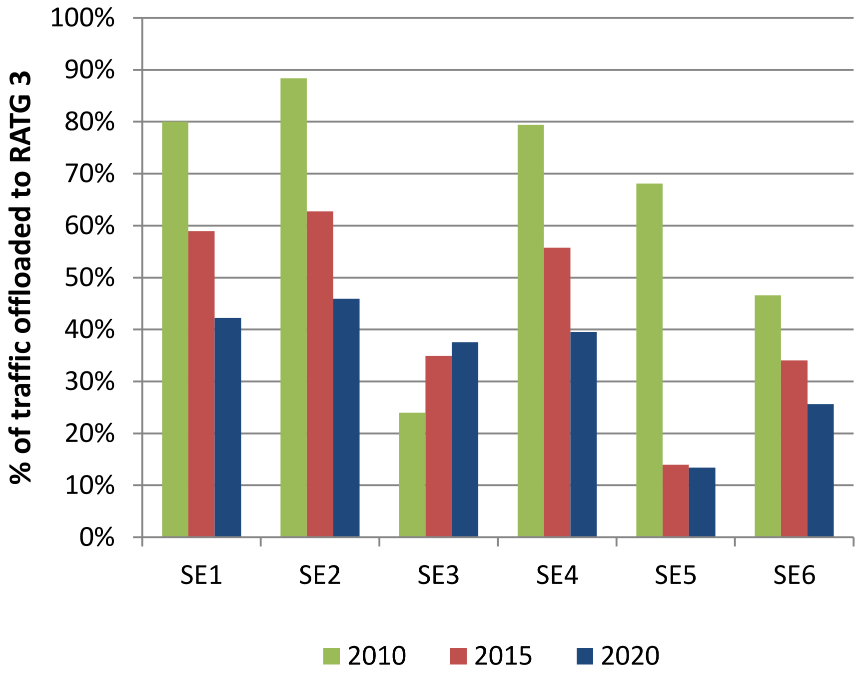

Figure 2-6: Proportion of traffic offloaded by service environment and year [Source: TMF/LS analysis of Speculator model]

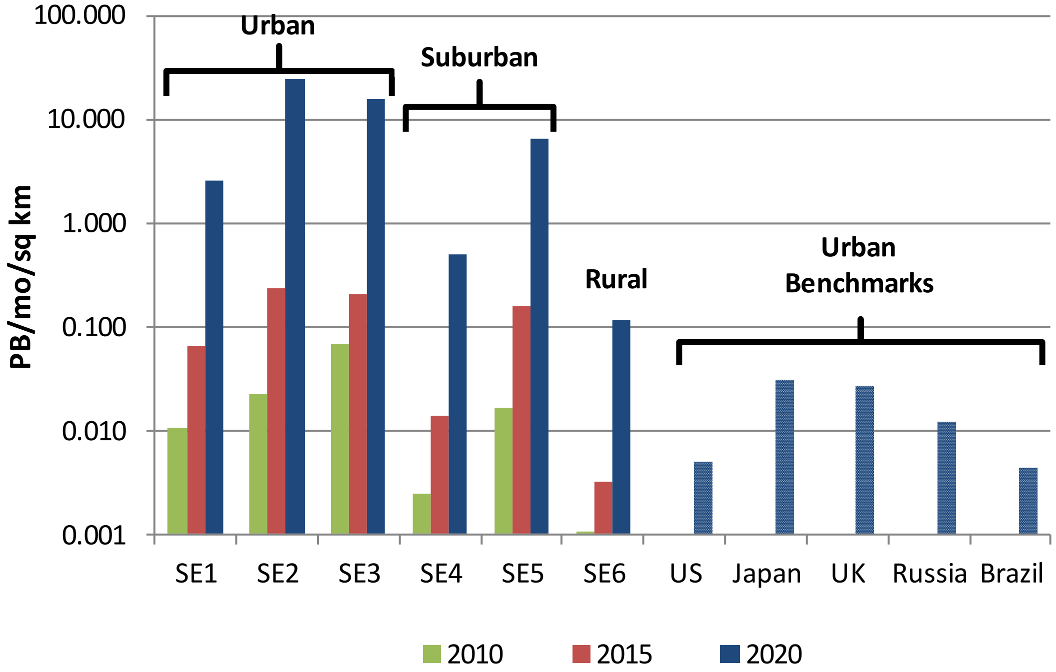

Figure 2-7: Traffic density by service environment and year compared to benchmarks in the low growth case [Source: TMF/LS analysis of Speculator model]

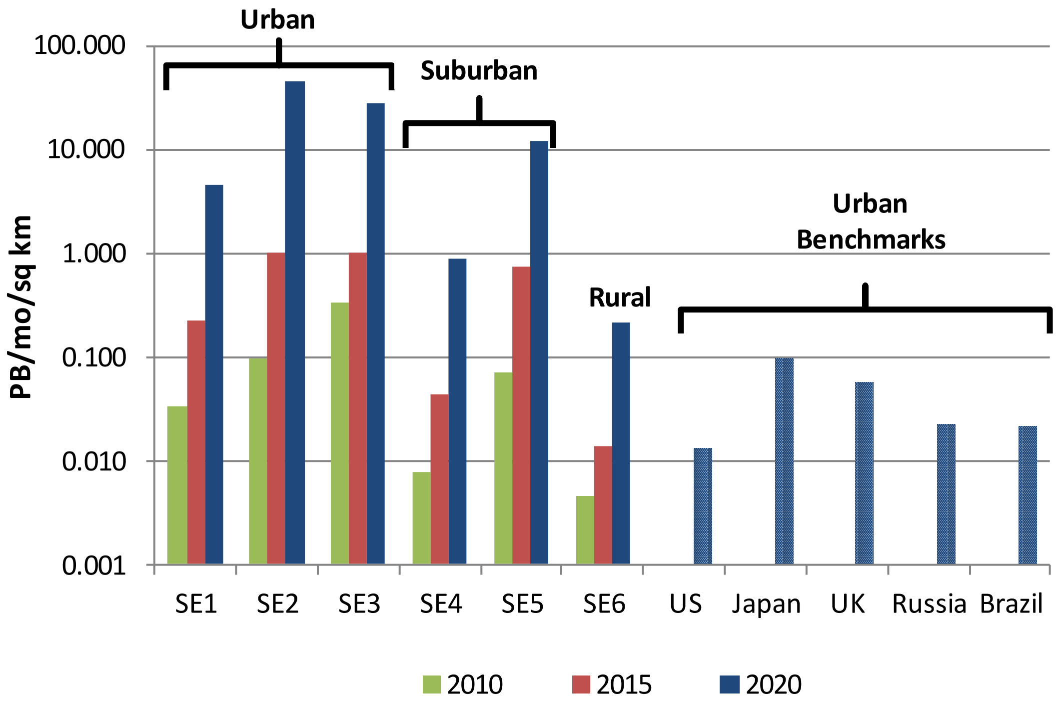

**Figure 2-8: Traffic density by service environment and year compared to benchmarks in the high growth case [Source: TMF/LS analysis of Speculator model]**

It is clear from Figures 2-7 and 2-8 that the traffic density projected for SE 5 (suburban office/public area) in 2020 dramatically exceeds our urban traffic density benchmarks for the US, Japan, the UK, Russia and Brazil by a factor of between 125 times (in the high growth case for Japan) to almost 1500 times (in the low growth case for Brazil). The scale of this inconsistency indicates that the traffic inputs assumed in the Speculator model must be in error. Even if the model is intended to represent areas of high demand within the suburban areas as a whole, then the traffic density is so great that these areas must account for only a tiny, unrepresentative fraction of suburban areas.

For example, as documented in the original version of a June 2013 Ofcom report produced by RealWireless[21], which claimed to use the Speculator model for its calculations, the UK as a whole was expected to have around 300 PB/month of traffic using licensed spectrum in the "low market setting" by 2020, but the traffic density in suburban areas was estimated to exceed 10 PB per month *per sq km* in that year and urban areas were estimated to have a traffic density of 100 PB per month *per sq km* (before traffic carried via unlicensed spectrum is deducted from the totals). Hence the traffic in an urban area of just 3 sq km would be equal to the total traffic forecast for the entire UK. Subsequently this report was revised to lower the projected traffic density by a factor of 1000 (to between 10 and 100 TB per month per sq km), which is more consistent with total UK traffic levels, but completely contradicts the Speculator model inputs documented above.

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[21] See http://stakeholders.ofcom.org.uk/binaries/consultations/cfi-mobile-bb/annexes/RW_report.pdf at Figure 40 (total UK traffic per month) and Figure 44 (ITU model estimated traffic per sq km per month). Note that the Real Wireless report uses an earlier version of the ITU model, and also appears to include all traffic, not just that allocated to RATGs 1 and 2. Thus the traffic density is slightly different to that calculated in Figure 2-7 above.

## 2.5 Source of traffic overestimation in the Speculator model

The source of the overestimate appears to result from a combination of an unrealistic user density (i.e. number of people using each application) *and* excessive traffic per user (i.e. data consumption per person using each application), as illustrated in the next two figures below. Figure 2-9 shows the assumed user density for the application (service category) with the highest number of users per sq km in the ITU model compared to the average urban population density in the US, Japan, the UK, Russia and Brazil in 2020 according to Demographia data. Figure 2-10 then shows the total usage per sq km divided by this user density in the Speculator model compared to the average usage per head of urban population according the UMTS Forum low growth forecasts. Comparable figures for the Speculator high growth case and the Cisco VNI traffic projections are shown in Figure 2-11 and 2-12. It can be seen that in SE 5 (suburban), the low growth case user density of 30,400 users per sq km is between 5 times (Brazil) and 32 times (US) the typical urban population density, while the low growth traffic of 212 GB per month per user is between 27 times (Japan) and 280 times (Brazil) the estimated usage per head of population in the UMTS Forum forecasts. In the high growth case, the user density of 55,900 users per sq km is between 10 times (Brazil) and 60 times (US) the typical urban population density, while the low growth traffic of 212 GB per month per user is between 9 times (Japan) and 57 times (Brazil) the estimated usage per head of population in the Cisco VNI forecasts.

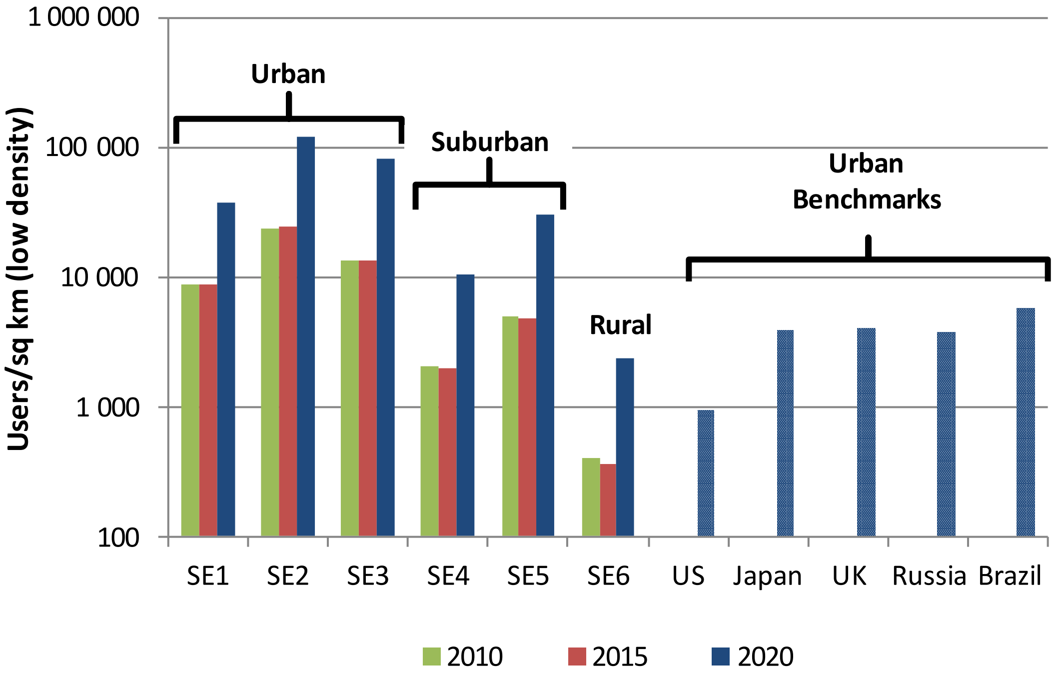
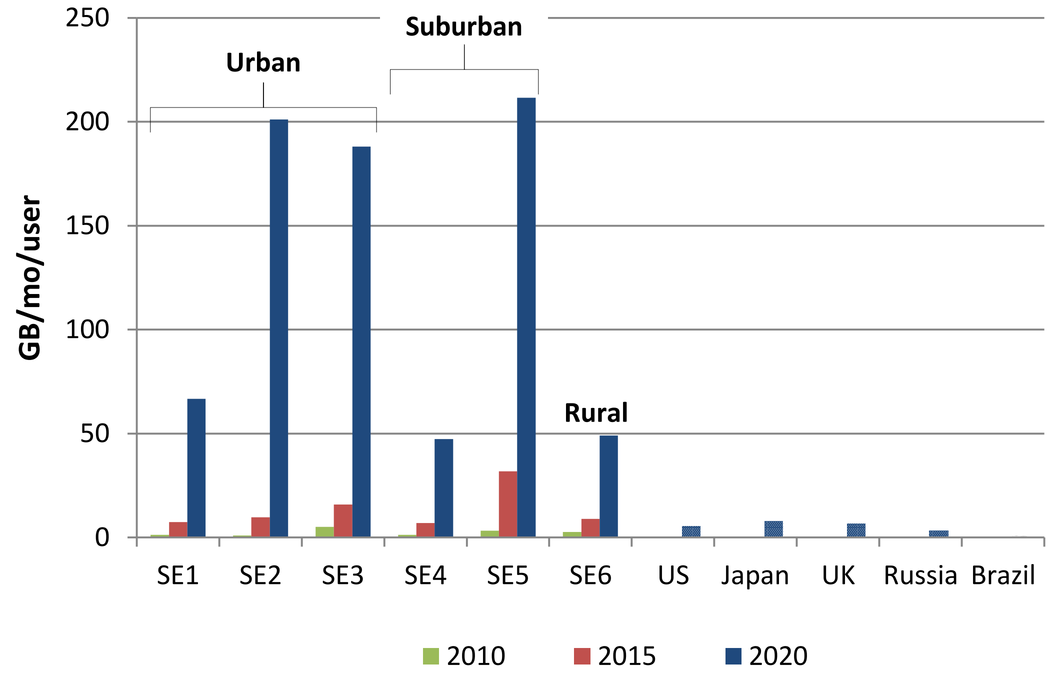


**Figure 2-9: User density by service environment and year compared to urban population density benchmarks in the low growth case [Source: TMF/LS analysis of Speculator model]**



| | | |
|---|---|---|
| SE1 Dense Urban Home | SE2 Dense Urban Office | SE3 Dense Urban Public Area |
| SE4 Suburban Home | SE5 Suburban Office/Public Area | SE6 Rural |

**Figure 2-10: Traffic per user by service environment and year compared to UMTS Forum traffic per head of population benchmarks in the low growth case [Source: TMF/LS analysis of Speculator model]**

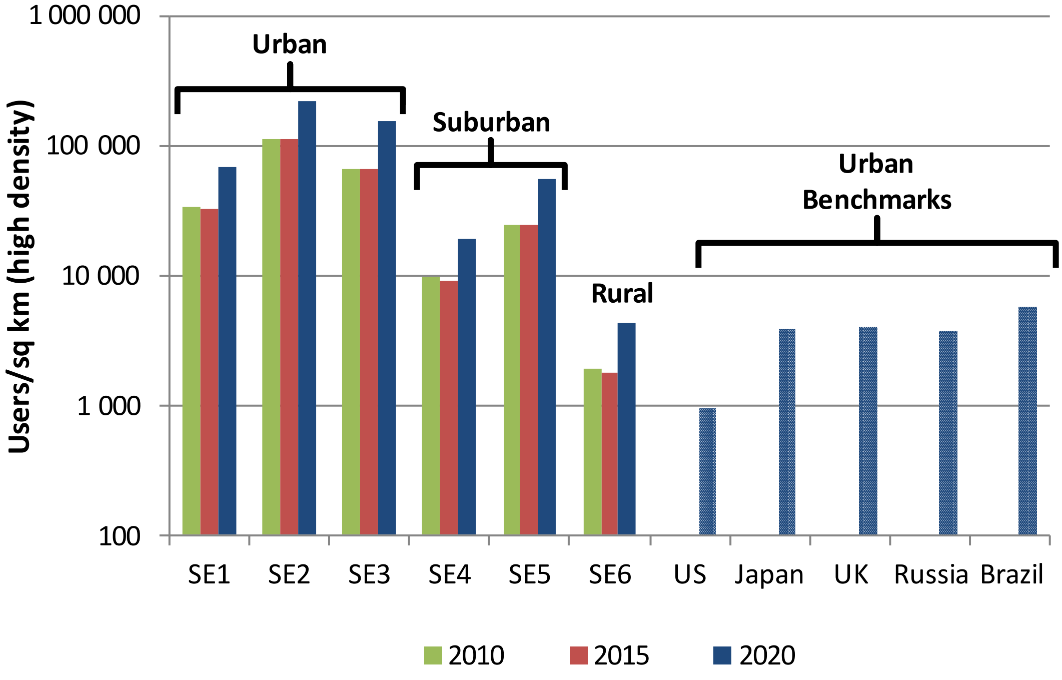
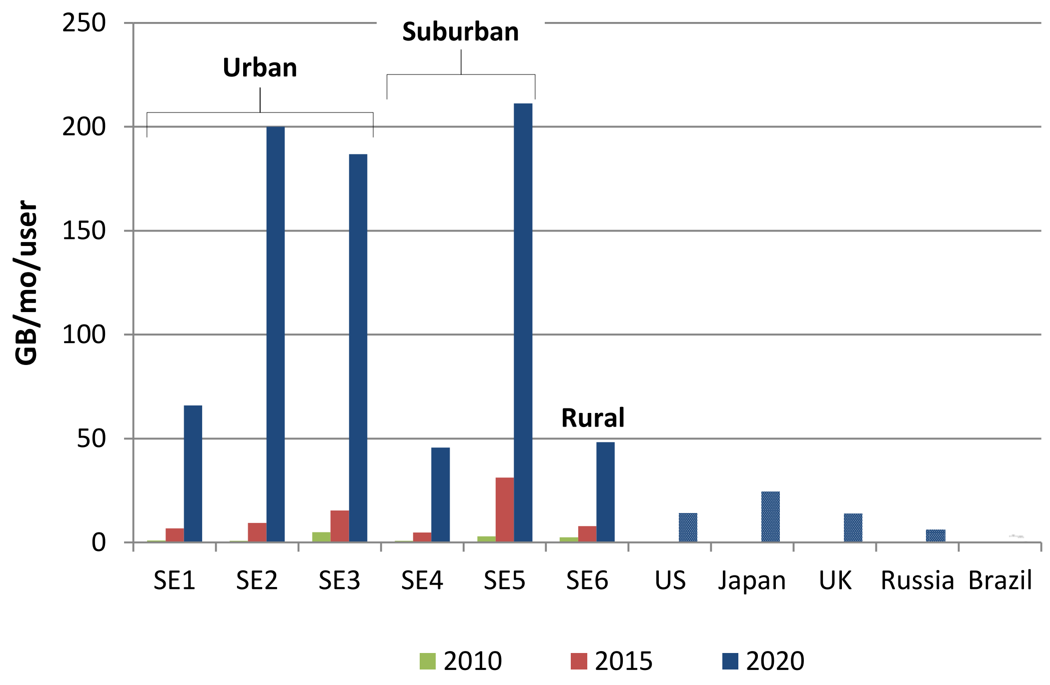


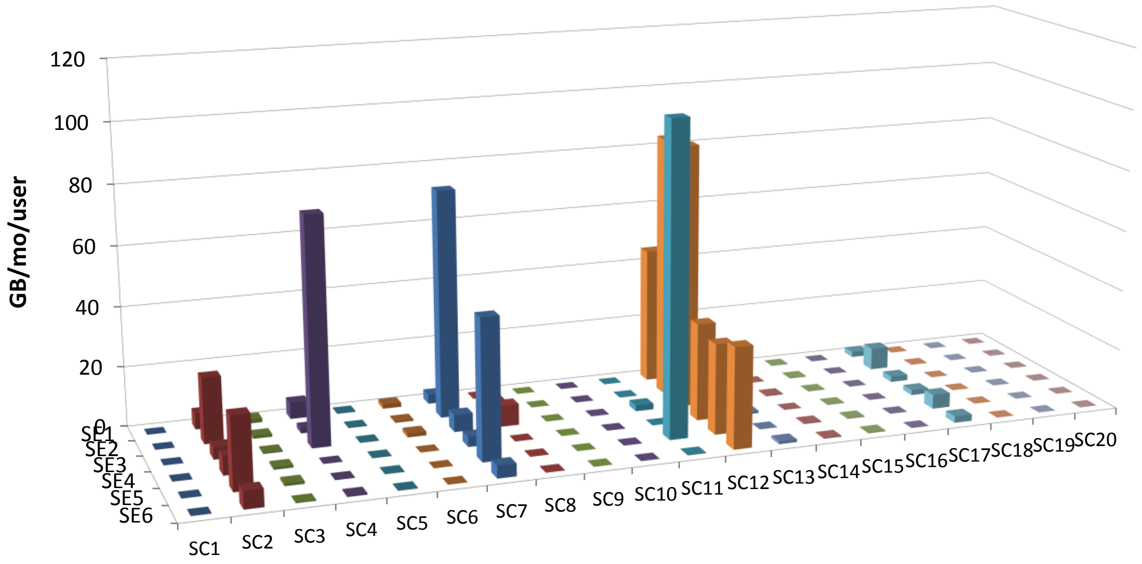
**Figure 2-11: User density by service environment and year compared to urban population density benchmarks in the high growth case [Source: TMF/LS analysis of Speculator model]**



| | | |
|---|---|---|
| SE1 Dense Urban Home | SE2 Dense Urban Office | SE3 Dense Urban Public Area |
| SE4 Suburban Home | SE5 Suburban Office/Public Area | SE6 Rural |

**Figure 2-12: Traffic per user by service environment and year compared to Cisco VNI traffic per head of population benchmarks in the high growth case [Source: TMF/LS analysis of Speculator model]**

Thus it is clear that the Speculator model not only has an excessively high user density (possibly traceable to the erroneous Chinese population data noted above in report M.2072), but also has far too much usage of certain applications. Figure 2-13 below gives a breakdown of the usage by application in 2020 for the low growth case, which highlights that the dominant contributors to traffic in SE 5 are streaming high speed multimedia (SC7), interactive super high speed multimedia (SC11) and interactive high speed multimedia (SC12). Examples of the applications in these service categories given in Report ITU-R M.2072 include video streaming (SC7), browsing and data downloads (SC11 and SC12). However, it is far from clear why users would choose to consume such a high volume of data on cellular networks, and why such applications are expected to be used so extensively in office or high mobility situations. (The economics of data consumption are analysed further in Section 4 below.)



| | | |
|---|---|---|
| SE1 Dense Urban Home | SE2 Dense Urban Office | SE3 Dense Urban Public Area |
| SE4 Suburban Home | SE5 Suburban Office/Public Area | SE6 Rural |

**Figure 2-13: Traffic per user by service environment and service category in 2020 in the low growth case [Source: TMF/LS analysis of Speculator model]**

It is hard to conceive of a high mobility environment where the user density is anything close to the 56,000 users per sq km projected for SE5: the busiest stretches of motorway in the UK carry around 200,000 cars per day, or roughly 30,000 cars per hour during rush hour[22]. At 50km/h (the minimum speed for “high mobility” in the model) there would be 600 cars in each km of motorway at any one time, implying a user density of no more than 1,000 potential users per sq km, many of whom would be unable to access streaming and similar applications if they are travelling on their own. Similarly, around 300,000 people pass through Waterloo station[23] (the busiest station in the UK) each day, or roughly 50,000 people per hour at rush hour. Thus even the busiest suburban train lines have no more than around 1000 passengers per km travelling in excess of 50km/hr.

One argument that has been made is that the Speculator model deliberately models traffic hotspots rather than typical user environments since these are the locations where traffic and demand for spectrum is likely to be highest. However, the projected traffic levels for 2020 appear excessive even for the most significantly traffic hotspots globally. For example, data published by AT&T and Verizon[24] indicates that during the busiest hour of the 2014 Superbowl in New York, AT&T carried

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[22] See https://www.direct.gov.uk/prod_consum_dg/groups/dg_digitalassets/@dg/@en/documents/digitalasset/dg_185830.pdf

[23] See http://www.rail-reg.gov.uk/server/show/ConWebDoc.11135

[24] See http://www.computerworld.com/s/article/9245976/Mobile_data_from_Super_Bowl_stadium_breaks_records

119GB of traffic and Verizon carried roughly 3 times more traffic than AT&T. Taking into account other carriers, total traffic is likely to be between 500 and 600 GB in the busiest hour of one of the busiest locations in the world. For comparison, the Speculator model assumes that even in the low growth case *typical* cellular network traffic (excluding WiFi) in the equivalent Service Environment SE3 (dense urban public area) will be 51 TB per hour per sq km, or roughly 100 times more traffic than the 2014 Superbowl. Figure 2-14 below highlights that in Service Environment SE3, the Speculator model predicts that in 2020 as much as 21 TB per hour per sq km of traffic will be generated by Service Category SC4 (conversational low rate data and low multimedia) alone, which is around 40 times the total traffic seen during the busiest hour of the Superbowl. This clearly makes little sense in the context of real world traffic levels in high traffic public areas today, especially as SC4 would be expected to already be widely used on existing networks in 2014.

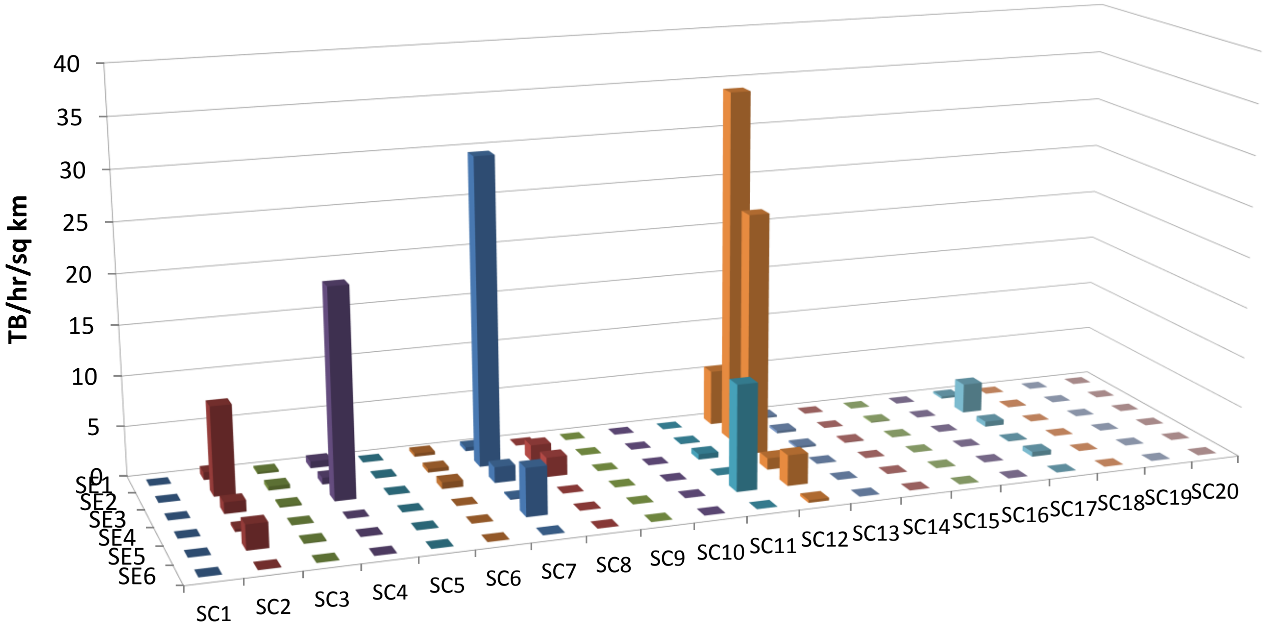

**Figure 2-14: Traffic per sq km *per hour* by service environment and service category in 2020 in the low growth case [Source: TMF/LS analysis of Speculator model, note different units]**

# 3 Alternative data and methodologies

## 3.1 Introduction

As noted above, the traffic density assumptions utilised in the Speculator model are not recognisable, and therefore the model does not provide a reliable basis for estimating future spectrum needs. This chapter reviews other studies of spectrum demand, some of which adjust the Speculator model inputs and others which take a completely different approach in order to determine the validity of different methodologies for estimating future spectrum requirements.

## 3.2 Other studies of spectrum demand

### 3.2.1 Comparisons using modified ITU model

In June 2013, Ofcom published a study by RealWireless[25], which analysed the Speculator model and set out a number of criticisms of the model and proposed adjustments to certain parameters. Many of the criticisms are valid, particularly with regard to the excessive amount of high mobility, ultra high speed application traffic in Service Environment SE5, which requires the use of macrocells (due to handover limitations on smaller cell types), and thereby increases the overall spectrum demand in this environment[26]. The Speculator model does not permit differentiation between the degree of mobility for different applications, which is a serious limitation because the vast majority of usage for applications which consume large amounts of data takes place indoors, and thus cannot require a high mobility architecture. However, as discussed in Section 2.4 above, the RealWireless study appears to overlook the inconsistency between the assumed traffic density and projected total traffic in the UK as a whole. Although RealWireless indicated that it attempted to “calibrate” the traffic against UK specific demand estimates, it does not appear that any benchmarking was conducted of estimated traffic density per sq km against the total UK traffic predicted for 2020.

In order to demonstrate these inconsistencies, the UK has been divided (using LS telcom population density data) into areas representing very high population density (over 10,000 people per sq km), high population density (over 4,000 people per sq km) and lower population density, note that these values differ from the Demographia data. This yields the results below:

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[25] See http://stakeholders.ofcom.org.uk/binaries/consultations/cfi-mobile-bb/annexes/RW_report.pdf

[26] Indeed, Real Wireless concludes that after adjusting various other parameters of the ITU model, spectrum demand in SE5 would be higher than in any other service environment

| Type | Area (sq km) | Population | Population density (per sq km) |
|---|---|---|---|
| Very High (Dense Urban) | 210 | 2,345,000 | 11,167 |
| High (Urban/Suburban) | 4,190 | 17,749,000 | 4,236 |
| Lower (Rural) | 238,600 | 42,239,000 | 177 |
| Total | 243,000 | 62,333,000 | 256 |

**Table 3-1: Population density and area for the UK [Source: LS telcom/TMF Associates]**

Applying the RealWireless traffic volume densities for the year 2020, the total volume of traffic indicated for the UK is in the range 55,000 – 176,000 PB/month as shown in the table below.

| Type | Area (sq km) | Traffic density (PB/month/sq km) | Traffic (PB/month) |
|---|---|---|---|
| Very High (Urban) | 210 | 30 - 100 | 6,300 – 21,000 |
| High (Urban/Suburban) | 4,190 | 10 - 20 | 41,900 – 83,800 |
| Lower (Rural) | 238,600 | 0.03 – 0.3 | 7,160 – 71,600 |
| Total | 243,000 |  | 55,360 – 176,400 |

**Table 3-2: Predicted monthly data traffic using RealWireless density figures [Source: LS telcom/TMF Associates]**

These values vary from 55 to 590 times greater than the total traffic for the UK as estimated by RealWireless for the year 2020 (300 to 1000 PB/month). Urban areas alone have traffic figures which exceed the total forecasts for the whole of the UK by a factor of between 6 and 70 depending on whether a low or high forecast is used. Similarly, even if urban and suburban traffic are ignored, the total rural traffic alone exceeds the forecasts by a factor of 7 or more. Though rural coverage may not reach 100%, and some of this traffic may be offloaded, the scale of the inconsistencies remains vast.

It is also noted that the traffic density figures cited in the RealWireless analysis are those from the Speculator's 'low' market setting and as such the total traffic which would result from the application of the 'high' market setting figures would exceed the total traffic forecasts for the UK by an even greater margin.

Certain other analyses have been conducted to estimate spectrum demand using the same methodology as the ITU spectrum model. China estimated, based on certain modifications to the Speculator model, that spectrum demand in the country would be between 1490 and 1810 MHz by 2020. The summary of results states that "certain adjustments" were made to "the market input parameters of service category (SC1-SC20) in service environments (SE1-SE6)." However, specific details were not given and it is therefore not possible to determine whether realistic or traceable traffic figures were used.

A critique of the Speculator model was submitted by the European Broadcasting Union (EBU) and ZDF, Germany to ITU WP 5D[27]. This submission highlights that certain input parameters "may not be realistic and therefore need to be reconsidered," citing in particular the impact of the "super high

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[27] "EBU, ZDF Comments on the draft new report ITU-R M.[IMT.2020.ESTIMATE]", 22 November 2013, Document 5/68-E

multimedia" service type with "assumed mean service bit rate in excess of 400 Mbits/s" combined with the "mobility ratio" which drives spectrum demand in Service Environment SE5. As shown in Figure 2-10, the super high multimedia applications (SC11) are a key driver of overall demand particularly in SE5, but we consider that demand density is so far out of line with properly benchmarked figures, even removing SC11 (which accounts for just over half of total traffic) would be insufficient to reduce demand density in SE5 to a realistic level.

### 3.2.2 Alternative forecasts

A very different analysis was submitted to the ITU by the Russian Federation in September 2012[28], which proposed a much simpler model of spectrum demand based on the expected increase in network efficiency and offloading over the period from 2010 to 2020 compared to the expected increase in traffic over this period. This proposal has the advantage of making the assumptions transparent, but is relatively conservative in some assumptions, such as offloading (where only 20% of traffic is assumed to be offloaded by 2020, when most independent estimates assume that the majority of traffic, i.e. over 50%, will be offloaded[29]) and the number of small cells which will be constructed in Moscow by 2020. Simply changing one of these parameters would cause a dramatic decrease in total spectrum demand, and conversely, assuming a higher growth in traffic (as we noted in Section 2.4, the UMTS Forum and Cisco forecasts differ by at least a factor of two) would result in a large increase in total spectrum demand.

This approach of analysing spectrum demand based on the increase in overall traffic divided by the expected improvements in re-use has been used by other analyses, such as the FCC estimate in October 2010[30] that 275 MHz of additional spectrum was needed in the US to support the growth in data traffic expected through 2014. A similar but somewhat more sophisticated approach was employed by Ofcom in its November 2013 mobile data strategy consultation[31]. An Australian study of spectrum demand published in May 2011[32] also employed a similar methodology, but concluded that **spectrum requirements could actually fall** beyond 2020 **as efficiency gains outpace traffic growth**.

Substantially different assumptions are made in the different studies even about the current "average" level of spectrum efficiency in existing networks. For example, the FCC model assumed an average spectral efficiency of 0.625 bps/Hz in 2009, and that this would double to 1.25 bps/Hz by 2014, whereas the ACMA (Australia) assumed that the spectral efficiency of pre-2007 networks was 1.85 bps/Hz and this would increase to 5.6 bps/Hz by 2015 and 15 bps/Hz by 2020. In contrast, the ITU spectrum model assumes that RATG 1 (2G, 3G and LTE) air interfaces will achieve spectral

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[28] "Future IMT Spectrum Requirements Assessment for the Russian Federation", 20 September 2012, Document 5D/118-E

[29] Cisco's February 2014 VNI forecast forecasts that 54% of Russia's mobile data traffic will be offloaded by 2018

[30] See http://download.broadband.gov/plan/fcc-omnibus-broadband-initiative-%28obi%29-technical-paper-mobile-broadband-benefits-of-additional-spectrum.pdf

[31] See http://stakeholders.ofcom.org.uk/consultations/mobile-data-strategy/

[32] See http://www.acma.gov.au/webwr/_assets/main/lib312084/ifc13_2011_toward_2020-future_spectrum_requirements.pdf

efficiencies of between 2 and 4 bps/Hz/cell and RATG 2 (LTE-Advanced) will achieve spectral efficiencies of between 4 and 7.3 bps/Hz/cell in dense urban environments. For RATG 1 which is a mix of GSM, UMTS and LTE, the figure of 2 to 4 bps/Hz/cell seems very high. Interestingly these values have changed little since the original version of the Speculator model in 2006, though there is now far greater clarity on the operational parameters of LTE-Advanced than there would have been in 2006. Note that the use of bps/Hz/cell is unusual, but in a single frequency network, as would typically be expected for 3G and LTE air interfaces, this efficiency measure should be roughly equivalent to the standard bps/Hz measure. As an example, Huawei claim that LTE-Advanced achieves a spectral efficiency of 2.3 bps/Hz/cell as shown in Figure 3-1 below.

**Figure 3-1: Huawei forecasts of spectrum efficiency of IMT technologies [Source: 'LTE-A and Beyond', Huawei, Latin American Spectrum Conference 2013]**

Other estimates suggest that spectral efficiencies could improve by as little as 3 times or as much as 15 times in the migration from RATG 1 to RATG 2 (see estimates from Report ITU-R M.2290, Real Wireless, WINNER and Holma/Toskala summarized in Table A-17). Efficiency gains are also likely to differ between urban and rural areas, since small cells in urban areas will potentially allow more customers to operate with higher order modulation schemes and thereby consume more bits per Hz of available spectrum. Further the use of MIMO antenna technology requires multiple paths between the cell site and the user, typically caused by reflections and there is greater scope for reflections in urban areas. As a result, the high level of uncertainty inherent in such estimates means that little weight can be placed on their reliability.

As one example, the FCC estimate has been dramatically wrong, and in fact, significant amounts of spectrum allocated in FCC auctions prior to 2010 remain unused, despite the fact that growth in data traffic in the US between 2009 and 2014 is still expected to be similar to the 35 times that the FCC assumed back in 2010 (CTIA statistics[33] indicate growth in data traffic of 8.3 times between 2010 and 2013 compared to 8.6 times growth assumed in the FCC model). The errors in the FCC model are in fact related to how effectively spectrum can be re-used by operators.

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[33] See http://www.ctia.org/docs/default-source/Facts-Stats/ctia_survey_ye_2013_graphics-final.pdf?sfvrsn=2

- Firstly, the FCC assumed that the number of cell sites in the US would grow at 7% p.a. to reach 322,340 by the end of 2013 and 344,904 by the end of 2014 and new cell sites would be uniformly distributed across the country. In fact cell site deployment to date has been even lower than the FCC's forecast, reaching only 304,360 sites by the end of 2013 (according to CTIA statistics) and these deployments were clearly focused on relieving hotspots where capacity was constrained rather than being distributed uniformly[34].
- Secondly, and more importantly, the efficiency gains (which assumed a doubling in average spectral efficiency between 2009 and 2014) were much greater than the FCC projected, due to faster than expected upgrades to LTE. By the end of 2013 Verizon was already carrying two-thirds of its data traffic (which equates to roughly 20% of all US mobile data traffic) on its 22MHz LTE network (which uses two 10MHz carriers).

As a result, rather than the 524 MHz of spectrum that the FCC estimated would be needed for data traffic at the end of 2013 (which was projected to increase to 708 MHz by 2014), roughly 100MHz of licensed spectrum would be able to accommodate all of the mobile data traffic generated in the US at the end of 2013 (assuming legacy customers upgraded to the current generation of LTE). Moreover, the deficit of 90 MHz of spectrum projected by the FCC for the end of 2013 has clearly not materialised, and in fact not all of the 547 MHz allocated by the FCC for cellular services back in 2010 has yet been deployed.

## 3.3 Alternative methodologies

As discussed above, the FCC's 2010 projections proved erroneous even though they were over a relatively short timeframe. Thus for the ITU process which attempts to project spectrum demand in 2020 (based in many cases on underlying forecasts which date back to 2011), there would be enormous uncertainty inherent in any assessment of spectrum demand based solely on estimates of improvements in average re-use and spectral efficiency.

A particular concern is that *average* spectrum re-use and total countrywide demand have little to do with the situation in those few hotspots, such as train stations or sports stadiums, where more efficient technologies may support higher traffic density with small cells offering considerably improved spectrum re-use. Even the Russian analysis noted above, which tries to assess demand just in Moscow, fails to take account of the fact that urban demand is not uniformly distributed, and any new cell site deployment would be optimised to address certain hotspots. Moreover, special measures, such as WiFi offloading and small cell deployment, which can be used to relieve capacity constraints in many hotspots, are very difficult to take into account in such a high level market assessment.

The strength of the Speculator model is that it does attempt to model specific service environments and take into account best practice in network deployment within those locations. However, as discussed in Section 2 above, the amount of traffic generated within these service environments has not been reconciled with overall traffic predictions, and it is very unclear whether the environments are supposed to represent a handful of hotspots, or are intended to be more typical of an urban or suburban area of (at least) several sq km. Further, it is unclear whether the specific scenarios being

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[34] Analyst reports indicate base station investment has shifted from macrocells for wide area coverage to small cells and distributed antenna systems (see for example http://www.rcrwireless.com/article/20121010/opinion/analyst-angle-goodbye-tower-power-hello-hetnet/)

considered by the ITU are based on assumptions about specific frequency bands. Are the high mobility applications highly dependent on sub-1 GHz spectrum, and are the urban ones assuming spectrum above 1 GHz? It may be that the demand indicated by the ITU requires sub-1 GHz spectrum and, of course, finding over 1 GHz of spectrum below 1 GHz is, quite literally, impossible.

Any revision to Report ITU-R M.2290 should set out more specifically what the modelled environments are intended to represent and reconcile the proportion of traffic generated in those locations with total nationwide traffic according to third party projections such as the UMTS Forum, Cisco, and so forth. A further cross-check could then be carried out against the number of base stations of different types that would be deployed nationwide (or regionally) if the actual network deployment was in accordance with the ITU's results, based on statistics for current network deployments and expected future investment. This is very similar to the recently published ACMA mobile network capacity forecasting model for Australia (developed by Analysys Mason),[35] which explicitly projects total countrywide traffic and allocates it to different service environments.

Figure 3-2 below summarizes our suggested adaptation of the Speculator methodology to cross-check and validate the assumptions and results for specific countries. We propose that for each country analysed, the share of land area associated with each service environment should be identified, and based on realistic projections of total traffic in the country in 2020, the share of that traffic associated with each service environment should be identified, just as in the ACMA/AnalysysMason model. Then the user density and traffic per sq km can be normalised to correspond to the identified traffic in that service environment. This will allow the network capacity to be assessed using a best practice network and spectrum-band deployment architecture, and the implied number of base stations that would be required to serve this traffic can also be cross-checked. Then the spectrum required to operate this network architecture in each service environment can be assessed and importantly, the economics associated with this network deployment (i.e. deployment cost vs potential revenue stream) can be understood.

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[35] See http://www.acma.gov.au/theACMA/Consultations/Consultations/Current/acma-mobile-network-capacity-forecasting-model

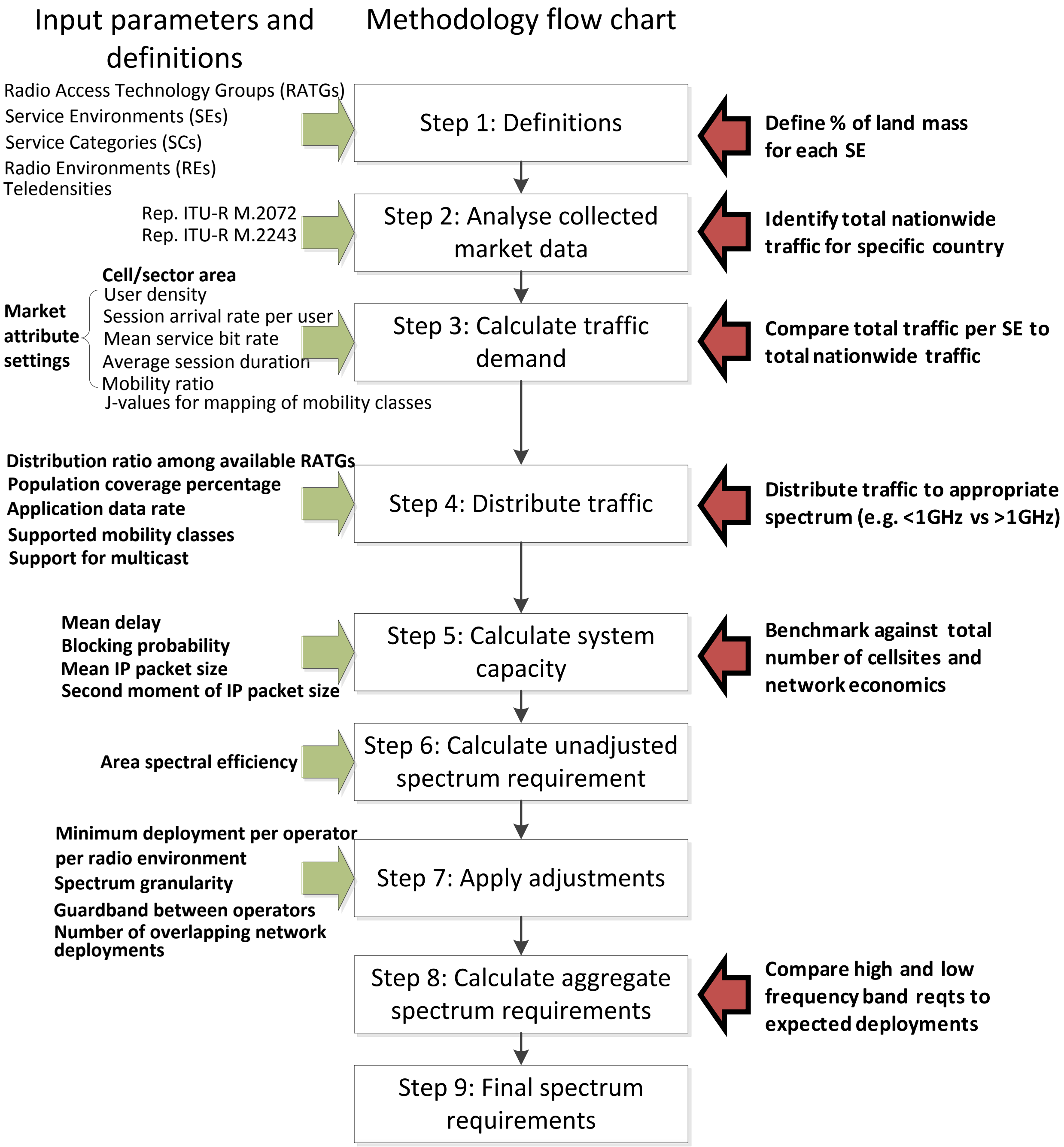

**Figure 3-2: Proposed adaptation of ITU spectrum demand model methodology to validate assumptions and results [Source: TMF/LS Telcom]**

# 4 Economic issues impacting spectrum demand

It is important to consider how best practice network designs can address realistic levels of traffic demand in different service environments based on expected trends in the cost of wireless network deployment and plausible levels of spending on wireless data services. This chapter discusses the economic issues which determine the appropriate traffic and infrastructure benchmarks and thereby influence the future level of spectrum demand.

## 4.1 Factors influencing traffic demand

The most important issue influencing traffic demand is the willingness of mobile subscribers to pay for data, which is largely determined by the price that operators charge, and in particular whether data subscriptions include unlimited usage or are constrained by metering or data bundles.

Since 2012 many countries have seen a rapid shift away from unlimited usage packages as operators have sought to deter excessive data consumption, and this has proved successful in restricting the amount of data consumed by the highest usage subscribers. For example, Cisco estimates that the share of traffic consumed by the top 1% of subscribers has declined from 52% of all monthly data traffic in January 2010 to 10% of traffic in September 2013[36]. The removal of unlimited usage packages led to a slow-down in rates of growth in data traffic, for example (according to CTIA statistics[37]) the US saw a sharp slowdown from 54% growth in data traffic in the second half of 2011 compared to the previous 6 months, to only 20% growth in data traffic in the first half of 2012 (again compared to the previous 6 months) after the two largest carriers stopped offering unlimited usage packages to their subscribers.

Once unlimited usage on cellular networks becomes unavailable, customers instead pay much more attention to how they can offload data from the cellular network, so that they do not use up their allocated data “bucket”. The obvious way to do this (and the solution that most wireless users adopted) is to make increasing use of WiFi, initially in the home, and subsequently in the office and public areas, whenever it is available unmetered and free of charge. The strong trend towards increased use of WiFi has been observed both in the US and many other countries, as reported by Mobidia in June 2013[38], and data traffic forecasts such as those by Cisco have consistently increased their projections of the share of wireless traffic that will be offloaded to WiFi in the future.

The result of this increased use of WiFi has been that Cisco and other analysts have reduced their projections of both near term and longer term data traffic growth using licensed spectrum. For example, Figure 4-1 shows how Cisco’s estimates of global mobile data traffic in 2012 and 2013 were reduced in each of their last two reports (released in February 2013 and 2014 respectively), which is particularly striking given the short term nature of these forecasts.

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[36] See http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.pdf

[37] See http://files.ctia.org/pdf/CTIA_Survey_MY_2012_Graphics-_final.pdf

[38] See http://www.informatandm.com/wp-content/uploads/2013/06/Mobidia-ITM-June-2013.pdf

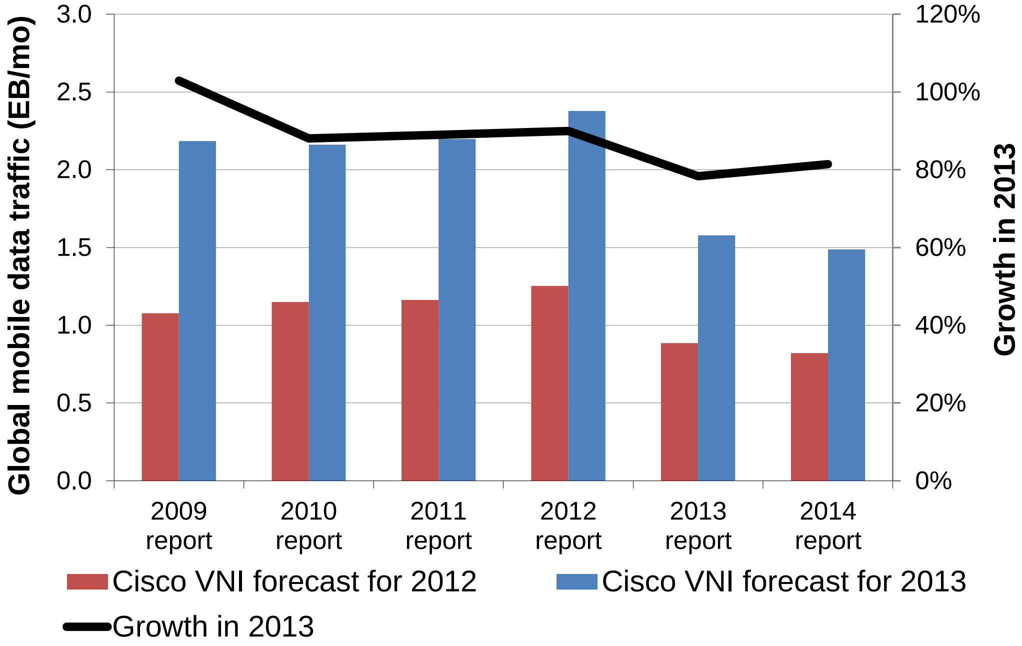

**Figure 4-1: Cisco estimates of global mobile data traffic in 2012 and 2013 (in EB/month at the end of the year) and associated annual growth [Source: TMF/LS Telcom]**

Recently, many carriers in the US and elsewhere have reported that usage increases when subscribers upgrade from 3G to LTE devices, reflecting the higher data speeds available on LTE. Some have even claimed that that the availability of more advanced LTE devices and networks can reduce end-users' reliance on Wi-Fi[39]. However, analysis from Mobidia indicates that "this phenomenon looks to be fleeting rather than permanent" which they consider to reflect the "increasing maturity of the most advanced LTE markets" once initially empty networks begin to experience more realistic loading patterns[40]. While much stronger growth in data traffic was seen in the US in 2013 (according to recent CTIA statistics), this is also likely indicative of a lack of capacity constraints on most LTE networks and recent moves by several mobile operators to increase data allowances and promote sharing of large data buckets by subscribers using family plans.

In other countries, application developers have begun to make more efficient use of data, in order to ensure that their customers do not limit use of their applications to avoid overages. For example, Facebook's CEO stated at the Mobile World Congress in February 2014 that Facebook's mobile app had reduced its average data consumption per user from 14MB per day to only 2MB per day in the last year, and the company eventually expected to reduce data usage to 1MB per day per user[41]. This could have a significant impact on future traffic growth, because Facebook accounted for nearly 10% of mobile traffic in North America in the first half of 2013[42].

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[39] See http://www.fiercewireless.com/europe/story/ee-lte-reducing-user-reliance-w-ifi/2013-08-20

[40] See http://www.informatandm.com/wp-content/uploads/2013/06/Mobidia-ITM-June-2013.pdf

[41] See http://www.fiercewireless.com/story/facebooks-zuckerberg-pushes-free-tier-wireless-internet-access-during-mwc-k/2014-02-24

[42] See https://www.sandvine.com/downloads/general/global-internet-phenomena/2013/sandvine-global-internet-phenomena-report-1h-2013.pdf (Table 4)

Fundamentally, consumers' desire to use increasing amounts of 4G data depends on their willingness to pay for larger bundles of data. As of early 2014, data pricing is typically tens of US dollars per Gbyte on an average basis (total data spend divided by total usage) and US$2 to US$10 per Gbyte on an incremental basis[43]. Video usage is expected to dominate cellular data consumption in the future, with Cisco estimating that mobile video exceeded 50% of cellular data traffic in 2012.[44] However, most video consumption is of short form video from YouTube, rather than long form streaming (TV programs and movies) via services such as Netflix[45]. With Netflix requiring up to 2.8 Gbytes/hour to deliver High Definition video[46], it is very unlikely that most users would be willing to pay tens of dollars to watch a movie via an LTE connection. Data prices, which will be determined by the cost of LTE infrastructure, would have to fall very significantly (to well below $1 per Gbyte) in order to support this type of application. Moreover, long form video is generally consumed in the home, where fixed broadband, cable and satellite connections are available at a much lower cost per Gbyte of data consumed (often with no data caps). As a result, even though demand for streaming video via fixed home connections has grown strongly in recent years, there is little evidence that the same patterns of consumption will carry over to mobile networks. Indeed, Cisco's forecasts of fixed and mobile data traffic suggest that only 12% of data will be consumed via mobile networks in 2018, despite WiFi and mobile devices accounting for 61% of total traffic generation.[47]

## 4.2 Factors influencing infrastructure supply

Fundamentally, the key determinant of whether high bandwidth consumer applications such as video streaming (where the willingness to pay is likely lower than for time critical applications such as email and location-based services) will be widely used on mobile networks is the cost of data to the end user. That in turn is dictating to a large extent by the cost of data delivery, i.e. the cost of constructing next generation networks.

According to the GSMA Mobile Economy paper of 2013, global revenue per mobile subscriber has seen a compound annual growth rate (CAGR) of -3.8% between 2008 and 2012. Whilst there is some suggestion that this decline has been caused by decreasing voice tariffs and a move towards lower priced pre-pay services, there is no evidence that the growth in data traffic over the same period has led to a sustained increase in revenue or that these trends will be reversed. The paper's authors, A. T. Kearney, state that although global capital investment in network infrastructure is expected to increase by 4% per year, due to the efficiencies that will result in conversion from GSM or 3G networks to LTE, 'total network cost per Gbyte will decline by at least 10% per annum in the years

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[43] See for example http://www.forbes.com/sites/tristanlouis/2013/09/22/the-real-price-of-wireless-data/ and https://gsmaintelligence.com/analysis/2014/1/4g-driving-data-usage-but-not-all-markets-reaping-the-rewards/412/

[44] See http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html

[45] See http://www.informatandm.com/wp-content/uploads/2013/06/Mobidia-ITM-June-2013.pdf

[46] See https://support.netflix.com/en/node/87

[47] See http://www.cisco.com/c/en/us/solutions/collateral/service-provider/ip-ngn-ip-next-generation-network/white_paper_c11-481360.html

ahead'. On the face of it, this seems like good news as the cost per bit will decline faster than the decline in revenue per subscriber.

However, the predicted growth in data consumption that is expected to occur over the same period is far more rapid than this decline in costs would permit. If this is the case, and if the cost and revenue decline in line with the GSMA paper, there is an irreconcilable difference between the network operators' ability to deliver users' data demand expectations and the price that they can afford. Based on the GSMA forecasts, by 2020:

- revenue per user will have dropped to 76% of today's value;
- cost per bit will have fallen to 48% of today's value.

Even if it is assumed that the revenue per user remains constant, the growth in data will far exceed the reduction in costs meaning that either the cost per bit will have to fall by an additional 20% per annum (i.e. three times faster than forecast) to sustain the same revenue per subscriber, or consumers will be faced with bills that may be 10 or more times higher than those of today if they want to continue to consume data in line with most growth forecasts.

A paper by NokiaSiemensNetworks (NSN)[48] considering the capacity and cost aspects of 3G and LTE concludes that, “monthly network Capital Expenditure and Operational Expenditure can be kept below 3 Euro per subscriber over an eight-year depreciation period. This is true if the average mobile broadband penetration is at least 500 subscribers per site, and if subscribers use less than 2 GB per month.” However some forecasts for growth in data consumption over an 8 year period suggest that the limit of 2 GB per month will prove inadequate in some countries, meaning that the 3 Euro per month per subscriber limit would also be exceeded. The paper states that at a limit of 10 GB per subscriber per month, the cost becomes nearer 5 Euro per month.

Another estimate is that the cost of delivering LTE data at present is around US$3 per Gbyte[49]. This is consistent with estimates that new operators such as LightSquared and Clearwire were planning to charge their wholesale partners around $7 per Gbyte in 2012[50] (given their need to make a profit on the costs of network deployment) and somewhat lower than Cisco’s 2012 estimate that mobile operators would be prepared to pay wholesale rates of $3 to $10 per Gbyte to offload traffic to WiFi[51]. As a result, in order to support retail prices well below $1 per Gbyte, as will be needed to stimulate significant consumption of long form video, the costs of delivery would need to fall by as much as 90%. If the GSMA estimates are accurate, this is unlikely to occur in the period up to 2020.

Nevertheless, it is possible that the costs of data delivery could fall more rapidly than the GSMA estimates imply, since as shown by Cooper’s Law (named for Marty Cooper, the inventor of the cellphone), which is illustrated in Figure 4-2 below, the carrying capacity of the radio spectrum has doubled every 30 months for the last century.[52] If network costs remained constant, this would imply that the cost of data delivery would be falling by about 30% per year, and would decline by 86%

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[48] “Mobile broadband with HSPA and LTE – capacity and cost aspect”, NSN White Paper, 2010

[49] See http://hettingconsulting.com/us-mobile-carriers-can-save-billions-with-combined-ltewi-fi-services/

[50] See http://www.fiercewireless.com/story/freedompop-looks-beyond-lightsquared-wholesale-access/2012-02-10 and http://www.dslprime.com/a-wireless-cloud/61-w/4759-netzero-free-200-meg-mobile-995-for-400-meg

[51] See https://www.cisco.com/web/about/ac79/docs/sp/SP_Wi-Fi_PoV.pdf

[52] See http://www.arraycomm.com/technology/coopers-law

between 2013 and 2020. However, it is important to note that according to Cooper, the million-fold improvement in network capacity that has been achieved over the last 45 years has resulted from a 25x increase in usable spectrum, a 25x increase in efficiency due to frequency division and improved modulation (i.e. an increase in the number of bits carried in each Hz of spectrum), but a 1600-fold increase in spectrum re-use through the use of smaller cells. Thus increased re-use has been and should be expected to continue to be the dominant contributor to future capacity increases, and many observers are recognising that deployment of small cells will become critically important to wireless operators in the next few years. Although operators may prefer to use new spectrum in the deployment of next generation networks, including their deployments of small cells, it is also feasible to re-farm existing spectrum that was used for less efficient second generation technologies such as GSM.

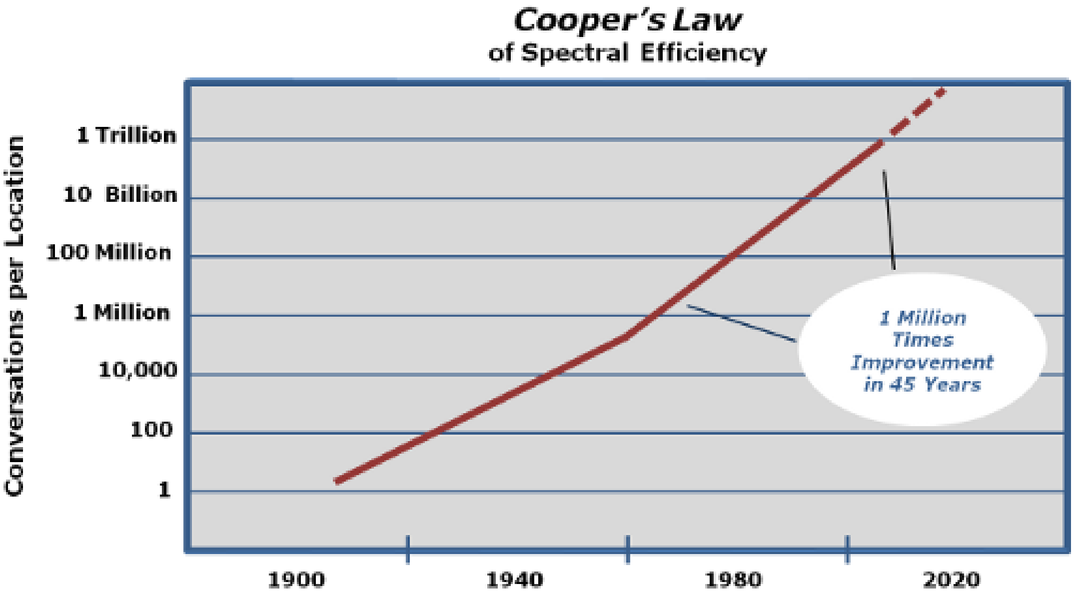

**Figure 4-2: Historical growth in wireless network capacity [Source: ArrayComm]**

Since consumers' spending on wireless services is flat or even falling in many countries at present, it is critical for operators to achieve capacity gains with as little incremental capex as possible. While this may provide a rationale for wireless operators to lobby for as much spectrum as possible to be allocated to cellular services (since a glut would allow operators to acquire additional spectrum relatively cheaply), there are innovative solutions on the horizon which can increase spectrum re-use dramatically with very modest levels of investment.

For example, plans set out by BT in the UK envisage small cells operating in the 2.5 GHz band being deployed in millions of home DSL routers[53]. As a benchmark, through a deal with FON, BT already makes WiFi coverage available to FON subscribers across the UK through over 4 million WiFi hotspots embedded in BT's DSL routers, and many of these hotspots will be converted to licensed 2.5GHz spectrum in the next few years. Similarly, in the US, DISH Network has plans to deploy a fixed wireless broadband network to its satellite TV dishes across the country, with a business plan that contemplated serving as many as 8 million homes by 2019, and DISH is widely expected to host small cells on many of these homes. Coverage will be even better than that provided by BT, because

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[53] See http://www.telegraph.co.uk/finance/newsbysector/mediatechnologyandtelecoms/10051578/BT-returns-to-mass-market-with-4G-network.html

the cell will be located on a rooftop satellite TV dish and therefore would not be subject to the building attenuation that will be experienced by a small cell collocated with an in-home DSL router. Deployments using satellite TV antennas to host small cells to boost network capacity are also very feasible in less developed countries, even if DSL or cable modem-based backhaul is unavailable.

When the US has only just over 300,000 cell sites today (according to CTIA figures[54]), and the UK has only around 60,000 operational cell sites[55], it is clear that a move to utilise millions of small cells would increase current cellular network capacities by an order of magnitude. Costs of these deployments can be in the hundreds of dollars per site rather than the tens or hundreds of thousands of dollars that a new macrocell deployment costs today. The cost-effective nature of such deployments mean that it is critical for any estimates of future spectrum demand to fully account for viable licensed small cell het-net deployment architectures (in addition to WiFi “offload”), rather than simply assuming that making more spectrum available is the optimum solution to meet growing wireless data traffic volumes.

There are also a raft of technological solutions being considered which would bring about increases in spectrum efficiency and capacity for mobile networks. Techniques such as distributed-antennas (DIDO), mathematical interference calculation (VFDM) and heterogeneous networks (HetNets) offer new techniques or topologies that will fundamentally change the relationship between spectrum and service delivery.

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[54] See http://www.ctia.org/docs/default-source/Facts-Stats/ctia_survey_ye_2013_graphics-final.pdf?sfvrsn=2

[55] Various sources including extrapolation of 2011 figure provided in http://www.mobilemastinfo.com/base-stations-and-masts/

# 5 Conclusions

## 5.1 Speculator Model

The advantage of the Speculator model is that it analyses network infrastructure capabilities in specific environments, rather than considering the average situation across an entire country. However, the assumptions used in the model are unrealistic, in that they significantly overestimate the traffic density in different service environments whilst claiming to be based on input data that is generally reasonable. In addition, a number of other inputs to the model are out-of-line with generally accepted values, casting greater doubt on the validity of the model's outputs.

Alternative simplified models which divide traffic growth by assumed network efficiency/re-use improvements are unlikely to give reliable estimates. Of the models reviewed, it appears that the ACMA/AnalysysMason model[56] represents the most promising approach to benchmarking traffic growth in different service environments and understanding the relationship between traffic demand and network infrastructure supply.

## 5.2 Economic and technological factors

From an economic perspective, there is an inconsistency between the expected growth in mobile data traffic and the cost at which that growth can be delivered, against a backdrop of falling revenue per subscriber. Though data costs will fall, if current network architectures are maintained, the cost of delivery will not fall as quickly as the expected growth in traffic meaning that consumers will have to pay more for data, or that consumption will have to be restricted. Thus the uptake of high bandwidth services as foreseen by Report ITU-R M.2290, based on traditional service architectures, is questionable.

In contrast, new service delivery models (such as the roll-out of millions of very small cells through domestic installations), air interface techniques and network topologies may fundamentally change the cost and nature of wireless services, and their relationship with spectrum, and such changes need to be factored into the Speculator model as a critical contributor to supporting faster growth in mobile data traffic in a cost effective manner.

## 5.3 Recommendations

Overall, we consider that with reference to the Speculator model, it is necessary to:

- **continue to work with the model** as it provides the most comprehensive means of assessing spectrum demand;
- **validate and benchmark the traffic forecasts** used in the model against a range of industry forecasts, as in the ACMA/Analysys Mason model;

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[56] See http://www.acma.gov.au/theACMA/Consultations/Consultations/Current/acma-mobile-network-capacity-forecasting-model

- **review and validate the technical parameters** used in the model to ensure that they are reflective of real-life implementations;
- **better define the scenarios** that the model is considering so that users can understand how applicable they are to their national situations;
- **ensure that foreseen developments** in network topologies, air interface techniques and service delivery models are clearly defined and integrated into the model's scenarios;
- **assess the economic viability of the scenarios** that the model is considering to ensure that they produce an outcome that would support the services they are intended to deliver at a price which is acceptable;
- **break spectrum demand into sub- and over- 1 GHz** bands so that it is clear where the greatest demand is focussed.

# A Detailed analysis of technical issues in the Speculator model

## A.1 Summary and conclusion

The ITU methodology for spectrum requirement estimations for the terrestrial component of IMT was initially described in Recommendation ITU-R M.1768[57] which was published in 2006. A software implementation of the ITU-R methodology is available as MS Excel tool “Speculator”. This software tool has been developed within research activity IST-2003-507581-WINNER[58]. Version 2.26 of Speculator was used by ITU in preparation for the WRC-07 Agenda Item 1.4 in Working Party ITU-R WP 8F.

In 2013 the Speculator tool was updated to Version 2.5 in order to implement the updated Recommendation ITU-R M.1768-1[59]. The technical analysis of the ITU methodology has therefore been based on an analysis of this version of the Speculator tool.

Any methodology to predict future spectrum requirements needs fundamental input data describing the future user behaviour in terms of services, mobility, data load and so on. The calculation of future spectrum requirements for terrestrial mobile networks is therefore a challenging task as the spectrum demand is dependent upon a multitude of overarching conditions which need to be defined.

User traffic has to be carried by the network(s) in a given amount of spectrum to provide the requested services, where the amount of spectrum depends in the first instant on the radio technology used by the network and the way in which the network is deployed. Within a fixed amount of spectrum a given network can carry a specific traffic volume with a given quality of service (QoS). QoS definitions can include the technical quality of the digital data streams based on required and achieved data rates and acceptable Bit Error Rates as well more general quality criteria such as the acceptable percentage of unsuccessful voice calls or delayed data packets due to network congestion. Thus predicted spectrum requirements are always a result of the following general input parameter and requirements:

- Traffic Volume to be carried by the networks
- Minimum Quality of Service to be provided (QoS)
- Technical Network Capabilities

A comprehensive model for spectrum requirement estimations therefore comprises the input parameters and the methodology (algorithms) - how the input parameters are processed to generate the spectrum requirements. Aside from the general input parameter groups for “Traffic Volume”, “Network Capability” and “QoS” the Speculator tool requires several other model specific input parameters to define the model behaviour. These parameters include, for example, definitions of how

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[57] Recommendation ITU-R M.1768, “Methodology for calculation of spectrum requirements for the future development of the terrestrial component of IMT-2000 and systems beyond IMT-2000, 03/2006

[58] www.ist-winner.org

[59] Recommendation ITU-R M.1768-1 “Methodology for calculation of spectrum requirements for the terrestrial component of International Mobile Telecommunications”, 04/2013

the input traffic is distributed to the different radio technologies, average cell areas to calculate the traffic per cell, or data rates offered by the different networks to be used during QoS calculations.

The recommended input parameters for traffic volume for the speculator tool are stated in Report ITU-R M.2078 which gives figures that are based on market forecast data provided in Report ITU-R M.2072 and updated with ITU-R M.2243.

Recommended technical parameters to be used with Speculator have been provided within the Excel implementations and are described in Report ITU-R M.2074[60] published in 2006 and recently updated with Report ITU-R M.2290.

The methodology used by the Speculator tool follows the following key concepts:

- The input traffic volume is derived from market data that consists of a combination of user densities given as users per sq km, session arrivals per hour and user, average session duration and mean bit rate. The input market data is defined for a combination of different service categories and service environments. Service categories are used to describe combinations of service type (e.g. low rate data or high multimedia) and traffic class (like streaming or interactive) to consider variations in user demands. Service environments give a combination of service usage pattern (e.g. home or office) and Teledensity (Dense Urban, Suburban or Rural).
- QoS is modelled separately for circuit switched data and packet switched data. For circuit switched data a multi-dimensional Erlang-B blocking model is used; the corresponding QoS parameter is the maximum allowed blocking rate. For packet switched data a queuing model is used where QoS requirements are defined as the maximum allowed packet delay.
- Network capability is expressed as area spectral efficiency giving the throughput in bits per second that can be achieved per Hz Bandwidth allocated per cell (bps/Hz/cell). As the spectral efficiency depends on the type of the cell deployment and the radio technology used (GSM, UMTS, LTE etc) the speculator tool defines spectral efficiencies for combinations of Radio Environments (macro-, micro-, pico cells or hotspots) and Teledensities. Radio Access Technology Groups (RAT Groups) are used to combine different radio technologies:
    - RATG 1 includes pre-IMT systems, IMT-2000 systems and enhancements such as GSM-EDGE, UMTS and HSPA thereby covering 2G and 3G systems
    - RATG 2 covers IMT-Advanced systems (4G systems).
    - RATG 3 is for radio LANs (e.g. WiFi).
    - RATG 4 contains digital mobile broadcasting systems and their enhancements

  Area spectral efficiencies are defined for a combination of RATG, RE and Teledensity.
- To determine the spectrum requirements the total forecasted traffic is distributed to the different Radio Environments of the four RATGs. The distribution to different RATGs and RE is based on a user defined distribution matrix and considers the technical capabilities of the different REs such as supported mobility and maximum provided data rates. During the ensuing calculation steps the spectrum requirements for each Radio Environment of RATG 1 and RATG 2 are determined by aggregating the offered traffic over the different service environments in each

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[60] Report ITU-R M.2074 “Estimated spectrum bandwidth requirements for the future development of IMT-2000 and IMT-Advanced”

Teledensity and RE and applying the QoS model to the aggregated traffic. This results in the required cell capacity per RE, Teledensity and RATG. Capacity requirements are then converted to spectrum requirements per RE and Teledensity by dividing the required capacity by the corresponding area spectral efficiency. Finally the bandwidth requirement per RATG is calculated by combining the spectrum requirements for different RE and Teledensities of this RATG and applying adjustments to consider guard bands between operators, minimum requirements per network and channel granularity.

- RATG 3 (Radio LAN) and RATG 4 (Broadcasting systems) are only used during the distribution process to simulate offloading of traffic from RATG 1 and RATG 2 networks. Thus the total traffic volume is reduced by the offloaded unicast traffic to RATG 3 and offloaded multicast traffic to RATG 4. No spectrum requirements are calculated for RATG 3 and RATG 4.

In total the Speculator tool calculations can be subdivided into 9 calculation steps. Each calculation step uses a different set of input parameters and some of the results of the previous calculation steps.

A verification of the spectrum calculations therefore needs to focus on the following three aspects:

- Validation of the data used to describe the traffic volumes (market data);
- Validation of the methods and algorithms used. This requires both the analysis of the selected methods as well as an analysis of the implementation
- Validation of the parameter sets used to describe the network capabilities and technical model behaviour.

The focus of the technical analysis summarised in section 0 has been set on the two latter aspects while the validity of the input marked data is discussed in section 2.4.

As a result of the analysis we have found that the model performs as would be expected. Changes of input parameters will result in the expected changes of the calculated spectrum requirements.

During analysis of the speculator tool some issues with technical parameters settings as recommended by ITU-R M.2290 have been identified. These issues are summarised in the table below, a more detailed discussion of the listed issues is found in section A.3:

| Area | Comment | Impact on Spectrum Demand |
|---|---|---|
| Area spectral efficiency | The recommended area spectral efficiencies are higher than found for existing and projected systems | Modification to lower area spectral efficiencies will increase the resulting spectrum demand calculations. |
| Cell Areas | The recommended cell areas for macro cells are at the lower end of typical areas found in current deployments. In particular, cell coverage areas for rural environments are much smaller than expected. | Modification to larger cell areas will increase the resulting spectrum demand calculations for the radio environment that is affected by the modified cells. This can also increase the total spectrum demands if the affected radio environment becomes the one with the highest spectrum requirements. |
| Traffic Distribution / Offloading | The used assignment of mobility ratio to Service categories tends to distribute traffic to higher mobility classes. Therefore the amount of traffic that could be offloaded will be reduced. | A modification of mobility requirements a lower mobility values for several SC would decrease the spectrum requirements as more traffic would be offloaded to RATG 3. |

| Area | Comment | Impact on Spectrum Demand |
|---|---|---|
| Distribution of traffic to circuit switched data and packet switched data; related QoS parameter | In the recommended settings all conversational and streaming services are delivered via circuit switched services. This is not an accurate reflection of current and future networks, where streaming services are assumed to be mainly based on packet switched services. The used QoS parameter (blocking probability and allowed packet delay) are more demanding than typically used. | The use of packet switched data for a wider range of services, and an increase of maximum allowed blocking probability and allowed packed delays could decrease spectrum requirements. |
| Application data rates and mean service bit rates | Application data rates for picocells and hotspots are set to 1 Gbps to be able to accommodate the high mean service bit rates defined for some service categories.<br>This could result in an overestimate of spectrum requirements for other SC if small traffic volumes will be carried by a radio environment with extremely high application bitrates. | Reduction of application data rates and extremely high mean service bit rates to smaller values could decrease spectrum requirements. |
| Minimum deployment per operator and carrier bandwidth | The figures used for minimum deployment per operator and carrier bandwidth are partly larger than expected. | Modification to lower values would result in a slight decrease of spectrum demand |
| Multicast video | Implementation of unicast services is somewhat inconsistent. The origin for market input data for multicast traffic is not very clear. | Proper adjustment of market input data to consider multicast demand could decrease unicast traffic and thus result in decreased overall spectrum requirements. |

**Table A-1: Areas where issues with parameter settings have been identified.**

It is obvious that a model to calculate spectrum requirements needs to make some simplifications to reduce the complexity of the calculations. Thus the accuracy of the outcome of the model could be improved by adding more level of detail for the input parameter and modelling assumptions. Several improvements that have for example also suggested by Real Wireless in the final report on their study on the future UK spectrum demand for terrestrial mobile broadband applications[61] are addressing such issues. But independent from this, the general methodology can be considered to be correct and thus it is essential that the used input parameters are correct to receive realistic spectrum demands.

## A.2 Model analysis

To analyse if the Speculator tool is line with the functional specifications given in ITU-R M.1968-1 and with general wireless communication and capacity calculation principles a variation of parameter sets

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[61] Study on the future UK spectrum demand for terrestrial mobile broadband applications, Section 5.5, Final Report Real Wireless, Version 3.0, 27 June 2013,

has been used. For this different tests have been performed where the input parameter have been selected in a way, that by specific variation of a subset of the input parameters an expected variation of the calculated spectrum results could be observed. The bandwidth requirements and their variations found in the ongoing sections are therefore not necessarily based on realistic input assumptions.

### A.2.1 Market Related Parameters

The Speculator tool uses market related parameters to define the input traffic volumes for the spectrum calculations. Basic input is the user density in user per sq km, while additional parameter like mean values for service Bitrate and session duration are used to express the traffic generated per user. In total four parameters can be individually defined for each combination of service category (SC) and service environment (SE):

- User Density
- Mean Session Duration
- Mean Service Bitrate
- Session arrival Rate

In addition to the above factors to define the input traffic volume a mobility factor is used to describe up to which maximum speed the services will be used. The mobility ratio can be assigned per SC.

#### *A.2.1.1 User Density*

The user density parameter defines the user concentration per sq km for each combination of service category (SC) and service environment (SE). The final user density of a specific SC is than the sum over all user densities of each service environment mapped to the service category. Speculator allows the definition of a minimum and maximum value for user densities, then the actual value used for the calculations is determined based on a user set parameter U which ranges from 0% to 100%. With a setting of 0% for U the minimum value for user densities will be used; a setting of 100% corresponds to the maximum user density.

Thus the expected model behaviour is that increasing the user density by increasing parameter U% will result in increased spectrum demands. **Table A-2** shows the results of variation of the user density by modifying parameter U:

| User Density Factor U[%] | Teledensity | Spectrum Requirement / MHz | | | |
|---|---|---|---|---|---|
| | | Macro | Micro | Pico | Hot Spot |
| 10 | Dense Urban | 99.35 | 33.99 | 52.45 | 33.21 |
| | Sub Urban | 98.29 | 27.66 | 8.66 | 3.91 |
| | Rural | 75.93 | 0 | 5.70 | 3.90 |
| 25 | Dense Urban | 105.27 | 70.72 | 54.43 | 33.44 |
| | Sub Urban | 119.04 | 41.43 | 9.73 | 3.92 |
| | Rural | 80.88 | 0 | 5.70 | 3.90 |
| 46 | Dense Urban | 112.69 | 119.70 | 56.11 | 33.57 |
| | Sub Urban | 145.77 | 60.24 | 12.12 | 3.96 |
| | Rural | 87.70 | 0 | 5.70 | 3.90 |

**Table A-2: Spectrum requirement in dependence of user density factor U**

It has been found that the model behaves as expected, since increasing the user density leads to an increase of the spectrum requirements in the different cell layers.

### *A.2.1.2 Mean session Duration*

The mean session duration is used to define the average time period in seconds during which resources on the radio interface are used by an individual user session. The parameter can be defined for each combination of service category (SC) and service environment (SE), the average session duration for a specific category is than computed as weighted average of average session durations over all services mapped to this service category. The weight is the session arrival rate per area.

Like for user densities Speculator allows to define a minimum and maximum value for the mean session duration. The actual value used for the calculations is determined based on a user set parameter Q which ranges from 0% to 100%. With a setting of 0% for Q the minimum value for mean session duration will be used; a setting of 100% corresponds to the maximum defined means session duration.

It would be expected that an increase of the mean session duration will result in increased bandwidth requirements as an individual session will require more resources of the radio interface. Table A-3 shows the results of a variation of the mean session duration by modifying parameter Q:

| Mean Session Duration Factor Q [%] | Teledensity | Spectrum Requirement / MHz | | | |
|---|---|---|---|---|---|
| | | Macro | Micro | Pico | Hot Spot |
| 10 | Dense Urban | 99.35 | 33.99 | 52.45 | 33.21 |
| | Sub Urban | 98.29 | 27.66 | 8.66 | 3.91 |
| | Rural | 75.93 | 0 | 5.70 | 3.90 |
| 25 | Dense Urban | 103.28 | 44.78 | 53.26 | 33.38 |
| | Sub Urban | 107.38 | 33.96 | 9.06 | 3.92 |
| | Rural | 79.25 | 0 | 5.70 | 3.90 |
| 40 | Dense Urban | 106.86 | 55.04 | 53.61 | 33.41 |
| | Sub Urban | 116.58 | 40.31 | 9.44 | 3.92 |
| | Rural | 83.04 | 0 | 5.70 | 3.90 |

**Table A-3: Spectrum requirement in dependence of Mean Session Duration Factor Q**

It has been found that the model behaves as expected, since increasing the user density is leading to an increase of the spectrum requirements in the different cell layers.

### *A.2.1.3 Mean Service Bitrate*

The mean service bitrate defines the required throughput for a user session in bits per second and can be defined for each combination of service category (SC) and service environment (SE). The final mean service bit rate for a certain service category is the weighted average of the mean service bit rates of each service environment mapped to this service category. The weight is the traffic volume (sum of the average durations of all sessions that arrive during a unit time) per area.

Speculator allows the definition of a minimum and maximum value for the mean session duration. The actual value used for the calculations is determined based on a user set parameter R which ranges from 0% to 100%. With a setting of 0% for R the minimum value for mean service bitrate will be used; a setting of 100% corresponds to the maximum defined mean service bitrate.

It would be expected that increasing the mean service bitrate will result in an increase of the spectrum requirements. Table A-4 shows the results of a variation of the mean session duration by modifying parameter R:

| Mean Service Bitrate Factor R [%] | Teledensity | Spectrum Requirement / MHz | | | |
|---|---|---|---|---|---|
| | | Macro | Micro | Pico | Hot Spot |
| 10 | Dense Urban | 99.35 | 33.99 | 52.45 | 33.21 |
| | Sub Urban | 98.29 | 27.66 | 8.66 | 3.91 |
| | Rural | 75.93 | 0 | 5.70 | 3.90 |
| 25 | Dense Urban | 103.77 | 56.27 | 112.78 | 74.34 |
| | Sub Urban | 113.12 | 36.69 | 11.12 | 4.46 |
| | Rural | 79.82 | 0 | 6.51 | 4.45 |
| 40 | Dense Urban | 108.26 | 78.51 | 173.10 | 115.47 |
| | Sub Urban | 127.90 | 45.74 | 13.57 | 5.02 |
| | Rural | 83.66 | 0 | 7.31 | 5.01 |

**Table A-4: Spectrum requirement in dependence of Mean Service Bitrate Factor R**

It has been found that the model behaves as expected, since increasing the mean service bitrate leads to an increase of the spectrum requirements in the different cell layers.

### *A.2.1.4 Session Arrival Rate*

The session arrival rate defines how many sessions are initiated per user per second. It can be defined for each combination of service category (SC) and service environment (SE) Final session arrival rates for a specific service category is the weighted average of session arrival rate per user of each service mapped to this service category. The used weighting factor is the user density.

Speculator allows the definition of a minimum and maximum value for the session arrival rate. The actual value used for the calculations is determined based on a user set parameter µ which ranges from 0% to 100%. With a setting of 0% for µ the minimum value for session arrival rate will be used; a setting of 100% corresponds to the maximum defined session arrival rate.

It would be expected that increasing the session arrival rate will result in an increase of the spectrum requirements as the number of sessions and thus the required resources at the radio interface increases. Table A-5 shows the results of a variation of the session arrival rate by modifying parameter µ:

| Session Arrival Rate Factor µ[%] | Teledensity | Spectrum Requirement / MHz | | | |
|---|---|---|---|---|---|
| | | Macro | Micro | Pico | Hot Spot |
| 10 | Dense Urban | 99.35 | 33.99 | 52.45 | 33.21 |
| | Sub Urban | 98.29 | 27.66 | 8.66 | 3.91 |
| | Rural | 75.93 | 0 | 5.70 | 3.90 |
| 25 | Dense Urban | 102.61 | 51.62 | 53.51 | 33.40 |
| | Sub Urban | 101.68 | 31.17 | 8.69 | 3.91 |
| | Rural | 79.31 | 0 | 5.70 | 3.90 |
| 40 | Dense Urban | 105.48 | 68.92 | 54.23 | 33.43 |
| | Sub Urban | 107.05 | 33.74 | 8.73 | 3.91 |
| | Rural | 83.22 | 0 | 5.70 | 3.90 |

**Table A-5: Spectrum requirement in dependence of Session Arrival Rate Factor µ**

It has been found that the model behaves as expected, since increasing the session arrival rate is leading to an increase of the spectrum requirements in the different cell layers.

### *A.2.1.5 Mobility Ratio*

The mobility ratio is used to define up to which maximum user speed a specific service will be used. The mobility ratio can be assigned per SC; three different categories are available. Mobility Ratio 1 corresponds to stationary/pedestrian mobility up to 4 km/h, Mobility Ratio 2 describes a velocity range from 4 km/h to 50 km/h, while Mobility Ratio 3 is used for speeds above 50 km/h.

During spectrum calculations the mobility ratio defined for a given SC is compared against the capability of specific Service Environment. Traffic will only be distributed to a service environment if the environment supports the required mobility.

With the given settings in Speculator only macro cells can support all three mobility ratios, micro cells support ratios 1 and 2, while pico cells and hotspots only support mobility ratio 1. This makes sense due to handover limitations in networks with small cells which limit support to lower velocity users.

To test if the traffic distribution based on mobility ratio definitions is implemented properly a variation of the mobility ratio can be used while the parameter settings for different cell types are set to same (hypothetical) value.

In this case it would be expected that an increase of the mobility ratio will result in a shift of traffic from smaller cells like pico and micro cells to macro cells thus increasing macro cell spectrum requirement and reducing pico and micro cell spectrum requirements.

Table A-6 shows the result of the variation:

| Mobility Ratio | Spectrum Requirement / MHz | | | |
|---|---|---|---|---|
| | Macro | Micro | Hot Spot | Total |
| 1 | 5.96 | 1.77 | 6.55 | 14.28 |
| 2 | 6.26 | 1.69 | 6.33 | 14.28 |
| 3 | 11.70 | 0.66 | 2.06 | 14.42 |

**Table A-6: Spectrum Requirement per cell type in MHz for different mobility ratios**

It has been found that the model behaves generally as would be expected, since increasing the mobility ratio results in an increase of the spectrum requirements for macro cells, while the spectrum requirements in the other cells are decreased. It is interesting, however, to note that the total requirement remains largely unchanged. Given the higher spectrum efficiency which the model gives to hot spots compared to macro cells, it might be expected that with a lower mobility ratio, the total spectrum requirement should fall.

## A.2.2 Radio Related Parameters

Speculator uses a set of parameter to define the capabilities of the assumed radio technologies. These definitions are mainly done per RATG. The following RATG specific parameters are used:

- Maximum supported velocity
- Application data rate
- Area spectral efficiency
- Sector Area
- Support for multicast
- Number of overlapping network deployments
- Minimum deployment per operator per radio environment

In addition to the above listed parameters a global parameter is used to define guard band between operators:

- Guard band between operators

### *A.2.2.1 Maximum supported velocity*

The parameter maximum supported velocity is used to define the maximum speed of mobile users for that a cell can support radio services. Thus the parameter can be defined per RATG and Service environment. The parameter settings are used during traffic distribution to to split the traffic of each service category to the available radio environments. For this the mobility ratio definition of the service categories is compared against the capabilities of the radio environments. The correct functionality of this parameter set has been tested in combination with the parameter “mobility ratio” in section A.2.1.5.

### *A.2.2.2 Application data rate*

The parameter application data rate is used to define the maximum supported data rate of a radio technology and service environment. Thus the parameter can be defined per RATG and SE. The parameter is used during the distribution of traffic to radio environments and RATGs. The mean service bit rate requirement of each service category is compared against the application data rate of the RATG in the given radio environment to determine whether the given service category can be supported or not.

It is expected, that higher application data rates result in higher spectrum requirements as more traffic will be distributed to a specific service environment.

Table A-7 shows the results of a simulation with two different sets for the application data rate in RATG 1 and RATG 2. Data rates in Set 2 have been twice as high as in Set1:

| | Teledensity | Set 1 | | | | Set 2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Macro | Micro | Pico | Hot Spot | Macro | Micro | Pico | Hot Spot |
| RATG 1 | Dense Urban | 93.39 | 294.60 | 30.44 | 15.78 | 292.75 | 194.60 | 30.44 | 15.78 |
| | Sub Urban | 83.67 | 160.49 | 15.56 | 9.17 | 329.18 | 80.49 | 15.56 | 9.17 |
| | Rural | 24.55 | 0.00 | 69.15 | 9.14 | 219.69 | 0.00 | 9.15 | 9.14 |
| RATG 2 | Dense Urban | 363.62 | 1172.06 | 63.50 | 13.02 | 362.81 | 1179.90 | 222.75 | 120.71 |
| | Sub Urban | 574.45 | 361.11 | 20.31 | 6.27 | 548.71 | 361.11 | 32.41 | 6.39 |
| | Rural | 327.09 | 0.00 | 7.35 | 5.01 | 306.96 | 0.00 | 7.35 | 5.01 |

**Table A-7: Application data rate influence on speculator results**

It has been found that Speculator behaves as expected.

### *A.2.2.3 Area spectral efficiency*

The area spectral efficiency is used to define how efficiently a RATG can use its available spectrum in terms of the data rate per bandwidth per cell. It is expressed in bit/s/Hz/cell and is used to transform capacity requirements into unadjusted spectrum requirements by dividing the capacity requirement per cell by the corresponding spectral efficiency.

Spectral efficiency generally reflects spectrum requirements in a linear way. By increasing the spectral efficiency with a constant factor a reciprocally proportional behaviour for the required spectrum should be found.

To test the linear behaviour of Speculator two parameter sets have been used where only the spectral efficiency is varied by a factor of 2. Table A-8 shows the results of this analysis:

| | Macro cell | | | Micro cell | | | Pico cell | | |
|---|---|---|---|---|---|---|---|---|---|
| | Dense Urban | Sub-urban | Rural | Dense Urban | Sub-urban | Rural | Dense Urban | Sub-urban | Rural |
| Spectral efficiency set 1 | 568.52 | 1097.04 | 471.39 | 2393.89 | 1528.78 | N.A. | 982.57 | 836.70 | 321.65 |
| Spectral efficiency set 2 | 284.26 | 548.52 | 235.69 | 1196.9 | 764.39 | N.A. | 491.29 | 418.35 | 160.82 |
| Decrease in Bandwidth requirement | 50 % | 50 % | 50 % | 50 % | 50 % | N.A. | 50% | 50 % | 50 % |

**Table A-8: Bandwidth requirements in dependence of area spectral efficiency**

Please note that in the given example the selected SC and SE combination does not support micro cells in rural teledensities. It has been found that Speculator behaves as expected, since an increase of the spectral efficiency by a factor of 2 decreases the spectrum requirements by 50%.

### *A.2.2.4 Sector Area*

Sector area is the parameter that defines the area in sqkm from which a cell collects traffic. The sector area can be separately defined for any combination of service environment (macro cell, micro cell, pico cell and hot spot) and teledensities (examples being dense urban, suburban and rural). Yet it is not possible to define different values for different RATGs.

The traffic collected by a specific cell type is based on the number of users per sector area that are calculated by multiplying the sector area with the user density. Thus at the first instance a linear increase of traffic volume with sector areas should be found. However this linear increase of traffic volume will not be reflected in a linear increase of spectrum requirements. Reason for this effect is the used QoS model. The QoS model determines the required system capacity as multiples of channel data rates. With increasing channel numbers the system capacity increases above average due to the trunking effect. Therefore a less than proportional increase of spectrum requirements should be found in the model.

To analyze the behaviour of Speculator in this respect, simulations with two parameter sets have been done. The cell areas in Set 2 have been twice as high as in Set 1. **Table A-9** gives the results of that analysis:

| Environment | Macro cell | | | Micro cell | | | Pico cell | | |
|---|---|---|---|---|---|---|---|---|---|
| | Dense Urban | Suburban | Rural | Dense Urban | Suburban | Rural | Dense Urban | Suburban | Rural |
| Spectral efficiency set 1 | 14785.03 | 2292.93 | 283.02 | 10558.89 | 1501.99 | N.A. | 693.62 | 424.31 | 161.43 |
| Spectral efficiency set 2 | 28320.79 | 3985.11 | 362.96 | 20034.58 | 2471.77 | N.A. | 951.14 | 442.12 | 162.11 |
| Increase in Bandwidth requirement | 91.6% | 73.8% | 28.2% | 89.7% | 64.6% | N.A. | 37.1% | 4.2% | 0.4% |

**Table A-9: Spectrum requirements in dependence of cell sizes**

Please note that in the given example the selected SC and SE combination does not support micro cells in rural teledensities. It has been found that Speculator behaves as expected.

### *A.2.2.5 Support for multicast*

The parameter “Support for multicast” defines whether a given RATG can or cannot provide multicast transmission, i.e. is capable to transmit the same traffic content via a shared channel to multiple users simultaneously. Depending on the setting of the parameter bandwidth requirements for multicast transmission are calculated or not.

An individual set of market parameters and area spectral efficiencies for multicast transmissions is used. The switching functionality was analysed to identify if multicast spectrum requirements are calculated additionally or not.

Table A-10 gives the results of a simulation for macro cells with and without multicast enabled.

| | RATG 1 | | | RATG 2 | | |
|---|---|---|---|---|---|---|
| | Dense Urban | Sub Urban | Rural | Dense Urban | Sub Urban | Rural |
| w/o Multicast | 89.43 | 166.49 | 99.00 | 272.45 | 476.39 | 253.32 |
| with Multicast | 292.74 | 329.18 | 219.69 | 362.81 | 548.70 | 306.96 |
| Increase in Bandwidth requirement | 227% | 98% | 122% | 33% | 15% | 21% |

**Table A-10: Multicast spectrum requirements in MHz**

It has been found that Speculator behaves as expected and the spectrum requirements increase if multicast traffic is considered.

### A.2.2.6 Number of overlapping network deployments

The parameter “Number of overlapping network deployments” allows the definition of the number of different operators within the same RATG. These networks are operated by different operators that do not share the same spectrum, thus this parameter is used to adjust spectrum requirements. If the number of overlapping network deployments is equal to one, no adjustments are made. When there are multiple overlapping network deployments, the raw spectrum requirement is first divided among the different network deployments. Adjustments are then applied in the form of minimum deployment per operator per radio environment and guard bands between operators and the spectrum requirements are aggregated over the overlapping network deployments. Correct implementation has been verified in combination with parameters “Minimum deployment per operator per radio environment” and “Guard band between operators” as detailed in sections A.2.2.7 and A.2.2.8.

### A.2.2.7 Minimum deployment per operator per radio environment

The parameter “Minimum deployment per operator per radio environment” is used to adjust the raw spectrum requirements resulting from the capacity calculations. The parameter gives the minimum amount of spectrum needed by an operator to build a viable network. The parameter can be separately defined for each combination of RATG technology and radio environment.

The adjustment is achieved by taking the maximum value from the raw spectrum requirements and the minimum required bandwidth for deployment.

Table A-11 gives the results of a simulation with a minimum deployment per Operator of 20 MHz.

| Cell Type | Unadjusted Spectrum Requirement / MHz | Adjusted Spectrum Requirement / MHz |
|---|---|---|
| Macro | 2.3 | 20 |
| Micro | 0 | 0 |
| Pico | 0.46 | 20 |
| Hot Spot | 1.012 | 20 |

**Table A-11: Unadjusted and adjusted spectrum requirements for a single SC and Se combination**

Table A-12 gives the results of a simulation with a minimum deployment per Operator of 20 MHz and a granularity factor of 20 MHz.

| Cell Type | Unadjusted Spectrum Requirement / MHz | Adjusted Spectrum Requirement / MHz |
|---|---|---|
| Macro | 292.75 | 300.00 |
| Micro | 194.60 | 200.00 |
| Pico | 30.44 | 40.00 |
| Hot Spot | 15.78 | 20.00 |

**Table A-12: Unadjusted and adjusted spectrum requirements for different cell types**

It has been found that Speculator behaves as expected.

### *A.2.2.8 Guard band between operators*

The parameter “Guard band between operators” is used consider the excess bandwidth that needs to be left between the bands of two operators to avoid interference. If the number of overlapping network deployments is equal to one, no guard bands are required and the raw spectrum requirement will not be adjusted. If the number n of network deployments is greater than one, than (n-1)-times the guard band is added to the raw spectrum requirement.

**Table A-13** below shows an example where RATG 1 is served by a micro cell layer with a minimum deployment per operator of 20 MHz and RATG 2 is served by pico cell layer with a minimum deployment per operator of 120 MHz and a guard band of 10 MHz between operators.

| | Required Spectrum [MHz] | | | | |
|---|---|---|---|---|---|
| # of Network Deployments | 1 | 2 | Difference | 3 | Difference |
| RATG 1 | 20 | 50 | 10 | 80 | 20 |
| RATG 2 | 120 | 250 | 10 | 380 | 20 |

**Table A-13: Guard band influence to spectrum calculation**

It has been found that the adjustments for guard bands are applied as expected.

## A.2.3 QoS Parameter

The Speculator tool uses a set of model specific parameter to define the QoS requirements for circuit and packet switched data. These parameter are:

- Allowed blocking probability
- Maximum allowable mean IP packet delay

The parameter “Allowed blocking rate” is used for circuit switched data, while the other parameters are used for packet switched data.

The parameter sets can be defined per service category.

### *A.2.3.1 Maximum allowable blocking probability*

The maximum allowable blocking probability parameter is used to define the quality of service for reservation or circuit switched based service categories. It is used to calculate the required cell capacity from the traffic volume collected by the cell. A multi-dimensional Erlang-B blocking model is used to determine the minimum number of traffic channels that allows the given cell traffic to be carried without exceeding the allowable blocking probability.

It is expected that for constant traffic volume the calculated bandwidth requirements decreases with increasing blocking probability as less channel resources are required to carry the traffic. **Table A-15** gives the results for simulations where the blocking probability has been varied:

| | | Macro | | | Micro | | | Pico | | | Hot Spot | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Blocking Rate | | 0.01 | 0.02 | 0.05 | 0.01 | 0.02 | 0.05 | 0.01 | 0.02 | 0.05 | 0.01 | 0.02 | 0.05 |
| RATG 1 | Dense Urban | 40.89 | 37.59 | 33.13 | 42.24 | 39.39 | 35.10 | 10.80 | 9.88 | 8.72 | 6.96 | 6.96 | 5.93 |
| | Suburban | 56.15 | 49.43 | 42.44 | 26.17 | 24.56 | 21.08 | 6.96 | 6.96 | 3.74 | 3.48 | 3.48 | 3.48 |
| | Rural | 34.97 | 29.88 | 27.93 | 0.00 | 0.00 | 0.00 | 3.48 | 3.48 | 3.48 | 3.48 | 3.48 | 3.48 |
| RATG 2 | Dense Urban | 99.29 | 94.77 | 87.58 | 189.22 | 182.03 | 170.20 | 99.48 | 97.80 | 95.72 | 60.67 | 60.51 | 59.31 |
| | Suburban | 127.42 | 120.45 | 109.76 | 93.50 | 88.11 | 79.74 | 8.36 | 8.35 | 5.64 | 1.96 | 1.91 | 1.91 |
| | Rural | 61.30 | 57.25 | 50.88 | 0.00 | 0.00 | 0.00 | 2.79 | 2.78 | 2.78 | 1.91 | 1.91 | 1.91 |

**Table A-14: Spectrum requirements in MHz for different blocking rates**

It has been found that with increasing blocking probability the spectrum requirements decreases and thus Speculator behaves as expected.

### *A.2.3.2 Maximum allowable mean IP packet delay*

The parameter “mean packet delay” is used to define the minimum required QoS for packet-switched service categories. It is used to calculate the required cell capacity from the traffic volume collected by the cell. A queuing block model is used determine the minimum number of traffic channels that allows to carry the given traffic without exceeding the allowable mean packet delay.

It would be expected that for constant traffic volume the calculated bandwidth requirements decreases with increasing allowable mean packet delay, as less channel resources are required to carry the traffic. **Table A-15** gives the results for simulations where two sets for the allowable mean IP packet delay has been used. The first set was based on the proposed standard values, for the second set the allowed packet delays has been doubled:

| | Macro cell | | | Micro cell | | | Pico cell | | | Hot Spot | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dense Urban | Sub-urban | Rural | Dense Urban | Sub-urban | Rural | Dense Urban | Sub-urban | Rural | Dense Urban | Sub-urban | Rural |
| Max IP packet delay set 1 | 0.08 | 30.05 | 34.71 | 92.86 | 85.52 | N.A. | 82.37 | 78.46 | 35.35 | 76.08 | 75.45 | 35.35 |
| Max IP packet delay set 2 | 0.04 | 15.52 | 19.65 | 69.71 | 48.18 | N.A. | 44.76 | 40.80 | 17.68 | 38.37 | 37.74 | 17.67 |
| Increase in Bandwidth requirement | 2.00 | 1.94 | 1.77 | 1.33 | 1.78 | N.A. | 1.84 | 1.92 | 2.00 | 1.98 | 2.00 | 2.00 |

**Table A-15: Influence of maximum allowable mean IP packet delays to spectrum requirements**

Please note that in the given example the selected SC and SE combination does not support micro cells in rural teledensities. It has been found that with increasing mean packet delay the spectrum requirements decreases and thus Speculator behaves as expected.

## A.2.4 Distribution Parameter

The speculator tool uses two types of parameter that are directly related to the way how traffic is distributed to the different RATG. These parameter are

- Traffic Distribution Ratio
- Population coverage percentage

Aside from these parameters, the parameters "mobility ratio", "maximum supported velocity", "Application data rate" and "mean service bitrate" are also used in the distribution process. The impact of these parameters has already been discussed in the above sections.

### *A.2.4.1 Traffic Distribution Ratio among available RATGs*

Speculator allows definition of the traffic distribution ratios among available RATGS in a distribution matrix, where the distribution ratio gives the percentage of traffic that might be distributed to a corresponding RATG. Yet it is important to note that during the traffic distribution process not necessarily the entire percentage of traffic as defined in the distribution matrix will be distributed to the corresponding RATG as additional constraints are considered. Limiting constraints are the maximum supported velocity and maximum available application data rate of the RATG for a given Radio Environment, thus the distribution ratio defines the maximum possible fraction of traffic that will be distributed to a RATG in best case.

The functionality of traffic distributing ratio has been tested by variation of the distribution ratio for RATG 3. It would be expected that an increasing distribution ratio for RATG 3 will result in a decreasing spectrum requirement as spectrum demand for RATG 3 is not included (offloading).

Table A-16 gives the results for the simulation:

| Cell Type | Pico cell | | | Hot Spot | | |
|---|---|---|---|---|---|---|
| Distribution Factor for RATG 3 | 0% | 50% | 100% | 0% | 50% | 100% |
| Spectrum Requirement / MHz | | | | | | |
| Dense Urban | 167.40 | 147.82 | 99.71 | 144.06 | 141.35 | 99.55 |
| Sub Urban | 87.26 | 84.41 | 39.21 | 80.14 | 77.84 | 35.51 |
| Rural | 37.63 | 37.60 | 35.35 | 37.60 | 37.60 | 0.00 |

**Table A-16: Traffic offloading to RATG 3 for pico cells and hot spots**

It has been found that with increasing distribution ratio for RATG 3 the spectrum requirements decreases as expected. It has also been found that the spectrum requirements do not become zero even if a distribution ratio of 100% for RATG 3 is used. This is because the additional limitations (such as mobility ratio) still apply and therefore not all traffic will be distributed to RATG 3.

### *A.2.4.2 Population coverage percentage*

The population coverage percentage parameter is used in the traffic distribution part of the methodology where the traffic is distributed to different radio environments and RATGs. The population coverage percentage denotes the ratio of the population that is in the service area of a given radio environment in a given service environment. It puts a limit to the fraction of traffic that can be distributed to a given radio environment.

## A.3 Issues related to parameter sets

### A.3.1 Area spectral efficiency

The ITU methodology uses area spectral efficiencies to determine which data volume can be carried by a technology in a given amount of spectrum. Spectral efficiencies are defined per RATG and cell type.

An accurate estimation of the areal spectral efficiency is difficult because it depends on various assumptions including site density, number of cells per site location and specific antenna configurations (like antenna heights in relation to buildings etc.) Also other factors such as intra-cell interference, cell load and overhead for signalling have an impact on the area spectral efficiency: therefore figures given in literature show a wide range of variation. Table 6-1 provides a comparison of the different spectral efficiencies defined by ITU-R M.2209, proposed by the study of Real Wireless for Ofcom, WINNER[62] model parameters and figures derived for UMTS and LTE by Holma and Toskala[63].

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[62] Spectrum Requirements for System beyond IMT-2000, IST-4-027756 WINNER II, D 5.10.2 v1.0, page 25, 2007

[63] Harri Holma and Antti Toskala: LTE for UMTS, Evolution to LTE-Advanced, Second Edition. John Wiley & Sons, Ltd., pp. 286 - 287, 2011

| Direction [UL / DL] | Air Interface | Spectral Efficiency [bit/s/Hz/cell] | | | |
|---|---|---|---|---|---|
| | | ITU-R M.2290 | Real Wireless | WINNER | Holma / Toskala |
| DL | RATG 1 (2G, 3G) | 2 ... 4 | 1.48 … 2.66 | 0.2 | 0.55 |
| UL | RATG 1 (2G, 3G) | 2 ... 4 | 1.48 … 2.66 | 0.2 | 0.33 |
| DL | RATG 2 (4G) | 4 ... 7.3 | 3.15 … 7.28 | 3 | 1.75 |
| UL | RATG 2 (4G) | 4 ... 7.3 | 3.15 … 7.28 | 3 | 0.75 |

**Table A-17: Comparison of spectral efficiencies for macro cells in dense urban environment**

From the above it is clear that the standard values for spectrum efficiency used in the Speculator model are optimistically high. Comparisons of HSDPA Release 6 and LTE Release 8 show an average increase of downlink efficiency from 0.55 bps/Hz/cell for HSPA (included in RATG 1) to 1.75 bps/Hz/cell for LTE (included in RATG 2) (Holma/Toskala). Thus the lowest figures for RATG 1 assumed by ITU for 2010 are even higher than those achieved in LTE Release 8 which belongs to RATG 2. The figures given by Holma/Toskala are given for a 10 MHz system bandwidth; with increasing system bandwidth a slight increase in the spectral efficiency is found, but this effect will not allow the achievement of the figures as used by the ITU. The Winner study gives even smaller spectral efficiencies for RATG 1 than Holma/Toskala. It is also important to note that uplink and downlink efficiencies are different from each other with even smaller values for uplink than for downlink (0.33 for HSUPA and 0.75 for LTE) while ITU assumes the same values for uplink and downlink. With 1 x 2 maximum ratio combining for HSPA Release 6 and 2 x 2 MIMO transmissions for LTE Release 8 the figures given by Holma/Toskala already include advanced technologies to improve data throughput in the networks.

The fact that the used spectrum efficiency values are higher than the ones found in realistic networks is also commented by the ITU; Report ITU-R M2290 includes the following Note[64]:

> *NOTE – The spectrum efficiency values in Tables A.12 and A.13 are to be used only for spectrum requirement estimation by Recommendation ITU-R M.1768. These values are based on a full buffer traffic model in accordance with Report ITU-R M.2135. They are combined with the values of many other parameters within the Recommendation ITU-R M.1768 methodology to develop spectrum requirement estimate for IMT. In practice, such spectrum efficiency values are unlikely to be achieved due to the random nature of traffic, errors caused by radio channel conditions or packet losses. Furthermore, stochastic 'file transfer' simulation models show that actual spectral efficiency values are lower than the values shown in Tables A.12 and A.13 above, depending on inter-site distance.*

Report ITU-R M.2135 does not give any figures for spectral efficiencies but refers to Report ITU-R M.2134 for a definition of cell spectral efficiencies and minimum requirements for IMT Advanced radio interfaces. Table A-18 repeats the corresponding figures:

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[64] Page 40, REPORT ITU-R M.2290-0 "Future spectrum Requirements estimate for terrestrial IMT", 13 January 2014,

| Environment | Spectral Efficiency [bit/s/Hz/cell] | |
|---|---|---|
| | Downlink | Uplink |
| Indoor | 3 | 2.25 |
| Micro cellular | 2.6 | 1.8 |
| Base coverage urban | 2.2 | 1.4 |
| High speed | 1.1 | 0.7 |

**Table A-18: Cell spectral efficiencies, minimum requirements for IMT Advanced systems, Table 1 page 4, ITU-R M2134**

A direct comparison of figures given in Table A-18 with those given in Table 6.1 is not possible as the used environments are different. But it seems reasonable that the minimum spectral efficiencies given in ITU-R M.2134 for “base coverage urban” should be comparable to the figures given for “macro cells in dense urban area”.  It has been found that the figures used in ITU-R M.2290 are, also in this case, much higher than the ones defined in ITU-R M.2134.

A decrease of areal spectral efficiencies will increase the spectrum requirements, a modification of the values proposed by ITU in ITU-R M.2209 to more realistic lower values would therefore increase the spectrum requirements calculated by the Speculator tool.

### A.3.2 Cell Areas

The cell areas in a network deployment have a significant impact on the spectrum requirements. On the one hand cell area and spectral efficiency are depending on each other, the smaller the cells the larger the spectral efficiency tends to be.  On the other hand increases the amount of traffic that is collected by a specific cell with the cell size thus resulting in higher bandwidth requirements.

The ITU model uses the explicit definition of cell areas to compute the traffic per cell from user densities given per sqkm.  Cell areas can be defined for each combination of radio environment (i.e. cell type like macro cell, micro cell, pico cell and hotspot) and teledensities (i.e. dense urban, suburban and rural). Yet it is assumed that all RATGs have the same cell sizes. It is also important to note that the Speculator model does not allow the definition of different cell areas for different frequencies, thus the inserted cell areas need to be either determined for one selected frequency or need to be calculated as average over different frequencies. Table A-19 compares the cell areas in sqkm as recommended by ITU in Report M.2290 and cell areas found from different other sources:

| **Teledensity** | **Radio Environment** | **Cell Area [km$^2$]** | | | | |
|---|---|---|---|---|---|---|
| | | **ITU-R M.2290** | **ITU-R M.1768-1** | **RealWireless** | **WINNER[65]** | **Holma / Toskala [66].** |
| Macro Cell | Dense Urban | 0.10 | 0.65 | 0.07 | 0.65 | 1.13 ... 6.15 |
| | Suburban | 0.15 | 1.5 | 0.25 | 0.65 | 7 ... 36.3 |
| | Rural | 0.87 | 8 | 11.57 | 1.5 | 36.3 ... 75.4 |
| Micro cell | Dense Urban | 0.07 | 0.1 | 0.05 | 0.10 | - |
| | Suburban | 0.10 | 0.1 | 0.10 | 0.1 | - |
| | Rural | 0.15 | 0.1 | 0.15 | 0.1 | - |
| Pico Cell | Dense Urban | 0.0016 | 0.0016 | 0.0016 | 0.0016 | - |
| | Suburban | | | | | |
| | Rural | | | | | |
| Hot Spot | Dense Urban | 0.000065 | 0.0016 | 0.000065 | 0.000065 | - |
| | Suburban | | | | | |
| | Rural | | | | | |

**Table A-19: Cell areas for different radio environment and Teledensity combinations**

It is important to note, that the figures in Table A-19 have been derived for different frequencies. Figures in ITU-R M.2290 are given for frequencies around 6 GHz, figures from Winner are for 5 GHz while the RealWireless' figures are based on "the mix of spectrum available in the UK today". Holma and Toskala calculated their figures for frequencies below 1 GHz. The figures have also been derived for different types of applications. Figures from ITU-R M.2290, Real Wireless and Holma and Toskala are including indoor penetration loss, while figures from ITU-R M.1768-1 and Winner are without penetration loss.

Cell areas in sqkm are not very illustrative; therefore the figures given for macro and micro cells have in Table A-19 have been converted to inter site distances assuming a hexagonal cell layout with three cells per site. Inter site distances for pico cells and hot spots have not been calculated as these cell types are typically not used to provide continuous area coverage and thus inter site distances and cell areas are not directly related to each other:

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[65] Spectrum Requirements for System beyond IMT-2000, IST-4-027756 WINNER II, D 5.10.2 v1.0, page 22 and 32, 2007

[66] Harri Holma and Antti Toskala: LTE for UMTS, Evolution to LTE-Advanced, Second Edition. John Wiley & Sons, Ltd., pp. 265 - 270,2011

| Tele-density | Radio Environment | Inter Site Distance / km | | | | | |
|---|---|---|---|---|---|---|---|
| | | ITU-R M.2290 | ITU-R M.1768-1 | Real Wireless | WINNER[67] | Holma / Toskala low | Holma / Toskala high |
| Macro Cell | Dense Urban | 0.589 | 1.501 | 0.492 | 1.501 | 1.795 | 4.162 |
| | Suburban | 0.721 | 2.280 | 0.931 | 1.501 | 4.162 | 10.194 |
| | Rural | 1.736 | 5.264 | 6.331 | 2.280 | 10.194 | 14.655 |
| Micro Cell | Dense Urban | 0.492 | 0.589 | 0.416 | 0.589 | | |
| | Suburban | 0.589 | 0.589 | 0.589 | 0.589 | | |
| | Rural | 0.721 | 0.589 | 0.721 | 0.589 | | |

**Table A-20: Inter Site distances computed for macro and micro cell network from cell areas as given in Table A-19**

A comparison of the values shows, that the figures for macro cells proposed by ITU-R M.2290 tend to the lower end of cell areas and therefore small inter site distances. Only for dense urban areas a smaller figure is found from the Real Wireless Report which assumes that in dense urban areas approx all 500 m a cell site will be deployed. For all other radio environments ITU-R M.2290 gives the smallest figure. The inter site distance of 0.6 km for macro cells in dense urban areas and distances of 0.8 km of capacity limited networks for larger suburban areas seem to be in an realistic range. Yet the inter site distance of 1.7 km for rural areas appears to be too small.

Increasing inter-site distances and thus cell areas will increase the bandwidth requirement for the corresponding cell layers. A modification of cell areas recommended in ITU-R M.2290 to larger values could therefore increase estimated spectrum demand.

### A.3.3 Traffic distribution to different RATG / Traffic Offloading

A basic principle in the ITU spectrum estimation methodology is the distribution of the total input traffic volume to four different RATGs. Traffic distributed to RATG 1 and RATG 2 are considered during spectrum calculations while for RATG 3 and RATG 4 no spectrum requirements are computed. Thus traffic distributed to these RATGs is offloaded traffic where RATG 3 is used for unicast traffic while RATG 4 represents offloaded multicast traffic.

Speculator allows the user to define the percentage of traffic that might be offloaded by means of a distribution matrix. Table A-21 gives the distribution matrix for year 2020 as recommended in ITU-R M.2290:

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[67] Spectrum Requirements for systems beyond IMT-2000, IST-4-027756 WINNER II, D 5.10.2 v1.0, page 22 and 32, 2007

| RATG Available | Distribution ratio (%) | | |
|---|---|---|---|
| | RATG 1 | RATG 2 | RATG 3 |
| 1 | 100 | – | – |
| 2 | | 100 | |
| 3 | – | – | 100 |
| 1, 2 | 10 | 90 | - |
| 1, 3 | 10 | – | 90 |
| 2,3 | - | 50 | 50 |
| 1,2,3 | 10 | 50 | 40 |

**Table A-21: Distribution ratios among available RAT groups in 2020**

At the first instant Table A-21 implies that, depending of available RATGs, between 40% and 90% of traffic is offloaded to Radio LANs and thus traffic offered tor RATG 1 and RATG 2 is considerably decreased by offloading

Yet it is important to note that during the traffic distribution process not necessarily the entire percentage of traffic as defined in the distribution matrix will be distributed to the corresponding RATG as additional constraints are considered. Limiting constraints are the maximum supported velocity and maximum available application data rate of the RATG for a given Radio Environment. From that perspective the distribution ratio is the maximum possible fraction of traffic that could be offloaded in best case.

Table A-22 gives the limiting radio parameter for RATG 3 (Radio LAN):

| Parameter | Macro cell | Micro Cell | Pico cell | Hot Spot |
|---|---|---|---|---|
| Application Data Rate | – | – | 50 | 500 |
| Supported mobility classes | – | – | Stationary/ pedestrian | Stationary/ pedestrian |

**Table A-22: Radio parameters for RATG 3 (ITU R.M2290)**

The table shows that RATG 3 can only provide service to users with low mobility (Stationary and pedestrian users) which is in line with the limitations of current Radio LAN technology, thus only traffic that is generated at low mobility will be offloaded to RATG 3 during spectrum estimations.

Within the ITU methodology three different mobility classes are used: Stationary/pedestrian mobility (SM), Low mobility (LM) and high mobility (HM). During traffic distribution the total traffic for any SC / SE combination is split to the three different mobility classes. The fraction of traffic that is assigned to each of the mobility classes is computed based on market parameters, a mobility ratio factor and a traffic weighting methodology. The mobility ratio can be defined per service category while the used market parameters are predefined and hard coded and cannot be modified by the user.

The mobility ratio can take values 1, 2 or 3. Using a mobility ratio of 1 for a service category will result in a traffic distribution where a higher fraction of traffic will be split to mobility class SM while using mobility factor 2 or 3 will result in traffic distribution where more traffic will be split to classes LM and HM and thus reduces the portion of traffic that will be offloaded.

Mobility factors for different service categories are defined in Table A2 and Table A3 of ITU-R M.2290. It has been found that only for SC11, which represents interactive super high multimedia traffic, a mobility factor of 1 is used. All other SCs have mobility factor 2 assigned. Thus the major part of applications is assumed to be used during motion and thus offloading to RAG3 is limited. However, as there is no specific offloading factor in the model, it becomes very difficult to predict how changes of mobility factors are reflected in the outcome of the spectrum calculations. This is also noted by ITU[68]:

*"The Recommendation ITU-R M.1768-1 methodology did not include a specific parameter or model that would easily allow considerations of the influence of the offloading effect. Table 24c corresponds to cases where several RATGs are supported in the same radio environment for a given service category and indicates how the traffic is split in those circumstances.*

*In the case that RATGs 1, 2 and 3 are all available and if distribution ratio to RATG 3 decreases (while distribution ratio to RATG 2 increases), then traffic demands of RATG 2 in the Picocell and Hot spot would increase significantly. For example, when distribution ratio to RATG 3 decreases from 40% to 10% (less mobile offloading to RLAN) and RATG 2 distribution ratio would be 80% then traffic in Pico cell and Hot spot would increase by about 40-60 %. As a single input parameter, a change in the traffic distribution ratios when RATGs 1, 2 and 3 are available will not necessarily have an impact on overall spectrum requirements."*

Yet it can be assumed that a modification of mobility requirements as defined in ITU R.M2290 to lower mobility values for several SC would decrease the spectrum requirements as more traffic would be offloaded to RATG 3.

### A.3.4 Distribution of traffic to circuit switched data and packet switched data

Speculator allows to define per SC whether the traffic inside a category is using circuit switched or packet switched transmission. According to the standard settings in Speculator all conversational and streaming services are delivered via circuit switched networks, which is in our opinion not an accurate reflection of current and future networks, where streaming services are assumed to be mainly based on packet switched networks which tend to be more spectrum efficient.

The QoS parameter for circuit switched traffic is the maximum allowed blocking probability. ITU uses a standard setting of 1 % for all service categories. This value is, according to our experience, at the lower end of blocking probabilities used by network operators that tend to use blocking probabilities in a range of 2% to 3%, sometimes even higher figures of up to 5% are accepted in bandwidth limited environments.

The QoS parameter for packet switched traffic is the maximum allowable mean packet delay. The standard model settings are using very low tolerable delays of 20ms for all service categories.

Figures for typical packet delay budgets in mobile networks are for example given in 3GPP Specification 3GPP TS 23.203[69]. Table A-23 gives some excerpts from table 6.1.7 of the 3GPP

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[68] Footnote to Table A15, Annex 1, Page 20, ITU-R. M2290

[69] 3GPP TS 23.203 "3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Policy and charging control architecture (Release 10); 2012-03

document. As recommended by 3GPP the figures have been reduced by 20 ms to achieve values for the radio interface:

| Service Example | Packet delay budget for Radio Interface |
|---|---|
| Real Time Gaming | 30 ms |
| Voice<br>Video (Live Streaming)<br>Interactive Gaming | 80 ms |
| Video (Buffered Streaming)<br>TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.) | 280 ms |

**Table A-23: Typical packet delay budgets for radio interface (based on 3GPP TS 23.203)**

Comparing figures given in Table A-23 with the standard value of 20 ms used by ITU it has been found that the model settings are using very low tolerable delays which can result in high spectrum demands for specific packet switched services like file transfer, browsing and messaging.

In summary it has been found that the used assignment of SC to circuit- or packet- switched transmission data in combination with the used QoS parameter will tend to increase the spectrum requirements. A modification of the parameter sets to a higher fraction of packet switched services and reduced QoS requirements should therefore result in a reduced overall spectrum requirement.

### A.3.5 Application rates

Two different categories of data rate definitions are found inside the ITU-R methodology. One category is the definition of maximum data rates that are supported by the different radio technologies. This definition is done for each combination of radio environment (cell type) and RATG. The following table shows the figures for RATG 1 to RATG 3 as used in ITU-R M.2290:

| | Application Data Rate in MBit/s | | | |
|---|---|---|---|---|
| | Macro cell | Micro cell | Pico cell | Hot spot |
| RATG 1 | 20 | 40 | 40 | 40 |
| RATG 2 | 50 | 100 | 1000 | 1000 |
| RATG 3 | – | – | 50 | 500 |

**Table A-24: Definition of Application Data Rate for different RATG (based on ITU-R M.2290)**

From ITU-R M.1968-1 it is not clear if this parameter presents average, maximum or cell edge throughputs, however ITU-R M.2074 states that this parameter represents a bit rate that *"… may be smaller than the available peak bit rate and may not be available throughout the whole cell*". In the light of this definition and considering the methodology of the spectrum calculations it seems reasonable that average values for this figure should be used. From that perspective it has been found that the application data rates for Pico Cell and Hot Spot for RATG 2 and hot spot for RATG 3 tend to be high and are very likely rather peak data rates than average data rates.

The other category where data rates are used is in the market input data where mean service bitrates for any combination of SC and SE are defined. Here a range of values from 6 kbps to 1 Gbps for both uplink and downlink is found. During the calculations these figures are adjusted by a correction factor. With the current settings used in ITU-R 2290 data set maximum average data rates of 418 kbit/s in downlink and 500 kbit/s in uplink are found. Also this data rates seem to be rather high.

During the traffic distribution process mean service bitrates are compared against the application data rates. Traffic for a specific SC/SE combination will be only distributed to a radio environment of a specific RATG if the application data rate of that RE is the same or larger than the mean service bitrate of the considered SC/SE environment. From this perspective it seems to be logical that at least one SE has the same application data rate as the maximum mean service bit rate as otherwise the predicted traffic could not be carried.

To estimate the fraction of total traffic volume that requires high application data rates an analysis of the market input data for 2020 has been done. Figure A-1 gives the results of this analysis.

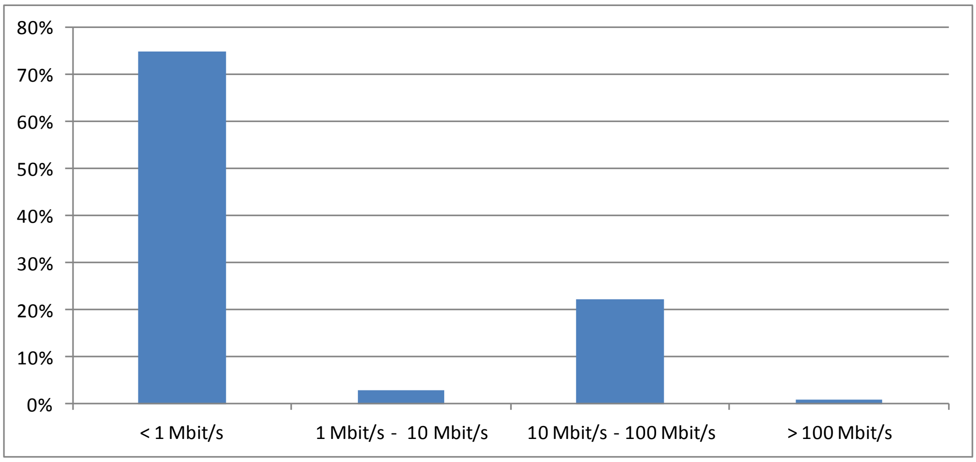

**Figure A-1: Fraction of total traffic volume requiring a specific service bit rate**

It has been found that only a very small fraction of less than 0.1 % requires service bit rates of more than 100 Mbit/s. Thus the very high settings of 1Gbps for application data rates are only required to carry a very small fraction of the input traffic. For these applications the spectrum demand will be determined correctly as the high application data rates are really necessary.

Yet, the required capacity for circuit switched data is determined in multiples of the application data rate defined for that RE. This could result in an overestimate of spectrum requirements if in a specific combination of input traffic and available RE a small traffic volume need to be carried by a RE with a high application data rate.

### A.3.6 Minimum deployment per operator and carrier bandwidth

The final spectrum requirements are adjusted to consider minimum required bandwidth per operator and required carrier bandwidth (spectrum granularity).

The minimum deployment per operator per radio environment parameter sets the minimum spectrum allocation that an operator needs to deploy a network of a particular radio access technology. This parameter varies with RATG and cell type in the model. The standard value for this parameter is 20 MHz in all cell types for RATG 1 and macro and microcell for RATG 2. The used minimum requirement for Pico cells and hotspots is 120 MHz. The settings for macro and microcells align with the maximum supported bandwidth for LTE networks. But LTE networks can be (and are being) deployed also in 5 MHz and 10 MHz blocks. Thus this setting could result in a slightly increased spectrum requirement in cases where the spectrum demand per operator is below the minimum deployment figure due to traffic volume.

The parameter “carrier bandwidth” is used to consider that radio technologies operate with fixed carrier bandwidths and thus spectrum as multiples of the carrier bandwidth is required. Therefore spectrum requirement are always given as multiples of the carrier bandwidth.

In model Version 2.26 the parameter setting for minimum deployment per operator has been used for this purpose. This could result in increased spectrum demands as the minimum deployment per operator is typically several times the carrier bandwidth. In Version 2.5 this problem has been fixed and an individual parameter set for spectrum granularity is available that models the “carrier bandwidth in an appropriate way”. The recommended setting from ITU is 20 MHz for all radio environments and RATG. This setting can result in a slightly increases bandwidth requirement, especially for RATG 1 that includes systems that have carrier bandwidth that are smaller than 20 MHz.

### A.3.7 Multicast video

The advantage of multicast transmission is that several users are sharing the same downlink channel to access the same media program. Therefore multicast could be an appropriate transmission media for video transmissions, where several users in the same cell area are watching the same video. Possible scenarios are for example large sport events where mobile networks are used to broadcast additional information and video clips to the spectators of the event. In this case multicast video could allow reducing bandwidth requirements as all users would use the same channel while in unicast each user would use his/her own dedicated transmission channel.

Multicast services can be implemented in to different ways. One possibility is to operate the shared transmission channel for multicast in the same bandwidth as used by unicast users. In this case both unicast and multicast transmission compete which each other for channel resources. Another possibility is to use dedicates spectrum for multicast services. This is for example the LTE version of MBMS (eMBMS), which has been standardised in various groups of 3GPP as part of LTE release 9. eMBMS supports broadcast only services and is based on a Single Frequency Network (SFN) and supports the same flexibility of channelization as LTE.

A key property of multicast services is that the spectrum demand of multicast transmission is independent of the user numbers and only depends on the transmitted content. This property is considered in the methodology of Speculator. At the first instant Speculator uses the same input methodology for unicast and multicast traffic, the input tables for market data shows also values for user densities. However the calculation of traffic volumes is only based on session arrival rates figures and the corresponding user density figures that are included in the spreadsheet are not used.

ITU-R M.1768-1 gives only very few information on how multicast traffic is handled, some more information is found from the description as provided by the winner project[70]. According to the WINNER document, multicast traffic is modelled as circuit switched service where capacity requirements are calculated independently from unicast services. This corresponds to a network implementation that uses individual spectrum like it is the case for eMBMS. Also the calculation uses

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[70] IST-4-027756 WINNER II, D 5.10.2 v1.0, Spectrum Requirements for System beyond IMT-2000

individual spectral efficiencies for multicast. Yet the same blocking probabilities like for unicast are used.

Speculator does not provide many means that allow to modify multicast calculations. The only way to affect the output is to modify the market input parameter for unicast. Like for unicast these parameter are based on ITU-R M. 2072. It is interesting to note that the corresponding tables in ITU-R M.2072 are named “Traffic data which are clearly described as downlink multicast” which implies that the market data for unicast might include traffic that could be carried in multicast mode. This could result in an overall reduced spectrum requirement if this traffic could be shifted from unicast to multicast mode.