Report
for Ofcom
4G Capacity Gains
Final Report - Appendices

Issued to: Ofcom
Issue Date: 27th January 2011

Version: 1.4

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About Real Wireless

Real Wireless is a leading independent wireless consultancy, based in the U.K. and working internationally for enterprises, vendors, operators and regulators – indeed any organization which is serious about getting the best from wireless to the benefit of their business. We seek to demystify wireless and help our customers get the best from it, by understanding their business needs and using our deep knowledge of wireless to create an effective wireless strategy, implementation plan and management process. We are experts in radio propagation, international spectrum regulation, wireless infrastructures, and much more besides. We have experience working at senior levels in vendors, operators, regulators and academia.

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

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Ofcom Disclaimer
This paper has been prepared by Real Wireless on behalf of Ofcom’s Technology Team to provide a forward looking, high level view of the evolution of mobile networks over the next 10 years. Its purpose is to generate a free and frank debate, to complement the critical testing of our policies. It represents the views of Real Wireless. It does not purport to set out an Ofcom policy position.
Appendix A  Additional spectral efficiency results

The following section is to be read in conjunction with Chapter 5 and provides additional results that are of interest to the study but do not contribute directly to the final spectral efficiency value due to the specific nature of each feature. For example the introduction of OFDM by LTE and WiMAX is not a sole contributor to spectral efficiency as there is also the consideration of higher modulation and coding schemes with AMC that demonstrates improved spectral efficiency.

Impact of the OFDM technology on spectrum efficiency

The OFDMA multiple access scheme is introduced in LTE and WiMAX\textsuperscript{39} and the spectral efficiency results shown below are not solely the difference in multiplexing but also adoption of MIMO and frequency selective scheduling. However it should be noted the spectral efficiency improvement for LTE also arises from the technology’s ability to handle the challenging and imperfect mobile environment more efficiently than previous multiple access techniques.

Impact of SIC and CQI on spectral efficiency

Successive Interference Cancellation (SIC) and Channel Quality Indicator (CQI) are features of LTE which can be optimised by vendors and operators. The results shown in the graph below compares the different combinations of SIC and CQI. It can be seen that marginal capacity gains are made by varying the combination in SIC and CQI. For example, with a higher rate CQI from 5ms to 2ms and SIC activated offers a small gain of 0.05 bps/Hz. However, when there is ideal CQI and SIC activated, there is a larger increase in the spectral efficiency.

The results were generated from a study conducted by Motorola \textsuperscript{3} whose focus concerned the performance verification to understand if the proposed LTE system designs were on track to meet the LTE system performance criteria. Also the study was conducted to understand whether any additional work needed to be done to improve the system performance further to meet the performance targets. The E-UTRA downlink performance was conducted using a full queue traffic model based on the assumptions outlined in \textsuperscript{[4]} and indicates the traffic types used.
Spectrum efficiency for different duplex modes

Figure A-3 plots the spectral efficiency results from simulations when the duplex mode was set to FDD and TDD. The increase in spectral efficiency arises from the increase in the number of antennas is apparent from in this figure and not necessarily the inclusion of CoMP.

Spectrum efficiency for different types of traffic

The type of traffic that is demanded (VoIP, video, file transfer, browsing, gaming) affects the number of users that are served concurrently by the cell. This is because the base station is required to serve all connected subscribers and distribute the resources according to the traffic demand and the scheduling algorithm. The amount of control bits that are required in the control channel is proportional to the number of users that are being served. This subsection takes into account the traffic scenario and discusses its effect on the spectral efficiency. Herein it is noted that the baseline assumption for other subsections is that the base station serves full buffer data traffic so that the number of control symbols per sub-frame L is average, i.e. L=2.

Figure A-4 plots the spectral efficiency results from simulations when the base station is requested to serve different type of traffic.
Spectrum efficiency for different bandwidths

This graph can be used in conjunction with Figure 5-2 in Chapter 5 comparing the spectrum efficiency for different bandwidths. The graph in Figure A-5 shows for two channels one 5MHz channel and one 20 MHz channel, the spectral efficiency are practically the same.

Impact of spectral efficiency across release

The particular results presented have been extracted from a Qualcomm source [2] and have been carefully derived using some adjustment so that comparisons can be made on a single graph. The simulations were conducted under the same deployment conditions. WCDMA followed by HSPA show the steady increase in spectral efficiency against each of the releases and demonstrates the evolutionary capacity performance enhancement for 3G.
The evolution of 3G enhancements is shown in Figure A-7 by showing the spectral efficiency of each HSPA configuration. There is a significant increase in spectral efficiency with each enhancement from 16QAM to 64QAM modulation and with 2x2 MIMO all within a 5 MHz carrier bandwidth demonstrates an efficient use of spectrum.

Figure A-8 compares WiMAX Release 1.5 and WiMAX Release 2 for the urban macro environment. This basic example demonstrates the improvement in spectral efficiency between releases and how WiMAX 2 offers almost a 25% increase in spectral efficiency over WiMAX 1.5.
Figure A-8 Spectral efficiency of WiMAX Release 1.5 and WiMAX Release 2, DL, FDD urban macro, Source: WiMAX Forum[6], ITU-R Document IMT ADV/4E [25]

Figure compares average spectrum efficiency for different topologies (macro, micro, indoor) for LTE and WiMAX. It is observed that a dramatic increase in spectral efficiency, more than 100%, can be achieved when deploying an indoor hotspot. The results were obtained from the ITU-R IMT-Advanced candidate Radio Interface Technologies for LTE and WiMAX[25,29].

Figure A-9 Spectral efficiency across topologies for WiMAX 2, DL, FDD, MU-MIMO, 4x2 2x20 MHz 2 GHz Sources: ITU-R Document IMT ADV/4E [25]
**Trials, simulations and stakeholder results**

The following figures show more detailed comparison of trials results versus simulations results from stakeholders.

**Figure A-10 Spectral efficiency of LTE compared to HSPA+ (Source Real Wireless stakeholder inputs [1])**

Figure A-10 shows results from HSPA + Release 7 2x2 64QAM which is on 2 carriers (10MHz), enhanced fractional DPCH for good control channel performance. The spectral efficiency value given here is high relative to preceding 3G releases (Release 5 and Release 6) due to the good implementation of fast dormancy (releasing control channels efficiency) and good Continuous Packet Connectivity implementation. The type of receive implemented also makes a difference to the spectral efficiency value produced. For example using a good type 3i receiver implementation with (rx diversity) results in cell spectral efficiency of 0.9 b/s/Hz compared to 0.72 b/s/Hz for release 6. However, the graph shows a comparison against LTE 2x2 results from simulations which shows almost 90% gain in spectrum efficiency.

**Figure A-11 Spectral efficiency of LTE 2x2 MIMO compared to HSPA (Rel 6) Source: MNO1 stakeholder [8]**

Figure A-11 shows results from LTE (FDD, 2x2) which is on 2 carriers (10MHz), enhanced fractional DPCH for good control channel performance. The spectral efficiency value given here is high relative to preceding 3G releases (Release 5 and Release 6) due to the good implementation of fast dormancy (releasing control channels efficiency) and good Continuous Packet Connectivity implementation.
The conditions used to generate the results shown in Figure A-11 were for a loaded network handling approximately 2Mbps DL / 5MHz carrier. In the LTE part of this trial the cells were in a loaded network measured roughly 20-30Mbps DL/20MHz carrier. This is based on both simulations and field trials. The set up included:

- FTP/UDP traffic.
- Typical small urban area network, 1.5km inter site distance, single frequency re-use
- Downlink only
- 2x2 Open Loop MIMO

![Figure A-12 Spectral efficiency of LTE and HSPA+ (Rel 7) Source: Stakeholder input from NEC]

The results were gathered from discussions with an infrastructure vendor and given in Figure A-12. The cell spectral efficiency for 3G HSPA+ Release 7 is 0.8 bps/Hz. The figure suggested for LTE 2x2 is 2-3x better at around 2.0 bps/Hz which seemed realistic and compared well with the recent LSTI trials results of 2.1 b/s/Hz

**Assumptions made for calculating conversion factors**

This section presents the assumptions made in arriving at the spectrum efficiency estimates across all LTE and WiMAX releases, based on the simulation results that were presented in Chapter 5. The spectrum efficiency values that are presented in this section refer to the same deployment scenario: IMT-Advanced UMa (3km/h, 2x10 MHz at 2.5 GHz, ISD=500m), full buffer, mixed traffic type (L=2).

In our endeavour to perform comparisons across releases, several assumptions about how the spectral efficiency varies with certain technology features were made, according to the variations of the spectral efficiency values that were presented in Chapter 5. The following conversion ratios were considered when synthesising the unavailable spectral efficiency values:

- Conversion between {3GPP Case 1} which is expressed in 3GPP Proposal on Candidate radio interface technology for IMT –Advanced presentation \(^{[31]}\) and IMT Urban Macro (UMa) which is expressed in 3GPP’s feasibility study of IMT-Advanced radio interface technology LTE Advanced (Release 10 and beyond) \(^{[31]}\). The factor is calculated in the following way:

\[
\text{Cell Spectral Efficiency for IMT-A UMa} = 0.78 \times \text{Cell Spectrum efficiency of 3GPP Case 1}}
\]
- Conversion between {Rake + signalling over HSPA} and {lack of these features} are based on cell spectrum efficiency from Qualcomm\(^2\), NGMN\(^10\), Connecting America: The National Broadband Plan, FCC\(^1\). The cell spectrum efficiency values are used from each source and converted in the following way:
\[ \text{\{Rake + signalling over HSPA\}} = 1.5 \times \text{\{lack of these features\}} \]

- Conversion between {16QAM} and {64QAM}. We take the cell spectrum efficiency from results with the same conditions but for different modulation schemes and converted in the following way:
\[ \text{\{64QAM\}} = 1.12 \times \text{\{16QAM\}}, \text{based on Nokia Siemens Networks} \] \(^{11}\)

- Conversion between {MIMO 4x4} and {MIMO 2x4}. We take the cell spectrum efficiency from results undertaken under the same conditions (E.g. ISD = 500m, channel conditions ITU 3km/h etc) but for different MIMO order and converted in the following way:
\[ \text{\{MIMO 8x4\}} = 1.35 \times \text{\{MIMO 4x4\}}, \text{based on} \] \(^{13}\)

- Conversion between {1x2 receiver diversity} and {MIMO 2x2}. We take the cell spectrum efficiency from results undertaken under the same conditions (E.g. ISD = 500m, channel conditions ITU 3km/h etc) but for different MIMO order and converted in the following way:
\[ \text{\{1x2 Rx diversity\}} = 0.83 \times \text{\{MIMO 2x2\}}, \text{based on} \] 3GPP R1-071991 – Motorola \(^{12}\)

- Conversion between {SISO 1x1} and {1x2 receiver diversity}. We take the cell spectrum efficiency from results undertaken under the same conditions (E.g. ISD = 500m, channel conditions ITU 3km/h etc) but for different MIMO order and converted in the following way:
\[ \text{\{SISO 1x1\}} = 0.70 \times \text{\{1x2 receiver diversity\}}, \text{based on} \] 3GPP r1-071956 Ericsson\(^{13}\)

- Conversion between {MIMO 4x2} and {MIMO 4x4}. We take the cell spectrum efficiency from results undertaken under the same conditions (E.g. ISD = 500m, channel conditions ITU 3km/h etc) but for different MIMO order and converted in the following way:
\[ \text{\{MIMO 4x4\}} = 1.37 \times \text{\{MIMO 4x2\}}, \text{based on} \] \(^{13}\)

- Conversion between {MIMO 4x2} and {MIMO 2x2}. We take the cell spectrum efficiency from results undertaken under the same conditions (E.g. ISD = 500m, channel conditions ITU 3km/h etc) but for different MIMO order and converted in the following way:
\[ \text{\{MIMO 4x2\}} = 1.35 \times \text{\{MIMO 2x2\}}, \text{based on} \] \(^{13}\)

- Conversion between {MU-MIMO} and {SU-MIMO}. We take the cell spectrum efficiency from results undertaken under the same conditions (E.g. ISD = 500m, channel conditions ITU 3km/h etc) but for different MIMO techniques and converted in the following way:
\[ \text{\{SU-MIMO\}} = 0.998 \times \text{\{MU-MIMO\}}, \text{based on} \] \(^{13}\)

- Conversion between {MU-MIMO} and {JP-CoMP}. We take the cell spectrum efficiency from results undertaken under the same conditions (E.g. ISD = 500m, channel conditions ITU 3km/h etc) but for different MIMO techniques and converted in the following way:
\[ \text{\{JP-CoMP\}} = 1.35 \times \text{\{MU-MIMO\}}, \text{based on} \] \(^{13}\)

<table>
<thead>
<tr>
<th>High-end WCDMA, adjusted for UMa</th>
<th>WCDMA Rel-99</th>
<th>HSPA Rel-5</th>
<th>HSPA Rel-6</th>
<th>HSPA+ Rel-7/8</th>
<th>LTE Rel-8</th>
<th>LTE-A Rel-10</th>
<th>Wimax Rel-1</th>
<th>Wimax Rel-1.5</th>
<th>Wimax Rel-2</th>
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<tr>
<td>WCDMA, adjusted for UMa</td>
<td>As HSPA (Rel-6), adjusted for lack of Rake + signalling over HSPA</td>
<td>Rx diversity 1x2 Case1, 15 codes, 16QAM, adjusted for 64QAM, adjusted for UMa</td>
<td>MIMO 2x2 Case1, 15 codes, 64QAM, adjusted for UMa</td>
<td>SU-MIMO 4x4 Case 1, 20MHz, adjusted for UMa</td>
<td>MIMO 4x4 JP-CoMP Case1, adjusted for 8x4, adjusted for UMa</td>
<td>Rel-1.5 SU-MIMO 4x2 UMa, adjusted for 4x4</td>
<td>Rel-2 MU-MIMO 8x2 UMa, adjusted for JP-CoMP</td>
<td></td>
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<tr>
<td>Typical expected rollout</td>
<td>WCDMA Rel-99</td>
<td>HSPA Rel-5</td>
<td>HSPA Rel-6</td>
<td>HSPA+ Rel-7/8</td>
<td>LTE Rel-8</td>
<td>LTE-A Rel-10</td>
<td>WiMAX Rel-1</td>
<td>WiMAX Rel-1.5</td>
<td>WiMAX Rel-2</td>
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<td>WCDMA, adjusted for UMa</td>
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<td>As HSPA (Rel-6), adjusted for lack of Rake + signalling over HSPA</td>
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<tr>
<td>Rx diversity 1x2 Case1, 15 codes, 16QAM, adjusted for UMa</td>
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<tr>
<td>SX-MIMO 2x2 Case1, 20MHz, adjusted for UMa</td>
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<tr>
<td>MU-MIMO 4x2 UMa</td>
<td>Rel-1. MIMO 2x2 UMa, 64QAM, adjusted for 1x2, adjusted for 16QAM</td>
<td>Rel-1.5 SU-MIMO 4x2 UMa, adjusted for 2x2</td>
<td>Rel-2 MU-MIMO 4x2 UMa</td>
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</table>

| Low-end WCDMA, adjusted for UMa |               |            |            |                |           |              |             |              |             |
| WCDMA, adjusted for UMa |               |            |            |                |           |              |             |              |             |
| As HSPA (Rel-6), adjusted for lack of Rake + signalling over HSPA |               |            |            |                |           |              |             |              |             |
| SISO 1x1 Case1, 5 codes, 16QAM, adjusted for UMa |               |            |            |                |           |              |             |              |             |
| MIMO 2x2 Case1, adjusted for SU, adjusted for UMa |               |            |            |                |           |              |             |              |             |
| SX-MIMO 2x2 UMa, 64QAM, adjusted for 1x2, adjusted for 16QAM | Rel-1.5 SU-MIMO 4x2 UMa, adjusted for 2x2 | Rel-2 MU-MIMO 4x2 UMa, adjusted for 2x2, adjusted for SU |

Table A-1 Detailed version of Table 5-7, highlighting which spectral efficiency values are directly available from references and which require synthesis from the available data
Appendix B  Impact of device mix in high demand scenarios on cell spectrum efficiency

As part of our analysis of high demand scenarios discussed in chapter 7, we considered the impact of a different device mix in some of the scenarios on the cell spectrum efficiency. For example, in the example scenario of a block of flats or student halls of residence we would expect the majority of users to be fixed indoor users with the opportunity to use larger form factor terminal devices with potentially more antennas and support for higher orders of MIMO. To investigate this effect the weightings shown in Table B-1 were applied to the baseline terminal device market mix applied in producing the roadmap of cell spectrum efficiency for our baseline urban macrocell environment in section 6. The result is shown in Figure B-2 and shows that the impact of device mix is minimal. We therefore have not considered the impact of device mix on cell spectrum efficiency further in our high demand scenarios in chapter 7.

<table>
<thead>
<tr>
<th>Device type</th>
<th>Weighting factor for high demand scenario relative to dense urban scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature phone</td>
<td>1</td>
</tr>
<tr>
<td>Smartphone</td>
<td>1</td>
</tr>
<tr>
<td>Laptop / Netbook</td>
<td>2</td>
</tr>
<tr>
<td>iPad</td>
<td>2</td>
</tr>
<tr>
<td>Dongles</td>
<td>2</td>
</tr>
<tr>
<td>Entry level phones</td>
<td>1</td>
</tr>
<tr>
<td>Other M2M</td>
<td>1</td>
</tr>
</tbody>
</table>

Table B-1: Weighting of device mix to allow for example scenario of a block of flats or student halls of residence

![Figure B-1: Cell spectrum efficiency over time for a dense urban environment](image-url)
Figure B-2: Cell spectrum efficiency over time for example scenario of a block of flats or student halls of residence
Appendix C  What is 4G?

This chapter highlights the meaning of the term “4G” as used within this project by defining the key technologies which form the “4G” group which are the subject of this project. In particular it includes a description of the main activities involved in defining 4G technologies within the International Telecommunications Union (ITU) under the IMT-Advanced banner, the work of the Third-Generation Partnership Project (3GPP) towards LTE-Advanced and the work of IEEE in defining the standards for IEEE 802.16m, best known as WiMAX. It also collates the targets and claims for spectral efficiency associated with those technologies under various conditions.

C.1 Introduction

There is no absolute definition of the difference between “4G” and “3G” technologies. Within the industry, 4G is taken to be the next generation of mobile technology which will increase user data rates and system capacity, but unlike previous generations there is also a focus on reducing cost, both for initial deployments and for ongoing network operations, recognising that most operators will need to run 4G networks alongside both 3G and 2G networks for many years to come. However, there is no clear dividing line between the technology generations and this confusion is exacerbated by the terms 3.5G or 3.9G which are often used to describe evolutions of 3G technology such as HSPA+, LTE (3GPP Release 8) or WiMAX Release 1.5.

The standards organisations involved in developing the next generation mobile networks avoid using the term 4G and concentrate on defining the technology path. For example 3GPP technology originates from the GSM standard and the evolutionary path leads to LTE-Advanced via LTE. The IEEE WiMAX standards originate from 802.16d\(^1\) via 802.16e\(^2\) to 802.16m\(^3\), which is the latest standard to meet the IMT-Advanced requirements.

The closest the industry has to a formal definition of 4G is the ITU’s requirements for an IMT-Advanced technology. ‘3G’ was similarly defined by their IMT-2000 requirements, where IMT stands for International Mobile Telecommunications. We therefore begin this chapter with a summary of the role of the ITU and its work on systems beyond IMT-2000 (3G) and IMT-Advanced (4G).

C.2 ITU-R IMT-Advanced Process

C.2.1 The role of ITU

The ITU is the United Nations agency for information and communications technologies. It facilitates the development and publication of the radio regulations, specific reports and recommendations for the establishment of radiocommunication services. The ITU coordinates the shared global use of the radio spectrum, promotes international cooperation in assigning satellite orbits and works to improve telecommunication infrastructure in the developing world. The ITU acts as an independent facilitator in creating the framework for new technologies in all spectrum bands.

The development of 4G falls within the category of technology development of the ITU-R and a specific group has been assigned to this work. ITU Working Party 5D (WP-5D) is responsible for the development and coordination of IMT (International Mobile Telecommunication) systems and some examples of their work includes\(^4\):

- Issuance of circular letters and addenda to interested parties
- Receipt of proposals for radio interface technologies (RITs) and sets of RITs (SRITs)
- Review to assess compliance with minimum requirements
- Consideration of evaluation results, consensus building and decision

---

\(^1\) Often known as fixed WiMAX

\(^2\) Mobile WiMAX

\(^3\) The basis for the IEEE’s IMT-Advanced candidate

\(^4\) Text developed from ITU-R \(^{18}\)
Support and assistance with development of radio interface Recommendation(s)

The aim of WP 5D is to assess and evaluate the requirements and criteria of the submissions for the candidate radio interface technologies (RITs) for IMT Advanced. The ITU-R published circular letter 5/LCCE/2 7 March 2008 to invite Member States and ITU-R sector members to submit proposals for candidate radio interface technologies for the terrestrial component of the radio interfaces of IMT Advanced and to participate in the subsequent evaluation. The procedures, processes and technology contributions are published on the IMT web page which is a ‘one stop shop’ that facilitates the development of proposals and evaluation work. The working party also helps to resolve issues and work towards consensus building and decisions relating to the candidate technologies.

C.2.2 IMT and IMT-Advanced

3G radio interface technologies are those which comply with the recommendations specified within ITU-R M-1645. The general concept of IMT-2000 was to create the framework for the future development of third generation mobile systems and systems beyond 3G focusing specifically on the radio access network and consideration for emerging relationships with other radio access networks.

At the time IMT 2000 and systems beyond IMT 2000 were being developed, the technologies that emerged included CDMA2000, UMTS FDD and TD-SCDMA (UMTS TDD) which all met the criteria set out for the evolution of third generation mobile communication systems. The IMT-2000 family now also includes GSM EDGE (Enhanced Data rates for GSM Evolution) and DECT (Digital European Cordless Telecommunications).

These systems are currently deployed widely across the world today for example, in 2009 it was reported that an estimated 330 million UMTS subscriptions had been made worldwide indicating the demand in 3G services and also the widespread deployment of UMTS networks.

The objectives of IMT 2000 consider the future development of third generation mobile systems to support new applications, services and products as user demand dictates. The specification for systems beyond IMT-2000 also included the requirements for new wireless access technology and specifically that they should support data rates of up 100 Mbps for high mobility users and up to 1Gbps for low mobility users by around 2010. These figures were seen as targets for further research and investigation and not targets to be achieved under the framework.

The relationship between IMT-2000 and IMT-Advanced was in part due to the introduction of OFDMA technology into the next generation of radio interfaces. The name IMT-Advanced was established as the new name for systems beyond IMT-2000 which also incorporated the addition of newly identified spectrum bands for use by IMT systems at WRC-07 (See section C.2.4). This inclusion of new spectrum was intended to allow for increased capacity and coverage requirements to be met by the next generation of mobile systems.

The following text was extracted from Document 5/68-E ITU-R M [IMT-REST] describing the considerations and evaluation requirements for IMT-Advanced.

"IMT-Advanced can be considered from multiple perspectives, including those of the users, manufacturers, application developers, network operators, and service and content providers as noted in § 4.2.2 of Recommendation ITU-R M.1645 [15]. Therefore, it is recognized that the technologies for IMT-Advanced can be applied in a variety of deployment scenarios, different service capabilities, and technology options. Consideration of every variation to encompass all situations is therefore not possible; nonetheless the work of the ITU-R has been to determine a representative view of IMT-Advanced deployment scenarios in accordance with the process defined in Resolution ITU-R 57 – Principles for the process of development of IMT-Advanced.

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5 ITU-R sector members are organisations other than administrative Member States that are allowed to participate in ITU sector activities with limited status and rights
6 Although this study focuses on the development of the terrestrial component of IMT-Advanced, the satellite component is also under investigation within ITU.
7 http://www.itu.int/ITU-R/go/rsg5-imt-advanced/
The intent of the requirements is to ensure that IMT-Advanced technologies are able to fulfil the objectives of IMT-Advanced and to set a specific level of performance that each proposed technology need to achieve in order to be accepted within ITU-R for IMT-Advanced. The requirements are not intended to restrict the full range of capabilities or performance that candidate technologies for IMT-Advanced might achieve, nor are they intended to describe how the IMT-Advanced technologies might perform in actual deployments under operating conditions that could be different from those presented in ITU-R Recommendations and Reports on IMT-Advanced.

Candidate technologies are evaluated against the requirements according to the criteria defined in Report ITU-R M.2135 – Requirements, evaluation criteria, and submission templates for the development of IMT-Advanced.

Key features of IMT 2000
High degree of commonality of design worldwide
Compatibility of services within IMT 2000 and with the fixed networks
High quality
Small terminal suitable for worldwide use
Capability for multimedia applications within a wide range of services and terminal
Worldwide roaming capability

Key features of IMT-Advanced
a high degree of commonality of functionality worldwide while retaining the flexibility to support a wide range of services and applications in a cost efficient manner
compatibility of services within IMT and with fixed networks
high quality mobile services
capability of interworking with other radio access systems
user equipment suitable for worldwide use
user-friendly applications, services and equipment
worldwide roaming capability
enhanced peak data rates to support advanced services and applications (100 Mbit/s for high and 1 Gbit/s for low mobility were established as targets for research)

Table C-1 Comparison of key features for IMT-2000 and IMT-Advanced
Source: ITU 15
There is clearly a close relationship between the features of IMT-2000 and IMT-Advanced due to the evolution from 3G technologies to 4G. The significant difference between the two systems is the specification of enhanced peak data rates which introduces the 1Gbps low mobility and 100 Mbps high mobility requirements for IMT-Advanced. There is also the capability of interworking with other radio access systems which was not required under IMT-2000. These additional features have led to the creation and proposal of advanced mobile technology solutions from industry.

The relationship aims to meet the ever increasing demand for the growing user requirements of wireless communication services, such as video, on-line gaming and media-rich content. In addition IMT-Advanced addresses the on-going developments of radio interface technologies that support the new capabilities of systems beyond IMT-2000.

Figure C-1 reflects the terminology in use at the time of its adoption. Resolution ITU-R 56 defines the relationship between “IMT-2000”, the future development of IMT-2000 and “systems beyond IMT-2000” which were later termed as IMT-Advanced. Through the ITU-R resolution process the term IMT-2000 encompasses enhancements and future developments. The use of the term “IMT-Advanced” should be applied to those systems, system components, and related aspects that include new radio interface(s) that support the new capabilities of Systems Beyond IMT-2000. The term “IMT” is the root name that encompasses both IMT-2000 and IMT-Advanced collectively.

Figure C-1 illustrates the capabilities of IMT-2000 and IMT-Advanced in terms of peak data rate as a function of mobility (user speed). The shape of the performance curve has led this to be known as the ‘VAN diagram’, where higher data rates are achievable at lower mobile speeds. The data rates outlined by the ‘Systems Beyond IMT-2000’ curve later became part of the IMT-Advanced requirements.

Data rates sourced from Recommendation ITU-R M.1645.
Figure C-1: Illustration of capabilities of IMT-2000 and IMT-Advanced systems (Source: ITU-R M1645\textsuperscript{15})

The development, submission, evaluation and review process of IMT Advanced is shown in Figure C-2. It outlines the main steps in the process and critical milestones to be achieved resulting in the production of a set of ITU radio interface recommendations.
The IMT Advanced evaluation and decision process is nearing completion as can be seen in the figure above. ITU-R working party 5D has held regular meetings since 2008 to complete the first 8 steps of the process. Steps 4 to 7 were completed in June 2010 with step 8 well underway and due for completion in early 2011. At time of writing this report, Working Party 5D was due to meet in October 2010 to complete Step 7 to agree the framework and characteristics of the submitted RITs and SRITs.

Below is a detailed outline of a nine step process which has been extracted from document IMT-ADV/2-E.

**Step 1 – Circular Letter to invite proposals for radio interface technologies and evaluations**
The ITU issued Circular Letter 5/LCCE/2 and its Addenda, which invited the submission of candidate RITs or SRITs addressing the terrestrial component of IMT-Advanced. The Circular Letter 5/LCCE/2 and its' Addenda also invited subsequent submission of evaluation reports on these candidate RITs or SRITs by registered evaluation groups in addition to the initial evaluation report endorsed by the proponent.

**Step 2 – Development of candidate RITs or SRITs**
In this step, the candidate terrestrial component RITs or SRITs are developed to satisfy a version of the minimum technical requirements and evaluation criteria of IMT-Advanced currently in force. An RIT needs to fulfil the minimum requirements for at least one test environment. The test environments as proposed by ITU-R report M 2135 include *Indoor, Microcellular, Macro Urban Coverage and High Speed* environments. An SRIT is defined as a number of RITs each individually fulfilling the minimum requirements for at least one test environment and complementing each other.

This can be summarised as:
- An RIT meets the minimum requirements of at least one test environment
- An RIT may meet the minimum requirements of all required test environments
- An SRIT meets the minimum requirements of more than one test environment
• An SRIT may meet the minimum requirements of all required test environments

Step 3 – Submission/reception of the RIT and SRIT proposals and acknowledgement of receipt
The proponents of RITs or SRITs include Member States, Sector Members, and Associates of ITU-R Study Group 5, or other organizations.
The submission of each candidate RIT or SRIT must include completed templates, together with any additional inputs which the proponent may consider relevant to the evaluation. Each proposal must indicate the version of the minimum technical requirements and evaluation criteria of the IMT-Advanced currently in force that it is intended for and make reference to the associated requirements.
The entity that proposes a candidate RIT or SRIT to the ITU-R (the proponent) shall include with it either an initial self-evaluation or the proponents’ endorsement of an initial evaluation submitted by another entity.
The ITU-R receives the submission of technical information on the candidate RITs and SRITs and acknowledges its receipt.9
The submissions are prepared as inputs to ITU-R Working Party 5D (WP 5D) and made available on the ITU web page for the IMT-Advanced evaluation process.22

Step 4 – Evaluation of candidate RITs or SRITs by evaluation groups
The candidate RITs or SRITs are evaluated by the independent evaluation groups. The ITU-R membership, standards organisations, and other organizations are invited to proceed with the evaluation. The evaluation groups submit their evaluation reports to the ITU-R which will be considered in the development of the ITU-R Recommendation describing the radio interface specifications.
The evaluation guidelines, including criteria and test models, are provided in draft new Report ITU-R M.[IMT.REST]23.
In this step the candidate RITs or SRITs will be assessed based evaluation methodologies developed by each independent evaluation group to complement the evaluation guidelines in draft new Report ITU-R M.[IMT.REST]. If an additional methodology is proposed then the evaluation group which proposing it should share this between the other evaluation groups and sent to the ITU-T10 for information to facilitate consideration of the evaluation results by ITU-R.
The evaluation groups are encouraged to share their findings and compare results to aid consistency of results and the process, to assist ITU-R in developing an understanding of differences in evaluation results achieved by the independent evaluation groups and to form some preliminary consensus on the evaluation results. Consensus building11 is encouraged, such as grouping and/or syntheses by proponents in order to better meet the requirements of IMT-Advanced.
The technical requirements and evaluation criteria for IMT-Advanced are subject to reviews which may introduce changes to the technical requirements and evaluation criteria for IMT-Advanced. Proponents may request evaluation against any of the existing versions of the technical requirements and evaluation criteria that are currently in force.

Step 5 – Review and coordination of outside evaluation activities
In this step ITU Working Party 5D acts as the focal point for coordination between the various evaluation groups.12 WP 5D monitors the progress of the evaluation activities, and provides appropriate responses to problems or requests for guidance to facilitate consensus building.

Step 6 – Review to assess compliance with minimum requirements

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9 Provides the confirmation to the sender that the submission was received by the BR and that the submission will be forwarded to WP5D for subsequent consideration.
10 ITU-T are the Telecommunications sector of the ITU and form part of the IMT-Advanced evaluation process for their input on the impact to other parts of the telecommunications network, such as the fixed network and backhaul.
11 Consensus building involved enabling proponents to liaise with the independent evaluation groups, thereby encouraging the refinement of standards from insights gained by the various evaluation groups.
12 A list of the evaluation groups can be found on the IMT-Advanced web page http://www.itu.int/ITU-R/index.asp?category=study-groups&rlink=rsg5-imt-advanced&lang=en
In this step WP 5D makes an assessment of the proposal as to whether it meets a version of the minimum technical requirements and evaluation criteria of the IMT-Advanced currently in force as described in draft new Report ITU-R M.[IMT.REST] as announced in Circular Letter 5/LCCE/2 and its Addenda.

In this step, RITs are assessed within one or more test environments which are described in Figure C-3. A candidate RIT qualifies if it can meet the requirements in at least one environment. The purpose of SRITs (sets of RITs) is to define complementary technologies which can cover multiple test environments. Therefore a qualifying SRIT must meet requirements in at least two of the test environments. It is possible that a single RIT/SRIT could meet requirements in all environments. Qualified RIT/SRIT will go forward for further consideration in Step 7.

![Figure C-3: Test Environments for IMT-Advanced](Source: Ericsson)

According to the decision of the proponents, earlier steps may be revisited to complement, revise, clarify and include possible consensus-building for candidate RITs or SRITs including those that initially do not fulfil the minimum requirements of IMT-Advanced.

WP 5D prepares the documents on the activities of this step and assembles the reviewed proposals and relevant documentation. WP 5D keeps the proponents informed of the status of the assessment.

The documentation produced and feedback resulting from this step helps facilitate consensus building that might take place external to the ITU-R in support of Step 7.

**Step 7 – Consideration of evaluation results, consensus building and decision**

The cut-off point for the evaluation report to the ITU-R was in June 2010, the next critical milestone in the process is when Working Party 5D decides on the framework and key characteristics of IMT-Advanced RITs and SRITs for completion by October 2010. This milestone sees the completion of the evaluation of the RITs and SRITs and the creation of a framework where an agreed set of the characteristics can be established in preparation for transfer into ITU-R recommendations.

In this step WP 5D considers the evaluation results of those RITs or SRITs that have satisfied the review process in Step 6. Consensus building is performed with the objective of achieving global harmonization and having the potential for wide industry support for the radio interfaces that are developed for IMT-Advanced. This may include grouping of RITs or modifications to RITs to create SRITs that better meet the objectives of IMT-Advanced.

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13 The evaluation report includes the evaluation of all RITs and SRITs proposed for IMT-Advanced to ensure they meet the requirements and criteria as set out in ITU-R M. 1645
An RIT or SRIT will be accepted for inclusion in the standardization phase described in Step 8 if, as the result of deliberation by ITU-R, it is determined that the RIT or SRIT meets the requirements of Resolution ITU-R 57, resolves 6 e) and f) for at least the required number of test environments. These requirements are specified in draft new Report M.[IMT. REST].

Step 8 – Development of radio interface Recommendation(s)

In this step a (set of) IMT-Advanced terrestrial component radio interface Recommendation(s) is developed within the ITU-R on the basis of the results of Step 7, sufficiently detailed to enable worldwide compatibility of operation and equipment, including roaming. This work may proceed in cooperation with relevant organizations external to ITU in order to complement the work within ITU-R, using the principles set out in Resolution ITU-R 9-3.

Step – 9 Implementation of Recommendation(s)

Although not on the official schedule this vital step in the process outlines the activities external to ITU-R which includes, the development of supplementary standards (if appropriate), equipment design and development, testing, field trials, type approval (if appropriate), development of relevant commercial aspects such as roaming agreements, manufacture and deployment of IMT-Advanced infrastructure leading to commercial service.

C.2.3 IMT-Advanced Candidates

The candidate radio interface technologies have now all been submitted to the evaluation committees and final review of each of the characteristics is due for completion in October 2010 at meeting number 9 of ITU-R Working Party 5D. The six IMT-Advanced candidates that have been submitted are published on the IMT-Advanced web page and are essentially part of two distinct technology families, notably variants of IEEE 802.16 and 3GPP Release 10 and beyond standards. A summary of each IMT-Advanced candidate is given below.

ITU Document IMT-ADV/4-E – Candidate submission from the IEEE standardisation body RIT Contribution 4 is based on IEEE – 802.16m Technology with TDD and FDD variants, supporting multiple antenna technology, interference aware scheduling, support of femtocells and self-organisation. This RIT supports interworking functionality with other radio access technologies including 802.11, GSM/EDGE, UMTS, LTE and LTE-Advanced.

ITU Document IMT-ADV/5-E – Candidate submission from Japan (ARIB) IEEE Technology RIT Contribution 5 based on IEEE 802.16m technology with TDD and FDD duplexing variants. The RIT supports multiple antenna technology, interference aware scheduling, femtocells and self-organisation as some example features.

ITU Document IMT-ADV/6-E – Candidate SRIT submission from Japan based on 3GPP Technology Contribution 6. This contribution is based on 3GPP – LTE Release 10 and beyond (LTE-Advanced) which includes both a TDD RIT and an FDD RIT component. Carrier aggregation, Coordinated Multipoint (CoMP) and relaying are included as novel techniques to enhance physical layer performance. Other techniques added to the SRIT for this candidate includes, scalable system bandwidth exceeding 20 MHz potentially up to 100 MHz, nomadic/local area and mobility solutions and automatic and autonomous network configuration and operation.

ITU Document IMT-ADV/7-E – IEEE Technology Candidate RIT submission from TTA (Telecommunications Technology Association, Korea) based on IEEE 802.16m technology Contribution 7. This RIT supports both TDD and FDD duplexing variants, multiple antenna technology such as Multi User MIMO, interference aware scheduling, support of femtocells and self-organisation. This RIT supports interworking functionality with other radio access technologies including 802.11, GSM/EDGE, UMTS, LTE and LTE-Advanced.

ITU Document IMT-ADV/8-E – 3GPP Technology Candidate SRIT from ARIB, ATIS, CCSA, ETSI, TTA and TTC, (Regional Standard Development Organisations) based on 3GPP LTE Release 10 and beyond (LTE-Advanced) Contribution 8. This candidate SRIT supports both a TDD RIT and an FDD RIT component. This candidate SRIT includes the same technology components as proposed in IMT-ADV/6E such as carrier aggregation, Coordinated Multipoint (CoMP) and relaying as the novel techniques to enhance physical layer performance.
This is due to both proponents using the same source technical report\textsuperscript{14} to define the mixture of technology components. ITU Document IMT-ADV/9-E – 3GPP Technology Candidate RIT from People’s Republic of China, based on 3GPP - TD-LTE Advanced Contribution 9\textsuperscript{90}. This based RIT is derived from the LTE-Advanced TDD standards developed in 3GPP. TDD offers some benefits such as the ability to operate in unpaired spectrum, and to asymmetrically split resources between downlink and uplink.

In the spectral efficiency charts below (Figure C-4 to Figure C-7) results are shown for both the Downlink and Uplink in TDD and FDD modes for each test environment, identified by their channel models as follows:

- InH – Indoor Channel Model
- UMi – Microcellular Channel Model
- UMa – Base Urban Coverage Channel Model
- RMa – High Speed Channel Model

Results for spectral efficiency from the technology simulations are included in the attachments of each RIT submission. For example, the spectral efficiency results for the IMT-Advanced candidate based on 3GPP technology can be found in document 3GPP TR 36.912 v9.0.0\textsuperscript{31}, 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Feasibility study for Further Advancements for EUTRA(LTE-Advanced) (Release 9).

Only submissions 4E, 5E (based on IEEE802.16e/WiMAX 2) and 6E (based on 3GPP / LTE-Advanced) are shown, since the other proposals show the same results and are based on the same technologies. Note that the cell edge spectral efficiency assumes 10 users sharing each cell and hence indicates a limiting quality level. Average spectral efficiency is taken across users throughout the cell, and therefore provides the most appropriate total capacity measure.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure_C-4}
\caption{FDD Downlink Spectral Efficiency for each IMT candidate}
\end{figure}

\textsuperscript{14} The technical report used by proponents of 3GPP technology used 3GPP TR 36.912 v 9.0.0\textsuperscript{11} for the candidate SRIT submissions which includes a number of specific technologies which are addressed in more detail in Appendix F.
Figure C-5: TDD Downlink Spectral Efficiency for each IMT Candidate

<table>
<thead>
<tr>
<th>ITU-R Req's</th>
<th>IMT-ADV \4E</th>
<th>IMT-ADV \5E</th>
<th>IMT-ADV \6E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Indoor</td>
<td>2.25</td>
<td>6.93</td>
<td>4.1</td>
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<tr>
<td>Edge Indoor</td>
<td>0.11</td>
<td>0.26</td>
<td>0.19</td>
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<tr>
<td>Avg Microcellular</td>
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<td>7.72</td>
<td>7.72</td>
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<tr>
<td>Edge Microcellular</td>
<td>0.13</td>
<td>0.14</td>
<td>0.14</td>
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<tr>
<td>Avg Urban Macro</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Edge Urban Macro</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Avg High Speed</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>Edge High Speed</td>
<td>0.03</td>
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</tbody>
</table>

Figure C-6: FDD Uplink Spectral Efficiency for each IMT Candidate

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<tr>
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<th>IMT-ADV \4E</th>
<th>IMT-ADV \5E</th>
<th>IMT-ADV \6E</th>
</tr>
</thead>
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<td>Avg Microcellular</td>
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<td>Edge Urban Macro</td>
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<td>Edge High Speed</td>
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</table>

Figure C-7: TDD Uplink Spectral Efficiency for each IMT Candidate

<table>
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<tr>
<th>ITU-R Req's</th>
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<th>IMT-ADV \5E</th>
<th>IMT-ADV \6E</th>
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</thead>
<tbody>
<tr>
<td>Avg Indoor</td>
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<tr>
<td>Edge High Speed</td>
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<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Several observations are apparent from these, which are common to all the candidates:

- All candidates claim to meet the targets, but by a bigger factor for cell average than for cell edge. The disparity between the typical (cell average) user experience and the limiting (cell edge) experience is very large, in the range 20-30 times.
- The cell average performance is best by far in indoor environments, and the ITU requirements were conservative in that environment.
- The macrocell environment – which represents the vast majority of today’s mobile networks – provides the worst performance in all cases.

C.2.4 ITU and Spectrum Requirements

The ITU identified spectrum from 400 MHz up to 3GHz (also known as ‘sweetspot’ spectrum) for third generation mobile services. It was not until 2000 that the technical specifications for the third generation mobile systems were approved and IMT-2000 was born. The spectrum requirements identified most recently by the ITU for use by IMT systems were considered at the last World Radio Conference WRC-07. The following spectrum bands including the amount of spectrum allocated can now be used by IMT-2000 and IMT-Advanced systems:

- 20 MHz of spectrum in the 450 – 470 MHz band, this spectrum is globally harmonised
- 72 MHz of spectrum in the 790-862 MHz band, this spectrum allocated in Region 1 (Europe) and parts of Region 3 (Asia)
- 108 MHz of spectrum in the 698 – 806 MHz band, this spectrum is allocated in Region 2 (Americas) and some countries in Region 3 (Asia)
- 100 MHz of spectrum in the 2,300 – 2,400 MHz band, this spectrum is globally harmonised
- 200 MHz of spectrum in the 3,400 – 3,600 MHz band, this spectrum has no global allocation, but is identified in 82 countries

In Ofcom statement “WRC-07 agenda item 1.4” it states the ITU has estimated that 1280 MHz of spectrum (including the 580 MHz identified for IMT-2000) will be required for IMT systems to be available around 2015.

It was expected by the ITU that evolution in technology such as adaptive antennas, adaptive dynamic channel assignment and spectrum sharing would all contribute to the efficient use of spectrum. It is also assumed by the ITU that major developments in mobile terminals will improve performance of next generation mobile systems. This includes the use of new components and hardware architectures, software platforms and improved user interfaces.

One of the key spectrum implications identified by the ITU is the availability of adequate spectrum to support future services. Some of the considerations which need to be addressed include:

- Traffic projections and requirements including ratio of asymmetry
- Service and application requirements
- Spectrum efficiency
- TDD and FDD schemes including duplex direction and separation
- Global roaming requirements and harmonized spectrum
- Technical solutions to facilitate global roaming
- Techniques dynamic spectrum sharing
- Sharing and compatibility analysis
- Evolution of IMT-2000 systems (i.e. IMT-Advanced)
C.3 3GPP Specifications (UMTS, HSPA, HSPA+, LTE and LTE-Advanced)

Long Term Evolution (LTE) is an evolving standard produced by the 3G Partnership Project 3GPP\textsuperscript{15} for mobile broadband networks. 3GPP asserts that it has no legal status in itself, but is an informal collection of regional standards development organisations\textsuperscript{16} (SDOs) and market representation partners (MRPs\textsuperscript{17}), with ETSI being the relevant SDO for Europe. The organisation of the 3GPP standardisation process is illustrated in Figure C-8. Strictly speaking, 3GPP produces specifications, and it is the SDOs which then publish these as standards.

![Figure C-8: The 3GPP Standardisation Process](Source: 3GPP\textsuperscript{13})

LTE is therefore part of the same family of standards as GSM and UMTS. As the name suggests, LTE and its companion core network standard SAE (System Architecture Evolution) were intended to represent an evolutionary path from existing UMTS systems, but is a major change from UMTS in its technical details. All-new equipment will be required, but a high level of support for handover to and from UMTS and GSM will be provided.

3GPP work begins with a Study Item, which investigates the feasibility of adding new features to the specifications. The study is captured in a Technical Report (TR), which outlines how the new feature(s) will be implemented and the technical specification documents that will need to be updated or created. There then follows a Work Item, which either generates changes to existing Technical Specifications (TS), or sometimes, as in the case of LTE, will result in entirely new specification documents.

Technical Specifications go through a drafting phase until they are mature enough to be frozen and go under a more formal process of “Change Control”, as defined in TR 21.900\textsuperscript{18}. Under change control, only essential corrections are permitted. The graph below illustrates change requests (CRs) per meeting associated with the core network specifications over a three year period (March 2005 - March 2008). The quantity of change requests is an indicator of the stability of a given release of the specifications, and generally reduces with time. It is therefore difficult to pinpoint the moment in time when a standard is ‘finished’, as changes can continue for some time. For example, the graph shows that Release 4 has been generating change requests for several years after being frozen\textsuperscript{19}.

Eventually, 3GPP may close a standard which means that no further changes are permitted. This may never happen however. Even the first release of UMTS, release 99, has not been closed on the grounds of the need to potentially add new frequency bands in the future for particular international markets.

\textsuperscript{15} www.3gpp.org
\textsuperscript{16} www.3gpp.org
\textsuperscript{17} Market Representation Partners of 3GPP are ARIB, ATIS, CCSA, ETSI, TTA, TTC
\textsuperscript{18} http://www.3gpp.org/ftp/specs/archive/21_series/21.900/21900-310.zip
\textsuperscript{19} http://www.3gpp.org/ftp/PCG/PCG_20/DOCS/PCG20_01r2.zip
The 3GPP work plan is continually updated, so the situation reflected in this report may change at any time. The current workplan, updated typically every 3 months, is available from 20.

### C.3.1 LTE Specifications

The requirements for LTE are set out in 3GPP TR 22.5.913, which was initiated in March 2005 (originally as TS 25.812) and was frozen in March 2006.

Requirements for next generation mobile networks are also set by a group of (mainly) operators within an industry group, the NGMN Alliance, who published a set of detailed recommendations (which are essentially requirements) in December 2006.

The first version of LTE and SAE as a whole form 3GPP release 8. The LTE 'physical layer' specification was frozen in December 2007 (specs TS 36.201, 211, 212, 213, 214). Other key specifications appeared in March 2008: TS 36.401, TS 36.300, TS 36.101, and 254). Substantial new versions continued to appear in the course of 2008. Release 8 was functionally frozen on 11th December 2008. It includes the first full release of LTE standards, including the bands, bandwidths and duplex modes of interest in the UK.

Release 9 was functionally frozen in December 2009, while some work items continued to March and June 2010. Release 9 included some additional features, particularly MBMS (Multimedia Broadcast and Multicast Service), network-based positioning, Home eNodeB (i.e. LTE femtocells) and support for the European 800 MHz band. Several areas of performance improvement in the existing LTE standards are also planned.

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21 [http://www.3gpp.org/ftp/PCG/PCG_20/DOCS/PCG20_01r2.zip](http://www.3gpp.org/ftp/PCG/PCG_20/DOCS/PCG20_01r2.zip)
22 A TS in 3GPP parlance is a normative technical standard which contains mandatory and optional elements which define compliance with the standard. 3GPP also produces TRs or technical reports which are not normative, but tend to contain the results of study items which are essentially feasibility studies or to provide useful background information to support the standard itself.
25 NGMN Alliance, “Next Generation Mobile Networks Beyond HSPA & EVDO”, December 2006,
26 Once a specification is frozen, only “essential corrections” are permitted.
C.3.2 LTE-Advanced Specifications

3GPP started work on an evolution beyond LTE, usually known as LTE-Advanced, via a workshop in November 2007\(^27\). A clearer view of the requirements and timeline for LTE was provided in a workshop in March 2008\(^28\). The requirements are defined more formally in TR 36.913\(^29\). The main requirements for LTE-A, based on 3GPP TR 36.913\(^30\), are summarised here:

- LTE requirements defined in\(^31\) are also valid for LTE-A.
- Target downlink peak data rate of 1 Gbps and an uplink peak data rate of 500 Mbps.
- Latency from idle to connected mode of less than 50 ms and from dormant to connected mode of less than 10 ms.
- Reduced user-plane latency compared with LTE (some areas for improvement are highlighted, but no numerical targets given).
- Downlink peak spectrum efficiency of 30 bps/Hz and uplink peak spectrum efficiency of 15 bps/Hz, assuming MIMO order of up to 8x8 for downlink and up to 4x4 for UL.
- Average cell spectral efficiency as shown in the table below in the operating conditions specified. Other environments (e.g. microcell, indoor and rural / high speed) are evaluated in more detail in TR 36.814\(^34\). The detail of these targets is defined in Chapter 3.

<table>
<thead>
<tr>
<th>Radio env.</th>
<th>Case 1 [bps/Hz/cell]</th>
<th>Simulation</th>
<th>CF</th>
<th>ISD</th>
<th>BW</th>
<th>PLoss</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL</td>
<td>1x2</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2x4</td>
<td>2.0</td>
<td>Cases</td>
<td>(GHz)</td>
<td>(meters)</td>
<td>(MHz)</td>
<td>(dB)</td>
</tr>
<tr>
<td>DL</td>
<td>2x2</td>
<td>2.4</td>
<td>1</td>
<td>2.0</td>
<td>500</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4x2</td>
<td>2.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4x4</td>
<td>3.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C.3.3 Mapping 3GPP features to releases and timing

The main features of the 3GPP specifications with particular relevance to network capacity are identified in\(^35\), organised by release starting from release 5, the first release in which UMTS was extended to HSPA. Figure C-10 shows the timing of when each release was frozen, noting that Release 10 is still subject to variation.

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29 http://www.3gpp.org/ftp/specs/html-info/36913.htm
31 3GPP TR 25.913: “Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)
Figure C-10: Release timing of 3GPP specifications (Source: 3GPP)
C.3.4 Commercialisation of the Standard

We used the information from the graph shown in Figure C-11 to demonstrate the timing taken in years from point of standards publication to 50 million subscribers.

This source of information was used as input to Chapter 6 to derive the roadmap of the 3G and 4G standards over our 10 year timeline, commencing from the standards release freeze date. The graph shows that on average it takes around 6 years from standards publication to 50 million subscribers and that for LTE that time frame is reduced by a year. This is due to the already large base of mobile broadband subscribers that can quickly migrate to LTE from HSPA using devices such as USB dongles that are likely to be available at launch of LTE.

Figure C-11 Mobile systems years to reach 50 million subs Informa [36]
C.4 WiMAX 2 Standardisation

C.4.1 The IEEE and WiMAX Forum

The IEEE is the standardisation body responsible for the development of fixed and mobile wireless access technologies. The IEEE family of standards for Wireless LAN, wireless MAN, wireless WAN are often known as 802 family of standards. The most notable and widely used IEEE standard is 802.11 otherwise known as Wi-Fi technology. The 802 family of standards includes a catalogue of various wireless access technologies including 802.16 whose working group is responsible for the development of fixed wireless access technologies such as WiMAX.

WiMAX technology was developed from fixed wireless access variant which adopts a point to multipoint network access configuration and as technology evolved, new radio access methods were introduced into the system profile which could be transformed into a reliable mobile communications system. The first WiMAX standard to be developed through the IEEE was IEEE 802.16d 2004, which specified wireless access for fixed services using OFDM as the multiplexing technique. The commercial aim of the technology was to offer an alternative to DSL which at the time was proving expensive to deliver due to the cost of digging up roads and wayleaves.

The next iteration of the IEEE standard emerged in 2005/2006 which was IEEE 802.16e-2005 the mobile variant of WiMAX. The Mobile WiMAX standard, when first published, contained the features and technologies of a next generation cellular communications system. The specification included features such as scalable bandwidths from 1.25 MHz to 20 MHz, orthogonal sub-channelisation, Hybrid Automatic Repeat Request (H-ARQ), inclusion of smart antenna technology such as beam forming, spatial multiplexing and space-time coding.

The WiMAX Forum is a not-for-profit industry led body that represents interested parties involved in production, development and promotion of WiMAX technology. A key role of the WiMAX Forum is to facilitate the formal equipment certification process so vendors’ products can interoperate with one another and are compliant for placement on the market. In addition the WiMAX Forum promotes the compatibility and interoperability of broadband wireless products based upon harmonised IEEE and ETSI standards. Specifically, the WiMAX Forum initiated several technical specifications to complement the IEEE 802.16 standardisation by defining minimum product interoperability requirements or system profiles to enable interworking between different vendors’ products.

Figure C-12: Mobile system technology deployment timeline up to IMT-Advanced

Source: University of Texas WNCG

The WiMAX Forum is a not-for-profit industry led body that represents interested parties involved in production, development and promotion of WiMAX technology. A key role of the WiMAX Forum is to facilitate the formal equipment certification process so vendors’ products can interoperate with one another and are compliant for placement on the market. In addition the WiMAX Forum promotes the compatibility and interoperability of broadband wireless products based upon harmonised IEEE and ETSI standards. Specifically, the WiMAX Forum initiated several technical specifications to complement the IEEE 802.16 standardisation by defining minimum product interoperability requirements or system profiles to enable interworking between different vendors’ products.
Similar to other technology focused forums the WiMAX Forum promotes the technology through structured training programs and regular global events such as the WiMAX Forum global congress. The IEEE and the WiMAX Forum are complimentary organisations and both contribute to the wholesale development of WiMAX technology. The WiMAX Forum, however, is independent of the specific technology proponents and supports any Wireless MAN/LAN/WAN standard that is proposed therefore, the WiMAX Forum also supports ETSI’s HiperMAN standard which is equivalent to the IEEE 802.16 family of standards but proposed from the European standardisation body.

C.4.2 WiMAX IEEE standards development

The broadband wireless access standard most adopted by WiMAX companies is the IEEE 802.16 family of standards. The popularity of this standard has been borne from feature rich (OFDMA), flat IP architecture that has been adopted in parallel with the timing of growth in demand for broadband services. The timeline in the diagram below outlines the progress of the proposed early WiMAX standards IEEE 802.16d-2004 and 802.16e-2005. It can be seen that Mobile WiMAX (802.16e) Release 1 was completed in 2006 with deployments emerging in late 2006 and early 2007. By 2008/9 Mobile WiMAX deployment growth had reached around 400 worldwide mainly in African and Asian-Pacific Markets.

The Release 1 system profile includes the mandatory features such as OFDMA, smart antennas and beamforming and also requires some of the optional features needed for enhanced mobility and QoS support. The Release 1.5 includes the FDD variant to enable use by operators with duplex spectrum and features that enhance MAC efficiency to enable technology competitiveness and align the system profile with advanced network services for interoperability with other advanced networks such as those from 3GPP. The commencement of the development of Release 2 (IEEE 802.16m) standard started with the creation of the systems requirements document in early 2007. The process follows a sequence of milestones to achieve a proposal ready for submission to the IMT-Advanced process as the candidate radio interface technology. The diagram below provides an overview of the 802.16m standards development process coinciding with the submission to ITU as an IMT-Advanced proposal.

Figure C-13: Timeline for development of IEEE 802.16 family of standards Source: Intel

The Release 1 system profile includes the mandatory features such as OFDMA, smart antennas and beamforming and also requires some of the optional features needed for enhanced mobility and QoS support. The Release 1.5 includes the FDD variant to enable use by operators with duplex spectrum and features that enhance MAC efficiency to enable technology competitiveness and align the system profile with advanced network services for interoperability with other advanced networks such as those from 3GPP. The commencement of the development of Release 2 (IEEE 802.16m) standard started with the creation of the systems requirements document in early 2007. The process follows a sequence of milestones to achieve a proposal ready for submission to the IMT-Advanced process as the candidate radio interface technology. The diagram below provides an overview of the 802.16m standards development process coinciding with the submission to ITU as an IMT-Advanced proposal.
The development of IEEE 802.16m standard was due for completion in March 2010 to coincide with the candidate RIT submission to the IMT-Advanced process for evaluation by the ITU. However, the standard has not been finalised and there is ongoing development within the 802.16 Task Group m. Minor amendments continue to be made to the standard with the aim of finalising and approval at the end of 2010 early 2011. The WiMAX Forum has indicated that early technology trials will be taking place by mid-2011 and the first set of product certifications to be made around December 2011. It is anticipated that early commercial availability of Release 2 equipment will be in mid-2012 with wider commercial availability with rich terminal offerings in 2013.

The WiMAX ecosystem established a set of procedures to support the implementation of each standard release, this included the amendment of the system profile for certification and interoperability coordinated by the WiMAX Forum. It is suggested there is a ‘wider’ gap in features between Release 1/1.5 and Release 2 and the WiMAX Forum has published a paper outlining the migration strategy from WiMAX Release 1 to WiMAX Release 2 which focuses on:

- The backwards compatibility of WiMAX Release 2 equipment to support all WiMAX Release 1 equipment
- The additional engineering developments required to upgrade existing Release 1 networks
- Support of Release 1 Terminals
- Transition phases
- Migration scenarios

This useful guide is aimed to support network operators with their transition from WiMAX Release 1 to Release 2 with minimal disruption and cost to their existing deployments.

C.4.3 Key features of WiMAX Releases 1/1.5 and 2

The distinction between the key features of WiMAX release 1 and release 2 is clearly shown in the table below. The differences in the features offered by Release 2 demonstrate the focus on achieving IMT-Advanced status and compliance with all the necessary requirements. In turn, the advancement of Release 2 over Release 1 shows the development has been built on an established legacy of technology rich features, such as multiple antennas, frequency selective scheduling etc.
Key features of Mobile WiMAX Rel 1/1.5 (IEEE 802.16e)
Orthogonal sub-channelisation
Supports multiple antennas MIMO
Time Division Duplex (TDD) Frequency Division Duplex (FDD) 5/10 MHz channels
Multicast and Broadcast service (MBS)
Frequency Selective Scheduling
Fractional Frequency Reuse
HARQ

Key features of WiMAX Rel 2 (IEEE 802.16 m)
Unified Single User/Multi User MIMO
Multi-Carrier support – Carrier aggregation
Multi-Hop Relay Enabled
Support of Femtocells and Self Organising Networks
Enhanced MBS
Co-existence with other RATs
Advanced interference mitigation
Advanced Location Based Services Support
FDD and TDD variants supported
1.25/3/5/10/15/20 MHz channels

Table C-2 Key features comparison table of IEEE 802.16e (Mobile WiMAX) and IEEE 802.16m (WiMAX Release 2)
Source: ITU

NB All Release 1 equipment is intended to be compatible with Release 2 equipment with no degradation in service and vice versa

The advanced features included in Release 2 aims to enhance spectrum efficiency, latency, and scalability of the access technology to wider bandwidths in multiple spectrum bands. One of the main objectives of WiMAX Release 2 is to ensure compliance with the requirements of IMT-Advanced and an indication of this can be seen in the table below\(^{32}\). It shows the spectral efficiencies, in a low user mobility scenario, against the various parameter configuration categories as specified by the IMT-Advanced requirements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Antenna Configuration</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak DL Spectral Efficiency</td>
<td>(2x2) MIMO</td>
<td>8.5 bps/Hz</td>
</tr>
<tr>
<td></td>
<td>(4x4) MIMO</td>
<td>17.0 bps/Hz</td>
</tr>
<tr>
<td>Average DL Spectral Efficiency</td>
<td>(4x2) MIMO</td>
<td>3.2 bps/Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.32 bps/Hz/User</td>
</tr>
<tr>
<td>DL Cell-Edge User Throughput</td>
<td>(4x2) MIMO</td>
<td>0.09 bps/Hz</td>
</tr>
<tr>
<td>Peak UL Spectral Efficiency</td>
<td>(1x2) SIMO</td>
<td>4.6 bps/Hz</td>
</tr>
<tr>
<td></td>
<td>(2x4) MIMO</td>
<td>9.3 bps/Hz</td>
</tr>
<tr>
<td>Average UL Spectral Efficiency</td>
<td>(2x4) MIMO</td>
<td>2.6 bps/Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.26 bps/Hz/User</td>
</tr>
<tr>
<td>UL Cell-Edge User Throughput</td>
<td>(2x4) MIMO</td>
<td>0.11 bps/Hz/User</td>
</tr>
</tbody>
</table>

Table C-3: Low user mobility spectral efficiency numbers for WiMAX Release 2 (Source: WiMAX Forum\(^{46}\))
The charts below show the peak and average data rates for DL and UL with comparing the WiMAX System Release 2 against the WiMAX System Release 1 data rates.

Figure C-15: Peak DL and UL channel rate in Mbps for WiMAX 2 (Source: WiMAX Forum\(^{46}\))
More details of the specific technology enhancements for WiMAX 2 are covered later in the report.

\(^{32}\) The average DL and UL spectral efficiency assumptions are: Frequency reuse =1, 10 users per sector or channel, full buffer data traffic, and Urban Microcell test environment as specified by IMT-Advanced
C.4.4 Current WiMAX deployment status

There are currently 539 WiMAX deployments across 149 countries according to the latest WiMAX Forum news release\(^7\) (August 2010). WiMAX now covers 620 million people across the world with growth estimated at 1 billion by the end of 2011. WiMAX has seen steady growth in emerging markets over the last four years, where fixed DSL is expensive and WiMAX offered similar benefits at a more cost effective price. The majority of the deployments are in the 3.5 GHz spectrum band which is likely to be due to the availability of spectrum and the regulatory conditions amongst the various markets, compared to 2.6 GHz spectrum which has taken longer to be released amongst more developed markets.

There are two particular high profile networks recently deployed which merit further discussion. These include Yota in Russia and Clearwire in the US. The reason for their particular interest is the rapid deployment strategies and large investment in WiMAX technology and spectrum holding. These operators are using nationwide 2.6 GHz spectrum for their operations and have rapidly deployed networks across their respective internal markets.

The commercial drivers and advantages being seized by the WiMAX community from the commercial networks give an interesting insight into the evolution of WiMAX. The following information relates to how WiMAX operators have been marketing their networks in relation to network performance and data rates:

- Sprint refer to their services as 4G however, this is aimed purely for marketing purposes and does in fact quote its data rates as up to 4-6 Mbps downlink and uplink 1-2 Mbps which is well below the target IMT- Advanced 4G data rate requirements.
- Yota in Russia refer to their services as 4G Internet and promote data rates up 10 Mbps.
- Yota also states that WiMAX delivers speeds comparable to a fixed line broadband connection which is the most widespread delivery platform in Russia.

Some vendors have expressed their commitment to the development of products to meet the specification of WiMAX 2. Intel and Samsung signed an MoU to accelerate the delivery of products based on the IEEE 802.16m standards. The companies expect to see products on the market based on WiMAX 2 by late 2011\(^8\). However, both Sprint and Yota have announced trials of TD-LTE equipment recognising the progress being made by 3GPP and support of its LTE standards.
Appendix D  Demand for 4G Mobile Services

D.1 Introduction

Although 3G networks have been deployed for some eight years, demand for mobile broadband services is still at a relatively early stage. Demand accelerated significantly only in 2007, following the introduction of low-priced internet connectivity based on 3G ‘dongles’. Smartphones have stimulated further demand, notably starting with the advent of the iPhone 3G in June 2008. This resulted in a complete change of the profile of demand in terms of volume per user, mobility and the principal locations in which services are used.

Given this early market stage, forecasting 4G demand over the timescales of relevance to this project is highly unlikely to be successful. Instead, we examine the main attributes of mobile broadband demand which are significant when considering the network capacity required to serve it. In particular, the attributes examined are:

- the devices which generate the demand;
- the services and applications which users access via their devices;
- the data volumes and data rates which users generate and require access to in order to support the relevant applications;
- the locations and mobility associated with the demand;
- the service quality which users require in order to support the services they demand.

These factors are examined via (recent) historical data and via forecasts from various sources. Since such forecasts typically extend for only five years, in lieu of an overall forecast we highlight the factors which may influence the demand which 4G networks will have to serve. We focus our attention on Global, Western Europe and UK demand.

D.2 Devices

The type of mobile broadband device employed plays a strong role in determining the form of demand placed on the mobile network. Devices have proliferated over the last few years, and the device type in turn impacts strongly on the applications which can be run, the volume of data generated and the nature of the quality of experience which is required to satisfy the user. Table D-1 shows how the device type impacts on the nature of the demand which various device classes place on the network. It is clear that MBB demand is strongly variegated amongst devices.

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33 3GPP refers to a device as a UE – user equipment, while for WiMAX it is a MS – mobile station.
<table>
<thead>
<tr>
<th>Device type</th>
<th>Volume of Data</th>
<th>‘Chattiness’</th>
<th>Location</th>
<th>Mobility</th>
<th>Data rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legacy phone</td>
<td>Near zero</td>
<td>Near zero</td>
<td>Everywhere</td>
<td>Full mobility</td>
<td>Very low</td>
</tr>
<tr>
<td></td>
<td>Apart from text (SMS) and some picture messaging (MMS)</td>
<td></td>
<td>2/3 of voice calls in-building</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source: Nokia(^{50})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feature phone</td>
<td>Low – but rising</td>
<td>Low – but rising</td>
<td>Everywhere</td>
<td>Full mobility</td>
<td>Medium</td>
</tr>
<tr>
<td>Source: Samsung(^{51})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smartphone</td>
<td>Medium</td>
<td>High</td>
<td>Everywhere</td>
<td>Full mobility</td>
<td>High</td>
</tr>
<tr>
<td>Source: Apple(^{52})</td>
<td></td>
<td></td>
<td>70-90% of data in-building</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source: Samsung(^{53})</td>
<td></td>
<td></td>
<td>Data predominantly consumed when stationary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USB Modem (‘Dongle’)</td>
<td>High</td>
<td>Low</td>
<td>Quasi-fixed</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>(or laptop with embedded MBB modem)</td>
<td></td>
<td>Long session times</td>
<td>Static in homes (broadband alternative) or transportable (‘road warrior’)</td>
<td>Consumption on trains is a notable exception</td>
<td></td>
</tr>
<tr>
<td>Source: Huawei(^{54})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Device type</td>
<td>Volume of Data</td>
<td>‘Chattiness’</td>
<td>Location</td>
<td>Mobility</td>
<td>Data rate</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>----------------</td>
<td>-----------------------</td>
<td>---------------------------</td>
<td>----------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Wireless home modem</td>
<td>High</td>
<td>Low</td>
<td>Fixed – homes only</td>
<td>Zero</td>
<td>High</td>
</tr>
<tr>
<td>Source: vcmnetwork.com</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBB – Wi-Fi router</td>
<td>High</td>
<td>Low</td>
<td>Quasi-fixed</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Source: Huawei</td>
<td></td>
<td></td>
<td>Static in homes (broadband alternative) or transportable (‘road warrior’)</td>
<td>Consumption on trains is a notable exception</td>
<td></td>
</tr>
<tr>
<td>E-book (and comparable MBB-enabled consumer devices)</td>
<td>Low</td>
<td>Low</td>
<td>Everywhere</td>
<td>Full mobility</td>
<td>Low</td>
</tr>
<tr>
<td>Source: Amazon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBB devices for M2M applications</td>
<td>Low</td>
<td>Low</td>
<td>Fixed</td>
<td>Zero</td>
<td>Very Low</td>
</tr>
<tr>
<td>Source: EVB</td>
<td></td>
<td></td>
<td>But deep in-building</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cisco forecasts that 91% of all mobile data traffic will be from smartphones and portable computers by 2014, due to the higher usage profile of laptops/netbooks and the suitability of smartphones for high-quality video. Thus smartphone take-up is an important predictor of mobile data growth. The corresponding forecasts for the UK, Western Europe and globally are shown in Figure D-1. Note that the proportion is expected to stabilise in the next five years and that UK is some way from being the leading market, with 32% in 2014 compared with, say, 67% in Italy. Smartphones create as much traffic as 10 basic “feature” phones (30 times for iPhones), while a laptop can generate as much as 1300 times such a feature phone (see Figure D-2). The increase in interest in tablet devices with larger form factors such as the Apple iPad seems set to continue this trend, as shown in Figure D-3.
Figure D-1: Percentage of smartphones over all mobile handsets (Source: Cisco, Real Wireless graph)

Figure D-2: Relative data-generating impact of mobile broadband devices (Source: Cisco, Real Wireless graph)
Apple’s iPhone has been much-cited as the source of particular growth in data generated by smartphones (an “iPhone effect” – see e.g. (59)). However, there are examples of significant growth from other smartphones such as those using the Android operating system. Figure D-4 shows how the “Droid” phone became the dominant source of mobile data on Verizon Wireless’ network in the US within three months of its introduction. Indeed, a US study (60) suggested that in the period January-May 2010 Verizon smartphone customers consumed on average 421 MB per month compared with 338 MB per month for AT&T iPhone users. At 350MB per month per subscription, the global average across all mobile subscriptions implied by Ericsson measurements in December 2009 is in this range.
D.3 Services and applications

D.3.1 A brief history of mobile services

The range of services available to users of mobile devices has increased rapidly in recent years. For the first decade of commercial mobile activity (approximately 1985-1995) the only services available were voice and text (SMS), and SMS only started to take off towards the end of that period, having been first introduced in the UK at the end of 1992\textsuperscript{62}. In the course of the second decade, texting grew strongly, from 0.4 messages per GSM customer per month in 1995 to 35 by the end of 2000 and UK volumes increased by around another factor of 4 over the course of the following five years\textsuperscript{63}. Although texting generated substantial revenue for operators (US$70bn in 2005, three times all Hollywood box office returns that year), it had relatively little impact on the network capacity required, being carried in very small amounts of data and on shared channels.

Low rate data service bearers such as GPRS\textsuperscript{34} were launched in 1999. Initial applications for these bearers such as WAP saw little uptake, and the use of GPRS for internet access produced an unsatisfying user experience. However, with the advent of specialist push email services over GPRS - notably via the RIM Blackberry phone - a new era of data services began, enabled by the high level of usability of email services on those phones. Email is particularly well-suited as an application for such bearers since it does not require uninterrupted data sessions, and because users have little perception of the time taken to receive or send emails provided this occurs within a few minutes of sending them.

In a similar vein, the early use of 3G starting in 2003 was expected to be in two-way mobile-to-mobile data sessions which would carry applications such as mobile video calling. In practice it was the advent of simple-to-use dongles for internet access, primarily to laptop computers, which yielded the first major growth in data applications, starting in 2006/07.

The Apple iPhone, which did not then support 3G, was launched in January 2007 but not sold until June of that year. It quickly established that services such as basic web browsing, calendar synchronisation and synchronised information services such as stock prices and local weather could be popular if the device usability was sufficient. It had previously been widely contended that the screen sizes and difficulty of accessing and controlling web pages would severely limit the use of such applications on devices of the form-factor of phones.

The Apple App Store launched in July 2008 and hugely expanded the range of services available to mobile phone users. It has continued to grow, and it appears that the wider the range of applications, the greater is the overall take-up, as shown in Figure D-5. By having such a wide range of applications almost any user has access to a motivating application, while applications can be optimised for the mobile form-factor and the characteristics of a mobile connection, helping to ensure a satisfying user experience. Similar initiatives such as the Android Market, have also seen significant take-up. The Android Market was launched to users in October 2008 and grew from 2,300 applications in March 2009 to 80,000 by August 2010 and over 1 billion downloads, with 10,000 additional applications being added monthly.

\textsuperscript{34} General Packet Radio Service
D.3.2 The impact of diverse services on mobile network capacity requirements

The increasingly diverse services and applications running in volume over mobile networks drive in their turn highly diverse data capacity and quality requirements. Clearly the data volumes have risen in response, but many have reported that the particular nature of mobile applications on smartphones creates particular challenges. 3G technology was designed to support large volumes of data, but the expectation was that this would mostly be in the form of relatively long, uninterrupted data sessions, typical of video calls etc. Many smartphone apps such as instant messaging, location services etc. download relatively modest quantities of data, but do so typically in the form of many small bursts and very frequently. Additionally, in order to optimise the battery life of a compact mobile device, it is common for the data ‘context’ to be established and stopped rather frequently when not needed (so-called ‘fast dormancy’). At the beginning and end of all such contexts, and again when bursts of data are exchanged, a series of signalling transactions is required. Although such transactions are not especially data hungry, when data sessions are short the signalling traffic rises as a proportion of the total traffic. For example, an individual instant message takes approximately the same amount of signalling traffic as a complete voice call. The result is that signalling traffic is rising even more rapidly than overall data traffic – see Figure D-6. Although smartphones still create less network load than a data card/dongle, the proportion of traffic associated with signalling is far higher for smartphones (see Figure D-7).
Although such effects are a significant challenge for 3G networks in the short term, there are advanced features within 3G to allow more efficient handling of such short data bursts\(^9\), and 4G technologies are much more directly engineered to handle a diversity of data characteristics. The offload strategies discussed in chapter 6 can also help with signalling capacity. As a result this may turn out to be a transient effect.

### D.3.3 Other service and application themes

A number of other themes can be identified which could significantly impact on the shape of future mobile broadband demand:

- **Mobile as a broadcast medium** – TV and similar services can be delivered over mobile technology. The efficiency of multicasting may be lower in basic implementations of the technology than the traditional broadcast media, but the advent of technologies such as MBMS can improve on this while also allowing a level of individualised and interactive content which is difficult to deliver via traditional approaches.

- **Machine-to-machine communications** – The use of embedded cellular modems in devices ranging from smart meters to vending machines and industrial process sensors could lead to a large increase in the number of devices in the future, causing penetration to increase well beyond 100% of users. Although for most of these applications the capacity requirement is low, such devices could also start to transport higher rate services such as CCTV.

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\(^9\) Notably “Enhanced Cell_FACH” (a 3GPP Release 7 feature) and the use of the Cell_PCH state, which is a ‘semi active’ state which saves battery life but allows rapid, low signalling-load transitions back to the usual DCH data state.
• Trend to consumption of multiple communication services simultaneously – There is increasing evidence that consumers of communication services use multiple services simultaneously, enabled by the use of multiple personal devices (smartphones, tablet devices) alongside traditional home media such as TV and streaming audio. Some of these service continue even without the user’s involvement, such as background media synchronisation and backup.

D.4 Data volumes and data rates
This section comprises three main elements:

1. Data concerning the actual growth in mobile broadband volumes over the last few years (section D.4.1)
2. Forecasts of future mobile broadband growth in the future (section D.4.2)
3. Considerations relating to longer term demand forecasting, since most forecasts extend over only around the next five years while the period of interest for this study extends to at least ten years

D.4.1 Mobile Broadband Growth to Date
The mobile broadband data market is still very much in its infancy. Although 3G networks were launched starting in 2003, the period of rapid growth of data volumes only began in 2007, so only two to three years of real data are available. Nevertheless, there have been numerous indicators of rapid growth since. These include:

1. A detailed study of usage in Finland in the period 2005-2007, measured directly on three operator networks, showed that the total data traffic in 2007 was 13 times larger in volume than the previous year. 92% of the data traffic was from computers rather than phones and this share of traffic was from just 2.1% of the devices on the networks.
2. Ericsson reported in March 2010 that mobile data traffic globally surpassed that of voice for the first time at around 140,000 terabytes per month in December 2009. The data traffic was from 400 million mobile broadband subscriptions, while the voice traffic was from 4.6 billion mobile subscriptions. Thus the average data per user at that time was already 11.25 times higher than the average voice traffic per user.
3. O2 reported in October 2009 that its network had experienced an 18-fold increase in data over the past year and that traffic was continuing to double every three months.
4. AT&T reported in February 2010 that data traffic on its network had grown more than 5,000 percent over the past three years and that this trend was expected to continue.
5. Telecom Italia reported that its mobile traffic grew 216% from mid-2008 to mid-2009.
6. Ericsson reported measurements of global mobile data traffic at nearly 225,000 terabytes per month as of the second quarter of 2010, being nearly three times the volume of a year previously and growing ten times faster than voice.

D.4.2 Cisco Visual Networking Index

7. This study is probably the most widely quoted source of mobile data traffic forecasts. It provides a global forecast of demand, updated annually, with a five-year horizon. The most recent issue was published in February 2010 to cover the period 2009-2014.
8. The headline statistic is that the compound annual growth rate will be 108% over this period from a 0.09 exabyte per month base in 2009 (cf 0.14 EB per month measured by Ericsson in December 2009). The forecast is heavily predicated on the growth of video traffic, forecast at 66% of the total

36 Unless otherwise noted, growth rates quoted are Compound Annual Growth Rates (CAGR), although many studies are imprecise on this point and use ‘growth rate’ rather loosely.
37 1 exabyte (EB) = 1,000 petabytes (PB). 1 petabyte = 1,000 terabytes (TB). 1 terabyte = 1,000 gigabytes (GB), 1 gigabyte = 1,000 megabytes (MB).
by 2014 and with the highest forecast growth rate of any application. The volume forecasts for global (+ outer space!) and Western Europe are shown in Figure D-8, together with a forecast for the UK assuming this is 10% of the total.

![Cisco data demand forecasts](image)

9. Cisco has also measured average mobile data speeds using direct measurements of large numbers of real handsets. If these are compared with the data volumes in the same regions, it is apparent that there is a strong correlation, as shown in Figure D-9. If this behaviour were to be replicated into the 4G era, it possible that the capacity benefits of 4G could be eroded - or even removed - by the stimulation of increased demand.
Figure D-9: Correlation between data speed and data volume (Source: Data from Cisco\textsuperscript{72}, Real Wireless analysis)

D.4.3 Informa Telecoms and Media

The Informa 2009 report\textsuperscript{74} on Future Mobile Broadband provides detailed forecasts over 5 years for mobile broadband demand, segmented by region, country and technology. The report focuses more on revenue and subscriptions than on data volumes, but it does include a much-quoted ‘exponential traffic growth, linear revenue growth’ forecast, where data grows by around 20x while revenue grows by only 2x over the period. As shown in Figure D-10, this implies that operators will need to reduce the effective cost per bit of data delivery by at a rate equivalent to -36% CAGR over this period in order to maintain the same value from mobile data as they currently generate.
Figure D-10: Mobile data traffic and revenue growth forecast (Source: Informa data, Real Wireless analysis. Note: Annual forecasts divided by 12 to yield monthly estimate)

The Ofcom Communications Market Report includes a similar figure relating to the historical data and revenue for the UK mobile industry, reproduced in Figure D-11.

**Mobile data volumes and revenues**

Source: Ofcom / operators

Note: Includes estimates where Ofcom does not receive data from operators; data revenue is likely to be understated as it excludes any data element included within standard pay-monthly tariffs.

Figure D-11: Historical UK mobile data and revenue growth (Source: Ofcom, reproduced from)

Informa forecasts based on their latest Intelligence Centre reports at August 2010 are shown in Figure D-12. The forecasts in the different scenarios, which relate mainly to the rate of recovery from the global economic recession, show a range of around 390% (Global) and 350% (UK / Western Europe) between the aggressive and conservative scenarios, over the six year period 2008 to 2014.
As shown in Figure D-13, Informa’s forecasts imply a small decline in UK traffic as a proportion of Western Europe.

**Figure D-12: Informa data demand forecasts**

**Figure D-13: UK mobile data traffic volume as a proportion of Western Europe**

### D.4.4 Analysys-Mason

Forecasts of mobile data growth produced by Analysys-Mason are provided in Figure D-14 [76].
D.4.5 PA Consulting

In a previous project on behalf of Ofcom, PA Consulting created forecasts of cellular data growth as a basis for estimating the potential for future UK spectrum shortages. These are unusual compared to other forecasts in extending out to 2025, in being specific to UK and in having a stated detailed basis for the forecasts. The forecasts are recast in units comparable with other analysts in Figure D-15. Six distinct scenarios are given, with meanings in the following table. For comparison with other forecasts we adopt the Reuse, AYCW and WFW scenarios as representative of the low, mid and high ranges of the PA forecasts.
Abbreviation | Scenario               | Selected scenarios
---|----------------------|-------------------
BAU | Business As Usual |                  
WFW | Wire-Free World     | PA Mid            
AYCW | All You Could Want | PA High           
DYST | Dystopian           |                  
FRAG | Industry Fragmentation |               
REUSE | Re-Use              | PA Low            

Table D-2 Table of different scenarios used in PA report

Figure D-15: PA Consulting forecasts for UK mobile data

D.4.6 Other forecasts

Ericsson forecast [68] an annual doubling of data traffic over the next five years in March 2010. Chetan Sharma Consulting forecasts a correlation between demand and both increasing data speed and reducing latency.
Correlation of Speed/Latency with Consumption (Smartphones)

Figure D-16: Correlation between data speed and consumption (Source: Chetan Sharma Consulting)

10. Credit-Suisse forecast\textsuperscript{79} ongoing increase in data volumes per user in the period to 2015 (Figure D-17).

Figure D-17: Growth in monthly mobile broadband data consumption per user (Source: Credit Suisse)

D.4.7 Summary of Data Volume Forecasts

Figure D-18 compares the global demand forecasts between analysts, while Figure D-19 provides the equivalent for Western Europe. Analysys-Mason and Cisco do not provide separate forecasts for the UK, so in their Western Europe forecasts are extended via the Informa forecasts of Figure D-13 for the proportion of Western Europe data accounted for by the UK. The aggregated UK forecasts to 2014 are shown in Figure D-20, and are extended to 2025 with the addition of the PA Consulting forecasts in Figure D-21.
Figure D-18: Global data demand forecasts

Figure D-19: Data demand forecasts for Western Europe
In summary, it is clear that, while all analysts are predicting substantial growth in mobile data for the foreseeable future, the extent varies hugely. For the UK, growth rates for the forecasts included in Figure D-21 vary between 24% and 102% CAGR (2.8x to 33x) for the period 2009-14, with a spread of a factor of 7 in
2014. The forecasts in 2025 span a range of 25x. Amidst such a wide range of demand forecasts, it is clear that mobile operators will need a high degree of flexibility in the technological solutions adopted and in the available spectrum resources to ensure they can meet the rising tide of demand while not committing too early to excessive expenditure.

D.5 Location and mobility
Location and mobility play important roles in establishing the nature of capacity required in mobile networks. In particular, two key aspects of capacity: the total quantity of spectrum and the maximum density of cells – are set by the times and locations of the peak demand, rather than the total quantity of demand in aggregate over the network. Mobile traffic is extremely non-uniform in demand for a variety of reasons, as described in the following sections.

D.5.1 Population Density

Measures of population density provide a useful starting point for examining the geographical spread of mobile usage, although it is only a rough indicator since it relates only the residential locations. Population density is strongly non-uniform, as shown in Figure D-22. This represents the variation in density of households according to the UK census, which shows a wide range between the highest and lowest population densities. Taken over the whole UK, the maximum population density (64,760 km$^{-2}$) is over 160 times higher than the mean and 12 times higher than the mean in the most densely populated 80% area. The mean density of the 80% area is exceeded in just over 2.2% of the land area.

![Figure D-22: UK population density](Source: Real Wireless analysis of UK census data)

When mobility is taken account, this disparity between the mean and peak population density increases dramatically, with busy business districts taking very high population densities. For example, the City of London, with an area of 2.9km$^2$ has a resident population of just 8,000, but around 320,000 people work there\(^8\), creating an increase in population density of a factor of 40 to over 110,000 km$^{-2}$. Nearly 10% of these work in the Broadgate estate each day\(^8\), with an area of 129,000 m$^2$, resulting in a density of over 232,000 km$^{-2}$. This is 580 times larger than the UK mean and 44 times that of the mean for the 80%
population area. This is not an isolated instance: the Office of Government Commerce recommends a maximum of 12 m$^2$ of office space per person, equivalent to a density of over 83,000 km$^{-2}$ or 15 times the UK 80% mean. These reveal an even larger disparity between the peak and the mean population densities as shown in Figure D-23.

![Figure D-23: Population densities for selected UK areas, noting that some cities overseas can have even higher population densities](Sources: Various, Real Wireless analysis)

These have great significance for spectrum allocation. The amount of spectrum required to deliver the overall capacity required across a country such as the UK is a tiny fraction of that required to serve the peak demand in the busiest areas. Conversely, if congestion is to be avoided at the locations of peak demand, the utilisation of spectrum over the vast majority of the country will be very low.

**D.5.2 Distribution amongst users**

As well as mobile usage demands being heavily concentrated into small areas, operators frequently report that particular users account for a disproportionate share of usage. A representative survey (Figure D-24) shows that 10% of users generate 85% of total traffic. AT&T reported at the end of 2009 that three per cent of smartphone users were generating 40 per cent of overall wireless data traffic. Although particular segments of users such as business users may on average be heavier users than domestic users, particular users may share use mobile broadband as an alternative to fixed broadband, use data-hungry applications such as file sharing, and share a single connection amongst multiple computers.
D.5.3 Indoor-outdoor distribution

The type of location also plays an important role in determining the capacity requirements for mobile networks. Assuming the demand is served from a network outside the building, the penetration losses into the building create an additional load on the power to achieve a given service quality. Additional power translates into additional interference and hence creates additional need to control interference via additional spectrum or conversely limits available capacity. Mobile usage has always been heavily oriented towards in-building use, with typically two-thirds indoors for voice traffic alone. The home is seeing a particular increase in usage. Mobile voice and data traffic in the home was estimated in 2007 at 40% of the total and was expected to reach 58% by 2013\textsuperscript{85}. However, the proportion indoors is increasing with the advent of increasingly media-rich data applications which demand the viewer’s attention to the screen, as shown in Figure D-25.
D.5.4 Time of day

If mobile traffic were evenly spread during the day, the capacity requirements on the networks would be much reduced. Figure D-25 shows daily variations in traffic for both mobile voice and data. Mobile networks were traditionally dimensioned to account for the ‘busy hour’ of voice traffic which was relatively well-defined and occurred towards the end of the working day. With the advent of mobile broadband, there is no clearly defined busy hour: traffic is spread through the latter half of the day and tends to be greatest out of traditional business hours. In one sense this actually makes more efficient use of the available capacity as networks are not lying idle for the majority of the day. However, it also means that users experience congestion near to the peak for a much greater proportion of the time, making it less plausible for operators to run networks near the very limits of capacity since this will significantly degrade the typical user experience.

![Figure D-25: Daily variations in traffic for mobile voice and data](image)

D.6 Summary of demand themes

The timescale of relevance to this project extends beyond the five-year period over which most analysts conduct forecasts. Even within that period there is very large variation amongst analysts as to the growth rates to be expected and this range of uncertainty will only increase as we extend to longer time periods. This does not, however, relate to any deficiencies in the forecasts, but to the intrinsic uncertainty involved in such an early stage market as mobile broadband. In barely four years, the market has already seen multiple shifts in the nature and volume of traffic associated with successive waves of devices, applications, pricing offers and network performance. Over the next ten years, as LTE, WiMAX, LTE-Advanced and WiMAX 2 are introduced we can confidently expect to see many more such shifts, making forecasting of the capacity requirements of networks (and the associated need for spectrum on the parts of regulators and expenditure on the part of operators) extremely difficult.

Despite this uncertainty, the recent history of mobile broadband allows us to identify a number of themes which are likely to continue:

1. The devices used to access mobile broadband services increasingly occupy multiple form factors and users increasingly access multiple devices and service simultaneously. Each device type has its own characteristics as far as the required bandwidth is concerned, which is not necessarily a simple function of the screen size, since the usability and degree of autonomy of a small device such as a smartphone can disproportionately increase its load on the networks.

2. The proliferation of mobile applications (over 7 billion downloads by late 2010) has increased the appeal of smartphones while also increasing the diversity of traffic requirements. It has also made the load on 3G networks in the form of signalling overhead disproportionately high compared to the traffic profiles expected when these networks were designed.
3. Two particular changes in mobile services which are anticipated in the future may significantly change the form of demand in the long term, namely i) machine-to-machine services ii) the use of mobile as a broadcast medium.

4. Forecasts agree that mobile broadband demand will continue to grow rapidly over the next five years, but disagree on the rate, with forecasts for the UK varying over a range of seven times in 2014. The most quoted figures have a growth rate of around 100% CAGR (in excess of 30x over 5 years), but other credible forecasts are as low as 43% CAGR (around 9x over 5 years).

5. Over the longer term (beyond 5 years) there are few forecasts, but even within a plausible range of scenarios the range between the highest and lowest forecasts in 2015 is at least a factor of twenty-five.

6. The density of mobile usage is exceedingly non-uniform across differing locations due to the non-uniform nature of the population distribution between cities and outside and between the working day and the evening. For the UK, the densest office areas are nearly six hundred times more densely occupied than the UK mean, and the standard for office space occupancy is 16 times the mean density occupied by 80% of the UK population. Thus, mobile networks will experience capacity challenges in very geographically isolated areas, but potentially in a very large number of these distributed widely across office space and homes around the country.

7. Mobile users differ hugely in their demand levels, with typically 10% of users generating 80% of the total data traffic.

8. Mobile usage is predominantly indoors within homes and offices and is expected to grow so that over 80% is indoors. Such traffic is the hardest to serve from an outdoor network.

9. Empirical evidence shows a strong positive correlation between the speed of mobile networks and the data consumption.

Data demand is increasingly spread through the day rather than being concentrated in a short period, so that any quality degradation arising from network congestion may be felt by users for a long period; conversely, network resources are better utilised than was the case for voice-only networks.
Appendix E  The Nature of Mobile Network Capacity

This appendix provides further details on the factors that impact capacity in a network and aims to provide further background to support the discussion in chapter 4.

E.1  Factors affecting SINR distribution across a cell

The distribution of SINR across a cell is impacted by:

- **Geotype (urban/suburban/rural etc.)**
  - The Urban geotype has tall buildings which obstruct direct ‘line of sight’ links between users and the cell site.
  - Suburban and Rural geotypes are more benign and the user can travel further from the cell site before noise becomes significant compared to the wanted Signal.

- **User distribution (indoor/outdoor)**
  - It is often assumed that users are evenly distributed across the coverage area, and generally they are outdoors. The signal quality distribution should really be sampled over the locations where users actually use the service, and with data networks this is often indoors. Signals are attenuated by building walls, so cells with a high proportion of indoor users will have a lower values of SINR compared to cells with mainly outdoor users.

- **Carrier frequency**
  - The lower carrier frequencies (e.g. 800MHz) can penetrate through obstructions better than the higher frequencies (e.g. 2.6GHz).
  - At lower frequencies, fewer cells are needed to cover an area with a given SINR distribution.

- **Topology (macrocell/femtocell/picocell etc.)**
  - Large cells tend to be coverage limited, where users near the cell edge have Signal strength comparable to Noise
  - In real environments, propagation losses are not constant with range. Many path loss models have a ‘break point’ beyond which the rate of loss with range increases due to the increasing presence of obstructions such as buildings, walls etc. A smaller cell will therefore tend to have a higher valued SINR distribution, with the obstructions providing isolation of interference from neighbouring cells.
  - The typical height of base station location varies with the size of the cell.
  - Large or macrocell networks tend to use towers to provide a unobstructed view of the surrounding area.
  - Smaller microcell sites tend to be down in the clutter (buildings and trees) at street level,
  - Femtocells and picocells tend to be indoors

- **Interference management or frequency reuse**
  - A capacity limited network is one where I>>N. Capacity increases can be realised by reducing the level of Interference, at least until the interference level is comparable with the noise
  - Interference co-ordination: Cells may interact with each other to indicate the presence of high power transmissions to/from cell edge users on certain (time, spectrum) resources. The neighbour can then avoid allocating this high interference resource to a ‘cell edge’ user.
  - Frequency reuse is a static version of this: Neighbour cells avoid using the same frequency resource.

- **Power control and Resource allocation**
  - In principle power control mechanisms can adjust both the base station and mobile station power to minimise interference (and increase battery life) while maintaining a given target level of quality. In some systems however – such as the LTE downlink - the same power is transmitted by the base station to all UEs, and so Interference to another cell is independent of the location of the receiving UE in the cell.
  - The UL has power control which can ensure signals from all UEs arrive at the cell site with approximately the same power spectral density, regardless of the UE range (at least within the
limits of the UE performance). UEs at the cell edge transmit more power and cause more interference to other cells.

- Scheduling more (time, frequency, power) resource to cell edge users (to compensate for their lower quality links) lowers the SINR distribution
- Figure E-1 shows that Uplink Power Control makes for a ‘fairer’ distribution of SINR, where the variation across the UE population is less than without PC. The ‘No PC’ scheme (all UEs transmit full power) actually gives the highest capacity, but has very poor coverage, with many UEs having no service at all. LTE includes a fractional PC scheme, which allows a flexible trade between capacity and fairness.

![Figure E-1: Impact of Uplink Power Control on the Signal Quality Distribution (Source: 3GPP)](image)

**E.2 Factors affecting link level performance**

Link level performance describes how well a technology (and implementation) can make use of the available signal quality in order to transfer information over the radio link. In the late 1940’s, Shannon proposed a bound for the maximum error-free information rate that could be sent over a link of given SNR, shown in Figure E-2. Higher SINRs allow more bits per second per Hz to be transmitted without error. Radio transmitters can use a combination of modulation order (bits per symbol) and coding rate (information bits/ transmitted bits) to allow a tradeoff between the information rate and SINR required for error free communication. Figure E-2 illustrates a family of such Modulation and Coding Schemes (MCS) to cover a range of SINR. With a low SINR of less than -5dB, only the ‘QPSK Rate 1/8’ will work. Other schemes would be corrupted and would not carry any information. At high SINR > 18dB, all the MCSs could be transmitted essentially error free, but 64QAM rate 4/5 would be the logical choice to maximise the data rate.
Most mobile technologies deployed today include Adaptive Modulation and Coding, which senses the channel quality and adapts automatically to maximise the data rate. Over time, implementations and coding schemes have improved to raise the information rate achievable with a given SINR, so that by appropriate selection amongst the schemes shown in Figure E-2 the overall link performance can approximate rather closely to the Shannon bound. However, it is not possible to exceed the rate described by the Shannon Bound for a link between a single pair of transmit and receive antennas in idealised conditions (a 1x1 link in AWGN (Additive White Gaussian Noise)). In theory, the Shannon bound can be exceeded for fading channels where channel state information is known at the transmitter. Furthermore, the use of Multi-Input Multi Output Antennas may also give what appears to be higher than Shannon throughputs for the device. Strictly speaking, MIMO is a combination of multiple radio links whereas the Shannon bound is defined for a single link.

3GPP network level simulations for LTE co-existence have approximated the link level performance to an attenuated and truncated form of the Shannon bound described in the Appendices of 88. Figure E-3 illustrates the UL and DL curves for the LTE DL (no MIMO). The attenuation represents implementation losses. The truncations indicate the range of SINR over which the code set works, visible in Figure E-3. This accounts for the presence of a maximum throughput given by the highest order MCS: this defines the peak rate of the system. There is also a minimum SINR, below which the lowest order MCS cannot work due to a loss of synchronisation between transmitter and receiver, which sets limits on the coverage. In Figure E-3 the DL assumes 64 QAM operation, and so has higher throughput than the UL, which only supports 16QAM for all but the top class of UE.
the cell site experience the most severe fading. Movement of the UE will cause the fading to change with time. LTE and WiMAX use channel estimation to measure, compensate and exploit such variations. However, rapid variations caused by higher UE speeds reduce the effectiveness of channel estimation, and ultimately reduce link level performance as illustrated in Figure E-4. Very high UE speeds reduce peak throughputs by around 60%. UEs towards the cell edge with lower SINR are not impacted as much. These measurements from were made in the laboratory with emulated channels. The 3km/h result is from the ITU-R’s ‘Pedestrian B’ channel, and the higher speeds for the ‘Vehicular A’.

![Figure E-4: Impact of UE Speed on Link Level Performance (LSTI Lab measurement) (Source: LSTI)](image)

LTE natively incorporates MIMO antenna technologies, which can improve link level throughput in the right channel conditions. Figure E-5 shows measured link level performance from early LTE prototypes of 1x2 (SIMO), 2x2 and 4x4 (MIMO) schemes. At high SINRs, we can see peak rates increasing with the number of MIMO streams: the single stream SIMO achieves ~60Mbps peak, the 2 streams achieves ~120Mbps and 4 streams 240Mbps. Figure E-6 shows a further comparison, which includes Space Frequency Block Coding, where multiple transmit antennas are used for transmit diversity rather than creating parallel streams as in the case of spatial multiplexing.

MIMO requires high SINR and low speeds for good channel estimation, as well as low correlation between antennas and rich multipath scattering in the channel which can be resolved into multiple streams. In practice, the full gains of MIMO may be limited due to:

- Rarity of high SINR conditions in the cell (see SINR distribution)
- Sufficient multipath scattering for users with high SINR to resolve multiple streams
- Space on small form factor UEs to design multiple antennas with low correlation properties, especially at lower bands where antennas need to be larger.

In summary the link level performance of a cell will vary with:

- SINR
- Fading severity and UE speed
- Channel rank i.e. level of multipath
Figure E-5: Benefit of MIMO on Link Level Performance (LSTI Lab measurement with 20MHz Bandwidth) Source: LSTI

Figure E-6: Comparison of Link Level Performance for different MIMO schemes (Source: Rysavy Research)

E.3 Providing quality of service across a cell

E.3.1 Scheduling of Spectral Resource amongst Users

The data rate of each UE is directly proportional to the amount of spectral resource allocated to it:

\[ \text{UE Tput (b/s)} = \text{link spectral efficiency (b/s/Hz)} \times \text{allocated resource (Hz)} \]

The amount of resource depends on:

- a) Total available spectrum
- b) Number of UEs sharing it
- c) Sharing scheme in the scheduler

A broader view of resources also includes the time domain for packet scheduling and the power available to the base station.
The resource scheduler has the role of managing the resources of the cell to satisfy the users by meeting their individual QoS requirements. The way in which resource is shared has a major impact on both cell capacity and quality for users.

Figure E-7: Role of the eNodeB scheduler

Figure E-7 illustrates the role of the resource scheduler, and some examples of different sharing schemes (the colours on the graph are not related to those in the drawing on the left). A ‘round robin’ (RR) scheme gives an equal share to all users. Users’ data rates are therefore proportional to their link spectral efficiency. This gives high cell capacity, but is not very fair, as cell edge users have significantly lower rates than other users.

Equal Throughput (EQT) on the other hand is completely fair. It works by allocating a share size inversely proportional to the UE’s spectral efficiency. Unfortunately, allocating the majority of resources to UEs with low spectral efficiency results in low cell capacity.

Proportional fair is a compromise between RR and EQT. The scheduler acts like Robin Hood, taking some resources from the rich (high SINR UEs) and giving it to the poor (cell edge UEs). This is fairer than RR, and still has reasonably high capacity. The resource scheduler also has to take into account the different QoS requirements of the users, such as ensuring that guaranteed bit rates are met, or that there is a regularly allocated resource for delay sensitive services. In practice, an operator is given some control over the tradeoffs between capacity and fairness, and equipment from different vendors may vary substantially as the performance of the scheduler is not specified by 3GPP.

E.3.2 User Throughput Distribution

The UE Tput distribution is a good indicator of the Quality of Service and fairness being provided. It reveals the range of data rates experienced by UEs at different locations within the coverage area of the network. This is usually analysed during fully loaded ‘busy hour’ conditions where UE data rates are lowest.

Figure E-8: Illustration of UE Throughput Distribution

Figure E-8 illustrates a typical UE throughput distribution, and the following quality metrics which can be derived from it.

Measures of QoS
As we have seen from the analysis of the scheduler, it is possible to tune each of these metrics individually, and so without some guarantee of fairness, we cannot assume for example, that high peak rates implies high average rates or good coverage.

Figure E-9 shows a normalised throughput distribution from the 3GPP performance verification work. The actual data rates are normalised to the average in order to compare them to a fairness criterion, illustrated by the pink line. The criterion is that 5% of UEs must achieve more than 5% of the average rate, and 10% more than 10% of the average rate, etc.

![Figure E-9: Normalised UE throughput distributions compared to 3GPP fairness criterion (pink) (Source: Motorola)](image-url)
Appendix F 4G Technology Components

This chapter presents an analysis of the component technologies which are being added to the already standardised “3rd Generation” Radio Access Networks in order to meet ITU-R’s requirements for IMT-Advanced. The following technology components are analysed:

- Support of Wider Bandwidths (Carrier Aggregation)
- Femtocells
- Co-ordinated Multi-Point (CoMP) Transmission and Reception
- Enhanced MIMO and Beamforming
- Relaying
- Offload

For each technology component we:

- describe how each component works
- highlight the potential benefits they bring to capacity, spectral efficiency, and the user throughput distribution
- indicate areas which are challenging in order to realise these benefits in practice
- highlight the implications for 4G spectrum

F.1 Support of Wider Bandwidths & Carrier Aggregation

F.1.1 Description

The need for wider bandwidths

In general, link capacity can be expressed as follows:

\[
\text{Link capacity} = \text{bandwidth} \times \text{spectral efficiency}
\]

LTE Release 8 can achieve a downlink capacity of 300Mbps in a 20MHz channel by combining 64 QAM modulation with 4x4 MIMO. As discussed elsewhere, LTE-A will enable up to 8x8 MIMO which, in the right conditions, could double the downlink capacity to 600Mbps. However, in order to achieve peak rates exceeding 1Gbps, bandwidths wider than 20MHz will be needed.

Carrier Aggregation

LTE Release 8 already supports scalable bandwidth, and can operate in channel bandwidths of 1.4, 3, 5, 10, 15 and 20MHz. For support of wider bandwidths in LTE-A, 3GPP decided to aggregate multiple ‘component carriers’ (CCs) rather than simply increasing the bandwidth of a single carrier. This has benefits for backward compatibility and support of aggregation over non-adjacent spectrum allocations, as outlined in the benefits section. Figure F-1 illustrates a number of different scenarios for support of variable bandwidth in both LTE rel-8 and LTE-A.
An outline of the proposed implementation of carrier aggregation in LTE-A can be found in Figure F-1. Some points to note are as follows:

- Up to 5 CCs can be supported by an LTE-A terminal, to provide up to 100MHz transmission bandwidth.
- For LTE FDD, it is not necessary to have the same number of CCs on uplink and downlink, nor need they sum to the same overall bandwidth. For TD-LTE there may be some constraints.
- LTE-A terminals can potentially transmit and receive simultaneously on multiple CCs. A rel-8 terminal can only transmit and receive on one rel-8 configured component carrier at a time.
- It is not clear from the feasibility study whether or not component carriers can only be aggregated if they originate from the same eNodeB.
- The DL control channel of one carrier can be used to schedule DL and UL resources on other carriers.
- 3GPP descriptions to date do not preclude the design of a new LTE-A only component carrier, which could be optimised to be used specifically as a component. e.g. no need for broadcast information.
- Further details of the implementation can be found in F.1.2

### F.1.2 Benefits

- **Data rates will increase in proportion to total aggregated carrier bandwidth.** Unlike some technologies, wider bandwidths improve performance for all UEs.
- **Combine non-contiguous spectrum allocations:** Component carriers do not need to be adjacent in frequency. Operators can deliver higher performance by combining any set of spectrum blocks.
- **Backwards compatibility:** Whilst LTE-A terminals will be able to combine multiple component carriers, legacy rel-8 terminals will still be able to connect to any one component.
- **Support of aggregation over two different bands:** For example, a terminal could communicate using both 800MHz and 2.6Ghz bands simultaneously. This may facilitate operators in providing both seamless coverage everywhere as well as high capacity to hotspots.
- **Simultaneous Communication with multiple eNodeBs (need to verify):** If component carriers were transmitted/received from different eNodeBs (e.g. an 800MHz grid and a 2.5GHz grid),’macro diversity’ type coverage benefits could be achieved.
- **Simplified RF emissions specification and testing:** Wider carriers create wider emission spectra, which can interfere with systems in neighbouring spectrum. By keeping to the 20MHz already specified for LTE...
rel-8, no new work will be needed. RF Specification for the many bandwidth combinations in LTE rel8 was complex.

F.1.3 Challenges

- **Co-ordination of band combinations that terminals will support.** Mobile equipment and chipset manufacturers will need to choose sets of bands over which aggregation will be supported. This issue generally applies to multi-band support rather than aggregation in particular.
- **Regulation to ensure operators have comparable spectrum portfolios.** Aggregation can be a powerful tool for operators to combine their spectrum holdings to be able to provide both wide coverage as well as higher capacity to hotspots. This will in turn place onus on the regulator to ensure that no one operator has a significantly advantageous portfolio compared to others.
- **Simultaneous transmit & receive in multiple components.** For 100MHz aggregation, the UE will need to simultaneously transmit and/or receive 5 components, possibly across multiple bands. It will be a significant challenge to manufacture RF components in terminals that can do this in practice and there will inevitably be a degradation in RF performance as the number of bands is increased.
- **Power Limits.** To fully realise the benefit of wider bandwidth, power spectral density should be constant, and thus total power will need to increase in proportion to the bandwidth. This has implications for health limits and battery life of terminals.

F.1.4 Summary of Impact & Opportunities for 4G Spectrum

Carrier aggregation presents a great opportunity for LTE operators to make more flexible use of blocks of spectrum without needing to re-organise into continuous allocations. It also allows regulators to make available spectrum for 4G services more progressively as particular bands are cleared of existing services, thereby delivering more capacity into the market at a given time and potentially allowing more operators to deliver a given level of service. It does not increase spectral efficiency, but does increase the accessibility of different blocks of spectrum in an operator’s portfolio. Figure F-2 shows a number of aggregation scenarios where spectrum resources of two networks can be combined. Note that in LTE-A, aggregation of up to 5 carriers is possible.
Since LTE FDD can allow different bandwidths and numbers of component carriers on uplink and downlink, it would be possible to vary the ratio of spectrum allocated to UL vs. DL. It may also be possible to deploy a DL (or UL) in an unpaired spectrum block, although this is likely to require a LTE-A component.
F.2 Femtocells

F.2.1 Description

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

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

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

Femtocells in the standards

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

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

Differences between home and enterprise femtocells

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

Motivation for enterprise femtocells is to:
- Provide coverage more easily in indoor environments
- Offload capacity from the macro layer to small cell architectures
- Improve user experience by providing a better SINR so data rates are better
- Reduce the cost of delivering high quality service to subscribers – papers from Signals Research Group (SRG) and Femto Forum indicate a 4-100 times cost reduction per GB with femtocells compared to macrocells, depending on the architecture, backhaul and traffic routing adopted in both the macrocell and femtocell layers [96].

A high level femtocell network architecture is shown in Figure F-3 which highlights where the femtocell is situated in the wider (macro layer) network context. The capacity enhancement takes place due to the dedicated network resource provision with little or no contention to access the radio network, combined with a typically higher SINR across most of the cell.
F.2.2 Benefits

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

Femtocells bring benefits to both users and operators.

The benefits to users include:

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

The benefits to operators include:

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

The two main benefits of deploying femtocells in relation to 4G capacity enhancements include:

- Femtocells provide enhancement to capacity
  a. Fundamentally femtocells enable spectrum to be reused at a higher density, delivering and increased capacity density which can be matched to hotspots of demand, provided interference between cells can be properly managed.
  b. The resulting capacity gains for the network as whole can be large, with for example a gain of around 100 times for a given user throughput indicated in [98] for 3G.
  c. Real-world deployments have now demonstrated femtocells working on the same carrier as macros without interference issues. For example, AT&T have indicated that they are successfully operating femtocells co-channel with both GSM and UMTS macrocells [99].
- Spectrum efficiency improvements
  a. Smaller cells give a better SINR distribution and result in improved spectral efficiency (see chapter 4)
  b. Higher channel rank should mean MIMO works better
F.2.3 Challenges

Many of the early challenges in femtocell deployment have been overcome. For example the interference issues that have been highlighted from early deployments have now been resolved by introducing interference mitigation techniques which enables co-channel operation between the femtocell and macrocell.[98]. Furthermore, the regulatory implications for unregulated use of spectrum by a consumer (that does not hold a licence) has been resolved in many territories, on the basis that the operator retains control of the femtocell transmission via the authenticated secure tunnel created between the femtocell and the operator’s core network.

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

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

F.2.4 Impact and Opportunities for 4G Spectrum

- Improvements to spectral efficiency can be realised through enhanced MIMO
- Speed up deployment/introduction of high end devices based as home mobile broadband access increases
- There are practical limitations to the deployment of femtocells such as the number of antennas that can be deployed within a residential environment. This will be limited based on the small equipment form factor. However, it may be more flexible to deploy more antennas for enterprise femtocells as there is likely to be a more professional installation.

F.3 Co-ordinated Multi Point (CoMP)

F.3.1 Description

In a cellular network, most UEs can hear (or be heard) by more than one cell. In a basic system, we consider the strongest signal to be the serving cell, and all others to be interferers. The premise of CoMP (Co-ordinated MultiPoint) is that cells share information to either reduce other cell interference or harness it to improve network capacity. Figure F-4 illustrates the key concepts of CoMP. In LTE, the X2 is an optional interface between eNodeBs which can be used for co-ordination.
Figure F-4: Co-ordinated Multipoint Transmission Concepts
We can imagine that the highest uplink theoretical capacity could be achieved by sending all the complex voltage waveforms received on each antenna element of all base stations to a massive central processing unit. This could extract and combine signals from each UE as well as cancelling known interference from other UEs. Similarly on the downlink, signals for all UEs could be optimally transmitted from all eNodes taking into account all complex channel responses of all UEs. In practice this approach would not be viable as the backhaul, synchronisation and processing requirements would be prohibitive. However, schemes have and are being specified for LTE and LTE-Advanced which can achieve some of the benefits with practical levels of information exchange and processing. These largely fall into two groups as follows:

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

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

Figure F-5 Intra and Inter eNodeB CoMP
The benefits of CoMP come at the expense of information sharing between cells. Such sharing is not always a problem as illustrated by the three scenarios in Figure F-5.

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

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

3) UE 3 uses intra eNodeB CoMP between different Remote Radio heads. Since these are linked to their controlling eNodeB with the OBRI interface (a digitised baseband waveform), CoMP does not impact the bandwidth requirement.

Furthermore it should be noted that intra eNodeB CoMP can use proprietary algorithms, whereas inter-eNodeB needs to be standardised to work in a multi-vendor environment.

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

**F.3.1.1 Downlink CoMP**

**Inter-Cell Interference Co-ordination (ICIC)**
ICIC is a simple CoMP scheme that was standardised in rel-8 LTE. This falls under the co-ordinated scheduling category, as each UE has one serving cell. Figure F-6 illustrates a scenario where co-ordination improves capacity. The diagrams show two cells each serving one user. In a) both UEs are near to their cells, so the wanted signal is much stronger than the interfering signal. Maximum capacity is achieved by both cells transmitting maximum power. In scenario b), the UEs are near the cell edge, so the wanted and
interfering signals are at similar levels. Working individually, each cell could maximise its UE throughput by transmitting more power. However the combined capacity will be higher if they co-ordinate so that only one of the cells transmits at a time (on a given frequency) and the other transmits nothing.

Figure F-6: Scenarios to illustrate benefit of Inter cell Co-ordination

In practice this can be achieved by categorising UEs as either cell-centre or cell-edge, and schedulers in adjacent cells co-ordinating to ensure no two adjacent cell edge UEs transmit on the same frequency resource as illustrated in Figure F-7. In this example, cell centre UEs have N=1 reuse (all cells reuse the same frequency resource), whereas the cell edge is effectively N=3 reuse, where each cell edge region can only use a third of the spectrum. This is similar to the frequency reuse patterns used in early 2G networks (before frequency hopping), where the reuse factor allows a trade between cell capacity and cell edge performance. The reader should be aware that in a real world propagation environment with terrain and clutter, the division between cell edge and centre would not be as neat as that shown in Figure F-7. The criteria for deciding whether a UE is cell edge or centre would be based on signal strength/quality rather than its geographical location relative to the cell sites.

Figure F-7: Fractional Frequency Reuse in ICIC 101 Omni eNodeBs shown for clarity

Static interference co-ordination requires cell planning to ensure no two neighbours share the same subset of the cell edge frequencies. This avoids any need for sharing of scheduling information over X2, but may have less benefit as it cannot adapt to time varying user distributions or variations in cell load. An example of this would be workers moving from offices areas to restaurant areas during their lunch break. Semi-static interference co-ordination allows reconfiguration of the frequency subsets over a timescale of a few seconds. This achieved in LTE rel-8 by signalling a bitmap over X2 whether each RB has a high power or a lower power. Other information relating to load or cell size may also be shared.

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

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

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

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

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

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

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

F.3.1.2 Uplink CoMP

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

**Co-ordinated Scheduling and Beamforming**

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

**Joint Reception**

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

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

F.3.2 Benefits

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

Results of the 3GPP feasibility study show clear benefits to downlink cell spectrum efficiency. With 4 tx antennas at the eNodeB, gains of over 30% are achieved with for Co-ordinated Scheduling and beamforming, and over 50% for Joint Processing CoMP, as shown in Figure F-8. Figure F-9 shows more simulation results with more modest gains in Cell SE for all but the most sophisticated of schemes. None of the Single User schemes achieve more than 11% benefit to SE compared to Rel8 LTE. Note that the antenna configuration has not been stated and a 2x2 configuration would result in lower gains, as shown by the 3GPP results in Figure F-8.
Figure F-8: Benefit of LTE-Adv DL CoMP Schemes over Rel8 LTE: Source 3GPP Feasibility Study103, Real Wireless Analysis

Figure F-9 shows benefits of CoMP for Cell edge User throughput of around 10-20% for the single user cases. It is these users with high interference levels that should get the most benefits of CoMP, and the result should be a fairer network able to guarantee a higher minimum throughput. Qualcomm results for CoMP shown in Figure F-10 support this view, but show that the benefit to cell edge UEs comes at the cost of the 50% and 95%-ile with median and peak UE throughputs, respectively. These results suggest that CoMP can alter the shape of the UE tput distribution, but do not bring a net improvement. The lack of benefit to the median (50%ile) UE Tput implies that cell spectral efficiency would not improve. The simulations assumed a 1x2 antenna configuration, which suggests that CoMP needs to be deployed in combination with MIMO to provide benefits. Figure F-8 above showed that higher gains are achieved with the higher order antenna configurations.

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38 Coordinated Beam Switching (CBS), Non-Coherent Joint Processing (JP-Nco), Coherent Joint Processing (JP-Co), Coordinated Beamforming (CBF) Intra-Site Coherent JP
Figure F-10: Qualcomm Paper on Joint Transmission in 1x2 configuration shows that whilst the proposed schemes improve 5%-ile UE Tputs, they actually degrade median and 95%-ile throughput.

Figure F-11: Co-ordinated Scheduling simulation results (Source: Alcatel-Lucent)

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

F.3.3 Challenges

- Inter site CoMP uses backhaul bandwidth on the inter eNodeB X2 interface. Increased backhaul provisioning may increase costs for operators.
- Benefits of inter-site CoMP are sensitive to backhaul latency for the X2 peer-peer interface between eNodeBs, as shown in Figure F-12. Low latencies less than 5ms are needed to realise useful gains. This could be a challenge for ‘untrusted’ backhaul networks, where X2 links must pass through centralised security gateways.
F.3.4 Impact and Opportunities for 4G Spectrum

- Enhances spectrum efficiency typically by around 10-20%, or as much as 60% in sophisticated configurations.
- Improves data rates for cell edge users by similar amounts, so has benefits for the minimum offered quality of service. CoMP works in interference limited scenarios (e.g. dense urban), but not in link budget limited scenarios (e.g. rural)

F.4 Enhanced MIMO and Beamforming

F.4.1 Description

LTE-Advanced will introduce the following MIMO enhancements over LTE release 8:

Downlink:
- **Up to 8 layer transmission** enables the use of up to 8 antennas at the eNodeB, which can increase peak rates and/or spectral efficiency given suitable antennas and propagation conditions. Higher numbers of layers are aimed for use in array antennas, possibly with cross polar elements. E.g. a four beam per sector dual polar antenna would require 8 layers.
- **Multi User MIMO, with fixed or adaptive beams.** MU-MIMO enables transmission for multiple UEs in the same spectral resource at the same time. This is akin to SDMA (Space Division Multiple Access) where a sector is further divided into beams, in which the spectral resource can be reused for several users. MU-MIMO was possible in the Rel8-uplink, and is being added to the release 10 downlink. MU-MIMO can work with fixed or adaptive beams, where the latter requires UE specific reference signals that undergo the same pre-coding as the user traffic. UE specific Reference signals enables correct evaluation of channel state information at the UE. It is expected that adaptive beam MU MIMO will bring higher capacity.
- **Network MIMO: another name for CoMP.** CoMP and MIMO are closely related as both involve processing of transmissions and/or reception over multiple antennas. CoMP can be distinguished by the fact that the multiple antennas are located at different eNodeBs. MIMO implies multiple antennas at a single eNodeB, but potentially multiple UEs, as in the case of MU MIMO.

Uplink:
- **Single User MIMO.** Enables a UE to transmit on multiple layers. Release 8 only supported a single layer per UE on the uplink (but did support MU-MIMO). This increases the peak rate that can be achieved at high SINRs.
- Up to 4 layers
- MU-MIMO Enhanced with CoMP. CoMP and MIMO are closely related as both involve
  Single User MIMO up to 4 layers (rel-8 only supported Multi-User MIMO on UL)
  Multi User MIMO enhanced by joint transmission (see CoMP)

**F.4.2 Benefits**

Figure F-13 illustrates the relative benefit of transmit and receive antennas in MIMO configurations. Doubling the number transmit antennas (1x2 vs. 2x2, or 2x4 vs 4x4) improves throughput at higher SINRs only, and so spectral efficiency will only occur in environments with a prevalence of higher SINR conditions, such as small cells. Increasing the number of receive antennas (2x2 vs 2x4) improves throughput across the whole range of SINR, and should therefore provide capacity gains in any environment.

![Figure F-13: Single User MIMO Benefits. Source 3G Americas, Real Wireless graph](image)

In addition to SINR, suitable combinations of multipath conditions and antennas are also required to ensure that the channel can be ‘decomposed’ into orthogonal propagation modes. This generally requires rich multipath scattering, although it should be noted that dual polar MIMO can provide orthogonal propagation modes without the need for scattering. MIMO channel and antenna combinations can be characterised by matrix parameters such as ‘rank’ which indicates the number of layers that can be supported and ‘condition number’, which indicates how reliably multilayer transmission can be achieved. Figure F-14 illustrates the prevalence of multilayer transmission (ranks higher than 1) in field trials of 2x2 and 4x4 MIMO with various cross polar antenna configurations. The impact on the user throughput distribution is also shown. The figure shows the importance of the UE antenna configuration, with the dual polar UE (labelled |-) achieving rank 2 significantly more than the single polar UE (||). Similar trends can be seen with the 4x4 configuration. Of note also is that the prevalence of rank 4 transmission is very low, occurring in only 1 or 2% of locations in the cell. This does not mean that 4x4 configurations are of no value, as significant throughput benefits can still be observed over 2x2. The 4x4 configurations have a higher prevalence of multi layer transmission (rank>1) than 2x2 configurations. Other trials results in the Ericsson paper showed that 4x4 increased average user throughput by 50% compared to 2x2. This is indicative of the gains in cell spectral efficiency that could be achieved, and aligns well with simulation results shown later in Figure F-16.
Figure F-14: Prevalence of Multilayer Transmission in MIMO Propagation Trials. Copied from Ericsson Review\textsuperscript{110}. Note that x indicates a cross polar eNodeB antenna, and | and – indicate vertical and horizontal UE antennas.

Figure F-15: Benefit of LTE-Advanced DL MIMO Schemes over LTE Rel. 8 4x2. Source: 3GPP\textsuperscript{111}, Real Wireless analysis. Assumes eNodeB antenna configurations of |||| and XXXX for 4 and 8 way tx, respectively.

Figure F-15 summarises the benefits of the LTE-Advanced MIMO schemes over a baseline Release 8 SU-MIMO 4x2 scheme, in both Macrocell and Microcell environments. The 4x2 configurations show the benefit of the enhanced MIMO processing is around 30-50%. Doubling the number of transmit antennas to 8 brings further gains, especially in the macrocell environment. This is the reverse of the mechanism seen in Figure F-13, where Tx antennas provided more gain in higher SINR environments. This may be because in this case, the number of Tx antennas (8) greatly exceeds the Rx (2).

Figure F-16 illustrates the benefits of higher order MIMO configurations with Rel 8 SU MIMO, as well as LTE-Advanced MU-MIMO and CoMP schemes. As before, we see that LTE-Advanced schemes are able to extract more benefit from the higher order schemes, with 4x4 JP CoMP achieving almost 2x the spectral efficiency as the 2x2 equivalent. The same antenna upgrade with Rel8 MIMO would only have brought 1.5x benefit.
In summary: Enhanced MIMO processing in LTE-Advanced can enhance the performance of a given MIMO configuration by 20-50%, with greater benefits for 4tx configurations than for 2tx. Increasing the number of antennas generally improves spectral efficiency. Both Trials and simulations of Rel 8 LTE indicate a 50% increase in cell spectrum efficiency is achieved with 4x4 compared to 2x2. With LTE Advanced schemes, up to 2x benefit could be achieved by doubling the number of antennas at both ends of the link. Upgrading the eNodeB to 8 antennas can bring further gains. 8x2 SU-MIMO gave over 2x the cell SE compared to the same scheme with 4x2 configurations.

F.4.3 Challenges
- It is difficult to design multiple diverse antennas on small form factor terminals, especially at low frequencies, see Varall
- MIMO cell site antennas may need to be larger, increasing site leasing costs
- MIMO requires high SINR and rich scattering. If this combination of conditions does not occur very often in the target environment, then benefits will be low.

F.4.4 Impact and Opportunities for 4G Spectrum
- Increasing the number of receive antennas in a MIMO configuration increases spectral efficiency
- Increasing the number of transmit antennas increases peak rates at high SINR, but will only increase spectral efficiency if higher SINRs are prevalent in the environment. Small cell environments tend to have higher SINRs, hence greater MIMO benefits.
- MIMO Gains may be greater at higher carrier frequencies, where the smaller wavelength facilitates better antenna design for a given form factor.

F.5 Relaying

F.5.1 Description
Relays can be deployed in a number of scenarios to improve performance. They can be used to extend coverage and/or improve data rates in areas which would otherwise low signal quality. Other applications are temporary sites (at events, or in emergency scenarios), or on a moving vehicle such as train, to improve link stability and handle ‘group handover’. Relays might also be used during initial roll out to reduce costs of installing dedicate bandwidth to each eNodeB. A relay can be ‘upgraded’ to a eNodeB when justified by capacity demand.
A relay is like an eNodeB that uses the LTE air interface itself as a backhaul link, rather than another technology such as fibre or microwave. It provides a benefit because the signal paths from ‘donor’ eNodeB to Relay Node (RN) to UE are better than a direct eNodeB – UE connection. For example, a relay may be located above local clutter, providing both good coverage of the local area as well as a clear link back to the donor cell.

Figure F-17: Types of Relay Considered for LTE-Advanced

Figure F-17 illustrates several types of relay under consideration for LTE-Advanced. A Type 1 relay looks to UEs like a separate cell. It has its own cell identity, and transmits synchronisation signals, reference signals etc. It appears to Release 8 UEs as a normal rel 8 eNodeB, whilst release 10 UEs will be able to differentiate a relay for potential performance enhancement. A type 1 relay operates ‘inband’ where the eNodeB-relay link (Un) shares the same carrier frequency as the relay – UE link (Uu). These links need to be time division multiplexed to avoid interference. A type 1a relay is the same as type 1, but operates ‘outband’ where the Un uses a different carrier frequency to the Uu.

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

F.5.2 Benefits

Relays are primarily a coverage enhancing technology rather than a capacity enhancer. Simulation results based on 3GPP assumptions show around 19% improvement to cell edge user throughput, and 10% gains to cell throughput or Cell spectral efficiency, as shown in Figure F-18.

Figure F-18: Benefits of Type 1 relays (3 RNs per cell, 2x2 DL MIMO). Source: 3G Americas
F.5.3 Challenges
Relays are not a new technology as such, and are already used in existing cellular networks. The main challenge of self interference can be overcome using time division multiplexing of signals to and from the relay node. Perhaps the main challenge is in the business model: Relays have all of the site costs of a normal cell site minus the backhaul, but provide only a fraction of the capacity and coverage enhancement of a normal eNodeB.

F.5.4 Impact and Opportunities for 4G Spectrum
An in-band relay uses part of the spectrum for access, and part for self backhauling. This makes better use of the mobile broadband spectrum, but may displace other technologies like microwave backhaul, so may reduce the usage of other types of spectrum.

F.6 Offload
Offload provides a way to divert certain internet traffic away from operator’s wide area cellular networks. The two components of offload are illustrated in Figure F-19. Consumers can connect to data services over an alternative access such as a Femtocell or a Wi-Fi hotspot, offloading the operator’s wide area Radio Access Network. Whilst this does not change the spectral efficiency of either technology, it does enhance the capacity available to consumers. Typically the access offload would be a low cost small cell technology that is deployed by the consumers (or organisations) where capacity is most needed.

A second component to offload is in the operator’s core network, where internet content can be separated from operator managed services (e.g. Voice or mobile TV). Only the managed services need to pass through the operators core. 3GPP are standardising a core offload technologies called SIPTO (Selective IP Traffic Offload) for LTE-Advanced. A similar technology called LIPA (Local IP Access) is used to offload traffic for local services such as printers or file servers. Details of these techniques can be found in 115

Benefits to Spectral efficiency: Offload does not increase the spectral efficiency of a cellular network. It provides an alternative access method which is better suited to certain user locations (indoors) and traffic types (internet). Since the majority of internet traffic is consumed from indoor locations, offload does however significantly improve the useful capacity, by increasing cell density and in the case of Wi-Fi, the accessible spectrum.
### F.7 Summary of Technology Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Benefit to Cell Spectrum Efficiency</th>
<th>Impact to Quality of Service</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Aggregation</td>
<td>1x</td>
<td>Wider bandwidths mean higher user rates Possible improvement in cell edge from macrodiversity</td>
<td>Agreeing subsets of bands that devices will support</td>
</tr>
<tr>
<td>Femtocells</td>
<td>1.6 - 1.7x</td>
<td>Improved indoor coverage</td>
<td>Getting SON to work on a very large scale. Developing low cost femtocells</td>
</tr>
<tr>
<td>CoMP</td>
<td>1.1 – 1.3x</td>
<td>Enables flexibility in trading cell edge for average and peak performance.</td>
<td>Backhaul latency</td>
</tr>
<tr>
<td>DL MIMO</td>
<td>1.3-1.5x same antenna config. 2x for 8x2 c.f. 4x2</td>
<td>LTE-Adv schemes improve cell edge users for given config, over rel 8</td>
<td>Antenna and multi radio design for small form factor terminals.</td>
</tr>
<tr>
<td>Relays</td>
<td>1.1x</td>
<td>Improve coverage and cell edge data rates</td>
<td>Relays have similar costs to eNodeB, but a fraction of the benefits</td>
</tr>
<tr>
<td>Offload</td>
<td>1x</td>
<td>Reduces loading on wide area networks -should improve QoS</td>
<td></td>
</tr>
</tbody>
</table>

Table F-1 Summary table of 4G technologies

![Figure F-20: 4G Technology components and their benefit to Cell Spectrum Efficiency. Note that technologies may bring other benefits not shown here, such as improved cell edge performance.](image-url)
Appendix G  Summary of stakeholder feedback

G.1  Stakeholder who participated in the study
As part of this study we contacted stakeholders in the cellular industry to get a first hand view of the expected gains of 4G networks and the factors impacting these. We are grateful to the following organisations for responding to our stakeholder questionnaire and/or taking the time to participate in stakeholder interviews:

- Operators
  - Four major cellular operators
- Vendors
  - Alcatel Lucent
  - Agilent
  - Anritsu
  - Nokia Siemens Networks
  - NEC
  - Motorola
- Industry associations
  - GSMA
  - GSA

G.2  Stakeholder views
Stakeholder comments are distributed throughout the final report to sanity check assumptions that we have made in this study. In this section we summarise the key areas that were consistently highlighted by stakeholders which were:

- Impact of traffic type and QoS requirements on spectrum efficiency in real networks
- Roadmap of features for 4G technologies
- Views on the gains of 4G and 3G
- Areas to be wary of when interpreting simulation results
- Good correlation between LTE trials results and performance expected from simulations

Impact of traffic type and QoS requirements on spectrum efficiency in real networks
Performance results from 3GPP and ITU for 3G and 4G technologies present cell capacity in two ways:
- Cell throughput in Mbps for full buffer streamed traffic
- Number of supported voice calls

Stakeholders have consistently highlighted that the mix of traffic in 4G networks is an important factor in determining capacity. It seems that this is an area of significant work amongst vendors currently but unfortunately relatively few public domain results were available in the time span of this study. Stakeholder comments collectively identified the following three factors that will alter spectrum efficiency in real network deployments due to QoS commitments:

- Loading - Chapter 4 includes results from NEC\textsuperscript{116} which show that loading must be reduced from the 100% levels implicit in full buffer simulations to guarantee a minimum mean user throughput for all users across the cell. The higher the target user throughput the lower the loading must be. Stakeholders indicated that cells may be loaded on average at 50% in real networks but that in peak demand areas this was likely to increase to up to 85%.
- Reduction in spectrum efficiency due to traffic type – Many vendors are currently examining the impact of different traffic types on spectrum efficiency. In particular many have run simulations for fixed filesize traffic scenarios where the scheduler is forced to support equal consumption of traffic


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across users in the network rather than the full buffer scenario where users with the best SINR will consume the most traffic. Unfortunately few results were available in this area in the timescales of this study and so this is an area recommended for further work.

- Potential trunking gains at wider bandwidths when high user throughputs must be guaranteed – Stakeholders indicated that when high user throughputs must be guaranteed there is some evidence that operators with wider bandwidth allocations i.e. 20MHz LTE as opposed to 10MHz will benefit from trunking gains. However, results in this area are sparse and so this area is recommended for further investigation.

**Roadmap of features for 4G technologies**

To support development of the roadmap of 4G features presented in chapter 6 we asked stakeholders their views on the timelines for LTE, LTE-A, WiMAX and WiMAX2. The following areas were highlighted:

- 4G handsets will take time to become available and so the initial focus in 4G networks will be on dongles and data only devices
- 8 antenna basestations are being developed for the Asian market and so are not as far off from a technical perspective as you might think. Deployment of 8 antenna basestations is therefore driven more by cost and the size restrictions on sites rather than being technically feasible.
- The industry is generally quite sceptical of the benefits of CoMP. It is seen as a very complex feature to implement that is likely to only give up 10% improvements in capacity in practice which doesn’t justify the deployment cost. Low latency backhaul is also a key barrier to the deployment of CoMP.
- Stakeholders consistently highlighted that smaller cell topologies will be central to 4G. They also highlighted that the availability of spectrum and any coverage requirements placed on it will determine the feasibility of having separate carriers for small cell networks.
- It was highlighted that spectrum rather than technology readiness will determine the deployment timescales of LTE in the UK.
- The operators we spoke to considered LTE and its evolutions rather than WiMAX as central to 4G networks in the UK.

**Views on the gains of 4G and 3G**

The table below summarises the comments received from various stakeholders on the improvements that they expect from 4G over 3G.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Comparison scenario</th>
<th>Stakeholder trials/expectations</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNO 1</td>
<td>LTE Rel-8, SU-MIMO 2x2 vs. HSPA Rel-6, SISO 1x1, 5 codes, 16QAM, Rake + signalling over HSPA</td>
<td>2.5 to 3.75 times</td>
</tr>
<tr>
<td>Vendor 1</td>
<td>LTE Rel-8, SU-MIMO 2x2 vs. HSPA Rel-6, Rx Div 1x2, 15 codes, Advc Rcvr + signalling over dual cell HSPA</td>
<td>1.8 to 2 times</td>
</tr>
<tr>
<td>MNO 2</td>
<td>LTE Rel-8, SU-MIMO 2x2 vs. HSPA+ Rel-7, MIMO 2x2, 16QAM</td>
<td>1.3 to 1.5 times</td>
</tr>
<tr>
<td>MNO 3</td>
<td>LTE Rel-8, SU-MIMO 2x2 vs. HSPA+ Rel-7, 64QAM, 15 codes</td>
<td>1.3 to 1.8 times</td>
</tr>
</tbody>
</table>

Table G-1: Summary of stakeholder comments re 4G Vs. 3G gains

**Areas to be wary of when interpreting simulation results**

Stakeholders highlighted that performance results from simulations are for idealised, standard test environments that may not necessarily be replicated in real networks. In particular concerns were raised
about how realistic the 3GPP test environments assumed for evaluating LTE-Advanced were and it was highlighted that the 3GPP evaluation of LTE differed from LTE-Advanced in the following areas:

- 3D antenna patterns are assumed for 3GPP LTE-Advanced performance evaluation
- A regular cell layout grid is assumed for 3GPP LTE-Advanced whereas a more realistic irregular grid was used for LTE field performance evaluation.

**Good correlation between LTE trials results and performance expected from simulations**

Stakeholder comments consistently highlighted that LTE trial results were meeting their performance expectations originally set from simulations. For LTE-A most stakeholders indicated that it is too early to say which of the features proposed will be realised in practice. In particular, CoMP was repeatedly highlighted as an LTE-A feature that looked likely to be complex to implement, with some uncertainty over whether gains promised by early simulations would be realised in practice. Further analysis of this feature is due under LTE release 11.
Appendix H  Typical macro and micro cell distribution in a
dense urban area

In this study we have assumed that a typical dense urban deployment will be similar to the ITU base urban coverage test environment which assumes an inter site spacing (ISD) of 500m. The next candidate test environment is the ITU microcellular environment which assumes an ISD of 200m. Real dense urban environments are likely to be a mixture of these two cases. In determining capacity gains through increased sector density of small cells it is important to understand what is a realistic sector density baseline for a dense urban scenario. Examining current basestation sites in a dense urban area of London on Ofcom’s Sitefinder it can be seen that site densities on 3G networks are closer to the ITU macrocell than microcell case.

Figure H-1 shows the Sitefinder results for basestations located in an area 750mx750m centred on the Ofcom offices at Riverside house in London. This is an example of a typical dense urban deployment. As can be seen from Table H-1 some operators have only macrocells in this area and others have a mixture of micro and macro cells. On average operators have 3 sites in this area giving an average cell area of 0.188km² and an ISD of 465m. This is closest to the ITU base urban coverage assumption.

<table>
<thead>
<tr>
<th>Base stations displayed in this square</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Single operator GSM technology</td>
<td>12</td>
</tr>
<tr>
<td>Single operator UMTS technology</td>
<td>1</td>
</tr>
<tr>
<td>Single operator TETRA technology</td>
<td>0</td>
</tr>
<tr>
<td>Shared base stations with more than one operator or more than one technology</td>
<td>12</td>
</tr>
</tbody>
</table>
Figure H-1: Sitefinder results for area 750mx750m centred on Ofcom building at SE1 9HA (Source: Ofcom)

Table H-1: UMTS sites from Sitefinder result for SE1 9HA

<table>
<thead>
<tr>
<th></th>
<th>Micro</th>
<th>Macros</th>
<th>Total sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Three</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Vodafone</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>O2</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>T mobile</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
<td>11</td>
<td>15</td>
</tr>
</tbody>
</table>
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