Lionel Fuependap Metuge Reya

4G Technology Features and Evolution towards IMT-Advanced

Faculty of Electronics, Communications and Automation

Thesis submitted for examination for the degree of Master of Science in Technology.

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Thesis supervisor:
Professor Jyri Hämäläinen

Thesis instructor:
Researcher Mika Husso (M.Sc.)

Aalto University
School of Science
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AALTO UNIVERSITY SCHOOL OF SCIENCE AND TECHNOLOGY	ABSTRACT OF THE MASTER'S THESIS

Author: Lionel Fuependap Metuge Reya

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Faculty of Electronics, Communications and Automation

Department of Communications and Networking Technology

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Supervisor: Professor Jyri Hämäläinen

Instructor: Researcher Mika Husso (M.Sc.)

The demand for affordable bandwidth in fixed and mobile services is growing rapidly around the world. The emergence of smart devices like the iPhone and Nokia N900, coupled with their high market penetration and superior user experience is behind this increased demand, inevitably driving the need for continued innovations in the wireless data technologies industry to provide more capacity and higher quality of service.

The term "4G" meaning the 4th Generation of wireless technology describes mobile wireless services which have been defined by the ITU's Radiocommunication Sector (ITU-R) and titled International Mobile Telecommunications-Advanced (IMT-Advanced). These are mobile systems that include the new capabilities of IMT that go beyond those of IMT-2000. Long Term Evolution-Advanced (LTE-Advanced) and IEEE 802.16m are the two main candidate technologies submitted for IMT-Advanced certification.

This thesis reviews the technology roadmap up to and including current 3G systems LTE from the 3rd Generation Partnership Project (3GPP) and IEEE 802.16e-2005 from the Institute of Electrical and Electronics Engineers (IEEE). Furthermore, new requirements and features for LTE-Advanced and IEEE 802.16m as well as a comparative approach towards IMT-Advanced certification are presented. Finally, the thesis concludes with a discussion on the market status and deployment strategies of LTE and IEEE 802.16e-2005, or Mobile WiMAX as it is being marketed.

Keywords: 4G, IMT-Advanced, 3GPP, LTE-Advanced, IEEE 802.16m, Mobile WiMAX

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Kiinteiden- ja mobiilipalveluiden kysyntä kasvaa nopeasti ympäri maailmaa. Älykkäiden päätelaitteiden, kuten iPhone:n ja Nokia N900:n markkinoilletulo yhdistettynä näiden korkeaan markkinapenetraatioon ja korkealuokkaiseen käyttäjäkokemukseen lisäävät entisestään palveluiden kysyntää ja luovat tarpeen jatkuvalle innovoinnille langattomien teknologioiden alalla tavoitteena lisäkapasiteetin ja paremman palvelunlaadun tarjoaminen.

Termi 4G (4th Generation) viittaa tuleviin neljännen sukupolven mobiileihin langattomiin palveluihin, jotka International Telecommunications Union:in Radiocommunication Sector (ITU-R) on määritellyt ja nimennyt International Mobile Telecommunications-Advanced (IMT-Advanced). Nämä ovat järjestelmiä, jotka pitävät sisällään IMT:n ne uudet ominaisuudet, jotka ylittävät IMT-2000:n vaatimukset. Long Term Evolution-Advanced (LTE-Advanced) ja IEEE 802.16m ovat IMT-A sertifiointiin lähetetyt kaksi pääasiallista kandidaattiteknologiaa.

Tässä diplomityössä esitellään kolmannen sukupolven järjestelmien kehityspolku LTE:hen ja IEEE 802.16e-2005 asti. Lisäksi työssä esitetään LTE-Advanced:n ja IEEE 802.16m:n uudet vaatimukset ja ominaisuudet sekä vertaillaan näiden lähestymistapoja IMT-A vaatimusten täyttämiseksi. Lopuksi työssä luodaan katsaus LTE ja IEEE 802.16e-2005 (markkinointinimeltään Mobile WiMAX) -järjestelmien markkinatilanteeseen.

Avainsanat: 4G, IMT-Advanced, 3GPP, LTE-Advanced, IEEE 802.16m, Mobile WiMAX

Dedicated to Sandra

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Espoo, 7 May 2010

Lionel F. M. Reya

Acronyms

3GPP	3rd Generation Partnership Project
3GPP2	3rd Generation Partnership Project 2
AAS	Adaptive Antenna System also Advanced Antenna System
ACK	Acknowledge
AES	Advanced Encryption Standard
AMC	Adaptive Modulation and Coding
A-MIMO	Adaptive Multiple Input Multiple Output (Antenna)
AMS	Adaptive MIMO Switching
ARQ	Automatic Repeat reQuest
ASN	Access Service Network
ASP	Application Service Provider
BRAN	Broadband Radio Access Network
CC	Chase Combining (also Convolutional Code)
CCI	Co-Channel Interference
CCM	Counter with Cipher-block chaining Message authentication code
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CINR	Carrier to Interference + Noise Ratio
CMAC	Cipher-based Message Authentication Code
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CSN	Connectivity Service Network
CSTD	Cyclic Shift Transmit Diversity
CTC	Convolutional Turbo Code
DL	Downlink
DSL	Digital Subscriber Line
DVB	Digital Video Broadcast
EAP	Extensible Authentication Protocol
EIRP	Effective Isotropic Radiated Power
ErtPS	Extended Real-Time Polling Service
ETSI	European Telecommunications Standards Institute
FCH	Frame Control Header
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FUSC	Fully Used Sub-Carrier
HARQ	Hybrid Automatic Repeat reQuest
HiperMAN	High Performance Metropolitan Area Network
HMAC	Hash Message Authentication Code
HO	Hand-Off or Hand Over
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
ITU	International Telecommunication Union
ISI	Inter-Symbol Interference
LDPC	Low-Density-Parity-Check
LOS	Line of Sight
MAC	Media Access Control
MAI	Multiple Access Interference
MAN	Metropolitan Area Network

MAP	Media Access Protocol
MBS	Multicast and Broadcast Service
MDHO	Macro Diversity Hand Over
MIMO	Multiple Input Multiple Output
MMS	Multimedia Message Service
MPLS	Multi-Protocol Label Switching
MS	Mobile Station
NACK	Not Acknowledge
NAP	Network Access Provider
NLOS	Non Line-of-Sight
NrtPS	Non-Real-Time Polling Service
NSP	Network Service Provider
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
PER	Packet Error Rate
PKM	Public Key Management
PUSC	Partially Used Sub-Carrier
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RRI	Reverse Rate Indicator
RTG	Receive/transmit Transition Gap
RtPS	Real-Time Polling Service
SDMA	Space (or Spatial) Division (or Diversity) Multiple Access
SGSN	Serving GPRS Support Node
SHO	Soft Hand-Off
SIM	Subscriber Identity Module
SIMO	Single Input Multiple Output
SINR	Signal to Interference + Noise Ratio
SMS	Short Message Service
SNIR	Signal to Noise + Interference Ratio
SNR	Signal to Noise Ratio
S-OFDMA	Scalable Orthogonal Frequency Division Multiple Access
SS	Subscriber Station
STC	Space Time Coding
TDD	Time Division Duplex
TEK	Traffic Encryption Key
TTG	Transmit/receive Transition Gap
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telephone System
USIM	Universal Subscriber Identity Module
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
VSM	Vertical Spatial Multiplexing
Wi-Fi	Wireless Fidelity
WAP	Wireless Application Protocol
Wi-Bro	Wireless Broadband (Service)
WiMAX	Worldwide Interoperability for Microwave Access

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1 INTRODUCTION

1.1 Problem Statement

The last few years have witnessed a staggering growth in the demand for high speed broadband services including internet access over mobile devices. To address this problem, the wireless telecommunication industry has been scrambling to define a new air interface for mobile communications so as to provide a framework for these high mobility broadband services and increase the overall system capacity, reducing latency, and improving spectral efficiency and cell-edge performance.

Not so long ago, 3G was discussed extensively and viewed as the future of wireless data technology. This technology is however still not universally available in many parts of the world, and already there is a race amongst new and emerging technologies to replace 3G. The term “4G” is a broad term that has been used in connection with several different aspects, and is therefore misleading. This is confirmed by a statement from N. Schmitz in 2005 [1]

> “Ask 10 people what 4G means and you’ll get 10 different answers. The more important question is: How do we get there?”

Today, one can easily get mixed up with the terms 3G and 4G which dominate advertisements and industry discussions and it is much more acceptable to speak of “Beyond 3G” technologies. It is important therefore to clarify the meaning of these terms amongst many others. It is also important to state what technologies fall under the different categories and how evolution is shaping the future of wireless broadband communication. In this thesis, the different technological paths leading up to 3G and beyond, including Long Term Evolution (LTE) by the 3rd Generation Partnership Project (3GPP) and Mobile WiMAX (IEEE 802.16e – 2005) are considered. In future references made in this document, the term 4G will refer to IMT-Advanced (International Mobile Telecommunications - Advanced) as defined by the International Telecommunications Union-Radiocommunication Sector (ITU-R) [2] and will include LTE-Advanced from 3GPP and IEEE 802.16m standard technologies, both candidates for the IMT-Advanced or 4G certification. In the mobile communications industry, it is generally agreed that 4G telecommunication systems will include an all-IP network, serving the end-users on an “anytime - anywhere” bases, with higher data rates than are currently available. The two IMT-Advanced candidates mentioned above will be considered in terms of their technological features as well as their individual approaches towards IMT-Advanced.

Finally, the current deployment and market status for LTE and Mobile WiMAX, supporting the need for a common unified and more advanced standard will be discussed.

1.2 Objectives and Scope

The main objective of this thesis is to create a better understanding of the term 4G as used in the telecommunications industry and the underlying technologies that are vying for this status, namely LTE-Advanced and IEEE 802.16m. A second objective of this thesis is the understand what factors today are driving the need for further enhancements in the mobile communications industry, forcing it to move from 3G to 4G and hence changing the way people will communicate in future.

The scope of the thesis includes:

- A review of the technology path adopted by the 3rd Generation Partnership Project (3GPP) up to and including Long Term Evolution (LTE).
- A review of the IEEE 802.16 standard evolution including IEEE 802.16e-2005.
- A study of the ITU-R's IMT-Advanced requirements and the enhancements carried out by the two main candidates for IMT-Advanced certification, IEEE 802.16m and LTE-Advanced.
- A discussion on the current deployments and market status of 3G systems, notably LTE and Mobile WiMAX as well as future trends in user demands which are driving the need for further enhancements and innovation in the mobile communications industry.

2 3GPP TECHNOLOGY PATH

2.1 Introduction

There is a tremendous increase in the demand and usage of wireless data nowadays. Accompanying this trend is the development of smart devices like the iPhone which are far reaching in their market penetration around the world. These smart devices make it possible for users to experience higher quality services never before conceived which in turn fuels demand for new data applications. To be able to keep up with this increasing demand from users, mobile communication technology companies are forced to review their strategies and to continue to work towards developing their wireless data technologies so as to be able to provide needed capacity as well as higher quality of service.

In 1998, a collaboration agreement known as The 3rd Generation Partnership Project (3GPP) was established [3]. 3GPP brings together several telecommunications standards bodies in the USA, Europe, Japan, South Korea and China and currently, 3GPP counts over 400 member companies and institutions. The current organizational partners are the Association of Radio Industries and Businesses (ARIB), the China Communications Standards Association (CCSA), the European Telecommunications Standards Institute (ETSI), the Alliance for Telecommunication Industry Solutions (ATIS), Telecommunications Technology Association (TTA) and the Telecommunication Technology Committee (TTC).

The original scope of 3GPP was to produce Technical Specifications and Technical Reports for a 3G Mobile System based on evolved GSM core networks and the radio access technologies that they support which included the Universal Terrestrial Radio Access (UTRA) in both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes [3]. Later, the scope was revised to take into account the maintenance and development of the Global System for Mobile communication (GSM) Technical Specifications and Technical Reports including evolved radio access technologies like General Packet Radio Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE). Figure 1 shows a timeline for 3GPP technology evolution.

In the rest of this chapter, a brief review of the different 3GPP technologies and their enhancements are presented, up to and including Long Term Evolution (LTE). In a subsequent part of this thesis, when we will be discussing the features of IMT-Advanced, we shall then have an opportunity to consider the latest 3GPP technology, LTE-Advanced, which is deemed to meet and even surpass the requirements for IMT-Advanced as stipulated by ITU-R.

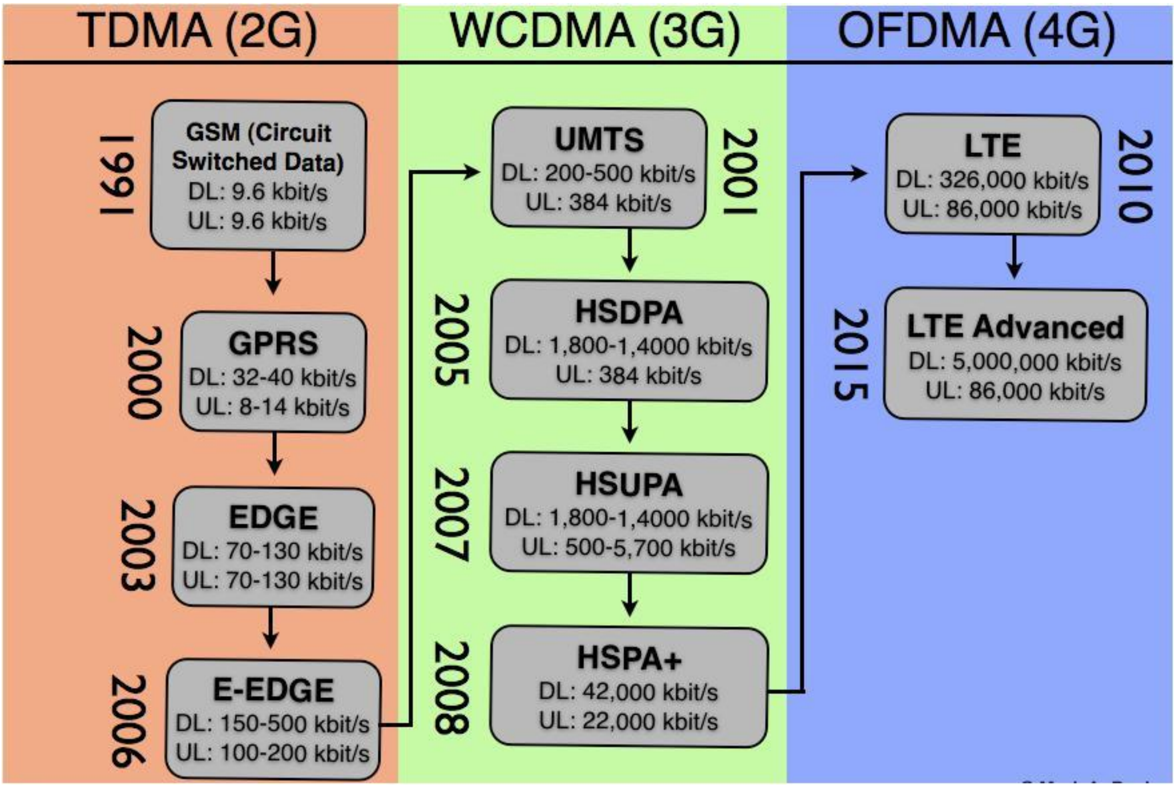

Figure 1: 3GPP technology evolutionary path [4]

2.2 GSM Technology – 2nd Generation (2G) System

The GSM system is the most widely used cellular technology in the world today. According to market data supplied by the GSM Association, which promotes GSM worldwide, about 80% of the global mobile market uses this standard [5]. The success enjoyed by the GSM standard was due to a variety of reasons amongst which was the fact that a user had the ability to roam worldwide with the certainty of being able to operate on GSM networks in exactly the same way - provided that billing agreements are in place.

The term GSM originally meant Groupe Speciale Mobile, but was changed to Global System for Mobile Communications when it became apparent that this technology was being used worldwide. The GSM network architecture as defined in the GSM specifications can be grouped into four main areas, namely: Mobile station (MS), Base-station subsystem (BSS), Network and Switching Subsystem (NSS) and the Operation and Support Subsystem (OSS). The components of some of these major areas as well as their functionalities are shown in Figure 2.

A. Mobile terminal

The Mobile Station (MS), terminal equipment (TE) or cell phones as they are mostly referred to are the section of a GSM cellular network that the user sees and operates. In recent years terminal size has fallen dramatically while the level of functionality has greatly increased. The two main parts of the cell phone are the main hardware and the SIM. The hardware itself contains the main elements of the mobile phone including the display, case, battery, and the electronics used to generate the signal, and process the data received and to be transmitted. It also contains a number known as the International Mobile Equipment Identity (IMEI). This is installed in the phone during manufacture and "cannot" be changed. It is accessed by the network during registration to check whether the equipment has been reported as stolen. The SIM or Subscriber Identity Module contains the information that provides the identity of the user to the network. It contains a variety of information including a number known as the International Mobile Subscriber Identity (IMSI).

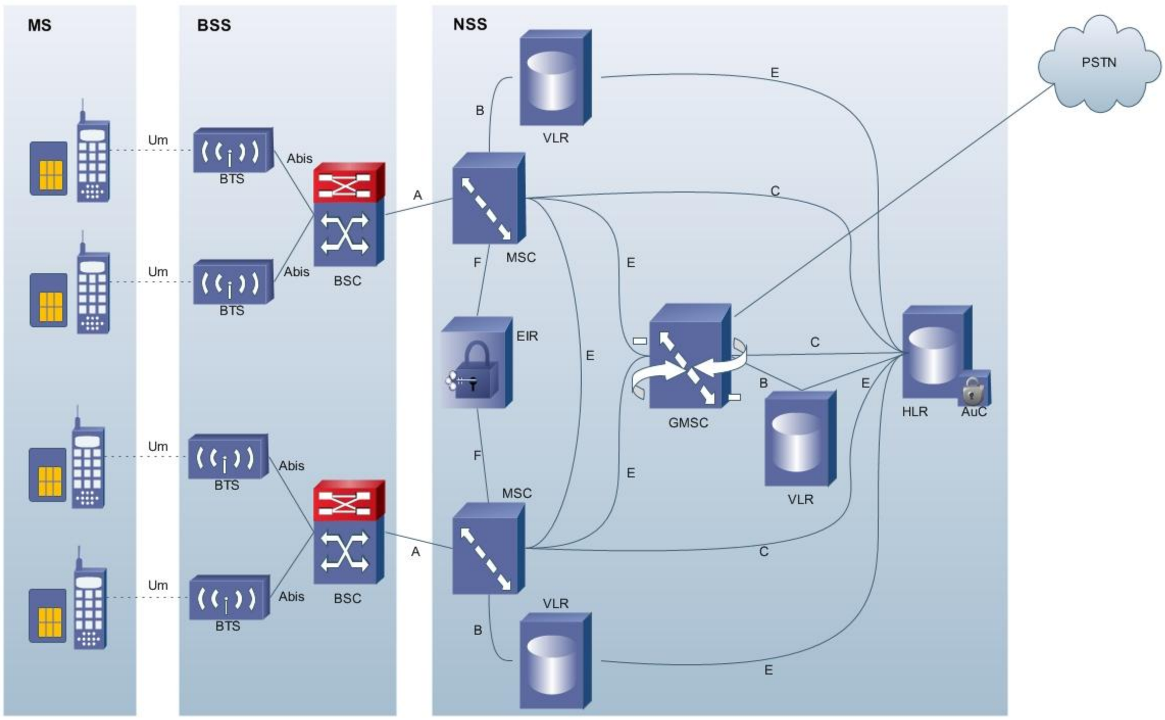

Figure 2: Structure of a GSM network [6]

B. Base Station Subsystem (BSS)

The GSM network architecture comprises of two parts:

- Base Transceiver Station (BTS): This is made up of radio transmitter receivers, and their associated antennas which communicate directly with the mobile devices by transmitting and receiving. In between the BTS and the mobile station is the Um interface with its associated protocols.
- Base Station Controller (BSC): The BSC is often co-located with one of the BTSs within the groups of BTSs it controls and communicates with them over the A-bis interface. It manages the radio resources, controls items such as handover within the group of BTSs as well as allocates channels.

C. Network Switching Subsystem (NSS)

Often referred to as the core network, the NSS provides the main control and interfacing for the whole mobile network and comprises of the following elements:

- Mobile Switching services Centre (MSC): The MSC provides additional functionality to enable the requirements of a mobile user to be supported. These include registration, authentication, call location, inter-MSC handovers and call routing to a mobile subscriber. Additionally it provides an interface to the PSTN through which calls can be routed from the mobile network landline phone, for instance. Calls can be made to mobiles on different networks through interfaces to other MSCs.
- Home Location Register (HLR): Here all the administrative information about each subscriber along with their last known location is stored and in so doing, the GSM network is able to route calls to the relevant base station for the MS. When a user switches on their phone, the phone registers with the network and from this it is possible to determine which BTS it communicates with so that incoming calls can be routed appropriately. Even when the phone is not active (but switched on) it re-registers periodically to ensure that the network (HLR) is aware of its latest position. Each network boasts one HLR, but they may be distributed across various sub-centres for operational reasons.
- Visitor Location Register (VLR): Selected information from the HLR is kept in the VLR and this enables the selected services for the individual subscriber to be provided. While the VLR can be implemented as a separate entity, it is commonly realized as an integral part of the MSC, so that access is made faster and more convenient.
- Equipment Identity Register (EIR): The decision to allow a MS onto the network is made here. All mobile devices are marked with a number known as an IMEI which is installed during manufacture and is checked by the network during registration. Depending upon the information held in the EIR, the mobile may be allocated one of three states - allowed onto the network, barred access, or monitored in case of problems.
- Authentication Centre (AuC): The AuC contains the secret key also contained in the user's SIM card and is used for authentication and for ciphering on the radio channel.
- Gateway Mobile Switching Centre (GMSC): The GMSC is where a MS-terminating call is initially routed, without any knowledge of the MS's location. For mobile terminated calls, it interacts with the HLR (Home Location Register) to obtain routing information. The "MSC" part of the term GMSC might be confusing, since the gateway operation has no link to the MSC as discussed above.
- SMS Gateway (SMS-G): The SMS-G is a device or service offering SMS transit; transforming messages to mobile network traffic from other media, or vice versa, allowing transmission or receipt of SMS messages with or without the use of a mobile

phone. Two gateways handle messages directed in different directions. The SMS-GMSC (Short Message Service Gateway Mobile Switching Centre) is for short messages being sent to an ME while the SMS-IWMSC (Short Message Service Inter-Working Mobile Switching Centre) is used for short messages originating from a mobile on that network.

D. Operation and Support Subsystem (OSS)

The OSS is an element within the overall GSM network architecture that is connected to components of the NSS and the BSC and from which the network operator monitors and controls the system. The OSS also provides cost-effective support for centralized, regional and local operational and maintenance activities as required for the GSM network. As the number of BS increases with the scaling of the subscriber population, some of the maintenance tasks are transferred to the BTS, allowing savings in the cost of ownership of the system.

2.3 GSM to IMT-2000: The road to 3G Systems

3GPP technologies have evolved from GSM, through EDGE and UMTS-HSPA-HSPA+ to provide increased capacity and user experience, and the evolution will continue in the coming years with further enhancements to HSPA+ and the introduction of LTE and LTE-Advanced. The path from 2nd generation systems to 3G is broad, depending on the starting point. For instance, CDMA-based systems have a very different road to IMT-2000 than their TDMA counterparts. Such systems point to ‘CDMA 2000’ systems as equivalent to ‘3G’, while for TDMA systems (including GSM), the Ericsson-proposed W-CDMA standard represents attainment of ‘3G’ [7]. It is interesting to note that, CDMA-based carriers believe that their migration path will be more inexpensive than that of GSM/TDMA-based carriers, because many will have only to change channel cards in the base stations and upgrade the network software as opposed to implementing entire network overlays. That notwithstanding, the focus of this section of the thesis remains the path of GSM towards 3G.

2.3.1 HSCSD (High-Speed Circuit Switched Data)

HSCSD is an improvement on the circuit-switched data (CSD) capability of the GSM network. GSM encoding techniques provided for 9.6 Kbps (or 14.4 Kbps with improved encoding techniques) maximum CSD speeds. Up to 8 time slots are available per user frequency in the GSM TDMA interface, but these are not always all occupied hence making it possible to extend the CSD into a much faster HSCSD having data rates of up to 38.4 Kbps as a result of increased data throughput. Apart from the use of multiple time slots at the same time to greatly improve data and transfer rates, HSCSD also allowed different correction methods to be used for data transfer based on the quality of the radio link. This means that in the best conditions 14.4 Kbps can be put through a single time slot that under CSD would only carry 9.6 Kbps, for a 50% improvement in throughput. Due to the increased charges for the user per connection time, probably as a result of more time slots allocated than normal, HSCSD was considered too expensive. An alternative technology GPRS which will be discussed next, became more attractive due to its comparatively lower pricing based on amount of data transferred rather than duration of connection.

2.3.2 GPRS (General Packet Radio Service)

GPRS as the name suggests, is a packet-based and overlay technology which essentially acts as an enhancement to the CSD services discussed earlier as well as in short message services (SMS). GPRS is well planted in the middle of 2G and 3G systems, promising data rates in the range 56-114 Kbps as well as continuous connection to the internet for phone and PC users. This is made possible by the fact that the GPRS packet-switching technology allows for radio resources to be potentially shared and used only when data is actually being transmitted by users. Several users can be served by a single cell, sharing the same bandwidth due to efficient use the available radio resources. GPRS also uses TDMA as in GSM but will improved the peak time capacity as it can simultaneously direct traffic that was sent using the original CSD through the overlay and at the same time, reduce the SMS Centre and signalling channel loading. This ability of GPRS in combination with the fact that the communication channels are shared between users based on packet needs, will bring down the overall cost for the users. In addition to Internet Protocol, GPRS also supports X.25 which is a packet-based protocol which was mainly used in Europe.

2.3.3 EDGE (Enhanced Data rates for GSM Evolution)

EDGE which is also referred to sometimes as “Enhanced Data rates for Global Evolution” and even “Enhanced GPRS” by some, is a radio-based high-speed mobile data standard which is capable of achieving data transmission speeds of 384 Kbps when using all available 8 time slots. As mentioned in [8], by using EDGE, operators can handle three times more subscribers than GPRS and triple their data rate per subscriber, or add extra capacity to their voice communications. This will only involve the addition of one extra EDGE transceiver unit to each cell. Originally developed for operators who failed to win spectrum for 3G networks, EDGE provides a cost-efficient way of jumping into complete 3G services while at the same time allows legacy GSM operators to offer their users high speed data services comparable to those of UMTS. EDGE uses the same structure as in GSM networks, which allows it to be overlaid directly onto an existing GSM network and is a simple software upgrade for many existing GSM/GPRS networks [8]. The focus here

is to improve capacity and efficiency over the air interface by ensuring more data is transferred per time slot with the help of more advanced coding schemes.
By efficiently implementing modulation changes that might be required later by UNMT, EDGE can provide an evolutionary migration path from GPRS to UMTS. The main idea behind EDGE was to squeeze out even higher data rates on the 200 kHz GSM radio carrier, by changing the type of modulation used, whilst still working with circuit- and packet-switched approaches. EDGE was deployed on GSM networks beginning in 2003.

2.3.4 IMT-2000 Technology

The concept of IMT-2000 (International Mobile Telecommunications) was discussed in the mid-1980s followed by several years of negotiations. In the year 2000, new technical specifications for third generation (3G) systems under the brand IMT-2000 were unanimously approved with spectrum allocation in the range 400-3000 MHz. The basic architecture of 3G networks is based on two main principles: mobile cellular networks should be structured to maximize network capacity and multimedia services should be offered independently of the place of the end-users.

The 3G umbrella encompasses a range of competing mobile wireless technologies, namely CDMA-2000 and WCDMA. ITU’s IMT-2000 vision of a global 3G mobile communication systems family included the Universal Mobile Telecommunications System (UMTS) which was standardized by the European Telecommunications Standards Institute (ETSI). WCDMA is a radio access scheme in the UMTS standard and was the next technology step in the path of 3GPP, created in 1998 to continue with the technical specification work.

2.3.5 WCDMA

W-CDMA (or WCDMA) which stands for Wideband Code-Division Multiple Access was the radio technology chosen by 3GPP in implementing UTRA (Universal Terrestrial Radio Access). W-CDMA is a spread-spectrum modulation technique and uses channels with much larger bandwidths compared to that of the data being transferred. This modulation technique encodes each channel such that a decoder, with knowledge of the code, can selectively pick out the desired signals from all other signals in the same band. Additionally, since knowledge of the code is required in order to identify separate channels, W-CDMA is therefore very secure from eavesdropping. By making use of wide frequency band, the system is by design resistant to many of the aspects of radio communication which plague narrow band systems, such as bursty noise, multipath reflections, and other interfering transmissions [9]. Other key operational features in W-CDMA include:

- High data rate transmission: 384 Kbps (wide area coverage), 2 Mbps (local coverage).
- Service flexibility: support of multiple parallel variable rate services on each connection.
- Support for Frequency Division Duplex (FDD) and Time Division Duplex (TDD).
- Built-in support for future capacity and coverage enhancing technologies like adaptive antennas, advanced receiver structures and transmitter diversity.
- Support for inter frequency hand over and hand over to other systems, including GSM.
- Efficient packet access.

2.3.6 HSPA

The key enhancement in WCDMA 3GPP Release 6 was a new transport channel in the uplink: enhanced uplink (EUL), also sometimes called HSUPA (high-speed uplink packet access). The combination of HSDPA (high-speed downlink packet access) and EUL is known as HSPA, referring to High-Speed Packet Access which extends and improves the performance of WCDMA protocols. HSPA specifications for the DL and UL and contained in the 3GPP's Release 5 [10] and Release 6 [11] specifications respectively. This enhancement improved throughput, reduced latency and increased capacity. HSPA improves the end-user experience by increasing peak data rates up to 14 Mbps (DL) and 5.8 Mbps (UL). In 2008, Evolved HSPA (or HSPA+) was released with subsequent adoption worldwide in 2010. HSPA improvements in UMTS spectrum efficiency are obtained by:

- Shared-channel transmission, leading to efficient use of available code and power resources in WCDMA.
- Shorter Transmission Time Interval (TTI), hence shorter round-trip time and improvement in tracking of fast channel variations.
- Link adaptation, which maximizes channel usage and enables the BS to operate close to maximum cell power.
- Fast scheduling which prioritizes users with the most favourable channel conditions.
- Fast retransmission and soft-combining, resulting in further increase in capacity.
- 16QAM (Quadrature Amplitude Modulation), yielding higher bit-rates.

To further boost the peak data rate and capacity, 3GPP Release 7 introduced HSPA evolution (also called HSPA+), which supports MIMO, 64QAM in the downlink, and 16QAM in the uplink. Release 8 supported two ways to give downlink bitrates of 42Mbps, one of which involves a combination of 64QAM and MIMO while the other is by using dual carriers with 64QAM modulation.

2.4 LTE – Long Term Evolution

2.4.1 Overview

The unprecedented take-up and demand for mobile broadband around the world, seeing connections jump from a few thousand in late 2006 to nearly 100M in early 2009, has been the real driver and the need now for ever higher data rates and capacities [12]. In 2004, 3GPP started the investigation of Universal Mobile Telecommunication Services (UMTS) Terrestrial Radio Access Network (UTRAN) Long-Term Evolution (LTE) by identifying the requirements from different players in the field [13]. These requirements included in the report [14] considered the following:

- Packet-switched domain optimization.
- Server to User Equipment (UE) round-trip time under 30ms and access delay below 300ms.
- Peak rates uplink/downlink 50/100 Mbps.
- Good level of mobility and security ensured.
- Improved terminal power efficiency.
- Frequency allocation flexibility with 1.25/2.5, 5, 10, 15 and 20 MHz allocations; possibility to deploy adjacent to WCDMA.
- High capacity compared with the Release 6 HSDPA/HSUPA reference case, in the downlink throughput 3 to 4 times and in the uplink 2 to 3 times reference scenario capacity.

The overall objective for LTE is to provide an extremely high performance radio-access technology that offers full vehicular speed mobility and that can readily coexist with HSPA and earlier networks [15]. Moreover, the 3GPP technologies continued to evolve, and as mentioned in [16], future releases by the 3GPP will see both combinations of dual carriers and MIMO as well as combinations of up to 4 carriers with both alternatives capable of supporting up to 84Mbps. Also higher bit rates are possible if combinations of MIMO and 4 carriers will be supported in the future. As specified in the 3GPP Release 8, OFDM/OFDMA technology is introduced for the LTE downlink, supporting very high data rates of up to 300Mbps while Single-Carrier FDMA (SC-FDMA) is used in the uplink with data rates of 80Mbps possible. Additionally, LTE supports operation both in paired and unpaired spectrum (FDD and TDD) using channel bandwidths of approximately 1.4MHz up to 20MHz.

Nowadays, it is possible to browse the Internet or send e-mails using HSPA-enabled notebooks. Fixed DSL modems can be replaced conveniently with HSPA modems or USB dongles and we can also send and receive video or music using 3G phones. LTE will make the user experience even better by enhancing more demanding applications such as interactive TV, mobile video blogging, advanced games and professional services. LTE offers several important benefits for users and operators, including the following:

- Performance and capacity – With LTE built to provide downlink peak rates of at least 100Mbps and allowance for speeds of more than 300Mbps as well as Radio access network (RAN) round-trip times of less than 10ms, LTE meets key 4G requirements compared to other comparable technologies.
- Simplicity – Flexible carrier bandwidths ranging from 1.4MHz up to 20MHz as well as frequency division duplexing (FDD) and time division duplexing (TDD) are supported by LTE. 3GPP has already identified fifteen paired and eight unpaired spectrum bands for LTE and with many more to come, operators will be able to introduce LTE in new bands where it is easiest to deploy 10MHz or 20MHz carriers and eventually deploy LTE in all bands. Features such as self-configuration and self-optimization will simplify and reduce the cost of network roll-out and management, hence simplifying the building and management of next generation LTE radio networks in the future. These will be deployed in parallel with simplified, IP-based core and transport networks that are easier to build, maintain and incorporate new services.
- Wide range of terminals – LTE modules can be embedded into devices like mobile phones, computers and other consumer electronic devices, such as notebooks, ultra-portables, gaming devices and cameras. These devices can have universal coverage from the onset as a result of LTE supporting handover and roaming to existing mobile networks.

As reported in [17], about 80% of the 3.4 billion broadband consumer subscriptions by 2014 will use mobile broadband. This is illustrated in Figure 3. There is an overwhelming acceptance and strong evidence to support predictions of an increase in mobile broadband usage. The different stages involved as we move towards full mobile broadband are intuitive and simple, especially with LTE that offers ubiquitous coverage and roaming with already existing 2G and 3G networks. By May of 2007, packet data traffic had overtaken voice traffic, based on a world average WCDMA network load as shown in Figure 4. This, according to [17] was mainly because of the introduction of HSPA in the networks. HSPA data cards and USB dongles have also become popular, with several operators reporting a four-fold increase in data traffic in the three months after launching HSPA.

There will be a wide range of broadband applications due to the enhanced mobility including search engines, community sites and content-sharing sites like Facebook and YouTube. The effect of mobility is that it will provide users the chance to concentrate on using the service rather than worrying about the WLAN connection settings, security or losing coverage. A host of these applications are run by user-generated content and this greatly affects traffic patterns, thus making the ability to uplink even more important. The high peak rates and short latency of LTE also enable real-time applications such as gaming and video-conferencing.

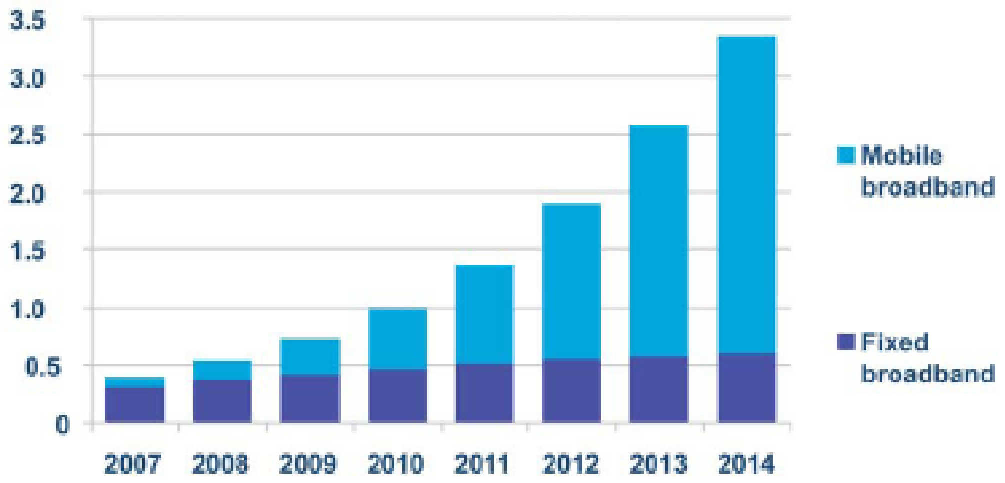

Figure 3: Broadband growth 2007 – 2014 [17]

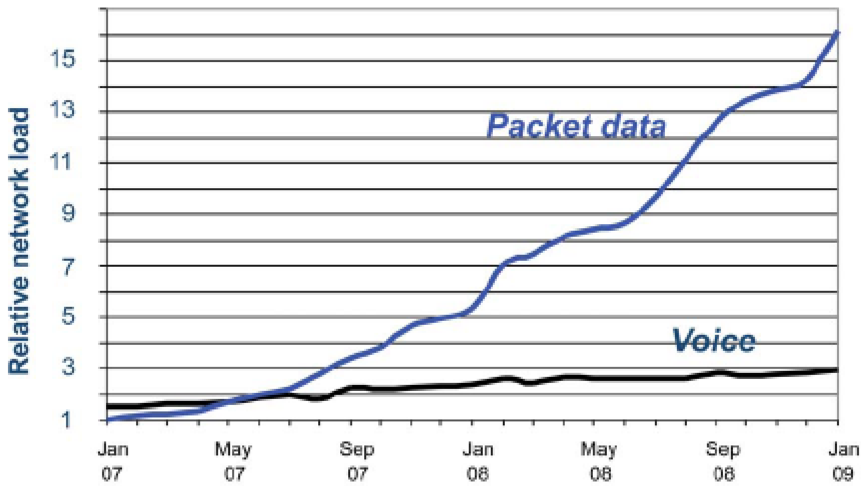

Figure 4: Strong growth of data traffic in WCDMA networks worldwide [17]

2.4.2 LTE: Architecture

In the period running from March 2005 to September 2006, a feasibility study was conducted by 3GPP on the Evolved UTRAN (EUTRAN) technology alternatives and a selection of the multiple access and basic radio access network architecture was made [13]. It was concluded that Orthogonal Frequency Division Multiple Access (OFDMA) will be used for downlink transmission while Single-Carrier Frequency Division Multiple Access (SC-FDMA) will be used for uplink. To support the choice for OFDMA as the preferred solution for the air interface have been some key developments as presented in [13] including larger bandwidth and bandwidth flexibility, flat architecture, an amplifier – friendly uplink solution with SC-FDMA as well as simpler multi-antenna operation.

In line with the LTE radio access, packet core networks are also evolving to the flat SAE architecture. This new architecture is designed to optimize network performance, improve cost efficiency and facilitate the uptake of mass market IP-based services. There are two nodes in the SAE architecture user plane; the LTE base station (eNodeB) which is the radio access part and the SAE Gateway which together with the Mobility Management Entity (MME) constitute the core network part, as shown in Figure 5 and Figure 6. This flat architecture reduces the number of involved nodes in the connections. The LTE base stations are connected to the core network over the so-called S1 interface. Existing 3GPP (GSM and WCDMA/HSPA) and 3GPP2 (CDMA) systems are integrated to the evolved system through standardized interfaces, thus providing optimized mobility with LTE. In the case of 3GPP systems, a signaling interface between the Serving GPRS Support Node (SGSN) is integrated with the evolved core network while for 3GPP2, integration is between the CDMA RAN and the evolved core network. By integrating in such a manner, both dual and single radio handover are supported with flexible migration to LTE guaranteed. On the core network side, the following entities are defined as such:

- Serving SAE Gateway and Public Data Network (PDN) SAE Gateway for processing user-plane data.
- Mobility Management Entity (MME) which handles the control plane signaling, separate from the gateway, facilitating optimized network deployments and enabling fully flexible capacity scaling.
- Home Subscriber Server (HSS) which presents the registers covering functionalities like the Home Location Register (HLR) and connects to the packet core through an interface based on Diameter and not SS7, as used in previous GSM and WCDMA networks.

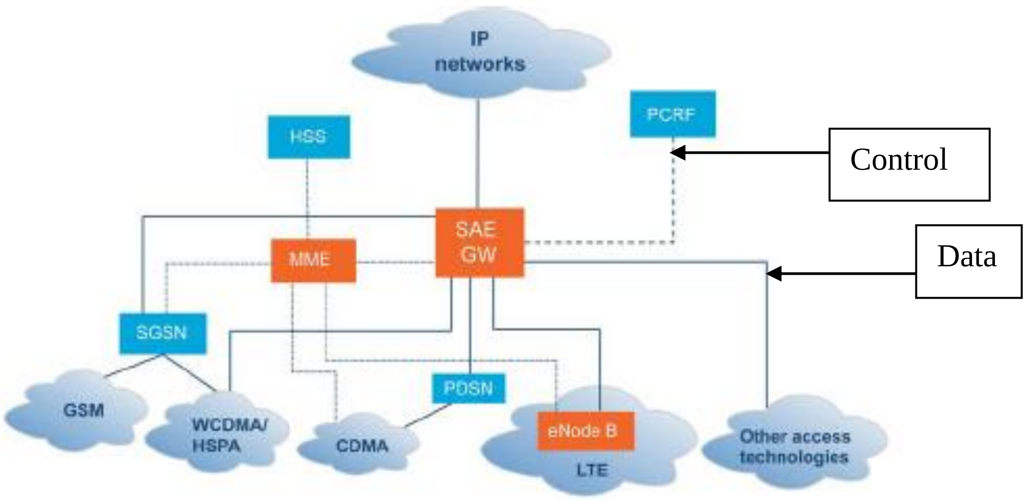

Figure 5: Flat architecture of LTE and SAE [17]

In order to provide a simple and effective solution for operators to offer differentiation between packet services, LTE–SAE has adopted a class-based QoS concept. The service quality as well as the type of charging policy being applied is dealt with by Policy and Charging Rules Function (PCRF).

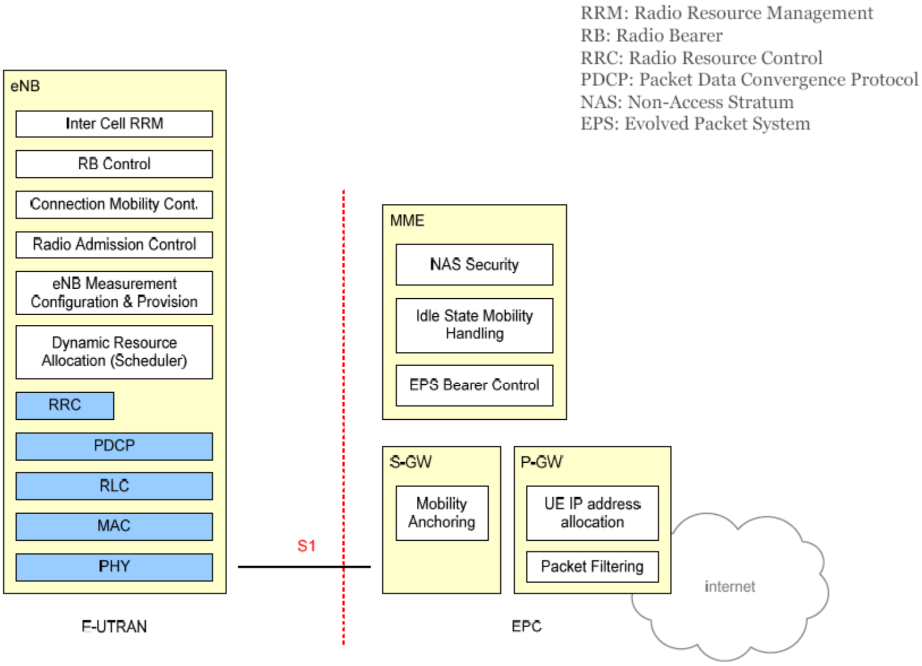

Figure 6: LTE network architecture [18]

2.4.3 LTE: OFDMA Technology

In LTE, the downlink (from the base station to the terminal) is based on OFDMA because it meets the demand for spectrum flexibility and at the same time enables cost-efficient solutions for wide carriers with high peak rates. Standards such as Institute of Electrical and Electronics Engineers (IEEE) 802.11a/b/g, 802.16, HiperLAN-2, Digital Video Broadcast (DVB) and Digital Audio Broadcast (DAB) have made OFDMA a well-known technology. OFDM uses a large number of narrowband, mutually orthogonal sub-carriers or tones for multi-carrier transmission. Figure 7 illustrates the basic LTE downlink physical resource shown as a time-frequency grid. The spacing between the sub-carriers in the frequency domain is given at 15 kHz. In addition, the OFDM symbol duration time is 1/f + cyclic prefix. The cyclic prefix is used to maintain orthogonality between the sub-carriers, even for a time-dispersive radio channel. One resource element carries QPSK, 16QAM or 64QAM modulated bits. For example, with 64QAM, each resource element carries six bits. The OFDMA symbols are grouped into resource blocks. The resource blocks have a total size of 180 kHz in the frequency domain and 0.5ms in the time domain. In this setup, “resource blocks” are allocated to individual users, in the frequency-time domain. The more resource blocks a user receives and the higher the modulation used in the resource elements, the higher the bit-rate. Which resource blocks and how many the user receives at a given point depend on advanced scheduling mechanisms in the frequency and time dimensions. Scheduling of resources can be taken every 1ms, which means two resource blocks, 180 kHz wide and in total 1ms in length, called a scheduling block. The scheduling mechanisms in LTE are similar to those used in HSPA and enable optimal performance for different services in different radio environments. Actual transmission is achieved by transmitting a signal after the Fast Fourier Transform (FFT) block, which is needed to change between time and frequency domain representations of the signal. Signals of this nature are ideal as one does not need an equalizer but only needs to compensate the channel amplitude and phase impact on the various sub-carriers. The FFT is used again in the receiver side to convert back to the original signal representation. It's worth noting that the FFT or Inverse FFT (IFFT) operations are old numerical principles with already well-established computational algorithms. Additional blocks such as widowing operation are required by a practical transmitter to satisfy the spectrum mask. In addition to windowing, a cyclic prefix is also deployed to combat the effects of inter-symbol interference. An important aspect of OFDMA is the ability to locate transmissions in different places in the frequency domain, unlike in WCDMA, thus the possibility of using a frequency-domain element in scheduling.

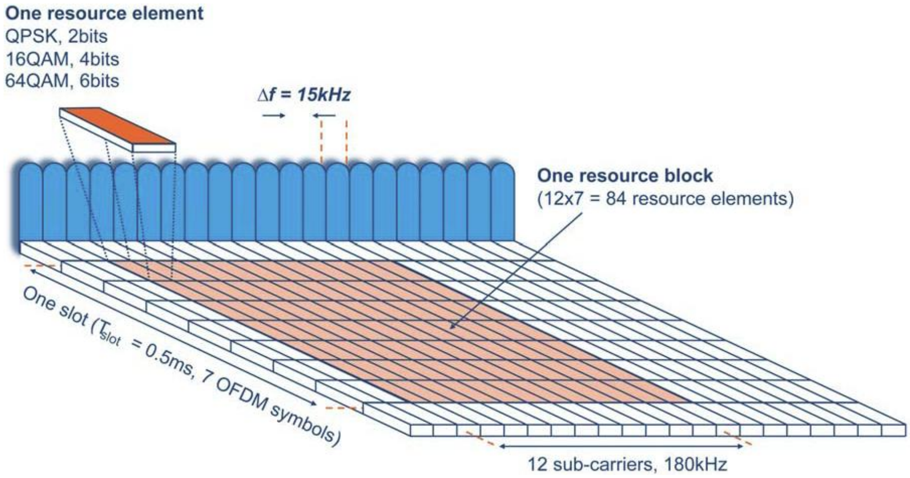

Figure 7: The LTE downlink physical resource based on OFDMA [17]

2.4.4 LTE: SC-FDMA Technology

LTE uses a pre-coded version of OFDM known as Single Carrier Frequency Division Multiple Access (SC-FDMA) for uplink transmission. The SC-FDMA with cyclic prefix has a very simple transmitter structure in its basic form which includes just a QAM modulator coupled with a cyclic prefix. Some of the benefits resulting from this kind of arrangement include enabling the low-complexity equalizer receiver by eliminating inter-symbol interference, low peak-to-average-power-ratio (PAPR), as only one information bit is transmitted at a time and the capability to reach performances similar to OFDMA, with the use of equalizers.

High PAPR as in OFDMA would require expensive and inefficient power amplifiers with high requirements on linearity, which increases the cost of the terminal and drains the battery faster. This problem is overcome in SC-FDMA by grouping together resource blocks in such a way that reduces the need for linearity and power consumption in the power amplifier. Coverage is considerably improved as well as cell edge performance when there is a low PAPR. Frequency-domain equalization of the SC-FDMA transmission describes when different transmitters or terminals use the FFT/IFFT pair to place otherwise equal bandwidth transmissions in the different uplink frequency blocks. By transmitting only a single symbol at a time, we can be sure of a low transmitter waveform, hence permitting the use of similar amplifiers without having to use over-dimensioning or additional power back-off.

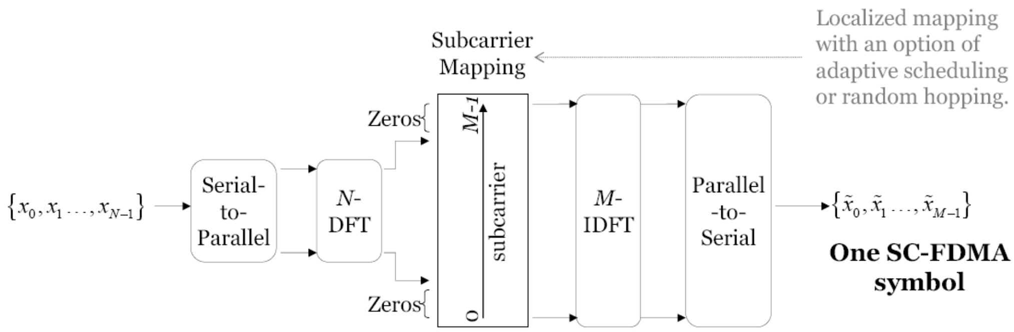

Figure 8: One SC-FDMA symbol [18]

2.4.5 LTE: Physical Layer Design

The LTE physical layer is designed for maximum efficiency of the packet-based transmission; hence only shared channels exist in the physical layer to enable dynamic resource utilization. Different bandwidths ranging from 1.4 MHz to 20MHz are used and parameters are chosen in such a way that FFT lengths as well as sampling rates are obtained easily for all operation modes. All resource allocations are short-term just as in HSDPA and HSUPA operations. The downlink transmission contains also the control information on the uplink resources to be used.

Within a single carrier, the different subframes of a frame can either be used for downlink transmission or for uplink transmission. In the case of FDD which involves operations in paired spectrum, all subframes of a carrier are either used for downlink transmission (a downlink carrier) or uplink transmission (an uplink carrier). This is illustrated in Figure 9a. Meanwhile, in the case of operation with TDD in unpaired spectrum (Figure 9b), the first and sixth subframe of each frame (sub-frame 0 and 5) are always assigned for downlink transmission while the remaining subframes can be flexibly assigned to be used for either downlink or uplink transmission. The reason for the predefined assignment of the first and sixth sub-frame for downlink transmission is that these sub-frames include the LTE synchronization signals. The synchronization signals are transmitted on the downlink of each cell and are intended to be used for initial cell search as well as for neighbour-cell search [19].

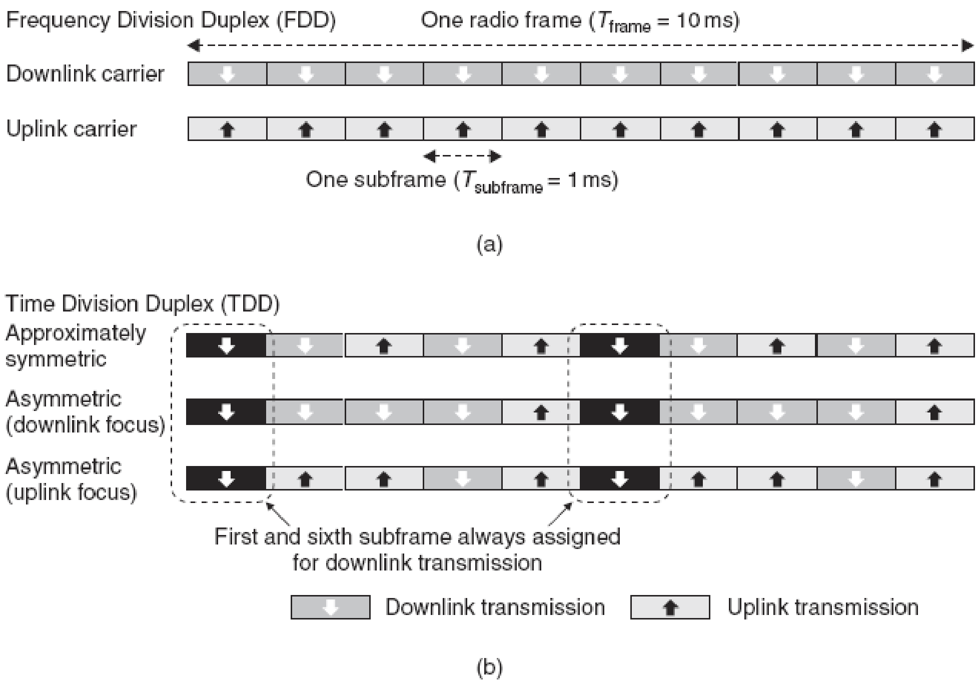

Figure 9: Examples of downlink/uplink subframe assignment in case of TDD compared with FDD.

For OFDMA symbols with a varying number of subcarriers depending on the bandwidth, it is common to allocate resources as blocks of 180 kHz, resulting in 12 sub-carriers each 15 kHz apart. This was illustrated in Figure 7 of Section 2.4.3. Such allocation of resources ensured a limitation to the signaling overhead. Resulting data rate for any one user will be determined by a number of factors including the modulation applied, the rate of channel coding, whether MIMO is used or not, amount of overhead as well as number of resource blocks allocated. User data can use the following physical channels:

- Physical Downlink Shared Channel (PDSCH) which supports QPSK, 16QAM and 64QAM modulations, in the downlink direction.
- Physical Uplink Shared Channel (PUSCH) supporting the same set of modulations, in the uplink direction but with optional use of 64QAM modulation.

Additional channels needed for signaling purposes and cell search operations include Physical Uplink Control Channel (PUCCH), Physical Downlink Control Channel (PDCCH) and Physical Broadcast Channel (PBCH). There also exist synchronization signals to facilitate cell search and reference signal to facilitate channel and channel quality estimation.

2.4.6 LTE: Protocols

The main objective regarding LTE protocol design is to put all radio-related functionalities in the BTS site in the eNodeB. In this way, the UE and eNodeB together handle all functions previously handled by NodeB and RNC in UTRAN. Figures 10a and 10b show typical user-plane and control-plane protocol stacks.

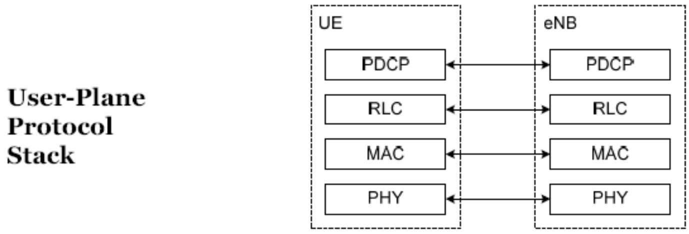

Figure 10a: LTE user-plane protocol stack distribution [13, 18]

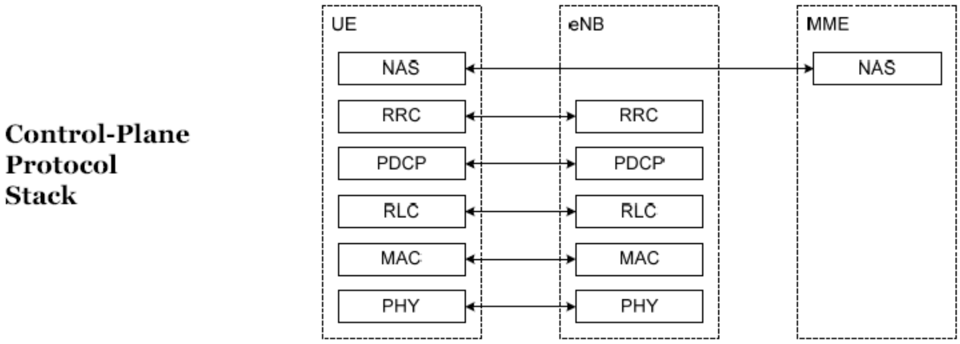

Figure 10b: LTE control-plane protocol stack distribution [18]

As illustrated by Figures 11a and 11b, the MAC layer handles such functions including scheduling, priority handling, retransmissions, multiplexing. As in WCDMA, the RLC handles provision of logical channels to higher layers, segmentation as well as retransmissions in case the lower layer (MAC and L1) fails delivery. The PDCP is then left with the job of ciphering and header compression. In the control plane of LTE, the RRC protocol will contain fewer states than in UTRAN. Basically only the “active” and “idle” states are projected and will be named as such:

- RRC_IDLE state, during which the device will monitor paging messages and uses cell reselection for mobility.
- RRC_CONNECTED state, during which the UE location is known on the cell level and data can be transmitted and received.

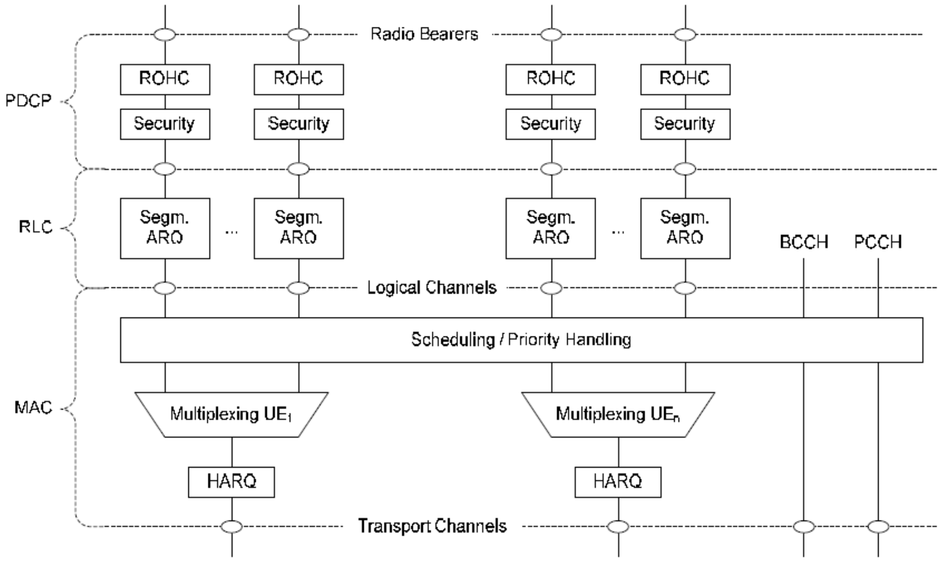

Figure 11a: Downlink Layer 2 structure [20]

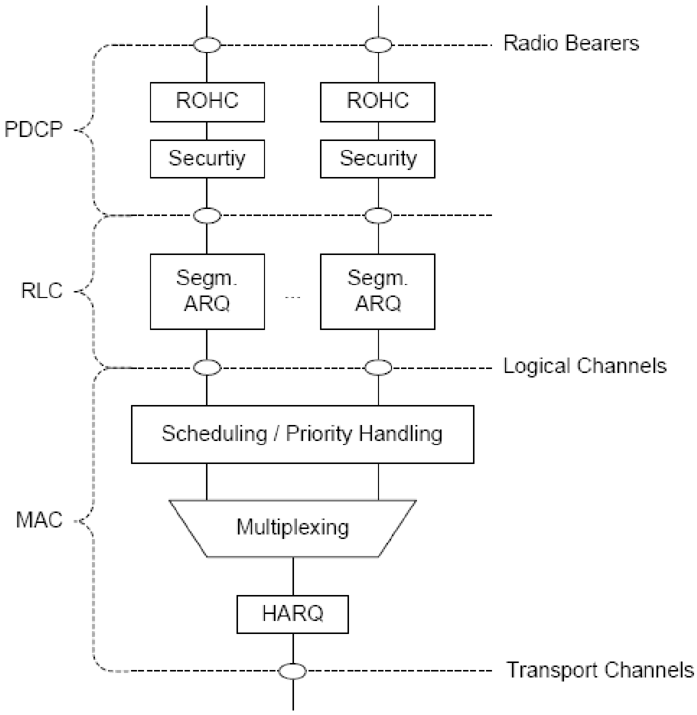

Figure 11b: Uplink layer 2 structure [20]

3 EVOLUTION OF IEEE 802.16

3.1 IEEE 802.16-2001 – IEEE 802.16a-2003: Humble beginnings

The IEEE 802.16 Working Group on Broadband Wireless Access Standards develops standards and recommended practices to support the development and deployment of broadband Wireless Metropolitan Area Networks [21]. IEEE 802.16 is a unit of the IEEE 802 LAN/MAN Standards Committee. In October 2001, the first version of the IEEE Standard 802.16-2001 [22], was completed and defined the WirelessMAN air interface specification for wireless metropolitan area networks (MANs). The main aim of this first release was to define a technology for fixed users to have broadband wireless access, instead of just cabled access networks like digital subscriber line (DSL). This led the original IEEE 802.16 to specify a point-to-multi-point (PMP) network architecture with shared resources by a central node called the base station (BS) and a set of subscriber stations (SS). QoS was a key feature supported by the connection-oriented medium access control (MAC) layer. The standard was also designed to evolve as a set of air interfaces based on a common MAC protocol, but with physical layer specifications which would depend on the used spectrum as well as the associated regulations. A frequency range of 10-66 GHz for line-of-sight (LOS) operations using single carrier transmission was assigned when the standard was approved in 2001. Two years later in 2003, a new version of the standard, known as IEEE 802.16a-2003 [23], was published with support for non-LOS operations and a frequency range of 2-11 GHz.

3.2 IEEE 802.16-2004 Onwards: Mobility Support

The year 2004 witnessed an even greater milestone in the IEEE 802.16 standards development with the introduction of two additional physical (PHY) layers to the existing standard. These two layers were Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA). These new additions to the new standard IEEE 802.16-2004 [24] also referred to sometimes as IEEE 802.16d, proved to be a very cost-effective fixed wireless alternative to cable and DSL services which were common with the previous standards. One year on, in 2005, a new version with amendments to the 2004 standard was ratified by IEEE, supporting a combined fixed and mobile operation in licensed frequency bands. The new standard, IEEE 802.16e-2005 [25] or simply IEEE 802.16e added a host of features related to mobile operations and mobile stations (MS), including power-saving, idle mode, handover as well as an improved OFDMA physical layer. Following the 2005 standard release, further standard developments continued with the following definitions:

- Management Information Base (MIB) for MAC and PHY in IEEE 802.16f [26].

- Management plane and procedures leading to IEEE 802.16g [27].
- Improved co-existence for license-exempt operation in IEEE 802.16h [28].
- Introduction of relay capabilities in IEEE 802.16j-2009 [29].

A further release IEEE 802.16-2009 [30], also commonly referred to as the 2009 release, refined the MAC and PHY procedures for mobile operations and brought some major changes including half-duplex mobile terminal operations in OFDMA frequency division duplexing (FDD), load balancing, robust header compression (ROHC), an enhanced mechanism for resource allocation, support for location based services (LBSs) as well as multicast and broadcast services (MBSs). For completion, the IEEE 802.16-2009 also incorporated the amendments for IEEE 802.16f and IEEE 802.16g as well as eliminating some old features like the mesh mode.

3.3 IEEE 802.16 and WiMAX Forum

Design of the IEEE 802.16 specifications were focused on flexibility and the standard only dealt with the MAC and PHY layers, without defining the over-the-air upper layer signaling nor the overall network architecture and protocols. The omission of these two factors led to the creation of the WiMAX Forum in 2001, with the goal of promoting and certifying compatibility and interoperability of broadband wireless products based on the IEEE 802.16 standards. Although the 802.16 family of standards is officially called WirelessMAN in IEEE, they are commercialized under the name “WiMAX” by the WiMAX Forum.

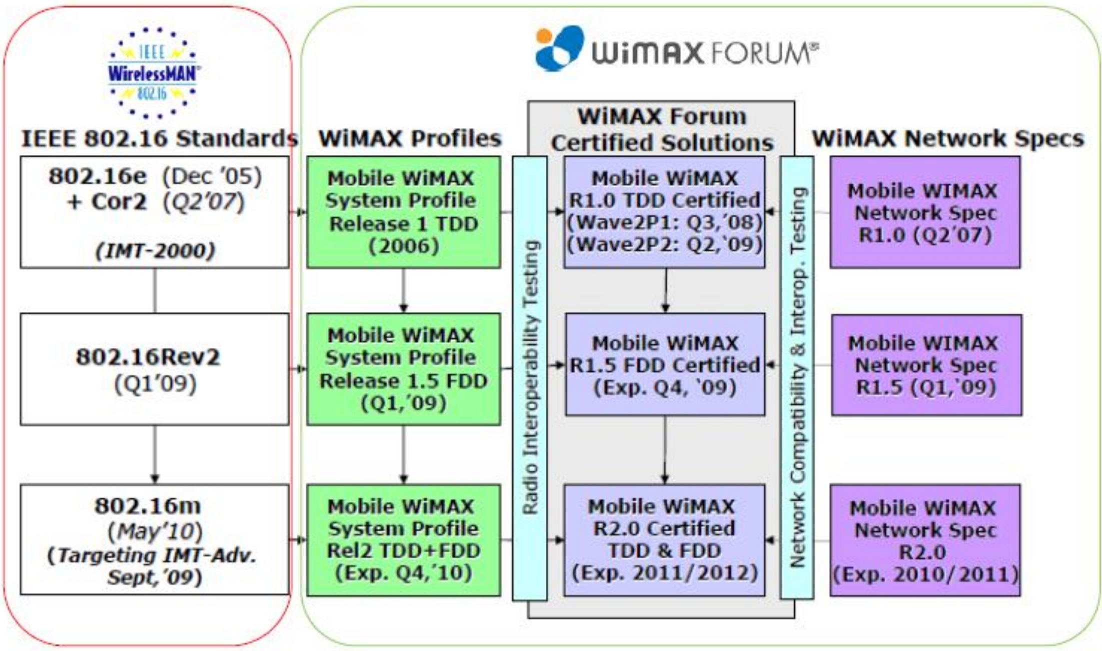

Figure 12: WiMAX and IEEE 802.16 Standardization and roadmap [31]

The most popular IEEE 802.16 standard is the IEEE 802.16e-2005 Amendment that is widely being deployed around the world in more than 100 countries by more than 300 operators and is sometimes called "Mobile WiMAX", after the WiMAX Forum for interoperability. IEEE 802.16e was completed in 2005 and the WiMAX Forum certified products were released starting 2007. The connection between the IEEE 802.16 standards and certified releases by the WiMAX Forum is illustrated in Figure 12.

In the next section of this thesis, a much detailed review of IEEE 802.16e-2005 (Mobile WiMAX) is presented. Also, the 802.16 Working Group is currently focusing on the specification for next-generation systems IEEE 802.16m in the 802.16m Task Group. WiMAX Release 2.0 will be based on this development which is targeted for completion in 2010 with certification in the 2011-2012 timeframe. The target requirements and main features under consideration for IEEE 802.16m are discussed in Chapter 4 of this thesis dealing with issues related to IMT-Advanced.

3.4 Overview of Mobile WiMAX (IEEE 802.16e-2005)

WiMAX refers to Worldwide Interoperability for Microwave Access by the WiMAX Forum [32], formed in June 2001 to promote conformance and interoperability of the IEEE 802.16 standard as mentioned in the previous section. According to [33], Mobile WiMAX is a broadband wireless solution that enables convergence of mobile and fixed broadband networks through a common wide area broadband radio access technology and flexible network architecture. Orthogonal Frequency Division Multiple Access (OFDMA) is adopted by the Mobile WiMAX air interface for improved multi-path performance in non-line-of-sight environments. Also, Scalable OFDMA (SOFDMA) is introduced in the IEEE 802.16e Amendment to support scalable channel bandwidths from 1.25 to 20 MHz [33]. Mobile WiMAX systems offer possibilities for future upgrades in both radio access technology and network architecture, thus providing a great deal of flexibility in network deployment options and services offered. It is worth noting that the system profile in IEEE 802.16e-2005 is not backward compatible with the Fixed WiMAX system profile. Presently, two waves of certification are planned for Mobile WiMAX equipment [16]:

- Wave 1: Mobile WiMAX system profile with single-input single-output (SISO) terminals for the 2.3GHz and 3.5GHz bands.
- Wave 2: Mobile WiMAX system profile with multiple-input multiple-output (MIMO) terminals and beamforming support for the 2.6GHz band (sometimes referred to as the 2.5GHz band).

Because IEEE 802.16 standardization only covers basic connectivity up to the media access (MAC) level, the WiMAX Forum also addresses network architecture issues for

Mobile WiMAX networks. The first network architecture specification (Release 1.0) focused on delivering a wireless Internet service with mobility. Release 1.5 introduced support for telecom-grade mobile services, supporting full IMS interworking, carrier-grade VoIP, broadcast applications, such as mobile TV, and over-the-air provisioning. Some prominent features supported by Mobile WiMAX include the following:

- High Data Rates: With the inclusion of MIMO antenna techniques amongst others, Mobile WiMAX technology is capable of supporting peak DL data rates up to 63 Mbps per sector and peak UL data rates up to 28 Mbps per sector in a 10 MHz channel.
- Quality of Service (QoS): The fundamental premise of the IEEE 802.16 MAC architecture is QoS. In addition, sub channelization and MAP-based signaling schemes provide a flexible mechanism for optimal scheduling of space, frequency and time resources over the air interface on a frame-by-frame basis.
- Scalability: Spectrum resources for wireless broadband vary greatly in different parts of the world. Mobile WiMAX technology is designed to be able to scale to work in different channelization from 1.25 to 20 MHz. This will allow diverse economies to realize the multi-faceted benefits of the Mobile WiMAX technology for their specific geographic needs such as providing affordable internet access in rural settings versus enhancing the capacity of mobile broadband access in metro and suburban areas.
- Security: WiMAX supports AES (Advanced Encryption Standard) and 3DES (Triple DES, where DES is the Data Encryption Standard). By encrypting the links between the BS (Base station) and the SS (subscriber station), WiMAX provides subscribers with privacy (against eavesdropping) and security across the broadband wireless interface. Security also provides operators with strong protection against theft of service. WiMAX also has built-in VLAN support, which provides protection for data that is being transmitted by different users on the same BS. The features provided for Mobile WiMAX security aspects are best in class with EAP-based authentication, AES-CCM-based authenticated encryption, and CMAC and HMAC based control message protection schemes. Support for a diverse set of user credentials exists including; SIM-USIM cards, Smart Cards, Digital Certificates, and Username-Password schemes based on the relevant EAP methods for the credential type.
- Mobility: Mobile WiMAX supports optimized handover schemes with latencies less than 50 milliseconds to ensure real-time applications like VoIP perform without service degradation. Flexible key management schemes like the Privacy and Key Management Protocol Version 2 (PKMv2) which is the basis of Mobile WiMAX security as defined in 802.16e, assure that security is maintained during handover. The 802.16e specification provides improved support for inter-cell handoff, directed adjacent-cell measurement, and sleep modes to support low power mobile station operation.

3.4.1 Mobile WiMAX Frame Structure

In addition to the changes made by the 802.16-2004 standard which included a 256-point Fast Fourier Transform (FFT) Orthogonal Frequency division Multiplexing (OFDM) PHY mode and a 2048-point FFT Orthogonal Frequency division Multiple Access (OFDMA) PHY mode, some mobility enhancements were later provided by the 802.16-2005 amendment. These later amendment enhanced further nomadic operations as well as portable and mobile wireless access. There was improved support for inter-cell handoff, directed adjacent-cell measurements and sleep modes to support low-power mobile station operations. Also included in the 802.16-2005 (802.16e) OFDMA PHY, were FFT sizes of 128, 256, 512 and 1024 in addition to the 2048, thus opening the possibility of scalable deployment.

A. TDD Frame Structure

According to [34], the 802.16e PHY supports TDD and Full and Half-Duplex FDD operations. While FDD profiles were later considered by the WiMAX Forum in order to address specific market opportunities, initially TDD profiles were the only ones released for Mobile WiMAX certification as shown in Table 1. TDD had several key advantages for use as the preferred duplexing mode as listed in [33]:

- TDD enables adjustment of the downlink/uplink ratio to efficiently support asymmetric downlink/uplink traffic, while with FDD, downlink and uplink always have fixed and generally equal DL and UL bandwidths.
- TDD assures channel reciprocity for better support of link adaptation, MIMO and other closed loop advanced antenna technologies.
- Unlike FDD, which requires a pair of channels, TDD only requires a single channel for both downlink and uplink providing greater flexibility for adaptation to varied global spectrum allocations.
- Transceiver designs for TDD implementations are less complex and therefore less expensive.

Table 1: Release-1 System profiles for Mobile WiMAX [35]

Channel BW	FFT Size	Other bands TBD	2.3-2.4 GHz	2.305-2.32, 2.345-2.36 GHz	2.496-2.69 GHz	3.3-3.4 GHz	3.4-3.8 GHz
1.25 MHz	128						
5.0 MHz	512		TDD	TDD	TDD	TDD	TDD
7.0 MHz	1024					TDD	TDD
8.75 MHz	1024		TDD				
10 MHz	1024		TDD	TDD	TDD	TDD	TDD
20 MHz	2048						

The OFDMA frame consists of a DL sub-frame and a UL sub-frame. The flexible frame structure of the TDD signal consists of a movable boundary between the DL and UL sub-frames. Placed between the DL and UL sub-frames are short transition gaps called transmit-receive transition gap (TTG). After the completion of the UL sub-frame, another short gap is added between this sub-frame and the next DL sub-frame. This gap is called the receiver-transmit transition gap (RTG). The minimum time durations for these transition gaps are called out in the 802.16 standard and are a function of the channel bandwidth and the OFDM symbol time. It is typical to define these transition gaps in terms of physical slot (PS) units whereby a PS is a unit of time defined as 4/fs (fs = sampling frequency). The sampling frequency is equal to the FFT size multiplied by the channel spacing. An example of a Mobile WiMAX frame is shown in Figure 13. This figure shows the time-frequency relationship where the symbol time is shown along the x-axis and the logical sub-channels along the y-axis. Logical sub-channels are groupings of frequency subcarriers assigned to individual users. Figure 13 shows the DL and UL sub-frames separated by the TTG and ending with the RTG. The figure also shows the relative position of the preamble, frame control header (FCH), downlink media access protocol (DL-MAP), and uplink media access protocol (UL-MAP) whose functions will be discussed subsequently. There are a number of significant differences in the UL signal compared to the DL. They reflect the different tasks performed by the BS and MS, along with the power consumption constraints at the MS. These differences include:

- No preamble, but there are an increased number of pilots. Pilots in the UL are never transmitted without data subcarriers.
- The use of special CDMA ranging bursts during the network entry process.
- Data is transmitted in bursts that are as long as the uplink sub-frame zone allows, and wrapped to further sub-channels as required.

Optimal system performance is ensured by the following control information present in the frame:

- Preamble: The DL sub-frame always begins with one symbol used for BS identification, timing synchronization, and channel estimation at the MS. This symbol is generated using a set of 114 binary pseudo random number (PN) sequences, called the preamble ID, of length 568. The data in the preamble is mapped to every third subcarrier, using BPSK, giving a modest peak-to-average power ratio (compared to the data sub-channels).
- Frame Control Header (FCH): The FCH follows the DL preamble with a fixed location and duration. The FCH contains the downlink frame prefix (DLFP). The DLFP specifies the sub-channelization, and the length and coding of the DL-MAP. The DLFP also holds updates to the ranging allocations that may occur in subsequent UL sub-

frames. In order that the MS can accurately demodulate the FCH under various channel conditions, a robust QPSK rate 1/2 modulation with four data repetitions is used.

- DL-MAP and UL-MAP: The DL-MAP and UL-MAP provide sub-channel allocations and control information for the DL and UL sub-frames. The MAP will contain the frame number, number of zones, and the location and content of all bursts. Each burst is allocated by its symbol offset, sub-channel offset, number of sub-channels, number of symbols, power level, and repetition coding.

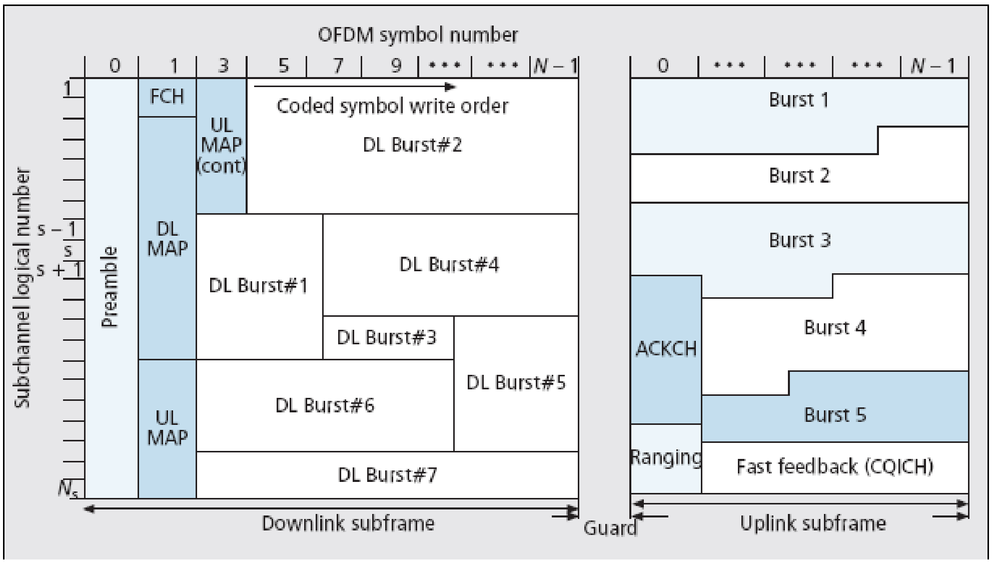

Figure 13: Mobile WiMAX OFDM (TDD) frame structure [36]

- UL Ranging: The UL ranging sub-channel is allocated for mobile stations (MS) to perform closed-loop time, frequency, and power adjustment as well as bandwidth requests.
- UL CQICH: The UL CQICH channel is allocated for the MS to feedback channel state information.
- UL ACK: The UL ACK is allocated for the MS to feedback DL HARQ acknowledge.

Some additional features included in the 802.16e OFDM PHY to boost coverage and capacity for WiMAX in mobile applications included Adaptive Modulation and Coding (AMC), Hybrid Automatic Repeat Request (HARQ) and Fast Channel Feedback (CQICH). The WiMAX OFDMA PHY supports sub-channelization in both DL and UL with the minimum frequency-time resource unit of sub-channelization being one slot, which is equal to 48 data tones (sub-carriers). There are two types of sub-carrier permutations for sub-channelization; diversity and contiguous. The diversity permutation draws sub-carriers pseudo-randomly to form a sub-channel, providing frequency diversity and inter-cell interference averaging. The diversity permutations include DL FUSC (Fully Used Sub-Carrier), DL PUSC (Partially Used Sub-Carrier) and UL PUSC and additional optional permutations. With DL PUSC, for each pair of OFDM symbols, the available or usable sub-carriers are grouped into clusters containing 14 contiguous sub-carriers per symbol period, with pilot and data allocations in each cluster in even and odd symbols. The structure of an UL PUSC is illustrated in Figure 14.

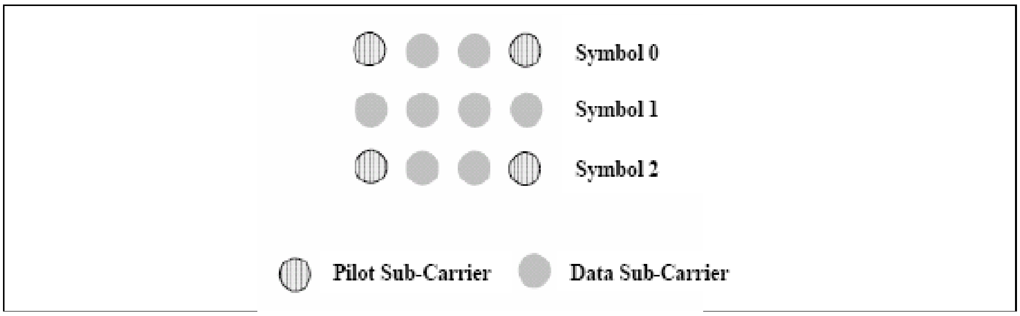

Figure 14: Tile structure of a UL PUSC [33]

The contiguous permutation groups a block of contiguous sub-carriers to form a sub channel. The contiguous permutations include DL AMC and UL AMC, and have the same structure. AMC permutation enables multi-user diversity by choosing the sub channel with the best frequency response. Diversity sub-carrier permutations generally perform well in mobile applications while contiguous sub-carrier permutations are well suited for fixed, portable, or low mobility environments. There are three modulation types available for modulating the data onto the subcarriers: QPSK, 16QAM, and 64QAM. In the UL, the transmit power is automatically adjusted when the modulation coding sequence (MCS) changes to maintain the required nominal carrier-to-noise ratio at the BS receiver. 64QAM is not mandatory for the UL. Binary phase shift keying (BPSK) modulation is used during the preamble, on the pilots, and when modulating subcarriers in the ranging channel. The BS scheduler determines the appropriate data rates and channel coding for each burst based on the channel conditions and required carrier-to-interference plus noise ratio (CINR) at the receiver.

B. Scalable OFDMA

Orthogonal Frequency Division Multiplexing (OFDM) is a multiplexing technique that subdivides the bandwidth into multiple frequency sub-carriers. In an OFDM system, the input data stream is divided into several parallel sub-streams of reduced data rate (thus increased symbol duration) and each sub-stream is modulated and transmitted on a separate orthogonal sub-carrier. The concept of scalability was introduced to the IEEE 802.16 WirelessMAN Orthogonal Frequency Division Multiplexing Access (OFDMA) mode by the 802.16 Task Group e (TGe). A scalable physical layer enables standard-based solutions to deliver optimum performance in channel bandwidths ranging from 1.25 MHz to 20 MHz with fixed subcarrier spacing for both fixed and portable/mobile usage models, while keeping the product cost low. The architecture is based on a scalable sub-channelization structure with variable Fast Fourier Transform (FFT) sizes according to the channel bandwidth. Scalable-OFDMA (S-OFDMA) supports a wide range of bandwidths to flexibly address the need for various spectrum allocation and usage model requirements.

The scalability is supported by adjusting the FFT size while fixing the sub-carrier frequency spacing at 10.94 kHz.

3.4.2 MAC Layer Description

Mobile WiMAX is based on IP or packet-switched services, which provide a common network core. Data transfer involves the creation of a service flow, a unidirectional transport mechanism from the MAC through the PHY. The MAC layer of the 802.16 standard was developed to support voice, data, and video under bursty conditions and high peak demands. The MAC is connection-oriented with each connection assigned a service class based on the type of quality of service (QoS) that is required by the MS. The MAC layer manages the radio resources to efficiently support the QoS for each connection established by the BS. There are five types of data delivery services available in the Mobile WiMAX profile. Table 2 shows a summary of the available service classes based on the typical application.

Table 2: Mobile WiMAX applications and QoS [33]

QoS Category	Applications	QoS Specifications
UGS Unsolicited Grant Service	VoIP	• Maximum Sustained Rate • Maximum Latency Tolerance • Jitter Tolerance
rtPS Real-Time Polling Service	Streaming Audio or Video	• Minimum Reserved Rate • Maximum Sustained Rate • Maximum Latency Tolerance • Traffic Priority
ErtPS Extended Real-Time Polling Service	Voice with Activity Detection (VoIP)	• Minimum Reserved Rate • Maximum Sustained Rate • Maximum Latency Tolerance • Jitter Tolerance • Traffic Priority
nrtPS Non-Real-Time Polling Service	File Transfer Protocol (FTP)	• Minimum Reserved Rate • Maximum Sustained Rate • Traffic Priority
BE Best-Effort Service	Data Transfer, Web Browsing, etc.	• Maximum Sustained Rate • Traffic Priority

A. MAC QoS support

Mobile WiMAX can meet QoS requirements for a vast range of data services and applications by making us of service flows shown in Figure 15. Service flow refers to is a unidirectional flow of packets that is provided with a particular set of QoS parameters.

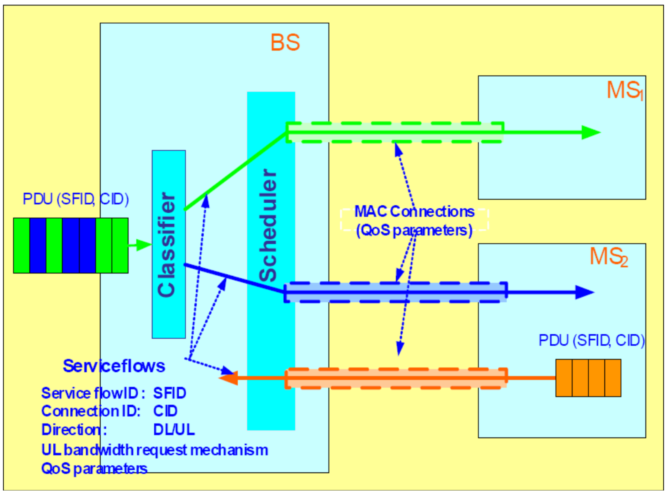

Figure 15: Mobile WiMAX QoS support [33]

Firstly a connection has to be established between the BS and MS, so that the connection-oriented QoS can accurately provide control over the air interface. The service flow parameters can be dynamically managed through MAC messages to accommodate the dynamic service demand. The service flow based QoS mechanism applies to both DL and UL to provide improved QoS in both directions.

B. MAC Scheduler

The MAC scheduler is located at each BS and is responsible for efficiently allocating the time and frequency resources in response to bursty traffic and channel conditions which vary with time. The resource allocations are delivered to the MSs using the DL-MAP and UL MAP located at the beginning of each frame. The scheduler determines the ordering of the data packets and the type of zone(s) on a frame-by-frame basis. With the ability to dynamically allocate resources in both DL and UL, the scheduler can provide superior QoS for both DL and UL traffic. Also, the scheduler can operate on different types of sub-channels. According to [33], frequency-selective scheduling can allocate mobile users to their corresponding strongest sub-channels as well as enhance system capacity with a moderate increase in Channel Quality Indicator (CQI) overhead in the UL.

C. MAC Handover and Mobility Management

The handover (HO) process allows an MS to switch to another BS in order to improve its QoS, which may have degraded due to movement across cell boundaries or changing channels conditions. It is very critical for mobile applications to be able to have a sustained battery life and smooth handoff. In the first case, Mobile WiMAX supports Sleep Mode and Idle Mode so as to enable power efficiency of the MS. Sleep Mode is a state in which the MS conducts pre-negotiated periods of absence from the Serving Base Station air interface. Meanwhile, Idle Mode provides a mechanism for the MS to become periodically available for DL broadcast traffic messaging without registration at a specific base station as the MS traverses an air link environment populated by multiple base stations. In the second case, the Mobile WiMAX profile specifies three techniques for hard HO and soft HO. Hard HOs use a break-before-make approach and are typically sufficient for data services. Soft HOs, while complex to implement and administer, are beneficial for applications that require low-latency such as VoIP.

D. MAC Security

Security aspects in Mobile WiMAX include features such as:

- Key Management Protocol, which manages the MAC security using PKM-REQ/RSP messages [33]. Also, PKM EAP authentication, Traffic Encryption Control, Handover Key Exchange and Multicast/Broadcast security messages all are based on this protocol.
- Device/User Authentication is supported by Mobile WiMAX using the IETF EAP protocol which provides support for credentials that are SIM-based, USIM-based or Digital Certificate or Username/Password-based.
- Traffic Encryption by making use of the AES-CCM cipher to protect all user date over the MAC interface. The Advanced Encryption Standard (AES) CCM is the cipher used for encrypting subscriber traffic Over the Air (OTA) Mobile WiMAX MAC interface. The WiMAX approach to AES encryption uses Counter Mode with Cipher Block Chaining Message (CCM) Authentication Code [35].
- Control Message Protection by the use of AES-based Cipher-based MAC (CMAC) or Message-Digest algorithm 5 (MD5)-based keyed-Hash MAC (HMAC) schemes.
- Fast Handover Support from a 3-way handshake scheme to optimize the re-authentication mechanisms for supporting fast handovers. This mechanism is also useful to prevent any man-in-the-middle-attacks.

3.4.3 Mobile WiMAX: Advanced Features

With OFDMA, it is possible to perform smart antenna operations on sub-carriers without the involvement of complex vector or matrix operations on the signals as a result of multiple antennas. Mobile WiMAX supports a full range of smart antenna technologies to enhance system performance [33]. Mobile WiMAX also supports adaptive switching between different techniques to maximize the benefit of smart antenna technologies under different channel conditions. Some of the smart antenna technologies are presented below.

A. Spatial Multiplexing

Spatial multiplexing involves transmission of multiple signal streams over multiple antennas. Spatial Multiplexing can be specifically applied to users who have the best signal quality, so that less time is spent transmitting to them. For those with extremely low signal quality conventional transmission is maintained as an alternative. In this way, an operator can offer higher data rates to some users and/or to serve more users. The advantages resulting from this scheme include higher peak rates and increased throughput.

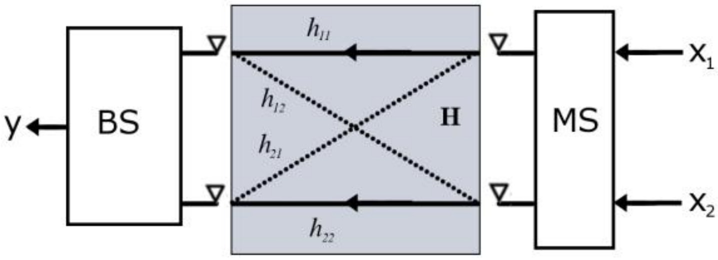

Figure 16: Spatial Multiplexing scheme [37]

B. Beamforming

This is the process whereby multiple antennas are used to transmit weighted signals. In this way, outage probability is reduced while system capacity and coverage are improved.

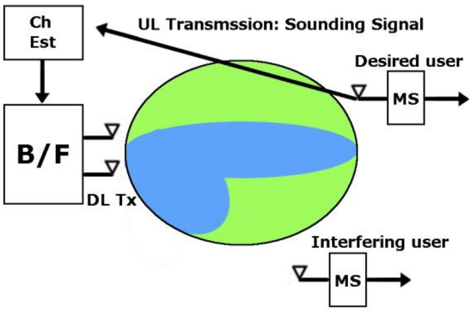

Figure 17: Beamforming scenario [35]

C. Adaptive MIMO Switching (AMS)

This is applied to maximize the spectral efficiency and peak data rates at the same time. Figure 18 illustrates this.

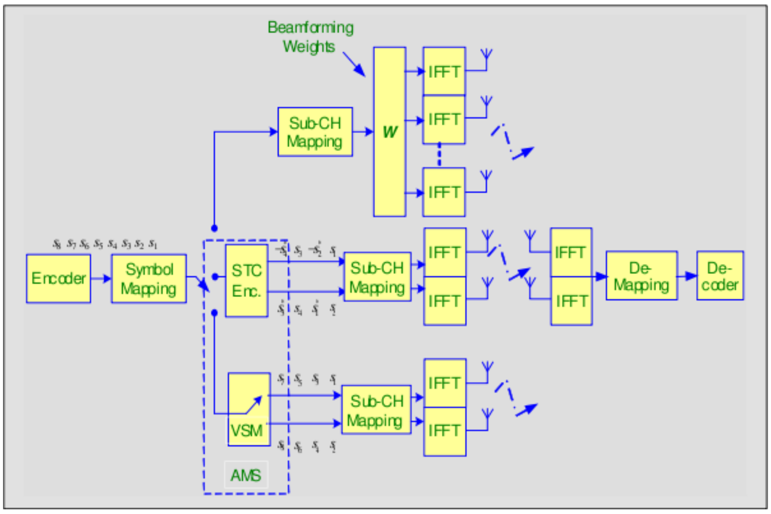

Figure 18: Adaptive MIMO switching scheme [37]

D. Space-Time Code (STC)

In STC, transmit diversity codes are used to provide spatial diversity with the net effect of reducing the fade margin.

E. Fractional Frequency Reuse

There is always the risk of intercellular-interference at cell edges when the same frequency band is used in each cell. Mobile WiMAX (802.16e) introduces the fractional frequency reuse whereby channels are subdivided into subsets with MSs closest to the BS being allocated more subsets while those farther away from the BS are allocated less subsets. The sub-channels on which users operate only occupy a small fraction of the whole channel bandwidth and this sub-channel reuse is made easy by sub-channel segmentation and permutation zone. This is illustrated in Figure 19.

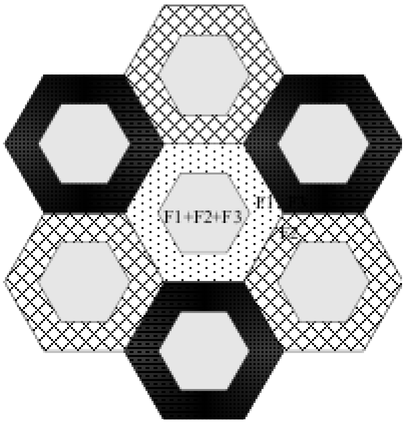

Figure 19a: Fractional Frequency Reuse (FFR) [37]

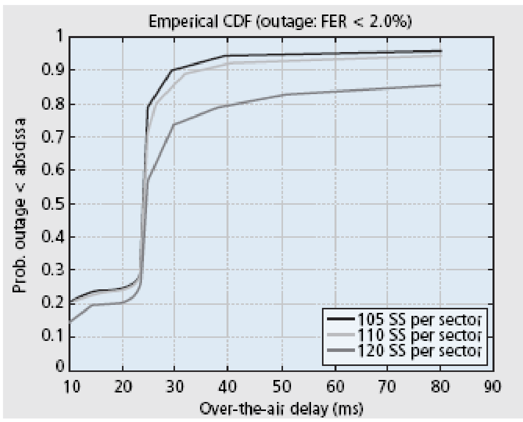

Figure 19b: Improvements of FFR over PUSC 1/3 and PUSC 1/1 [36]

F. Multicast and Broadcast Service (MBS)

This makes use of the best features offered by DVB-H, MediaFLO and 3GPP E-UTRA [33]. In this way, several requirements are satisfied, including high data rate and coverage using a Single Frequency Network (SFN), flexible allocation of radio resources, low MS power consumption, support of data-casting in addition to audio and video streams and low channel switching time. The flexibility of Mobile WiMAX to support integrated MBS and unicast services enables a broader range of applications. Figure 20 shows the DL/UL zone construction when a mix of unicast and broadcast service are supported.

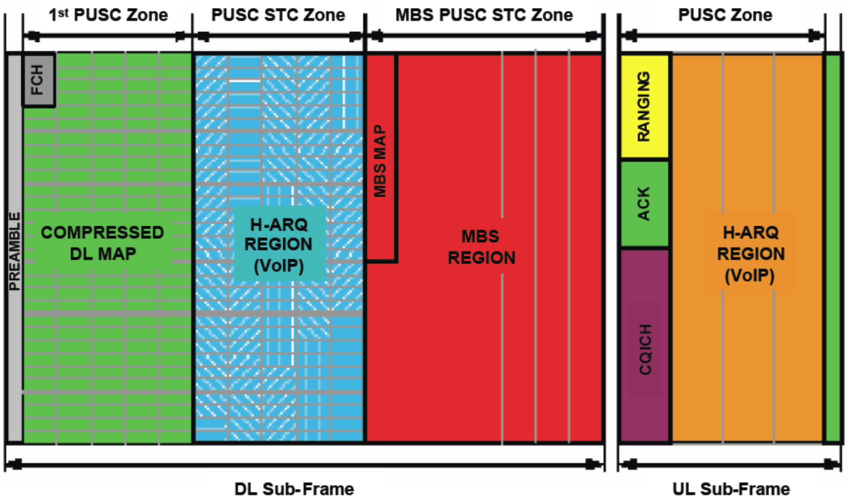

Figure 20: Embedded MBS Support with Mobile WiMAX – MBS Zones [33]

4 IMT-ADVANCED REQUIREMENTS AND FEATURES

4.1 Introduction

The International Telecommunication Union (ITU) is currently defining “Fourth Generation” (4G) mobile wireless services with its Radiocommunication Sector (ITU-R) in the process of establishing an agreed and globally accepted definition of 4G wireless systems using the name IMT-Advanced. In the past, ITU’s project on International Mobile Telecommunications 2000 (IMT-2000) was used to determine current 3G systems. A document titled “Recommendation ITU-R M.1645: Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000” [38] was published by ITU to provide the basis for the 4G project. In March 2008, the ITU-R placed an open invitation for the submission of candidate technologies for IMT-Advanced [39]. The term IMT-Advanced was used in describing radio-access technologies beyond IMT-2000 and these systems should provide access to a wide range of telecommunication services including increasingly packet-based advanced mobile services which are supported by both mobile and fixed networks. The ITU-R’s Working Party 5D (WP 5D) - IMT Systems, defines key IMT-Advanced features to include:

- 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.
- Capability of inter-working with other radio access systems.
- High quality mobile services.
- 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).

Target requirements defined for IMT-Advanced are contained in Report ITU-R M.2134 Requirements Related to Technical Performance for IMT-Advanced Radio Interface(s) [40]:

“International Mobile Telecommunications-Advanced (IMT-Advanced) systems are mobile systems that include the new capabilities of IMT that go beyond those of IMT-2000. Such systems provide access to a wide range of telecommunication services including advanced mobile services, supported by mobile and fixed networks, which are increasingly packet-based.”

By establishing the requirements for the IMT-Advanced, provisions are made which guarantee the basic requirements for a consistency in the definition, specification, and evaluation of the candidate Radio Interface Technologies (RITs) or Sets of RITs (SRITs) for IMT-Advanced. In combination with the establishment of other Recommendations and Reports like the report on the evaluation criteria “Guidelines for evaluation of radio interface technologies for IMT-Advanced” [41] and the circular letter framework [42], the IMT-Advanced requirements will be implemented. As mentioned in [43], these requirements ensure that IMT-Advanced technologies are able to fulfil the objectives of IMT-Advanced, and to set a specific level of minimum performance that each proposed technology needs to achieve in order to be considered by ITU-R Working Party (WP) 5D for IMT-Advanced. It is also worth noting that the requirements mentioned here places no restrictions on the full range of capabilities or performance that candidate technologies for IMT-Advanced might achieve, nor are they designed 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. These requirements, detailed in the Report ITU-R M.2134 include:

- Cell spectral efficiency: the aggregate throughput of all users.
- Peak spectral efficiency: the highest theoretical data rate assignable to a single mobile station when all available radio resources for the corresponding link direction are utilized. Minimum requirements (15 bps/Hz Downlink, 6.75 bps/Hz Uplink).
- Bandwidth: scalable up to 40 MHz or even be extended to 100 MHz by candidates.
- Cell edge user spectral efficiency: 5% of cumulative density function (CDF) of the normalized user throughput.
- Latency: different forms of delay including control plane (C-Plane) latency, user plane latency or transport delay, etc.
- Mobility: mobility classes include stationary (0 km/h), pedestrian (0-10 km/h), vehicular (10-120 km/h) and high speed vehicular (120-350 km/h).
- Handover: defined as the time duration when the user terminal cannot exchange user plane packets with any base station. IMT-Advanced proposed handover interruption times include intra-frequency (27.5 ms), inter-frequency (within same spectrum band 40 ms and between different spectrums 60 ms).
- VOIP capacity: the minimum of the calculated capacity for either link direction divided by the effective bandwidth in the respective link direction.

In a meeting held by the ITU-R WP 5D at the German city of Dresden from 14-21 October 2009, six candidate technology proposals were submitted. The six proposals aligned around 3GPP’s LTE Release 10 and beyond (LTE-Advanced) with specifications expected to become available in 2011 and the IEEE 802.16m technology [44]. In October 2010, the selected technologies are expected to be accorded the official designation of IMT-

Advanced, thus qualifying as true 4G technologies. In accordance with the principles defined by ITU for acceptance of any technology into the 4G family, such a technology must be capable of meeting all aspects of growth in the market place beyond 2010, thus taking into consideration and building upon the existing and constantly expanding 3G business environment. Fully functional and widespread IMT-Advanced systems will become common place only in the next decade but already, mobile operators and vendors are considering ways of taking advantage and enhancing current operational systems like LTE and WiMAX, so as to meet the requirements for IMT-Advanced. A set of agreed-upon requirements need to be used to verify each technology before it can qualify as "4G". This will happen in the future when the requirements are outlined by the ITU and for any particular technology to claim "4G" status prior to an established definition by the ITU is, in fact, simply marketing spin, creating market confusion and deflating the importance of the telecommunications industry standards. In the following sections, we carry out a more detailed consideration of the candidate technologies vying for 4G status (i.e. LTE-Advanced and IEEE 802.16m) as well as a discussion on their different approaches in satisfying the requirements for IMT-Advanced as defined by ITU-R.

4.2 LTE-Advanced Features

3GPP LTE Release 10 and beyond, LTE-Advanced, is developed so as to meet the diverse requirements of advanced applications that are set to become common place in the foreseeable future of the wireless services industry. It is expected to also drastically reduce the Capital Expenses (CAPEX) and Operational Expenses (OPEX) of future broadband wireless networks. Anticipating the invitation from the ITU, 3GPP already in March 2008 initiated a study item on LTE-Advanced, with the task of defining requirements and investigating the technology components of the evolution of LTE, an evolution including extending LTE to meet all the requirements of IMT-Advanced as defined by the ITU [45].

Furthermore, LTE-Advanced will be an evolution of LTE, thus making it possible for backward compatibility with LTE and it also designed to meet or even exceed all IMT-Advanced requirements including enhanced data rates of up to 1Gbps in the downlink and 500 Mbps in the uplink, increased capacity with the possibility of high data rates provided over a larger portion of the cell as well as low cost of deployment. The backward compatibility requirement for LTE-Advanced has a direct implication in the sense that, for an LTE terminal, a network with LTE-Advanced capabilities should appear as an LTE network. It is of critical importance to have such spectrum-compatible systems in order to achieve a smooth, low-cost transition to LTE-Advanced capabilities within the network and this can be likened to the evolution of WCDMA to HSPA.

In the rest of this section, some key technological components being developed as we evolve from LTE to LTE-Advanced will be discussed but before getting to that, it is important to note at this point that current cellular systems including LTE have a link performance close to the Shannon limit. For developers to be able to achieve the extremely high data rates expected for LTE-Advanced, a higher signal-to-noise ratio (SNR) compared to current standards, has to be taken into account. Although some link improvements are possible, for example, using additional bandwidth as a means to improve the coding/modulation efficiency, it is necessary to find tools for improving the SNR, for instance, by means to allow for a denser infrastructure at reasonable cost. The goals of LTE-Advanced and the manner in which these goals can be met are summarized below [46]:

- Flexible and faster network deployment achieved with the help of heterogeneous networks.
- Better coverage and improved spectral efficiency (cell edge and average) achieved through robust interference management.
- Greater flexibility with wideband deployments by employing wider bandwidth by carrier aggregation across bands.
- Ubiquitous & cost-effective broadband using higher peak user rate by higher order DL and UL MIMO.

In the following subsections, some examples of technologies considered for LTE-Advanced are outlined.

4.2.1 Carrier Aggregation/Wider band Transmission & Spectrum Sharing

Carrier Aggregation (CA) is being cited as a major technological enhancement that will be essential if LTE-Advanced is to meet the requirements for IMT-Advanced, particularly the requirement for the support of larger bandwidths than those currently supported in LTE while at the same time maintaining backward compatibility with LTE. Recall that in LTE Rel-8 (the first LTE release), there was extensive support for deployment in spectrum allocations ranging from 1.4 MHz to 20 MHz in both paired and unpaired bands. One of the goals for LTE-Advanced is to exploit spectrum allocations up to 100 MHz so as to meet the expectations of very high peak-data rates. This can only be possible by increasing the transmission bandwidth provided by the first release of LTE, hence carrier aggregation. CA simply combines or aggregates multiple component carriers on the physical layer to provide the required bandwidth. LTE-Advanced can then take advantage of these aggregated bandwidths in total, while each component carrier will still appear as just a single LTE carrier when seen from the perspective of an LTE Rel-8 terminal.

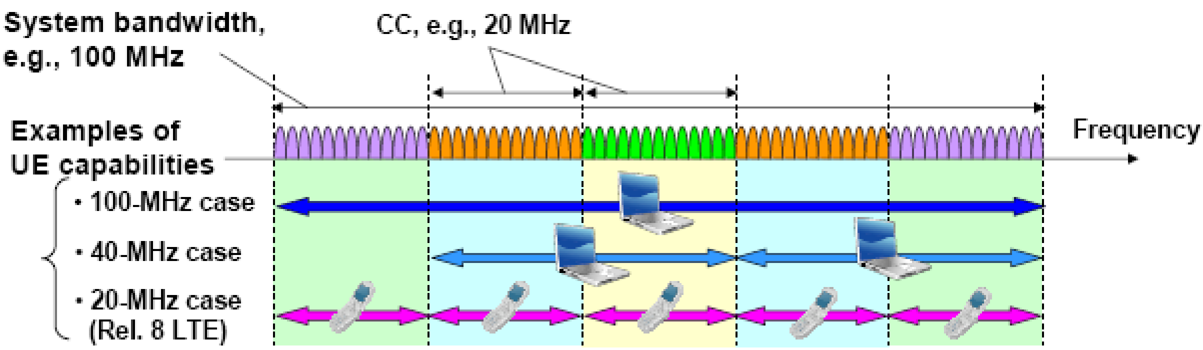

Figure 21: Carrier aggregation for LTE-Advanced systems illustrating flexible spectrum usage [47]

In Figure 21, the case of contiguous component carriers is illustrated even though, from a baseband perspective, this might not always be the case (i.e. access to large amounts of contiguous spectrum, in the order of 100 MHz, may not always be possible). LTE-Advanced could, therefore, allow for aggregation of non-contiguous component carriers in, possibly, separate spectrum to handle situations where large amounts of contiguous spectrum are not available and in this case we talk of spectrum aggregation. Spectrum aggregation could be classified into three categories as illustrated in Figure 22:

- Intra-band adjacent.
- Intra-band non-adjacent.
- Inter-band.

Though spectrum aggregation is supported by basic specifications, it will be challenging to implement due to constraints including a specifications of only a limited number of aggregations scenarios and also by the fact that only the most advanced terminals will be capable of supporting aggregation over such a dispersed spectrum. As described in [49], for a component carrier to be accessible by an LTE terminal, synchronization signals and broadcast channels need to be present meanwhile, for an LTE-Advanced terminal capable of receiving multiple component carriers, it is sufficient if these signals are available on one of the component carriers only.

In this way, an operator can control which part of the spectrum is accessible to LTE terminals by enabling or disabling synchronization signals. It will also be possible for an LTE-Advanced terminal to aggregate a different number of component carriers of possibly different bandwidths in the UL and the DL. However, the number of component carriers in the UL and DL are typically the same for TDD deployments. Access to higher transmission bandwidths is not only useful from a peak-rate perspective, but also, and probably more important, as a tool for extending the coverage of medium data rates. Component carriers can be aggregated at different layers in the protocol stack.

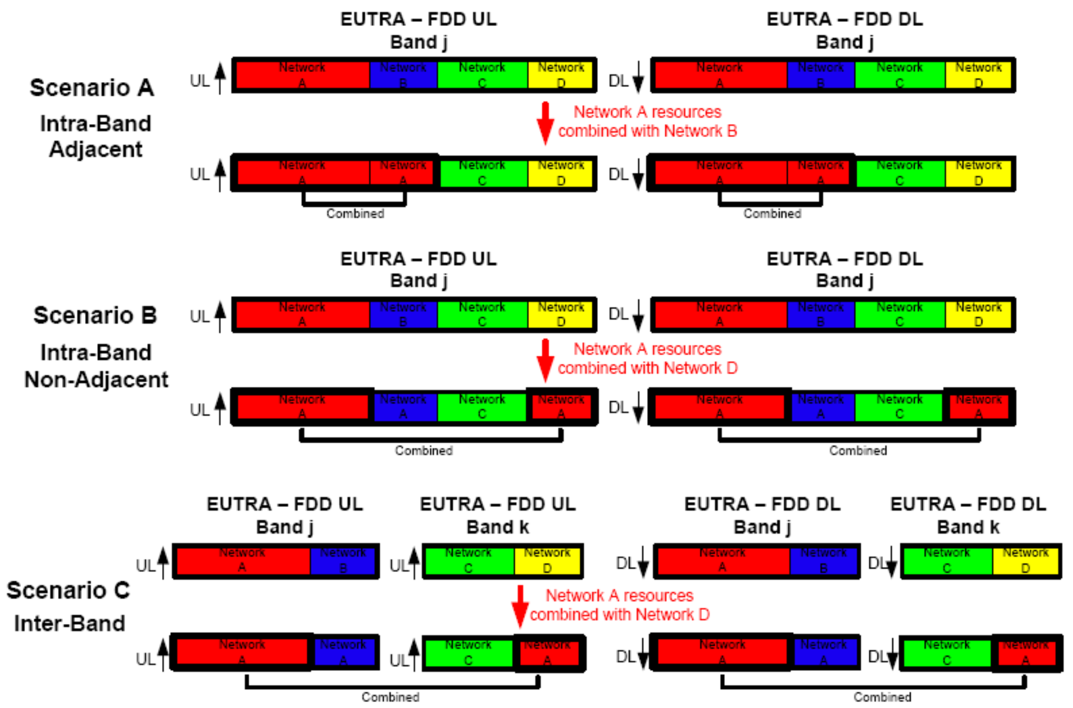

Figure 22: Spectrum aggregation scenarios for FDD [48]

As shown in Figure 23, for LTE-Advanced, the data streams are aggregated above the MAC layer from the different component carriers. In terms of the MAC and PHY mapping strategy, one transport block, HARQ entity and HARQ feedback will support each component carrier. In this way, we can be sure of maximum reuse of Rel-8 functionalities and better HARQ performance due to carrier component-based link adaptation though there is a drawback with multiple HARQ feedback in each TTI.

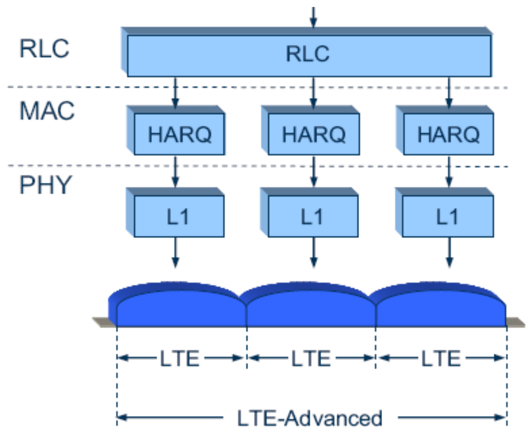

Figure 23: Carrier aggregation [49]

Processing of each component carrier at the PHY layer is identical to Rel-8, thus beneficial for implementation and specification purposes. In this way, existing implementations can, to a large extent, be reused, thereby shortening the time-to-market for LTE-Advanced equipment [49].

4.2.2 MIMO/Multi-antenna solutions

An important component in meeting the goals of LTE-Advanced is multi-antenna technology. These include things like beamforming and spatial multiplexing, which are already playing major roles in LTE. Enhancements of MIMO technologies for LTE-Advanced are driven by the need for increased peak rates, improvement of system level performance and support of various transmission schemes with a universal structure. As outlined in [50], the scope of MIMO in LTE-Advanced will include the following:

- Downlink (DL) higher-order MIMO.
- Enhanced DL multi-user MIMO (MU-MIMO).
- Uplink spatial multiplexing.
- Uplink transmit diversity with multiple transmit (Tx) antennas.
- Coordinated Multi-Point (CoMP) transmission/reception.

In order to improve the spatial efficiency of the downlink, extension of LTE downlink spatial multiplexing (SM) up to eight layers is considered part of the LTE evolution and in the case where carrier aggregation is used, SM with eight layers per component carrier will be supported. This means up to 8-rank transmissions and up to 2 codeword transmissions as illustrated in Figure 24. Meanwhile, in the case where there are a large number of terminals in a cell, the cell spectral efficiency can be further increased through the use of MU-MIMO [48]. Current LTE designs which support up to four antenna ports and hence spatial multiplexing of up to four layers, results in peak-data rates of 300 Mbit/s. When this is combined with a total bandwidth of 100 MHz, as a result of carrier aggregation discussed earlier, the spatial multiplexing schemes being considered for LTE would increase the peak-data rates to about 1.5 Gbit/s, which goes beyond the requirements of LTE-Advanced.

In addition to the steps listed above, the LTE uplink must be also extended with the support of uplink MIMO (multilayer) for it to be fully compliant with IMT-Advanced. Under consideration by 3GPP, on one hand, are techniques that depend on channel reciprocity and on the other hand, techniques that do not rely on channel reciprocity. Techniques under the first group include beamforming and MU-MIMO. For these, the enhanced NodeB (eNB) by using a sounding reference signal from the terminal is able to determine the state of the channel while assuming that the channel is seen in the same way by both the eNB and the terminal, and then forms transmission beams accordingly. Techniques which do not rely on channel reciprocity fall into three groups:

- Open-loop MIMO (OL-MIMO) which is used in cases where the transmitter has no knowledge of the Channel-State Information (CSI). Since the terminal has no knowledge of the CSI from the eNB, these techniques cannot be optimized for the specific channel condition seen by the eNB receiver but they are robust to channel variations. As a result, these techniques are well suited to high-speed mobile communication.

- Closed-loop MIMO (CL-MIMO) is used when the eNB can send CSI to the terminal and can be used to significantly increase the spectral efficiency. In general, it can be assumed that CL-MIMO has better performance than OL-MIMO in low-speed environments but has worse performance than OL-MIMO in high-speed environments.
- MU-MIMO which when enhanced can greatly improve the spectral density and it is also possible to carry out joint processing within a single base station or across multiple base stations.

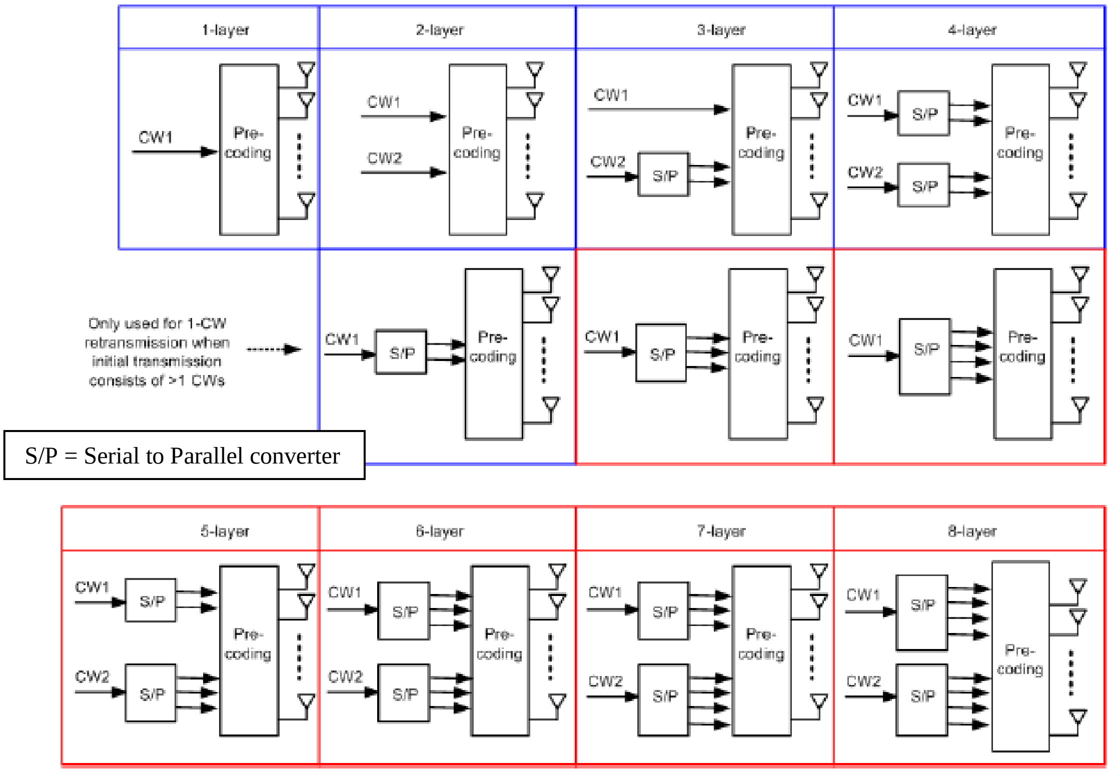

Figure 24: Codeword to layer mapping in LTE-Advanced downlink MIMO [50]

4.2.3 CoMP (Coordinated Multiple Point) Transmission/Reception

A significant improvement in the SINR at terminals is essential to meeting the targeted data rates for LTE-Advanced. A couple of methods are available to carry this out, amongst which is beamforming. However, there exist other ways to make improvements on current data rates. One of these is Coordinated Multi-Point transmission/reception (CoMP), which according to 3GPP can be used to improve coverage, cell-edge throughput, and system efficiency [48]. CoMP works in a way that user equipment (UE), or a terminal in a cell region would be capable of receiving signals from several cell sites and by coordinating these signals using techniques like interference avoidance, the DL performance can be significantly improved. Likewise, it would also be possible for the UE's transmissions to be received at multiple cell sites irrespective of the load in the system and by coordinating the scheduling from different sites, link performance can be significantly improved. Networks already make use of multiple, dispersed antennas connected through a central base band unit as a means of reducing the overall cost of network construction. Unlike the case of MIMO where antennas are deployed on a single site, CoMP interconnects antennas deployed at a number of sites that are in proximity to one another [51].

CoMP operations can be classified as either intra-site whereby the coordination is within a single cell or inter-site, involving the coordination of several cell sites as illustrated in Figure 25. Unlike inter-site CoMP which would require backhaul transport, hence increasing the burden on backhaul design, intra-site CoMP does not require backhaul as all communication happens within a single site, thus making it possible for a large amount of information to be exchanged.

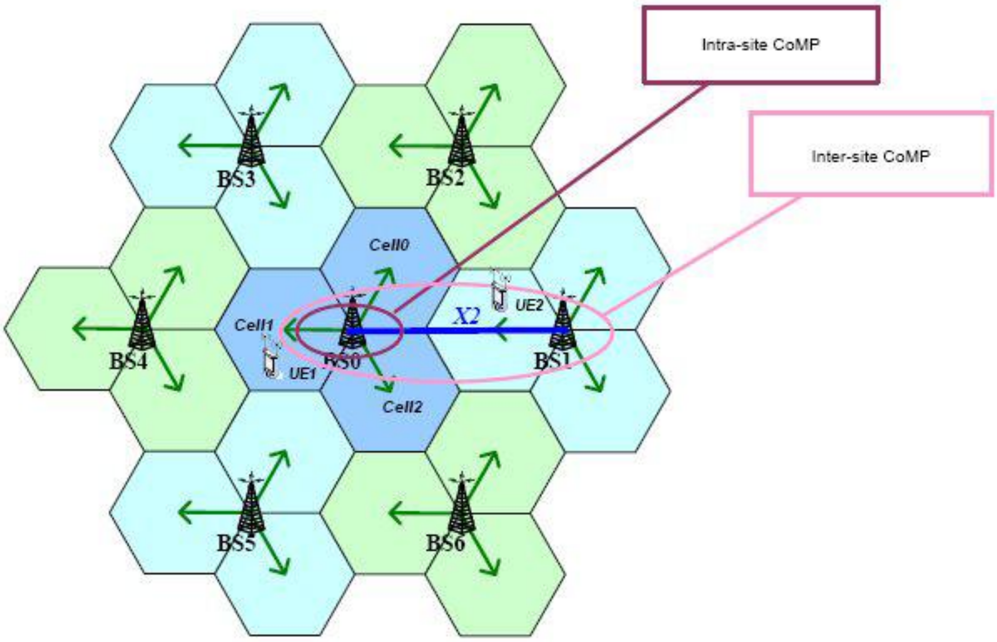

Figure 25: An illustration of inter-site and intra-site CoMP [52]

The manner in which coordination is performed in CoMP can be further separated into two categories: Coordinated scheduling / coordinated beamforming (CSB) and Joint Processing and Transmission (JPT) from multiple cells. These schemes are shown in Figure 26.

In the case of CSB, the transmission to a single terminal is done from the serving cell, just like in non-CoMP transmission. However, the scheduling, as well as any beamforming functionality, is dynamically coordinated between the cells so as to control and/or reduce the interference between different transmissions.

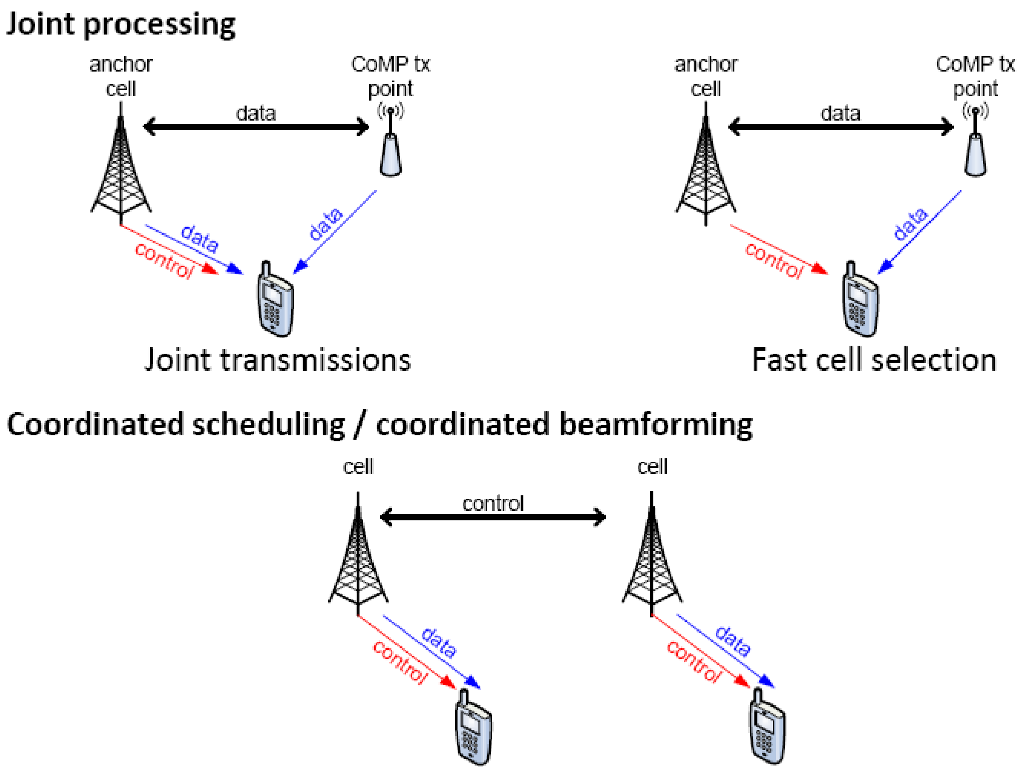

Figure 26: Different CoMP scenarios [50]

The best serving set of users will in principle be selected in such a manner that the transmitter beams are constructed to reduce the interference to other neighbouring users, while increasing the signal strength of the served user. Alternatively, with respect to JPT schemes, transmissions can be carried out to a mobile terminal jointly from multiple transmission points located on several cell sites. This helps in not only reducing the interference but also increasing the received power. The transmission from the cell sites can also take the instantaneous channel conditions into account, thereby achieving multi-cell beamforming or precoding gains. The higher performance gained by this scheme though comes at the expense of a much more tight requirement of backhaul communication.

Uplink CoMP mainly describes reception of transmitted signals at multiple points separated geographically and is mainly an implementation issue rather than a specification one since it impacts mostly the scheduler and receiver. Interference is handled by coordination of scheduling decision between cooperating units which in this case can be anything from separate eNB's remote radio units or relays. For the uplink, coordinated multipoint reception is mainly a question of applying the relevant signal processing at the receiver which is very similar to macro diversity, used already today in many cellular systems. As written in [49], maximum-ratio combining and interference-rejection combining are examples of schemes that can be used to combine the uplink transmission received at multiple points.

4.2.4 Heterogeneous Networks

Improving on the performance of LTE within the framework of LTE-Advanced has led 3GPP to consider a host of technologies including higher order MIMO, carrier aggregation (multiple component carriers), as well as heterogeneous networks (relays, pico and femto). As reported in [53], improvements in spectral efficiency per link is approaching theoretical limits with 3G and LTE, therefore future technologies are considering improvements on the spectral efficiency per unit area. This means that users anywhere within a specific cell have to have a smooth and uniform experience and this can be achieved by implementing a new deployment strategy using heterogeneous networks which is different from traditional network topology. Basically, heterogeneous networks will enable flexible and low-cost deployments by using a mix of macro-, pico-, femto-, and relay base stations. Unlike current deployments which are typically homogeneous networks in a macro-centric approach having a series of base stations (with similar transmit powers levels and antenna patterns) in a planned layout and serving a collection of user terminals, heterogeneous networks will incorporate advances in wireless systems in which a single base station can achieve near optimal performance. Heterogeneous networks will combine a variety of low power nodes with distinct characteristics, deployed throughout a macro eNB cell layout and in a manner which guarantees an improvement in the spectral efficiency per unit area. These low power nodes will include micro, pico, remote radio head (RRH), relay and femto nodes, some of which are shown in Figure 27.

It is important to note that, while the macro base stations transmitting at high power levels of about 5W – 40W are deployed in a carefully planned manner, the micro, pico, femto and relay base stations typically transmit at very low power levels ranging from 100mW – 2W and are deployed on mainly an ad hoc bases, with just enough information on coverage issues and traffic density (like hotspots) with the network.

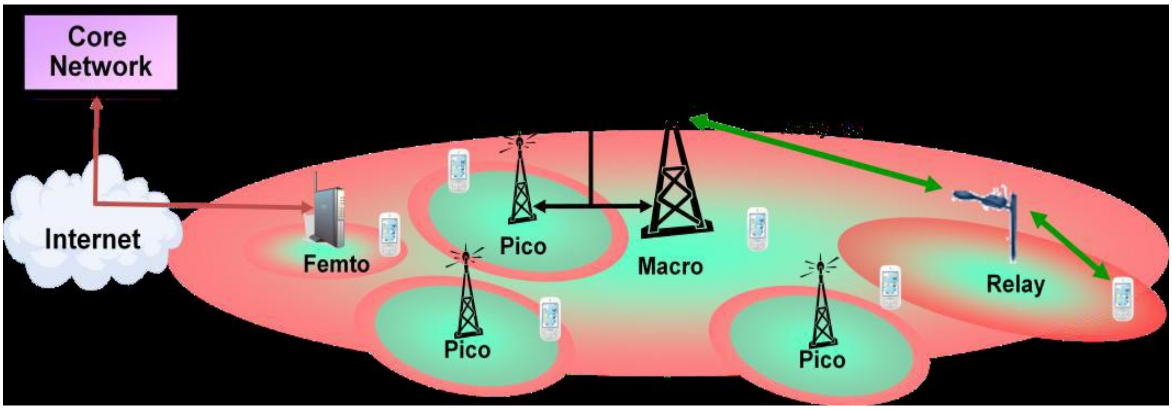

Figure 27: Heterogeneous Network with mix of macro, pico, femto and relay BSs [53]

The small size of these low-powered base stations makes them especially suitable when dealing with challenging site acquisitions as well as for offering flexible backhaul in situations where wireline backhaul is not possible or too costly. Some heterogeneous network scenarios currently being studied in 3GPP are mainly related to hotzone deployments although some indoor-related aspects are also being discussed and these scenarios include the following: Indoor Home eNB clusters, Outdoor Hotzone cells, and Indoor Hotzone scenario. The key design issues to be considered for heterogeneous networks are range extension and advanced interference management.

As a result of the low transmit power of pico base stations coupled with unplanned deployment, the networks in which these base stations are located will cover large areas but with low SINR. This will especially affect downlink coverage due to the disparity between a pico and macro base station. This is however not so severe when considering uplink coverage, since the signal strength from the terminals to the different base stations is similar. This difference in the uplink and downlink characteristics causes mismatch between uplink and downlink handoff boundaries as well as difficulty in server selection. Therefore it is critical to balance the load between the macro and pico base stations by expanding the coverage of the pico base station and subsequently increase cell splitting gains [53], hence range extension.

In the presence of a macro base station, a user terminal needs to perform both control and data channel interference coordination with the stronger macro interferers before it can get service from a low powered base station. If the low power base station is a femto base station, allowing only the owner or subscribers to have access, it becomes really difficult for other users in the vicinity of the femto base station, who have limited or no access to it yet suffering from serious interference due to these low power base stations. This therefore means that a much more coordinated scheme involving resource partitioning would be required in order to manage inter-cell interference, hence Inter-cell Interference Coordination (ICIC) which constitutes one method of Advanced Interference Management (AIM). A basic ICIC technique involves resource coordination amongst interfering base-stations, where an interfering base-station gives up use of some resources in order to enable control and data transmissions to the victim user terminal [53]. Another method of AIM is Slowly-Adaptive Interference Management (S-AIM) whereby the negotiation and allocation of resources happens over time frames which are considerably larger than the scheduling intervals. The objective of S-AIM is to harmonize and combine the transmit powers of all base stations and user terminals within a given space or area, and over all the time and frequency resources, in a manner that would maximize the efficiency of the network. This can be measured in terms of delays in QoS flows, user data rates or other metrics of fairness. Figure 28 illustrates the gains made on both cell-edge and median user rates by employing the methods described above (i.e. range extension and AIM).

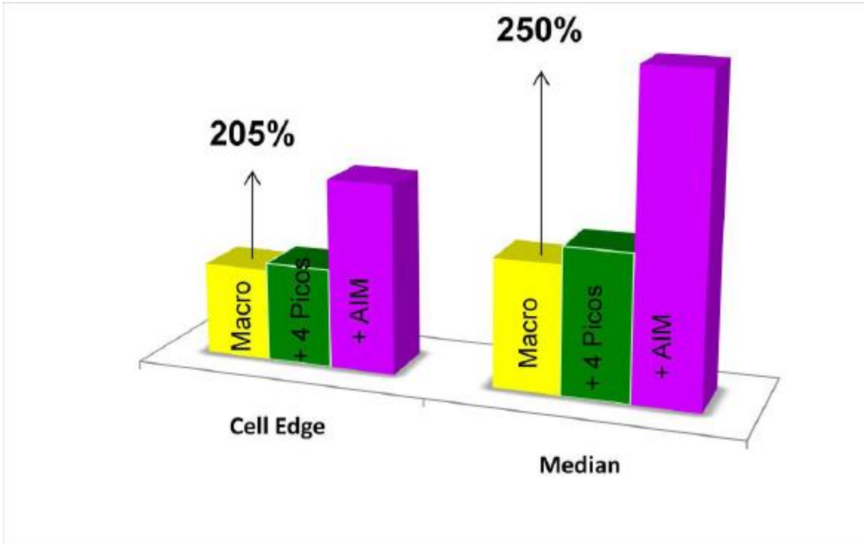

Figure 28: Downlink throughput improvement in the presence of mixed Macro/Pico deployment and Advanced Interference Management (AIM) [53]

4.2.5 Relays and Repeaters

The use of a Relay Node (RN) opens up new possibilities for increasing the density of infrastructure deployed with the aim of cutting the distance between transmitters and receivers, hence allowing for higher data rates. In addition to higher data rates, the idea of RN deployment would also support improvements in group mobility, cell edge coverage as well as extend coverage to heavily shadowed areas or areas beyond the cell range. Another potential benefit of this scheme is to cut back on the CAPEX and OPEX by having cells of relatively large sizes. Repeaters which are already used today for dealing with coverage holes also play a key role by simply amplifying and forwarding the received analogue signals. In a typical relay network scenario, the RNs are connected through a donor cell to the radio access network. The RN connects to the donor eNB via the Un interface while the user terminals connect to the RN via the Uu as illustrated in Figure 29.

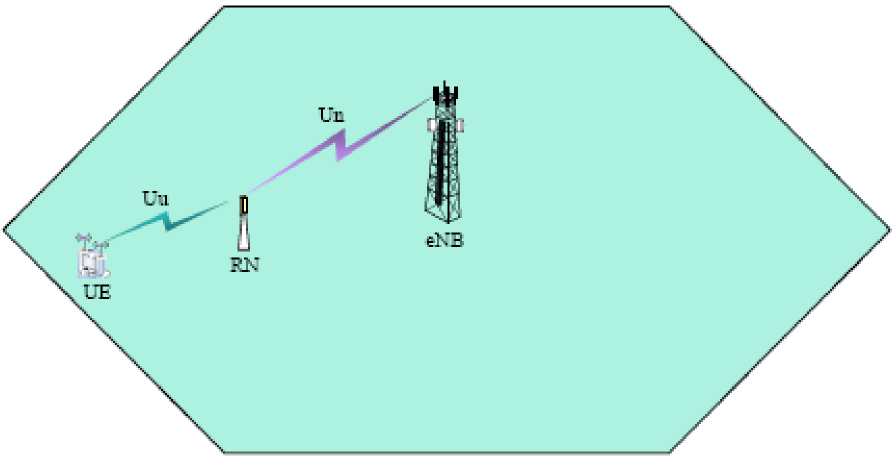

Figure 29: A typical relay network [48]

The different relay types under consideration by 3GPP include:

- Layer 1 (L1) Relay, which is also known as Amplify-and-Forward Relay, is like a much more advanced repeater structure and is easy to implement through RF amplification with relatively low latency. This is not however very practical as undesired noise and interference are also amplified together with the desired signal.
- Layer 2 (L2) Relay carries out decode-and-forward operations, with more freedom to achieve performance optimization. In this case, an intermediate node would decode and re-encode any received data prior to forwarding it to the served users or next hop. A significant amount of delay (> 1ms, size of LTE sub-frame duration) is introduced as the intermediate node decodes and re-encodes received data. However, no noise is forwarded by the relay node and rate adaptation may be performed individually for each link. This kind of relay can eliminate propagating the interference and noise to the next hop, so it can reinforce signal quality and achieve much better link performance.
- Layer 3 (L3) Relay, also referred to as Self-Backhauling, is when forwarding is performed on Layer 3 instead of Layer 2 as in L2. L3 has very similar characters to L2 (e.g. both introduces delays, neither suffers from noise amplification), the self-backhauling solution has much less impact on the eNB design and does not require any new nodes, protocols or interfaces to be standardized as the existing solutions are reused and may, therefore, be preferable over their L2 counterpart. On the other hand, L3 may cause more overhead than L2.

While a relay network may involve more than one hop as illustrated in Figure 30, current 3GPP considerations are focused on single hop relays with the self-backhauling L3 as main candidate.

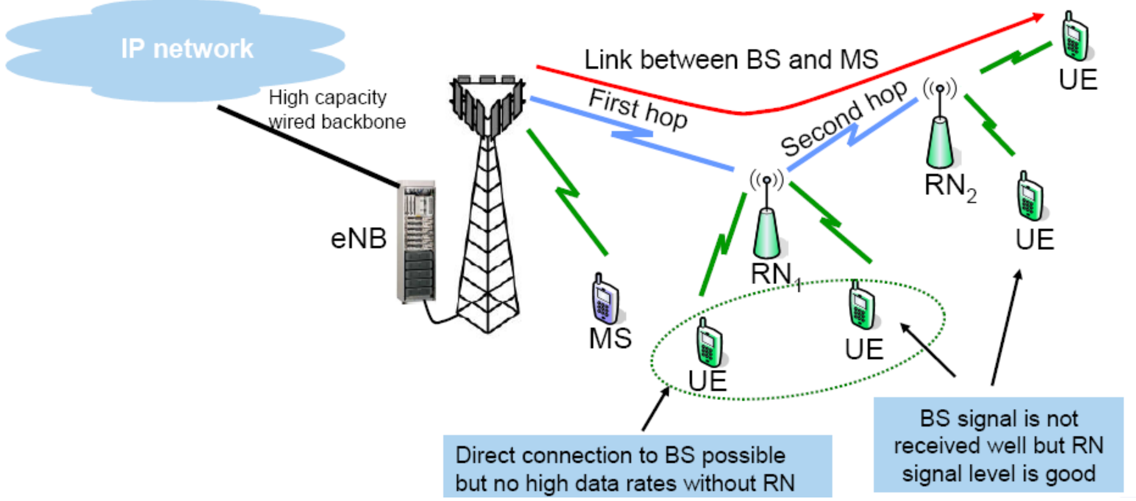

Figure 30: Relay network with multiple hops [54]

Relays under consideration by 3GPP can also be classified as transparent or non-transparent from the point of view of the user equipment. In transparent relay, the UE is not aware that it is communicating with the eNB via a relay and this type of relay was proposed for scenarios where the intention was to achieve throughput enhancement of UEs located within the coverage of the eNB with less latency and complexity but could also be used for filling in coverage holes. In non-transparent relay the UE is aware of its communicating with the eNB via a RN. In this case, the data traffic and control signal transmissions between the user terminal and the eNB are forwarded along the same relay path. Non-transparent relaying may be applicable for almost all cases where the UE is within the coverage of eNB or coverage holes, but may not be an efficient way for all scenarios, because both the data and control signaling are conveyed multiple times over the relay links and the access link of a relay path. There also exist another grouping of relay nodes into Type 1 and Type 2. A Type 1 relay node has the following characteristics:

- It controls cells, each of which appears to a UE as a separate cell distinct from the donor cell.
- The cells shall have its own Physical Cell ID (defined in LTE Rel-8) and the relay node shall transmit its own synchronization channels, reference symbols, etc.
- In the context of single-cell operation, the UE will receive scheduling information and HARQ feedback directly from the relay node and send its control channels (SR/CQI/ACK) to the relay node.
- It appears as a Rel-8 eNB to Rel-8 UEs (i.e. it will be backwards compatible).
- To LTE-Advanced UEs, a Type 1 relay node could appear differently than an eNodeB, thus allowing for further performance enhancement.

Meanwhile, Type 2 relay nodes are characterized by not having a separate Physical Cell ID and thus would not create any new cells, transparent to Rel-8 UEs, thus making it unaware of the presence of a Type 2 relay node, and also, they can transmit PDSCH.

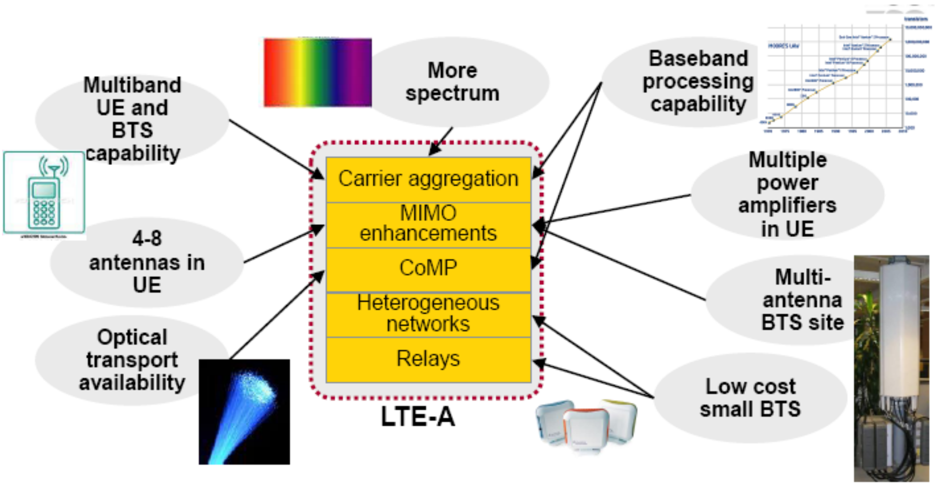

Figure 31: Key LTE-Advanced benefits [55]

According to [48], LTE-Advanced will support the so-called "Type 1" relay node. LTE-Advanced benefits from technology evolution in baseband and RF area, the new available spectrum and the optical fibre availability. In a nutshell, the advantages derived from these new techniques are illustrated in Figure 31.

4.3 Mobile WiMAX 2.0 (IEEE 802.16m) Key Features

As already described in much detail earlier, IMT-Advanced systems are mobile systems that include the new capabilities of IMT that go beyond those of IMT-2000, thus providing access to a wider range of telecommunication services which can be supported by increasingly packet-based mobile and fixed networks. Following the call by ITU-R for submission of candidate technologies for the new terrestrial components of the IMT-Advanced radio interface, IEEE expressed its intention to submit a candidate radio interface technology (RIT) which was based on the 802.16m project.

The IEEE Project 802.16m was authorized in December 2006 [56], and carried the title: "Air Interface for Fixed and Mobile Broadband Wireless Access Systems - Advanced Air Interface". The scope of the project was to amend the IEEE 802.16 WirelessMAN-OFDMA (IEEE 802.16-2009) specification to provide an advanced air interface for operation in licensed bands. It was also designed to meet the cellular layer requirements of IMT-Advanced next generation mobile networks as well as continuing support for the legacy WirelessMAN-OFDMA equipment. By early 2007, four key documents or work items were identified for development by the 802.16m Task Group m (TGm) and Figure 32 shows a timeline for the activities of the TGm. The key documents included:

- System Requirements Document (SRD) [57], which discussed amongst other things, a set of high level requirements (performance targets and features) which would meet or even exceed IMT-Advanced requirements. This is also the Stage 1 standardization procedure.
- Evaluation Methodology Document (EMD) [58], dealing with link-level and system-level simulations as well as spatial channel model parameters. The EMD will also be used to evaluate IEEE 802.16m requirements.
- System Description Document (SDD) [59], which discusses architecture and design of the 802.16m air interface amendment and enables simulations and analysis of the performance benefits of the air interface together with the EMD.
- Amendment Working Document (AWD) [60] which comprises the draft 802.16m standard.

As mentioned earlier, the SRD aims at describing the high-level requirements of the new standard and these can be grouped into functional requirements, baseline and target performance requirements, and operational requirements. In terms of the general requirements, IEEE 802.16m shall meet the IMT-Advanced requirements and shall provide continuing support and interoperability for the legacy WirelessMAN-OFDMA Reference System as defined by WiMAX Forum Mobile System Profile, Release 1.0 [62]. According to [63] however, the network operator has the ability to disable legacy support (i.e. green-field deployments). IEEE 802.16m shall support scalable bandwidths from 5 to 40 MHz at least, by using single or multiple RF carriers. IEEE 802.16m shall also support beamforming operation or other advanced antenna techniques including single-user and multi-user MIMO techniques. Baseline performance requirements show that IEEE 802.16m would have at least two times better performance compared to WirelessMAN-OFDMA Reference System in terms of average user throughput, cell edge user throughput, and VoIP capacity while at the same time the link budget of the limiting link (e.g. DL MAP, UL bearer) of IEEE 802.16m shall be improved by at least 3 dB compared to the WirelessMAN-OFDMA Reference System [64].

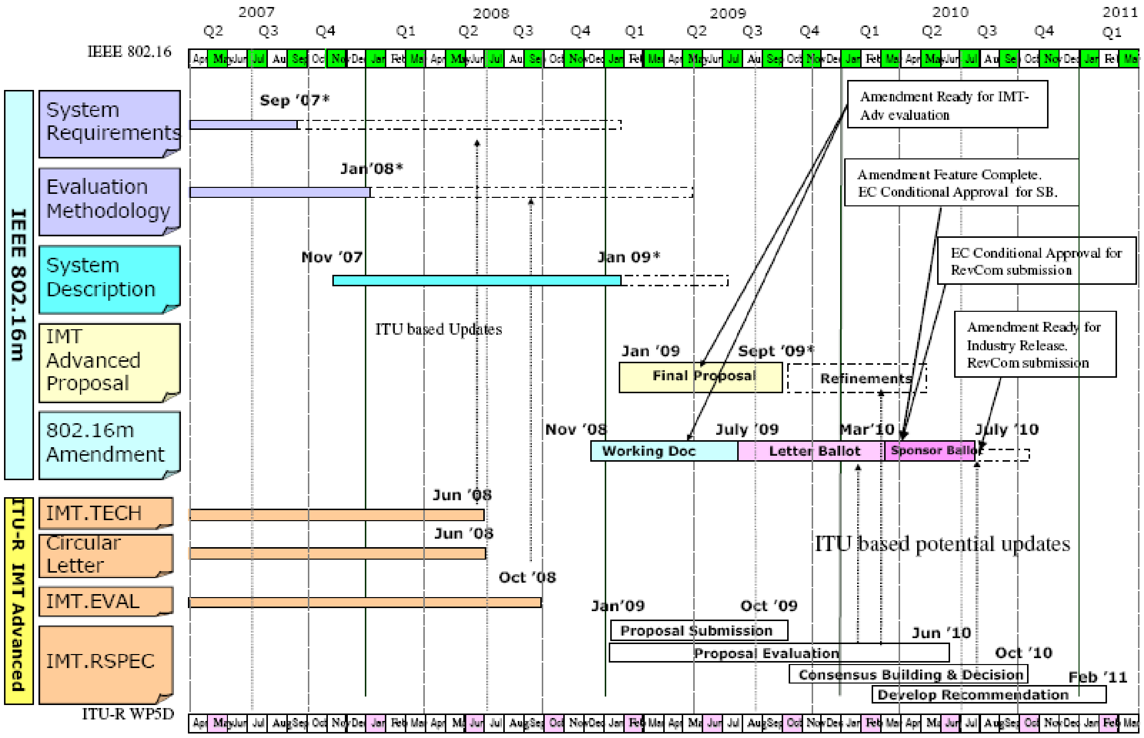

Figure 32: 802.16 TGm timeline [61]

From an operational standpoint, IEEE 802.16m will enhance support for multi-hop relay, co-deployment with other networks, self-organizing network (SON), and femto cells. For IEEE 802.16m to be able to satisfy the targeted requirements and future service needs, a range of improvements and extensions need to be performed. Performance enhancement areas in IEEE 802.16m include increased efficiency, lower latency, lower MS power consumption, and lower overhead. Other enhancements are listed below:

- Higher mobility: Support for vehicular speeds up to 350 km/h (and up to 500 km/h) enabled through improved link adaptation and shorter link access delays.
- Higher spectral efficiency and peak data rates: Downlink and uplink peak spectral efficiencies in the excess of 15 and 6.75 bps/Hz using 4x4 and 2x4 antenna configurations, respectively.
- Unified MIMO architecture: Higher-order single-user and multi-user open-loop and closed-loop MIMO schemes with single-stream and multi-stream capability per user.

In addition to the performance enhancements already listed, some key functional enhancements will also be needed in order to meet the IEEE 802.16m targets including:

- Higher flexibility for deployment through support of TDD and FDD duplexing schemes with maximum commonalities in MAC and PHY as well as the use of complementary scheduling to enable efficient Half-duplex FDD (H-FDD) terminal operation in FDD networks.
- Support for multi-hop relay architecture.
- Support of different IMT band classes (from 450 to 3600 MHz) and support of wider RF channel bandwidths up to 100 MHz to meet IMT-Advanced requirements.
- Support of multi-carrier operation and RF bandwidths up to 100 MHz through aggregation of contiguous and/or non-contiguous RF channels using a single MAC instantiation.

Table 3 illustrates the key system requirements for IEEE 802.16m side-by-side with those of IMT-Advanced. A careful look at the requirements for IMT-Advanced reveals that they are a subset IEEE 802.16m system requirements and are less strict; therefore, the IEEE 802.16m standard should qualify as an IMT-Advanced technology. In the rest of this section, a more detailed look at the enhancements and extensions of the legacy system functionality and features that have been carried out in order to satisfy the targeted requirements are presented.

Table 3: IEEE 802.16m and IMT-Advanced system requirements [63]

Requirements	IMT-Advanced [3]	IEEE 802.16m [6]
Peak data rate (b/s/Hz)	DL: 15 (4 × 4) UL: 6.75 (2 × 4)	DL: 8.0/15.0 (2 × 2/4 × 4) UL: 2.8/6.75 (1 × 2/2 × 4)
Cell spectral efficiency (b/s/Hz/sector)	DL (4 × 2) = 2.2 UL (2 × 4) = 1.4 (base coverage urban)	DL (2 × 2) = 2.6 UL (1 × 2) = 1.3 (mixed mobility)
Cell-edge user spectral efficiency (b/s/Hz)	DL (4 × 2) = 0.06 UL (2 ×4) = 0.03 (base coverage urban)	DL (2 × 2) = 0.09 UL (1 × 2) = 0.05 (mixed mobility)
Latency	*C*-plane: 100 ms (idle to active) *U*-plane: 10 ms	*C*-plane: 100 ms (idle to active) *U*-plane: 10 ms
Mobility (b/s/Hz at km/h)	0.55 at 120 km/h 0.25 at 350 km/h (link-level)	Optimal performance up to 10 km/h Graceful degradation up to 120 km/h Connectivity up to 350 km/h Up to 500 km/h depending on operating frequency
Handover interruption time (ms)	Intrafrequency: 27.5 Interfrequency: 40 (in a frequency band) 60 (between frequency bands)	Intrafrequency: 27.5 Interfrequency: 40 (in a frequency band) 60 (between frequency bands)
VoIP capacity (Active users/sector/MHz)	40 (4 × 2 and 2 × 4) (Base coverage urban)	60 (DL 2 × 2 and UL 1 × 2)
Antenna configuration	Not specified	DL: 2 × 2 (baseline), 2 × 4, 4 × 2, 4 × 4, 8 × 8 UL: 1 × 2 (baseline), 1 × 4, 2 × 4, 4 × 4
Cell range and coverage	Not specified	Up to 100 km Optimal performance up to 5 km
Multicast and broadcast service (MBS)	Not specified	4 b/s/Hz for ISD 0.5 km 2 b/s/Hz for ISD 1.5 km
MBS channel reselection interruption time	Not specified	1.0 s (intrafrequency) 1.5 s (interfrequency)
Location-based services (LBS)	Not specified	Location determination latency < 30 s MS-based position determination accuracy < 50 m Network-based position determination accuracy < 100 m
Operating bandwidth	Up to 40 MHz (with band aggregation)	5 to 20 MHz (up to 100 MHz through band aggregation)
Duplex scheme	Not specified	TDD, FDD (support for H-FDD terminals)
Operating frequencies (MHz)	IMT bands 450–470 698–960 1710–2025 2110–2200 2300–2400 2500–2690 3400–3600	IMT bands 450–470 698–960 1710–2025 2110–2200 2300–2400 2500–2690 3400–3600

4.3.1 IEEE 802.16m Protocol Structure and Network Reference Model

An important feature in the IEEE 802.16m design is a multi-hop relay architecture having a combined relay and access link which varies with mobility. This sort of design would provide new options in designing the air interface relay functions which could simply be configured as a simple intermediate relay node linking a much more complicated BS, and providing all the functions that would have been otherwise provided by the BS. As illustrated in Figure 33, optional relays to be specified by IEEE 802.16m could be added to the non-hierarchical end-to-end Mobile WiMAX network reference model [65], so as to enhance coverage and performance. In future releases of WiMAX network architecture, it is expected that reference points between the BS and Relay Station (RS) and between two RSs in a multi-hop network will be clearly specified.

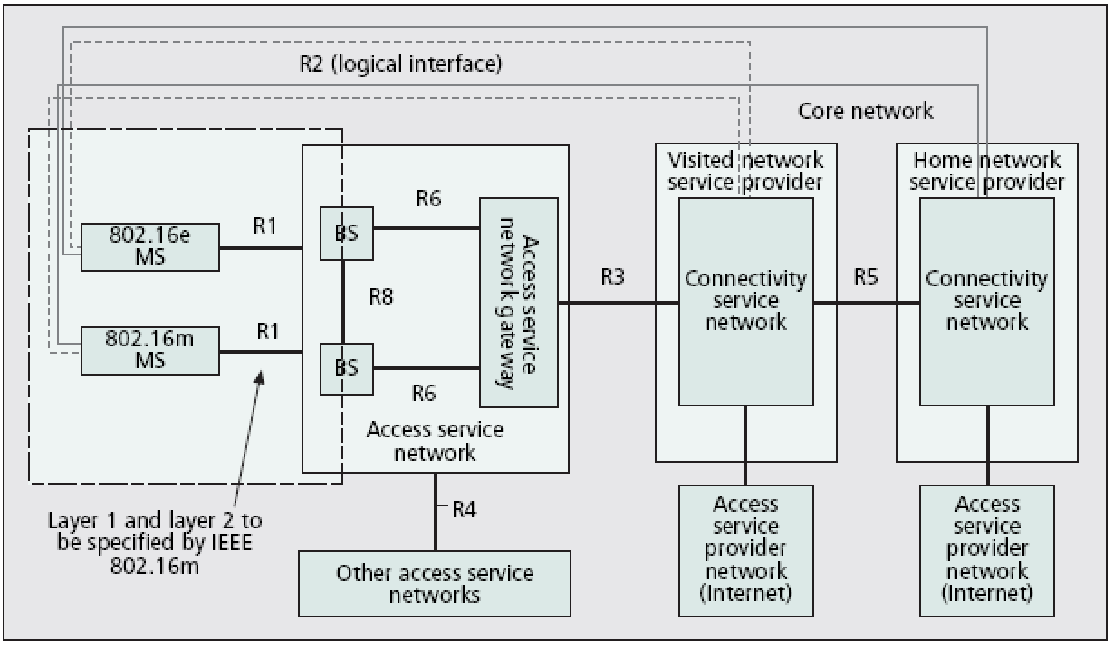

Figure 33: IEEE 802.16m network reference model [63]. The network reference model and the reference points R1-R8 are specified in [66]

The system reference model for IEEE 802.16m is very similar to that of the IEEE 802.16-2009 with the exception of soft classification (i.e. no SAP is required between the two classes of functions) of the MAC common part sublayer into radio resource control and management functions and medium access control as illustrated in Figure 34.

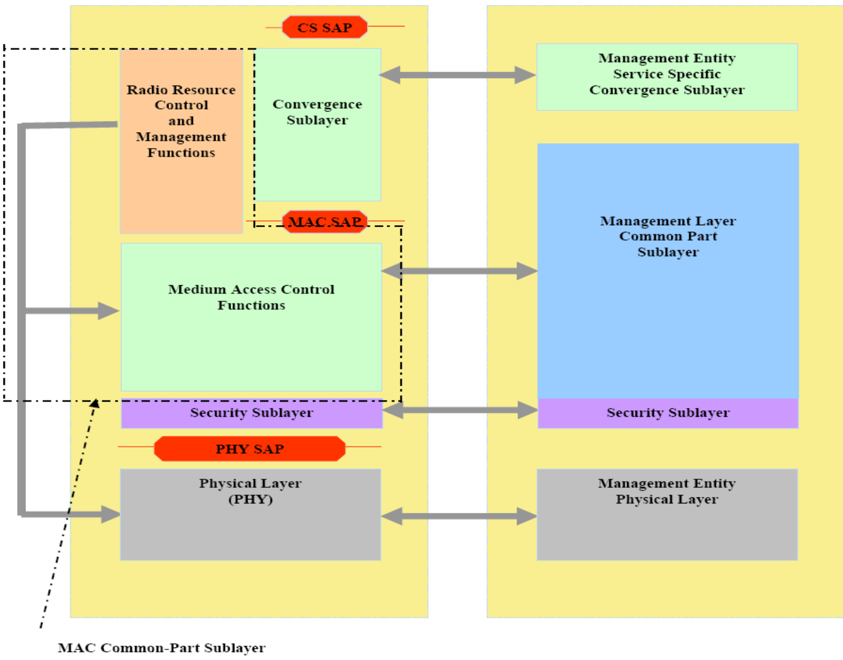

Figure 34: IEEE 802.16m system reference model [59]

Both the MAC and PHY are described by the IEEE 802.16 standard for fixed and mobile broadband wireless access systems and their functions can be classified into three categories, namely:

- Data plane, whose functions include those of the data processing path such as header compression as well as MAC and PHY data packet processing.
- Control plane whose function is to support the various radio resource configurations, coordination, signaling and management.
- Management plane whose functions include external management and system configurations.

The resource control and management functional group comprises several functional blocks shown in Figure 35, including the following:

- Radio resource management block for adjusting radio network parameters related to the traffic load, and also includes the functions of load control, admission control and interference control.
- Mobility management block scans neighbour BSs and decides whether the MS should perform a handover operation.
- Network-entry management block controls initialization and access procedures. Management messages during initialization and access procedures are also generated here.
- Location management block supports Location-Based Service (LBS), generates messages including the LBS information, and manages location update operations during idle mode.
- Idle mode management block controls idle mode operation, and generates the paging advertisement message based on paging message from paging controller in the core network.
- Security management block performs key management for secure communication. Traffic encryption/decryption and authentication are performed by using the managed key.
- The system configuration management block manages system configuration parameters, and generates broadcast control messages such as the DL/UL Channel Descriptor (DCD/UCD).
- The Multicast and Broadcast Service (MBS) block controls and generate management messages and data associated with the MBS.
- Connection management block allocates Connection Identifiers (CIDs) during initialization/ handover service flow creation procedures. It also interacts with the convergence sublayer to classify MAC Service Data Units (MSDUs) from upper layers.

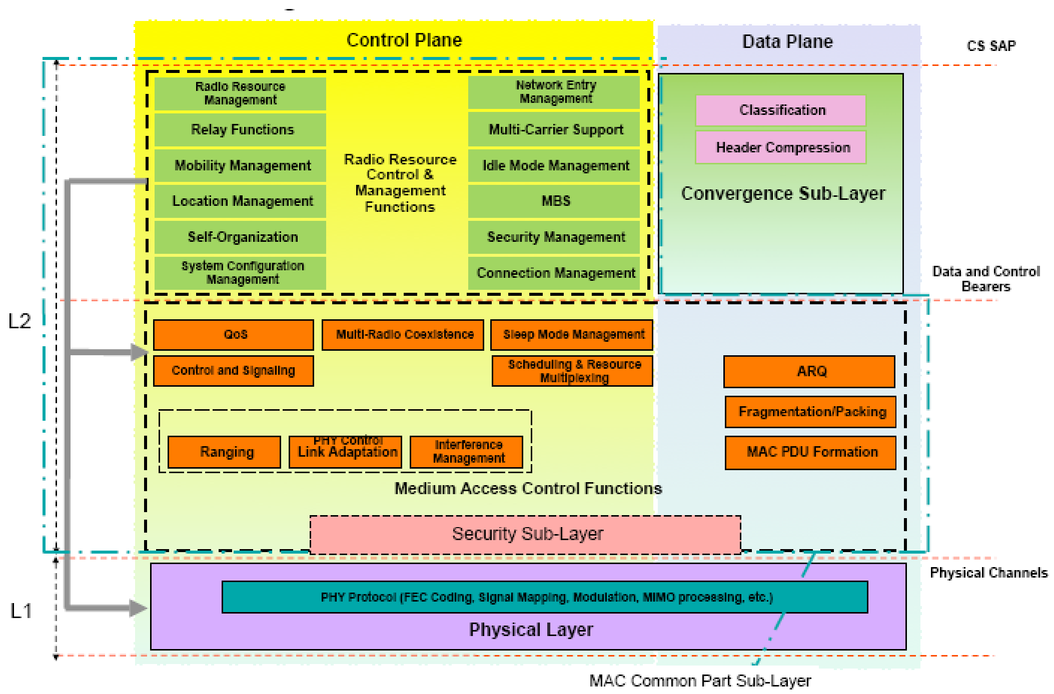

Figure 35: IEEE 802.16m Protocol structure [59]

The lower class MAC functional group is made up of functional blocks which are related to the physical layer and link controls. These blocks include the following:

- The PHY control block, whose responsibility is for PHY signaling including ranging, Channel Quality measurement/feedback (CQI), and HARQ Acknowledgment (ACK) or Negative Acknowledgment (NACK) signaling. The PHY control block performs link adaptation by adjusting Modulation and Coding Scheme or power level after the MS channel environment is estimated based on CQI and HARQ ACK/NACK signals.
- The control signaling block, which generates resource allocation messages like DL/UL MAP as well as specific control signaling messages, and other signaling messages not in the form of general MAC messages, such as the DL Frame Control Header (FCH).
- The sleep mode management block, which handles sleep mode operation and generates management messages related to sleep operation, and may communicate with the scheduler block in order to operate properly according to the sleep period.
- The QoS block, which performs rate control, based on QoS input parameters from the connection management function for each connection.
- The scheduling and resource and multiplexing block, which schedules and multiplexes packets based on the properties of connections.
- The ARQ block performs the MAC ARQ function. For ARQ-enabled connections, the ARQ block logically splits MSDUs and sequences logical ARQ blocks. The ARQ block may also generate ARQ management messages such as a feedback message.
- The fragmentation/packing block performs fragmentation or packing of MSDUs based on input from the scheduler block.

- The MAC Protocol Data Unit (PDU) formation block constructs MAC PDUs to be used by BSs/MSs for transmitting user traffic or management messages into PHY channels. The MAC PDU formation block may add subheaders or extended subheaders as well as MAC Cyclic Redundancy Checks if necessary, and a generic MAC header.

As stated earlier, the basic concept of the IEEE 802.16e-2009 protocol structure will be maintained in IEEE 802.16m. To meet the IMT-Advanced requirements, some additional functional blocks will be introduced in order for newly proposed features to be effective. These additional blocks include the following:

- The fragmentation or packing block to perform fragmentation or packing of MSDUs based on input from the scheduler block.
- Routing (relay) functions to enable relay functionalities and packet routing.
- Self-organization and self-optimization functions to enable the home BS for femtocells and plug-and-play form of operation for the indoor BS.
- Multi-radio coexistence functions to allow non-disruptive operation of multiple radios on a user terminal by coordinating the operation of those radios to minimize intersystem interference.
- Multi-carrier functions to enable control and operation of a number of adjacent or nonadjacent RF carriers (virtual wideband operation) where the RF carriers can be assigned to unicast and/or multicast and broadcast services. A single MAC instantiation will be used to control several physical layers as illustrated by the generalized multi-carrier protocol structure in Figure 36.

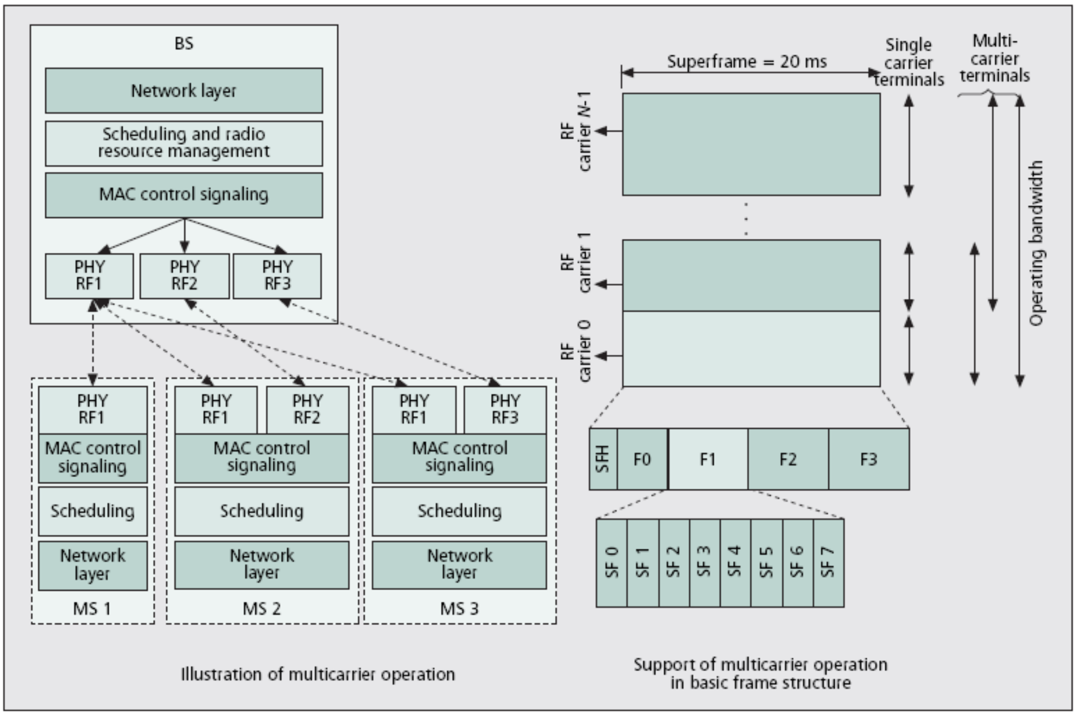

Figure 36: IEEE 802.16m multicarrier protocol stack and frame structure [59]

Figure 37 shows an example of a data plane protocol stack terminations in the BS, RS or MS when relay functionality is enabled in the network. Some of the radio resource control and management functions may not be available in the relay stations (RSs). This will depend on whether those functions are performed in a centralized or a distributed mode as well as whether the RSs are deployed with full functionalities of a BS.

Furthermore, in order to ensure that the security of the network will not be compromised by unreliable entities, having access to indoor BSs or femto cell access points, security functions may be limited in the nodes that are outside of the direct control of the network operator. The security sublayer is a new function in the control plane protocol stack that would enable certain management messages to be ciphered.

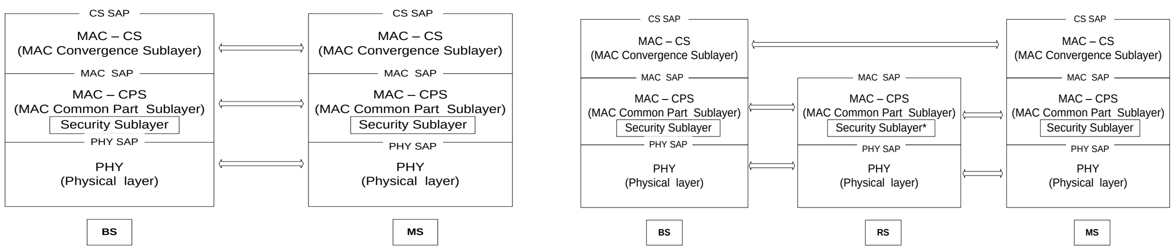

Figure 37: IEEE 802.16m Data plane protocol stack (a) without relay station (b) with relay station

4.3.2 IEEE 802.16m: Advanced Mobile Station (AMS) State Diagram

The state diagram of the Mobile Station (MS) is not detailed in the IEEE 802.16e-2005 standard. The state diagram defines a set of states and procedures between which the MS transits to receive and transmit data when operating in the system. Four transition states can be identified for the IEEE 802.16m AMS based on the understanding of the reference system as illustrated in Figure 38. These states include the following:

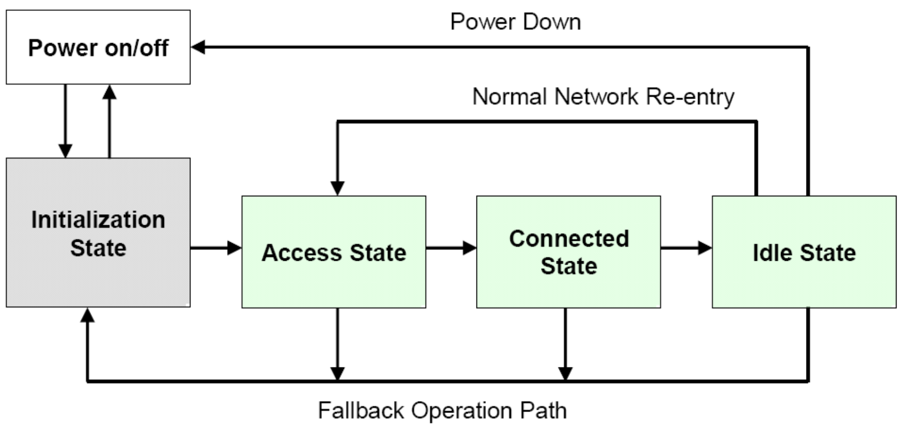

Figure 38: IEEE 802.16m AMS state transition diagram [59]

* Initialization State: In this state, the cell selection is executed by the AMS by scanning and synchronizing to an ABS preamble and then acquiring the system configuration information through the broadcast channel before entering the Access State. During this state, if the AMS cannot adequately perform the system configuration information decoding and cell selection, it returns to the scanning and DL synchronization step, meanwhile successful decoding of the system configuration information and selection of a target ABS leads to transitions into the Access State.

* Access State: Network entry with the target ABS is performed by the AMS in the Access state. The process of network entry as shown in Figure 39 begins with an initial ranging process, so as to obtain UL synchronization. This is then followed by basic capability negotiation as well as the authentication and authorization process. Next, the AMS performs the key registration process with the ABS and service flow establishment. The MS receives the 802.16m specific user/station identification (ID) as part of access state procedures and establishes at least one connection using the transitions to the Connected state. Failure to complete any of the steps of network entry mentioned would cause the AMS to revert to the Initialization State.

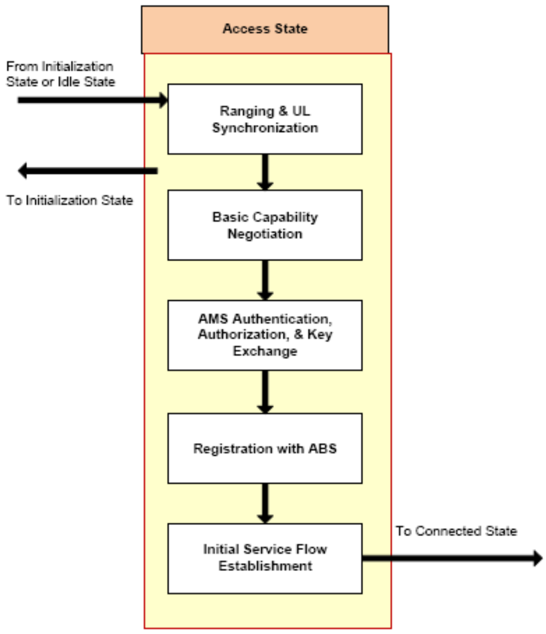

Figure 39: IEEE 802.16m AMS Access state procedure [59]

* Connected State: When in the connected state, the AMS can be in one of three possible modes (sleep, active or scanning) and maintains two connections established during the Access state. Additional transport connections may be formed by the AMS and ABS. Connection state may be maintained by the AMS during handover and transition to the Idle state is based on a command from the ABS. In order to reduce power consumption of the AMS, the AMS or ABS can request a transition to sleep or scanning mode. Also, the AMS can scan neighbour ABSs to reselect a cell which provides more robust and

reliable services. In the Active mode, the AMS and ABS perform normal operations to exchange the DL or UL traffic. In sleep mode, the AMS may enable power-saving techniques and in scanning mode, the AMS performs scanning operation and may temporarily be unavailable to the ABS.

- Idle State: The Idle state consists of the Paging Available Mode and Paging Unavailable Mode based on its operation and MAC message generation. During Idle State, the AMS may perform power saving by switching between Paging Available Mode and Paging Unavailable Mode.

In the AMS state diagram for IEEE 802.16m, the four states are similar to that of the reference system with the exception that initialization state is simplified to reduce the scan latency and to enable fast cell selection or reselection. According to [63], a simplified initialization procedure leads to power saving in the AMS.

4.3.3 IEEE 802.16m Physical Layer

To be able to meet the performance targets set by IEEE 802.16m SRD [57], legacy Mobile WiMAX technology has to undergo some basic modifications on key aspects like frame structure, HARQ operation, synchronization and broadcast channel structures as well as CQI measurement and reporting mechanism. The modifications, as reported in [67, page 457] will result in faster HARQ retransmissions for improved application performance and higher capacity, fast cell-selection, mobile-aware relay operation, multi-user MIMO and multi-carrier operation. OFDMA is used as the multiple access schemes in both the DL and UL for IEEE 802.16m which also supports a number of duplex modes including TDD, FDD as well as the half-duplex FDD (H-FDD) in AMS operations. Both duplex schemes share the same properties with respect to their frame structure and baseband processing.

A. Frame Structure

In IEEE 802.16m, the idea of a superframe is introduced. A 20ms superframe is made up of four equally-sized 5ms radio frames and begins with a superframe header (SFH) which carries short-term and long-term system configuration information. To decrease the air-link access latency, each 5ms radio frames is further divided into eight subframes, where each subframe comprises an integer number of OFDMA symbols as shown in Figure 40. The transmission time interval (TTI) is defined as the transmission latency over the air-link and is equal to a multiple of the subframe length (default one subframe).

A subframe is assigned for either DL or UL transmission and four types of subframes can be identified [59]:

- Type-1 subframe made up of six OFDMA symbols.
- Type-2 subframe comprising seven OFDMA symbols.
- Type-3 subframe which consists of five OFDMA symbols.
- Type-4 subframe consisting of nine OFDMA symbols. This type is applied only to UL subframe for the 8.75 MHz channel bandwidth when supporting frames of the IEEE 802.16-2009 standard.

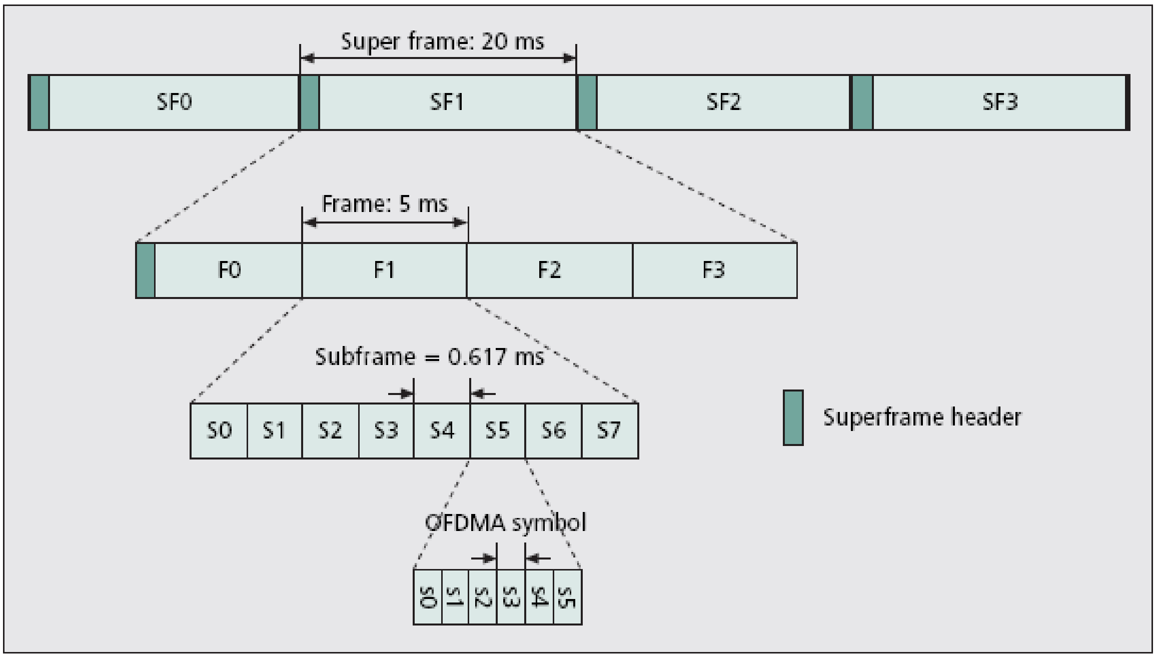

Figure 40: Basic frame structure for 5, 10 and 20 MHz channel bandwidths [63]

IEEE 802.16m systems will be designed and developed to incorporate new and improved schemes for resource allocation, sub-channelization and pilot structure. For these new developments to occur while at the same time maintaining cooperation between new and legacy systems, the concept of time zones is introduced for both TDD and FDD operations. A time zone is defined as an integer number (greater than 0) of consecutive subframes. For DL transmission, both the new and legacy systems use Time-Division Multiplex (TDM) across the time zones while in the case of UL transmission, both TDM and Frequency-Division Multiplex (FDM) approaches are supported. All the nonbackwards-compatible improvements and features are restricted to the new zones and while backwards-compatible features and functions are used in the legacy zones, in the absence of any legacy system, the legacy zones will disappear and the entire frame will be allocated to the new zones. New features for IEEE 802.16m like the preambles, SFH and control channels are accommodated by a fixed number of subframes in new radio frames compared to legacy radio frames. Multiple-RF carriers can be accommodated with the same frame structure that is used for single-carrier operation and all RF carriers are time-aligned at the frame, subframe, and symbol level as we saw earlier in Figure 36.

B. Physical and Logical Resource Blocks

Control and user data blocks can be multiplexed over time, frequency and code (as in Code Division Multiplex) in several ways. In DL scenario, control and data blocks are defined within certain subframes where they are mapped to one-dimensional resource blocks which are the basic logical unit for distributed and localized resource allocations. A logical resource unit comprises 18 sub-carriers × 6 symbols. In IEEE 802.16m, the six symbols are OFDMA symbols. The distributed resource units are used to achieve frequency diversity gain while the localized resource units are used to achieve a frequency-selective scheduling gain. In the case of hybrid TDM/FDM, the control channel is limited within the boundaries of a subframe and the number of subcarriers in the frequency domain is an integer multiple of the number of subcarriers in a one-dimensional resource block. For efficient utilization of the radio resources and to reduce complexity, the control information is allocated in the units of one-dimensional physical resource blocks and unused physical resource blocks in the subframes that contain the control channel can be used for scheduling user data. In the UL, subframes are grouped into a number of frequency partitions, each comprising a set of physical resource units over the available number of OFDMA symbols in the subframe. Each frequency partition can include localized and/or distributed physical resource units unlike in legacy system where each zone can accommodate only localized or distributed sub-channels. The UL resource petitioning and mapping is similar to that of the DL.

C. Modulation and Coding

MCS index	Modulation	Code rate
0000	QPSK	31/256
0001	QPSK	48/256
0010	QPSK	71/256
0011	QPSK	101/256
0100	QPSK	135/256
0101	QPSK	171/256
0110	16QAM	102/256
0111	16QAM	128/256
1000	16QAM	155/256
1001	16QAM	184/256
1010	64QAM	135/256
1011	64QAM	157/256
1100	64QAM	181/256
1101	64QAM	205/256
1110	64QAM	225/256
1111	64QAM	237/256

Figure 41: MCS table for downlink and uplink data channels [63]

In both the UL and DL, quadrature-phase-shift keying (QPSK), 16-QAM and 64-QAM modulation are support by IEEE 802.16m. Power inefficiencies as a result of multilevel modulation formats usually decrease performance of adaptive modulation due to the variations in bit reliabilities caused by the bit-mapping onto the signal constellation.

To overcome this, a constellation rearrangement scheme is utilized where a signal constellation of quadrature amplitude modulation (QAM) signals between retransmissions is rearranged resulting in averaging the bit reliabilities over several retransmissions and lower packet-error rates. Convolutional code and convolutional turbo code with variable code rate and repetition coding are both supported in IEEE 802.16m. The modulation and coding schemes used in a data transmission are selected from a set of 16 modulation coding schemes (MCSs) as shown in Figure 41.

D. Pilot Structure

To be able to achieve channel and frequency offset estimation as well as channel quality measurements like CQI, transmission of pilot sub-carriers in the DL is required. IEEE 802.16m supports both common and dedicated pilot structures. While all mobile stations can use the common pilots, the dedicated pilots exceptionally can be used with both localized and distributed allocations and are assigned specific fractional-frequency-reuse (FFR) groups, so that only mobile stations assigned to that group can use the pilots. Up to eight transmission streams are defined for the pilot structure with a unified design for common and dedicated pilots. Pattern A of dedicated or common pilots is used for one or two spatial streams, and pattern B is utilized in the case of four spatial streams.

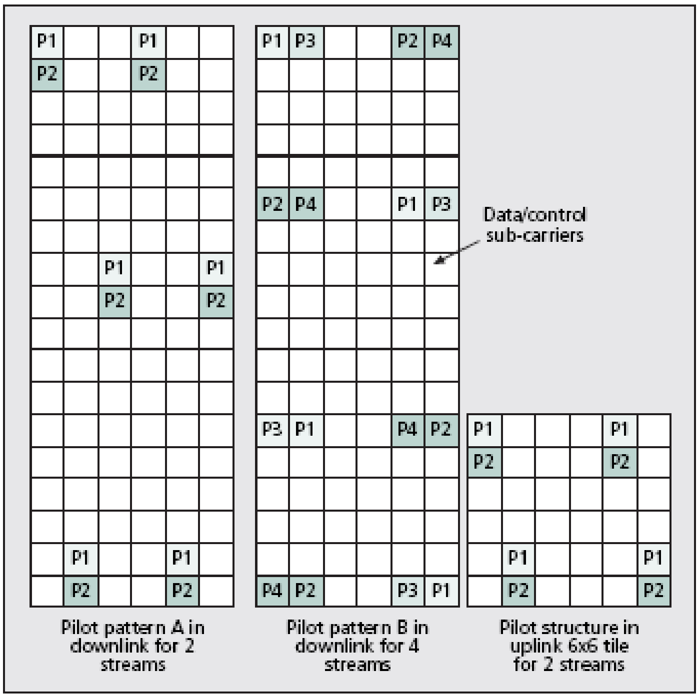

Figure 42: Downlink/Uplink pilot structure for 1, 2 and 4 streams [63]

In the UL pilot structure are dedicated to localized and distributed resource units and are pre-coded using the same precoding as the data subcarriers. When the pilots are power-boosted, each data subcarrier has the same transmission power across all OFDMA symbols in a resource block. The 18x6 UL resource blocks use the same pilot patterns as the DL counterpart for up to four spatial streams but the pilot pattern for 6x6 tile structure is different as illustrated in Figure 42.

E. Control Channels

The control channels include both the DL and UL control channels. The UL control channels carry different types of classified control information to support air-interface procedures. The DL control channels carry essential information for system operation and based on the type of control signaling, information is transmitted in different time intervals. While the system configuration parameters are transmitted at the superframe intervals, control signaling related to user data allocations is transmitted at the frame/subframe interval. The superframe header carries system configuration information and its content falls into two categories, the primary and secondary superframe headers which are transmitted using multiple antenna schemes to improve coverage and reliability.

F. Advanced Preambles

IEEE 802.16m supports hierarchical synchronization with two levels at superframe and frame intervals. The superframe begins with the first set of preamble sequences known as the Primary Advanced Preamble (PA-PREAMBLE). These are common to a group of sectors or cells, carrying partial cell ID information including BS type, sector information, or grouping of cell ID and can support limited signaling. The PA-PREAMBLE which has a frequency reuse factor of one in the frequency domain has a fixed bandwidth of 5 MHz and can be used for initial acquisition, superframe synchronization and sending additional information. The second set of advanced preamble sequences, the Secondary Advanced Preamble (SA-PREAMBLE) carrying a minimum of 512 distinct cell IDs, are used for fine synchronization, and cell/sector identification (ID) and is repeated every frame, spanning the entire system bandwidth as illustrated in Figure 43.

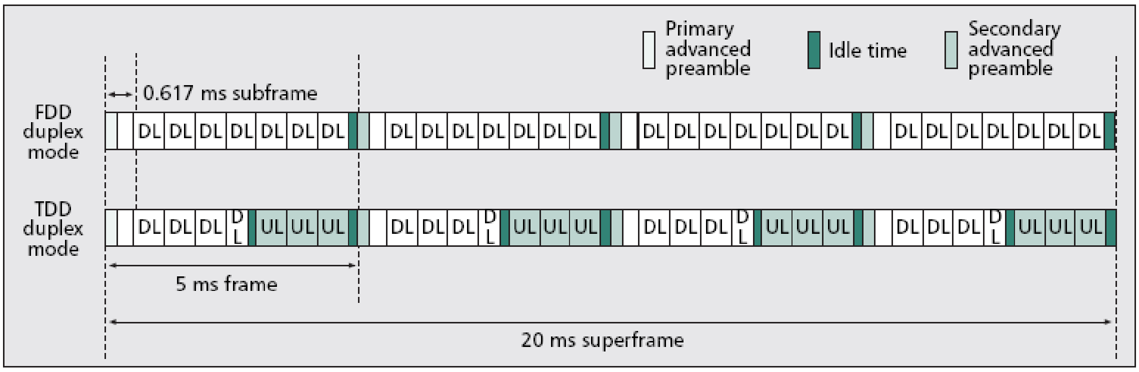

Figure 43: Structure of IEEE 802.16m Advanced Preambles [63]

G. Multi Antenna Techniques in IEEE 802.16m

Several antenna techniques are supported by IEEE 802.16m including single- and multi-user MIMO in both spatial multiplexing and beamforming, as well as transmit diversity schemes such as Open-loop and Closed-loop transmit diversities. For single-user MIMO (SU-MIMO), only one user is scheduled in one Resource Unit (RU) and only one FEC block exists at the input of the MIMO encoder, meanwhile for multi-user MIMO (MU-MIMO), multiple users can be scheduled in one RU, and multiple FEC blocks exist at the input of the MIMO encoder. Figure 44 shows the architecture of the downlink MIMO transmitter.

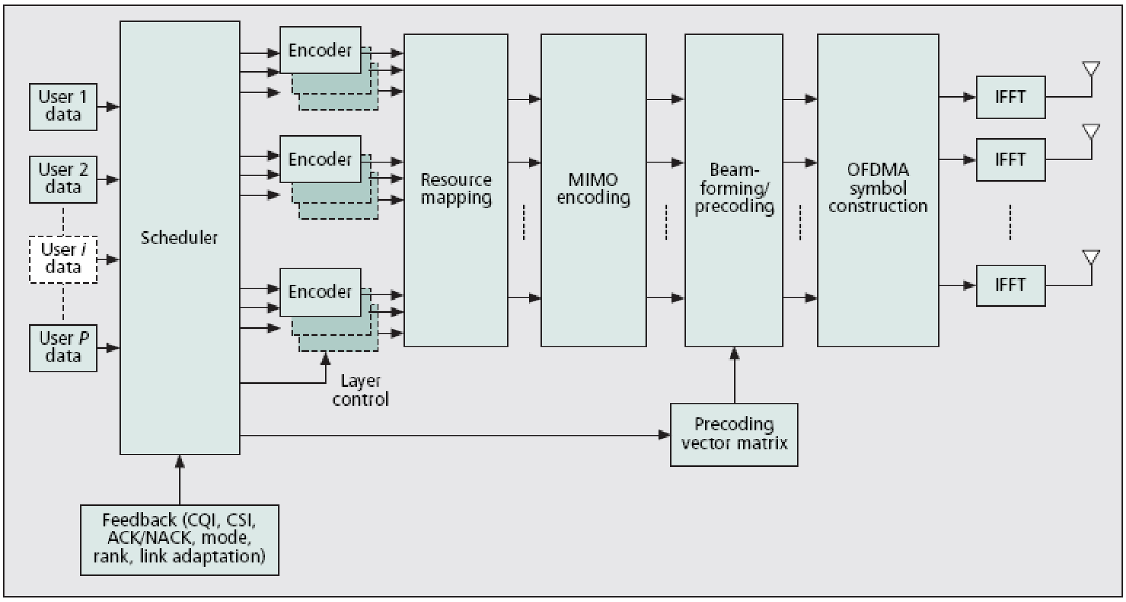

Figure 44: IEEE 802.16m DL MIMO architecture [68]

The different block components function as follows:

- The resource mapping block maps the complex-valued modulation symbols to the corresponding time-frequency resources.
- The MIMO encoder block maps the layers onto the streams, which are further processed through the beamforming or the precoding block.
- The Precoding/beamforming block maps stream(s) to antennas by generating the antenna-specific data symbols according to the selected MIMO mode.
- The OFDMA symbol construction block maps antenna-specific data to the OFDMA symbols.
- The Feedback block contains feedback information such as CQI and channel state information (CSI) from the AMS.
- The Scheduler block schedules users to resource units and decide their MCS level, MIMO parameters (MIMO mode, rank). This block is responsible for making a number of decisions with regards to each resource allocation, including allocation type, single-

user (SU) versus multi-user (MU) MIMO, MIMO mode, user grouping, rank, MCS level per layer, boosting, and band selection [59].

The ABS uses a minimum of two transmit antennas and configurations of 2, 4 and 8 transmit antennas are supported while the AMS employs a minimum of two receive antennas. For open-loop spatial multiplexing and closed-loop SU-MIMO, the number of streams is constrained to the minimum of number of transmit or receive antennas [63].
IEEE 802.16m is able to adapt between SU-MIMO and MU-MIMO in a predefined and flexible manner. Furthermore, Multi-BS MIMO techniques are supported for improving sector and cell-edge throughput by making use of multi-BS collaborative precoding, network coordinated beamforming, or inter-cell interference cancellation. Figure 45 shows the UL-MIMO transmitter architecture.

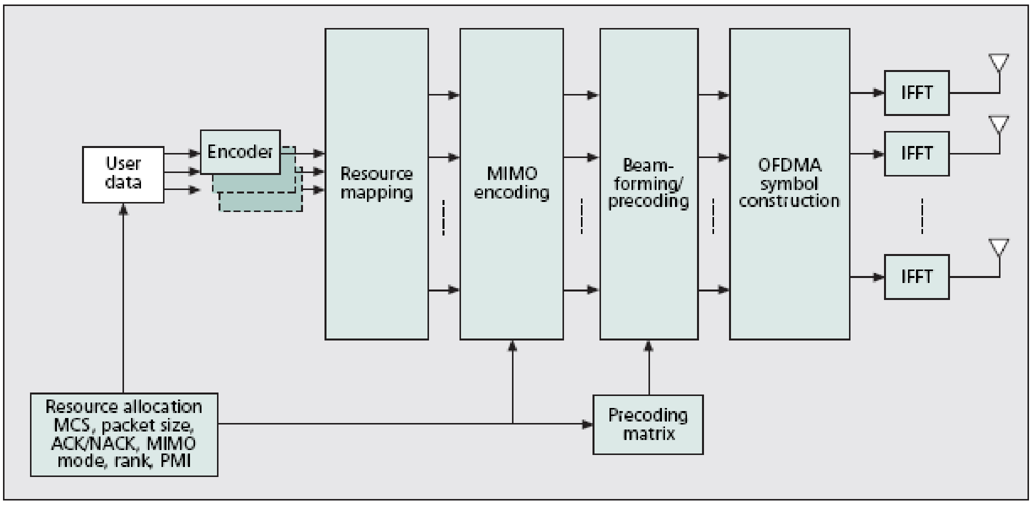

Figure 45: IEEE 802.16m UL MIMO architecture [63]

From the diagram, it is easy to notice the similarities in the MIMO baseband processing for the UL and DL. In the UL, the AMS measurements of the channel are based on DL reference signals like common pilots or a mid-amble. In UL MU-MIMO, both open-loop and closed-loop MU-MIMO are supported and multiple AMSs can be spatially multiplexed on the same radio resources. The AMSs with single transmit antenna can operate in open-loop MU-MIMO mode and unitary codebook-based precoding is supported for both TDD and FDD.

4.3.4 IEEE 802.16m MAC Layer

IEEE 802.16m is designed as all IP network with a flexible MAC scheme which enables adaptation to requirements of future Internet services in a timely manner with minimal effort. Efficient traffic management is provided by the definition of persistent and group resource allocations for traffic with recurrent transmission patterns (e.g. VoIP) as well as for users with similar QoS requirements. To enable mixed deployments in brownfield scenarios and co-existence with other radio access technologies like UTRAN LTE, different time zones (LZone for legacy and MZone for 802.16m access) are supported by an efficient and flexible frame concept. Additionally, adaptation of QoS flow parameters, Hybrid ARQ for mitigation of channel fading (synchronous in uplink and asynchronous in downlink) and advanced power management mechanisms to increase battery lifetime in mobile station are supported. In the rest of this section, we take a deeper look into some of the MAC features mentioned above which makes IEEE 802.16m a true 4G contender and IMT-Advanced candidate.

A. MAC Addressing

A global (permanent) address and a logical (temporary) address are used by IEEE 802.16m AMSs to identify the user and its connections when in operation. The global address which can also be applied to ARS and ABS is a unique 48-bit IEEE Extended Unique Identifier (EUI-48) and is based on the 24-bit Organizational Unique Identifier (OUI) value issued by the IEEE Registration Authority [69]. In addition to the global address, the AMS is also assigned the following logical identifiers:

- A 12-bit station identifier (STID) assigned by the ABS during network entry and re-entry in some instances that uniquely identifies the AMS within the domain of the ABS. Certain specific STID are reserved for broadcast, multicast and ranging.
- A 4-bit flow identifier (FID) that uniquely identifies AMS transport and management connections. Some FID may be pre-assigned.

B. Network Entry

This refers to the steps by which an AMS locates and makes a connection with a cellular network and includes the following sequence; Ranging and UL synchronization with ABS by acquiring the preambles, basic capability negotiation, authentication, authorization and key exchange, registration with ABS and finally service-flow establishment. Search for neighbour ABSs is done by using the same DL signals as the initial network search (for example A-PREAMBLE), except for the fact that the serving ABS provides some information through advertisements.

C. QoS

IEEE 802.16m provides QoS by allocating a unidirectional flow of packets having particular QoS requirements with a service flow. The flow identifier (FID) is used to map each service flow to one transport connection. According to [59], ABS and AMS provide QoS according to the QoS parameter sets, which are pre-defined or negotiated between the

ABS and the AMS during the service flow setup procedure and the QoS parameters can be used to schedule and police the traffic.

D. MAC Control/Management Messages

IEEE 802.16m supports fast and reliable transmission of MAC control messages in order to satisfy the network entry, handover and state transition requirements. To guarantee reliable transmission of the MAC control messages, they can be fragmented into multiple MSDUs and in the situation where HARQ is used during transmission, a retransmission can be initiated by the MAC message management entity in the transmitter in the case of a failed HARQ burst or an unsuccessful HARQ process.

E. ARQ and HARQ Functions

HARQ is used for unicast data traffic in both the UL and DL by IEEE 802.16m and the operation is based on an N-process (multi-channel) stop-and-wait protocol. In the case of the DL, adaptive asynchronous HARQ is used and the resource allocation and transmission format for the HARQ retransmission may be different from the initial transmission. In the UL, non-adaptive synchronous HARQ is used and the retransmission parameters and resource allocations are known in advance. Both ABS and AMS are capable of maintaining multiple HARQ channels [59]. An ARQ block is generated from one or multiple MAC SDU(s) or MAC SDU fragment(s) of the same flow and they can be variable in size. In the event that both ARQ and HARQ are used, if the HARQ entity in the transmitter determines that the HARQ process terminated unsuccessfully, it informs about the failure of the HARQ burst to the ARQ entity in the transmitter which can then initiate retransmission and resegmentation of the ARQ blocks that corresponds to the failed HARQ burst.

F. Power Management

IEEE 802.16m provides AMS power management functions including sleep mode and idle mode to reduce AMS battery consumption. In the connected state, an AMS in sleep mode conducts pre-arranged periods of absence from the serving ABS air interface and is provided with a series of temporary listening and sleep windows. The listening window is the time in which the AMS is available to exchange control signalling and data between itself and the ABS. IEEE 802.16m is able to dynamically adjust the duration of sleep and listening windows within a sleep cycle based on changing traffic patterns and HARQ operations. Idle mode enables the AMS to become periodically available for DL broadcast-traffic messaging such as paging a message without registering with the network, hence reducing power usage.

G. Security

IEEE 802.16m security functions provide users with privacy, confidentiality and authentication across the network by encrypting MAC PDUs across connections between ABS and AMS. The security architecture comprises a security management as well as an encryption and integrity logical entity. The security management entity functions include overall security management and control, EAP encapsulation/decapsulation, Privacy Key Management (PKM) control, location privacy, as well as authentication and security association control. Functions of the encryption and integrity protection entity include transport data encryption/authentication processing, management message authentication processing and management message confidentiality protection.

H. Mobility Management and Handover

Both network-control and mobile-assisted handover (HO) are supported by IEEE 802.16m. According to [59], there exist four possible HO scenarios as listed below:

- Case-1: AMS handover from serving R1 BS to target R1 BS.
- Case-2: AMS handover from serving ABS to target R1 BS.
- Case-3: AMS handover from serving R1 BS to target ABS.
- Case-4: AMS handover from serving ABS to target ABS.

Legacy handover procedures are applied in Case 1 for the IEEE 802.16m network and MS while new procedures apply to the other cases listed. Figure 46 illustrates a general HO procedure which is divided into the following three stages; HO initialization, HO preparation, and HO execution after which the AMS is ready to perform network re-entry with the target BS.

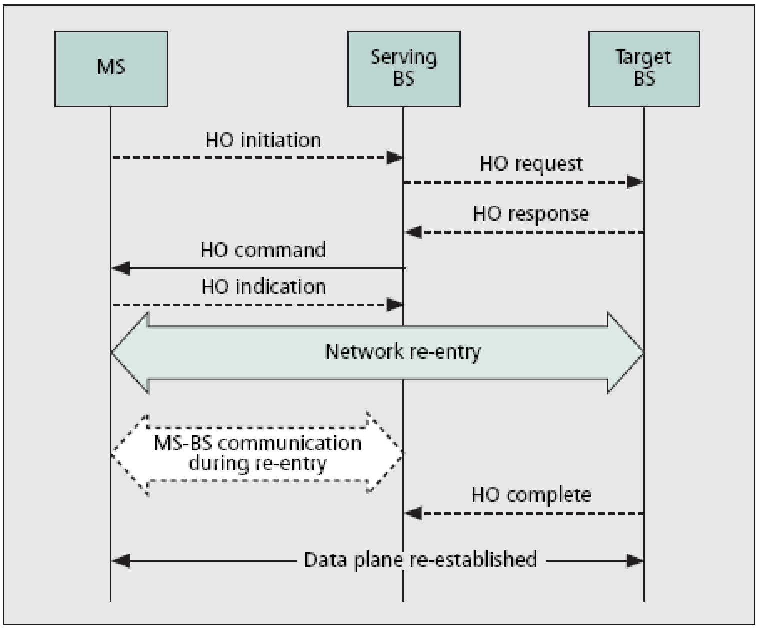

Figure 46: General HO procedure [63]

4.3.5 IEEE 802.16m Advanced Features

As already mentioned briefly under the IEEE 802.16m protocol structure and network reference model, some advanced features are incorporated into the IEEE 802.16m system in order for it to adequately satisfy the requirements for IMT-Advanced. These are discussed further below.

A. Support for Femtocells and Self-Organization

Femtocell base stations are small-scale and cheap devices installed in the premises of subscribers and enables very high data rates due to the close distance of the mobile devices to the base stations. The control of the radio functionalities and QoS provisioning to the user is enabled by core network connections over DSL. A number of features for femtocells will be supported in the standard, including a low-duty mode on base station side for interference mitigation and energy efficiency.

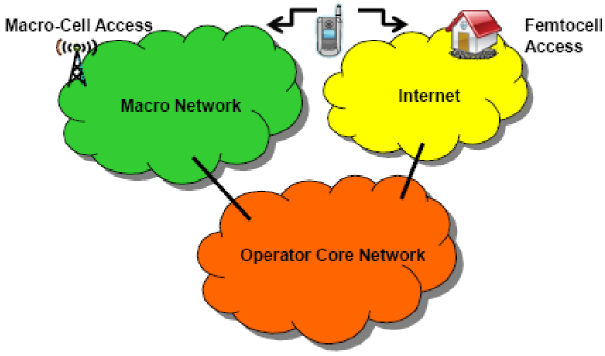

Figure 47: Basic femtocell scenario [70]

An important aspect to note is that while most femtocell architectures require a new (dual-mode) handset which works with existing home/enterprise Wi-Fi access points, a femtocell-based deployment will work with existing handsets but requires installation of a new access point.

A self-organizing network (SON) is supported by features for neighbour discovery, interference mitigation and load balancing and is especially useful in femtocell deployment scenarios where proper planning of operational parameters (e.g. transmit power, carrier frequency, frequency re-use) are difficult to implement due to unknown site locations. IEEE 802.16m provides:

- Very high data rates and service continuity in smaller cells including indoor pico-cells, femto cells, and hot-spots. It is also possible to deploy the small cells as an overlay to larger outdoor cells.
- Self-optimization by allowing automated optimization of network performance with respect to service availability, QoS, network efficiency and throughput.

- Self-configuration by allowing real plug-and-play installation of network nodes and cells, including the update of neighbour nodes and neighbour cells as well as means for fast reconfiguration and compensation in failure cases.

B. Support for Multi-Radio Co-existence

Protocols for the multi-radio coexistence functional blocks for communication between AMS and ABS via air interface are supported by IEEE 802.16m. AMS generates control/management messages to report its co-located radio activities to ABS which in turn generates management messages to respond with the corresponding actions to support multi-radio coexistence operation. The multi-radio coexistence functional block at ABS communicates with the scheduler functional block to operate properly according to the reported co-located coexistence activities.

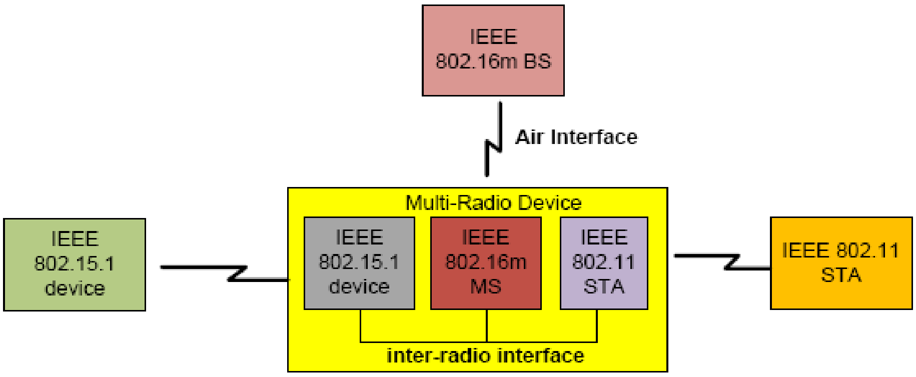

Figure 48: Multi-Radio device with co-located 802.16m MS, 802.11 STA, and 802.15.1 device [70]

C. Support for Multi-hop Relay Architecture

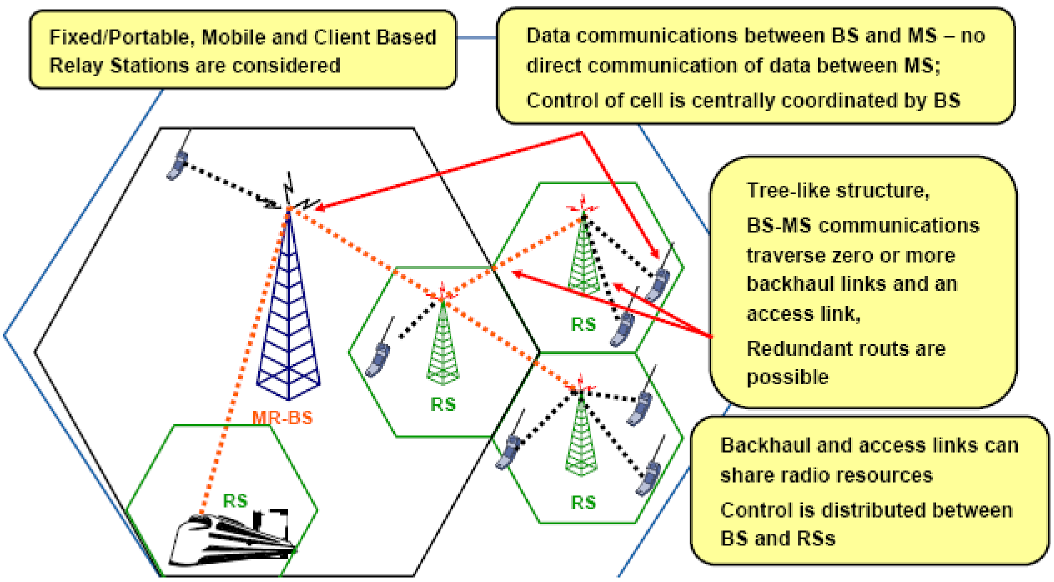

Figure 49: Multi-hop relay architecture [71]

Relays increase coverage by closing “blind areas” in unfavourable radio environments. Relay stations are downscaled, low-cost base stations with repeater functionality and otherwise very limited capabilities. IEEE 802.16m will support multi-hop relaying over several relay stations.

4.4 Comparison: LTE-Advanced and IEEE 802.16m approach to IMT-Advanced

IMT-Advanced is the ITU description for systems beyond IMT-2000 as discussed in much detail earlier. Candidate technologies for IMT-Advanced are required to meet certain minimum performance requirements for parameters like peak and average channel spectral efficiency, cell-edge user spectral efficiency, VoIP capacity, Control and User Plane Latency, Handover, Channel bandwidth and Mobility. There also exist some additional IMT-Advanced requirements addressing features required for anticipated applications, services, and the expected needs of users and operators; including QoS, roaming as well as interworking with other wireless networks.

In the previous sections of this thesis, the two main candidates for IMT-Advanced certification (LTE-Advanced and IEEE 802.16m) have been presented along with the steps taken to satisfy the requirements for IMT-Advanced. A thorough look at the approach adopted by each of the candidates reveals slight differences as they move towards a common goal. In the rest of this section, some of the major concerns or goals required to be addressed in order to satisfy IMT-Advanced requirements and the manner in which these goals are met by LTE-Advanced and IEEE 802.16m are revisited so as to reveal some of their underlying differences.

4.4.1 Data Throughput

Data throughput is an important metric for quantifying network throughput performance. Unfortunately, the ways in which various organizations quote throughput statistics vary tremendously which often leads to misleading claims. To address the issue of improved data throughput, both LTE-Advanced and IEEE 802.16m are implementing relay technologies which have great application potential. The performance of relay transmissions however, is greatly affected by the collaborative strategy, which includes the selection of relay types and relay partners (i.e. to decide when, how, and with whom to collaborate). LTE-Advanced uses two types of relay stations (RSs), Type-I and Type-II while IEEE 802.16m uses non-transparency and transparency RSs (adopted from IEEE 802.16j).

Basically, a Type-I (or non-transparency) RS can help a remote user terminal/equipment, which is located far away from an eNB (or a BS), to access the eNB. So a Type-I RS needs to transmit the common reference signal and the control information for the eNB, and its main objective is to extend signal and service coverage, as shown in Figure 50. Type-I RSs mainly perform IP packet forwarding in the network layer (layer 3) and can make some contributions to the overall system capacity by enabling communication services and data transmissions for remote user terminals.

Type-II (transparency) RSs, on the other hand, can help a local user terminal, located within the coverage of an eNB (or a BS) and having a direct communication link with the eNB, to improve its service quality and link capacity. So a Type-II RS does not transmit the common reference signal or the control information, and its main objective is to increase the overall system capacity by achieving multipath diversity and transmission gains for local user terminals. According to corresponding 3GPP and IEEE standards, an RS shall have the full functions of an eNB/BS and there should be no difference between the cell controlled by an RS and that controlled by a normal eNB. While there is little difference between Type-II and transparency RSs as defined in 3GPP LTE-Advanced and IEEE 802.16j standards, Type-I and non-transparency RSs, have some differences which includes IEEE 802.16j's support for multi-hop communications in a cell and generation of longer delay in relay transmissions, while 3GPP LTE-Advanced supports only two-hop relay transmissions which leads to shorter latency. Also, LTE-Advanced guarantees backward compatibility by introducing a fake multicast broadcast single-frequency network (MBSFN) technique to help legacy user terminals to avoid incompatibility. The LTE user terminal will not try to receive the common reference signal or measure the channel quality in an MBSFN subframe that has been allocated for eNB-to-RS transmission. CoMP is another technique employed by LTE-Advanced to increase power gain, reduce interference as well as achieve frequency diversity with overall gain in data throughput.

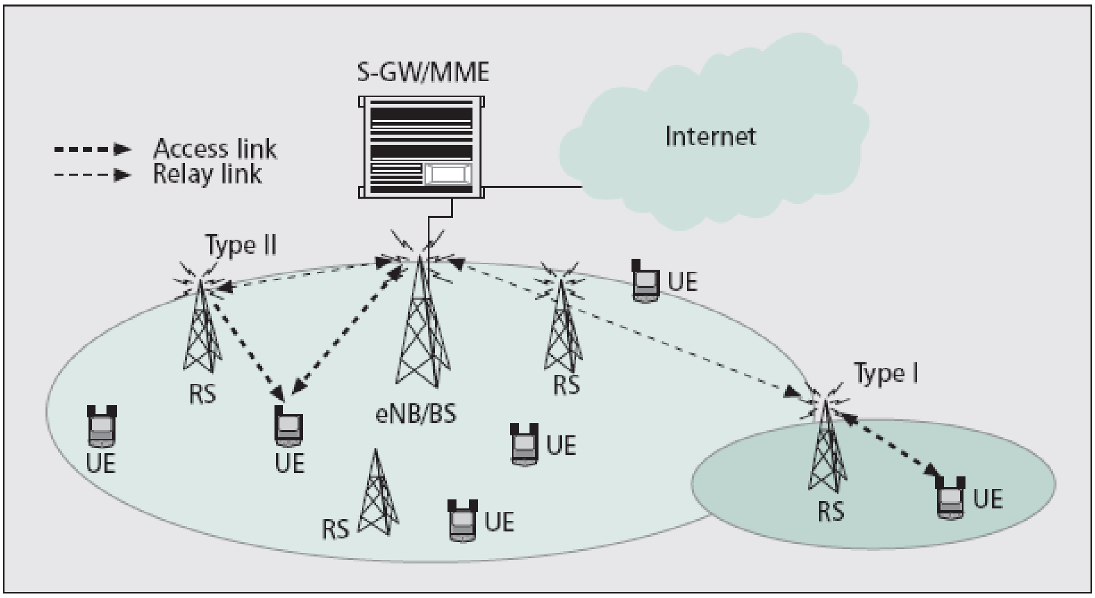

Figure 50: A network scenario with multiple RSs and user equipment (UE) units [72]

4.4.2 Latency

Another very crucial factor in meeting IMT-Advanced requirements is network latency, which is defined as the round-trip time it takes data to traverse the network. Latency values have been dropping constantly since the era of GPRS and stood at an impressive 70 ms in HSDPA networks. However, with further improvements in HSUPA to about 50ms and with the use of 2ms Transmission Time Interval (TTI), it was just a matter of time before this value would be cut again. While IEEE 802.16m is targeting less that 10ms in the user plane (UL and DL) and under 100ms (from idle to active) in the control plane, LTE-Advanced is targeting under 10ms also in the user plane and less than 50ms latency in the control plane.

4.4.3 Spectral Efficiency

The amount of bandwidth in a wireless network is ultimately determined by two factors: the spectral efficiency of the wireless interface and the amount of licensed spectrum a carrier owns. Spectral efficiency is measured as the amount of data (bits/s) that can be transmitted for every Hz of spectrum and the higher the number (bits/s/Hz) the better. As the wireless-data market grows, deploying wireless technologies with high spectral efficiency is becoming increasingly important. Increased spectral efficiency however is very costly as it would require greater complexity for both user terminals and BS equipment. This, therefore, means that operators and vendors must balance market needs against network and equipment costs if they are to last in the market. LTE-Advanced uses advanced interference management (AIM) techniques to provide robust performance, improve inter-cell fairness in heterogeneous networks and increase spectral efficiency but of even more importance is the multi-antenna techniques employed by both LTE-Advanced and IEEE 802.16m. The latter make gains in downlink and uplink peak spectral efficiencies in the excess of 15 and 6.75 bps/Hz using 4x4 and 2x4 antenna configurations, respectively meanwhile LTE-Advanced supports up to 8-stream transmissions with a resulting peak spectral efficiency of 30 and 15 bps/Hz in the downlink and uplink respectively.

4.4.4 Summary

In addition to the differences outlined above, there exist other issues which have not been fully explored in this thesis and are left for future research as the final approval of the IMT-Advanced candidate technologies is still some way off. In Table 4, some of the issues already discussed here as well as other differences between the two technologies are highlighted.

Table 4: Comparable features of IEEE 802.16m and LTE-Advanced

Parameter	IEEE 802.16m	LTE-Advanced
MIMO technique	DL: up to 8x8 UL: up to 4x4	DL: up to 8x8 UL: up to 4x8
Latency (ms)	C-Plane:100 (idle to active) U-Plane:10	C-Plane: 50 U-Plane: 10
Duplex Schemes	TDD, FDD and H-FDD	TDD, FDD
Mobility support	– Up to 500 km/hr.	- Max. at speed <15 km/hr - High Performance(120 km/hr - Maintain Links (350 km/hr)
Modulation	BPSK, QPSK, 16QAM, 64QAM, SC	QPSK, 16QAM, 64QAM
Multicarrier support	up to 100MHz with channel aggregation	100 MHz with carrier aggregation
Scalable bandwidth (MHz)	5, 7, 8.75, 10, 20, and 40	20 - 100
Peak Spectral efficiency (bps/Hz)	DL: 15 (4x4) MIMO UL: 6.75 (2x4) MIMO	DL: 30 (8x8) MIMO UL: 15 (4x4) MIMO
Peak data rates (Mbps)	DL: >1000 (low mobility) DL: > 100 (high mobility) UL: > 130	DL: 1000 UL: 500
Access Scheme	DL: OFDMA UL: OFDMA	DL: OFDMA UL: SC-FDMA
Cell edge spectral efficiency (bps/Hz)	DL: 0.09 (2x2) UL: 0.05 (1x2)	DL: 0.12 (4x4) UL: 0.07 (2x4)

5 LTE AND MOBILE WIMAX: STATUS & DEPLOYMENT STRATEGIES

Before diving into the current status of LTE and Mobile WiMAX, it's important to consider some of the underlying issues that are driving the market by briefly discussing the wireless data trends and forecasts. In the US alone for example, despite the downturn in the economy, the International Association for the Wireless Telecommunications Industry (CTIA), reported a year-to-year gain for wireless data service revenues of over US$19.4 billion during the first half of 2009 which was a 31% increase from a year earlier [43]. 25% of this total revenue was generated by wireless data alone (i.e. non-voice services). Additionally, the report also found that consumers today were in possession of over 246 million data-capable devices including smart phones, wireless-enabled PDAs, wireless-enabled laptops and notebooks. The increasing use of these smart devices is putting a strain on carrier networks around the world, thereby forcing them to move faster in deploying LTE or Mobile WiMAX. In [73], Chetan Sharma noted that 2010 will mark the first year when the total number of mobile broadband connections worldwide will exceed the total number of fixed broadband connections. In a report from the consulting firm Ovum [74], it is forecasted that users of mobile broadband services (3G and 3G+ technologies) will grow from 181 million in 2008 to over two billion in 2014 while users accessing the Internet via mobile broadband-enabled laptops and handsets will generate revenues of US$137 billion globally in 2014, over 450% more than in 2008. In a separate report [75], it is stated that Ovum predicts LTE will have approximately 109 million connections worldwide by 2014 while growth of Mobile WiMAX will slow down to 55 million in the same period. Supporting this fact is another statement, this time from Informa Telecoms & Media which predicts that by the end of 2014, the global 3G wireless market will include over 3.3 billion subscriptions, of which 2.8 billion will be 3GPP family technologies with 84 percent share of market and LTE connections will be approximately twice that of WiMAX with the share advantage only intensifying in coming years.

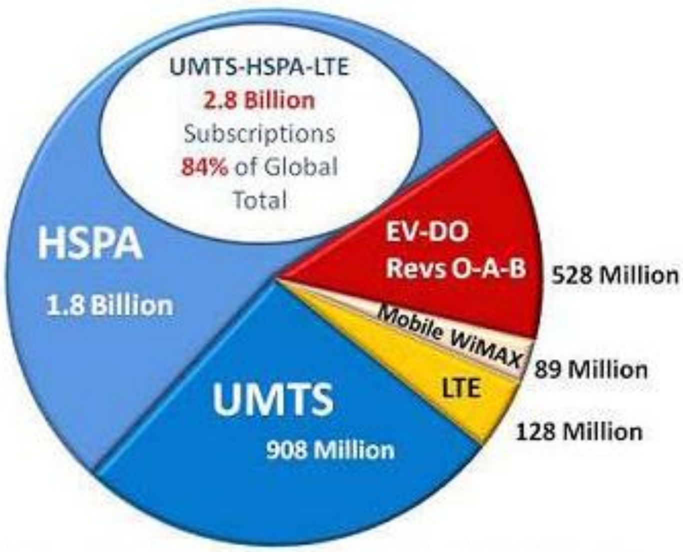

Figure 51: 3G Global Cellular Forecasts for 2014 [76]

Figure 51 shows a forecast for global 3G cellular forecasts for 2014 but what are the underlying factors driving this growth and how are operators and the industry as a whole reacting especially with regards to LTE and Mobile WiMAX?

5.1 Technology: OFDM and MIMO

Consumers in many parts of the world have already been making use of 2.5G and 3G networks for accessing data using hand-held devices but as use of these data services increase as mentioned earlier in the forecast, and with users demanding higher services on an anywhere-anytime bases, the amount of data traffic is inevitably going to shoot up. There is no doubt that in the foreseeable future, while voice and data will continue to be served using the 2.5G and 3G networks, these networks will eventually become capacity-constrained hence requiring the deployment of new networks capable of supporting new open internet models along with new devices while at the same time, accommodating the business model needs of operators.

MIMO and OFDM, both supported by LTE and Mobile WiMAX are suitable technologies of choice to satisfy this growing need for faster, reliable and cost-effective wireless broadband connections. LTE supports very high spectral efficiencies of about 100 Mbps in a 20MHz band and peak data rates are expected to climb to over 300 Mbps with the use of 4x4 MIMO antenna system. These sorts of data rates will also be possible in future releases of Mobile WiMAX. Additionally, by supporting both TDD and FDD, LTE allows for flexible deployment and co-existence with other radio access technologies, enhanced by the flat Evolved Packet Core architecture with a lesser number of network elements. Also because of the flat architecture, LTE can deliver high throughput with latency as low as 5ms for small IP packets, hence delivering a real-time experience. While there is no doubt as to the advantages brought by the data-optimized technologies like OFDMA and MIMO, deploying the networks that support high rates require new spectrum with much wider bandwidths and it will take several years before coverage can reach the levels attained by 2G and 3G networks today. Therefore, operators will most likely maintain existing 2G and 3G networks to be used for voice and narrow-band data services while gradually deploying LTE and Mobile WiMAX. The deployment of the OFDMA-MIMO mobile broadband data overlay network involves deployment of new base station line cards and clients as well as upgrades to the core network to support high amounts of IP traffic. Once the data overlay network is in place, operators may offer multi-mode devices as this would make it easier for users to enjoy seamless roaming across voice-optimized and data-optimized networks. Multi-mode handsets and modems are also offered in order to bridge the gap and provide both coverage and high speed, while deployments of the new systems are ongoing. Since LTE uses SC-FDMA technique for uplink transmissions, less power is used and a low power consumption results in a longer battery life in mobile devices thus giving LTE an advantage over Mobile WiMAX. For larger devices like laptops, the radio power consumption is of less importance because battery it forms only a small part of total power need.

Operators who have already deployed mobile WiMAX include SK Telekom, Korea Telecom and Sprint while in a report by Informa Telecoms and Media released in February 2009, there were already 119 LTE commitments at different levels including giants like NTT DoCoMo, T-Mobile, Vodafone, Verizone Wireless and AT&T, just to name a few. However, a much more comprehensive study carried out by the Global mobile Suppliers Association (GSA) in its Evolution to LTE report, counted 31 real commitments in April 2009 and that number jumped more than 100% by April 2010 to 64 operator commitments in 31 countries. Figure 52 shows the major LTE network operator commitments.

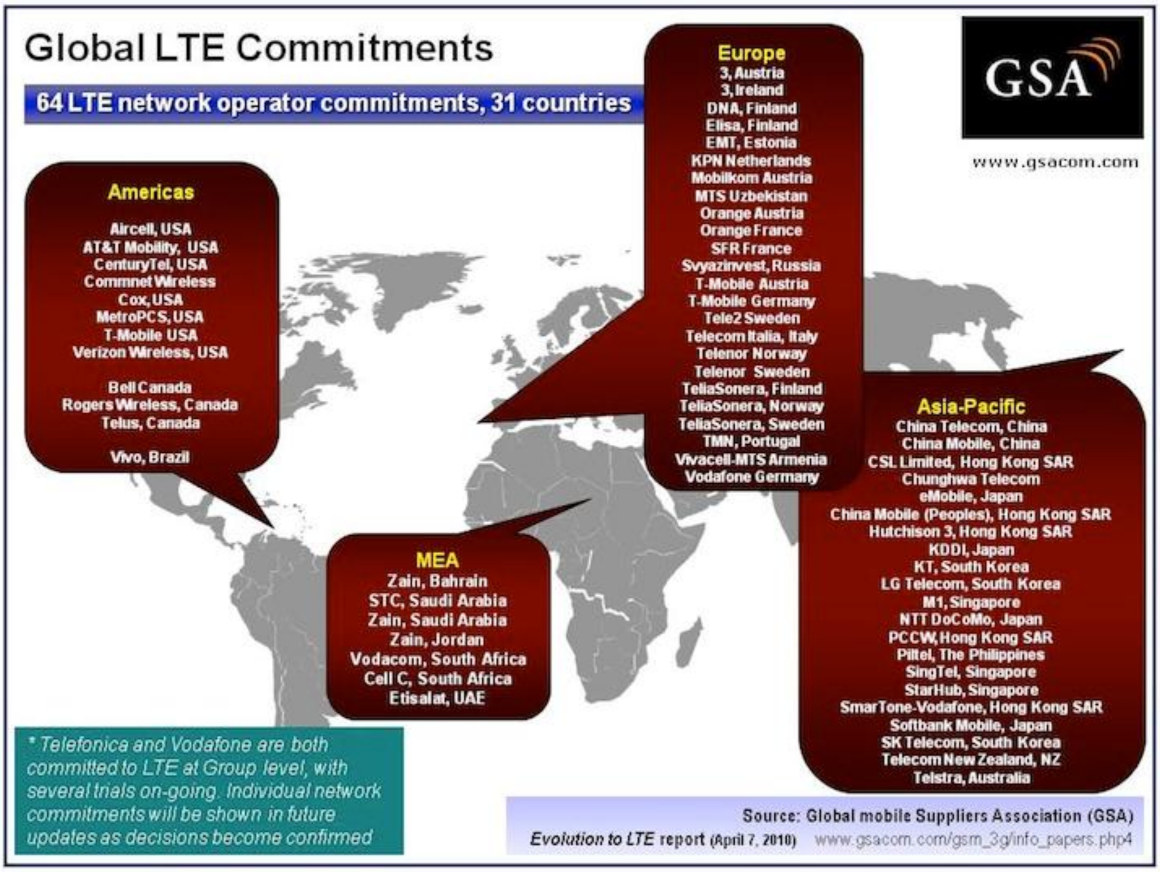

Figure 52: LTE network operator commitments as of April 2010 [77]

5.2 Time and Cost Factors

From the completion of standards to availability of interoperable products in the market, time is of the essence. The mobile WiMAX standard which was ratified in December 2005 and the availability of mobile WiMAX devices in 2007 give it an advantage over LTE. With legacy WiMAX present nowadays in numerous countries around the world and several deployments already functioning, the switch to mobile WiMAX will happen earlier if not already before LTE hits the market sometime in 2011 or 2012.

Migration to LTE can happen in a couple of ways. Carriers like NTT DoCoMo and Verizon Wireless having 3G networks based on technologies which are not in the 3GPP family are expected to make a jump to full LTE deployment unlike other operators with GSM networks who have the option of moving slowly through HSPA and HSPA+. Those moving for full LTE deployment will no doubt face some challenges especially with regards to CAPEX, availability of equipment and devices which supports LTE, the readiness of an IP backhaul capability across the entire wireless network and above all, availability of spectrum in the different geographical locations. Another path to LTE, especially for those operators with existing 3GPP-family 2.5 or 3G networks would be to continue profiting from their investments by just deploying HSPA, HSPA+ and femtocell support through slow upgrading to LTE. This would be a short term solution with immediate benefits but in the long run, delivering a hybrid, multimode service including LTE would be far more challenging. The use of femtocells is attractive because, most data traffic originates and terminates indoors, such that even HSPA/HSPA+ solutions are faced with problems of poor indoor performance in current macro-cell deployment. The mixed roll-out of LTE femtocell indoors over an existing macro network provides an attractive business case as carriers can deploy wireless broadband as quickly as they can deploy base stations, with little impact on the density of the macro network usage. Compared to a complete LTE network deployment, this save carriers short-term deployment costs and allows them roll out LTE coverage gradually, starting in the areas with the most advantage. There exist some key challenges in this scenario however including the fact that the femtocells must be able to effectively handle RF interference, location determination, and up-link and downlink handoffs including those with legacy technologies, QoS as well as provide secure device management. Also the presence of several thousand femtocells would pose some performance challenges to the core network.

5.3 Ecosystem

With Mobile WiMAX already being offered and LTE becoming a reality, it’s never too soon for operators and vendors to clearly identify their migration strategy. This strategy has to be based on certain key factors including the demand for network services, current deployments and competition from other market sectors. The ecosystem around this transformation is also an important factor as was noticed in the case of initial 3G deployments which were not backed by the availability of enough applications, so it took time for it to fully take off. So, the deployment of Mobile WiMAX and LTE should be met by equally capable devices so as to fully exploit the potential of rich applications like live video streaming, location-based services and social networking. In the US, for example, Sprint recently released its first WiMAX-enabled phone, the HTC EVO 4G and even though LTE is not fully ready, it was leaked that Dell is entering into the phone market with its Dell Lightning phone which boasts LTE capability and is expected to hit the market in 2011. Other well-known operators like Verizon Wireless are expected to kick off their launching with some USB dongles and a home modem probably.

Overall, 2G and 2.5G (GSM/GPRS/EDGE) will remain the dominant technologies for the next four to five years, while CDMA market will remain relatively flat. WCDMA subscriptions will probably decrease as operators tend to deploy and offer HSPA and HSPA-enabled devices. HSPA will therefore grow steadily while operators wait for LTE to be mature. During the same five year period, Mobile WiMAX will probably grow steadily as it is still very popular around the world especially with non-3GPP operators, most of whom are regional telecom operators especially in developing countries or multiple service operators wanting to offer mobile broadband services but are not ready to build an entirely new WCDMA/HSPA network or wait for full LTE maturity. In the 2010/2011 timeframe, Japan's NTT DoCoMo, Verizon Wireless of the US and China Mobile plan to launch their first LTE networks with the first products being USB modems and laptop cards as well as small volumes of handsets. Most LTE devices are expected to be dual mode, capable to supporting handover between 2G and 3G technologies. As seen in the projected forecasts at the beginning of this section, the momentum behind LTE will drive the volume of handsets and mobile PCs marketed to new levels. To conclude this section, the following observations are made:

- For operators who are looking to cash in and make the early jump to LTE, spectrum availability will be a key factor. These operators will need to lobby the regulators in order to get wider spectrum bands (e.g., 20 MHz) in order for provide the highest quality services possible with LTE. The prices also have to be carefully negotiated while providing assurance of the benefits of deploying LTE networks.

- A significant number of mobile services providers have increased their areas of interest to include a wide range of service offerings so as to boost their market share and drive usage and revenue growth. These new service offerings demand much wider bandwidth deployments and an effective way to distribute to users. According to [78], LTE offers the most efficient progression path with typical cost per downlink megabyte (assuming maximum use of network) of about €0.01 for LTE compared to €0.03 for HSPA and €0.06 for WCDMA.

- For the high quality services offered to the customers, capable handsets have to be available. Large screens, high-quality resolution and long battery lives counts amongst the specifications that will ensure effective delivery and an enjoyable user experience. Industry experts agree that there needs to be investments in innovation of new handsets in order to keep up with the launching schedule of the new networks, starting in 2010.

- While the uptake and contribution from developing markets will gradually increase, the main consumers for LTE services will come from Western Europe and developed parts of Asia. These regions combined will account for about 50-60% of LTE subscribers and 70-80% of the total revenue [79].

- There is a strong case for LTE deployments in developed markets according to projections and there is further indication that for operators, the break-even could occur after about 3-4 years following deployment and net present value to the operator being in the order of €1–3 billion. It is assumed, however, that the deployment would make use of the existing BS sites and the operator’s radio spectrum assets. In the developing markets, the case for operators is more marginal and would greatly depend on the competitive environment [78].

- Mobile WiMAX is ideal for emerging markets and especially in cases where low frequency bands are available. LTE, on the other hand, is an ideal technology for a more developed market and for operators already working with GSM technologies. Finally, it’s safe to say LTE and mobile WiMAX are about 75% compatible technology-wise and hence would offer almost similar performances on any given day.

6 SUMMARY AND CONCLUSIONS

Standards in the telecommunications industry are constantly changing as advances are made in new technologies and the public demand for a richer content, delivered at faster speeds and at all times is the main driving force behind these technological developments. Nowadays, many of the devices we own including mobile phones and laptops, are capable of connecting to 3G or 3rd Generation networks with speeds ranging from 3.6 – 7.2 Mbps, depending on the network operator, coverage area and the device platform. With demand for this high speed broadband services set to grow constantly, the ITU's Radiocommunication sector (ITU-R) came up with recommendations for the design of a new air interface which would support this growing demand. Such systems would be considered 4G or IMT-Advanced systems. The two main candidates seeking IMT-Advanced certification are LTE-Advanced from 3GPP and IEEE 802.16m which will be marketed as Mobile WiMAX Release 2.0.

This thesis began by looking at the technological evolution path adopted by the two industry bodies, 3GPP and the IEEE 802.16 working group. 3GPP has evolved from originally producing technical specifications and reports for a 3G mobile system based on evolved GSM core networks and their supported technologies to maintaining and developing new evolved radio access technologies based on GSM including GPRS and EDGE. The IEEE 802.16 Working Group develops standards and recommended practices to support the development and deployment of broadband Wireless Metropolitan Area Networks. The two latest standards from these industry bodies currently making their way into the market, LTE and IEEE 802.16e-2005 (Mobile WiMAX) were reviewed in detail with some significant technological differences noted. LTE, coming about two years after Mobile WiMAX packs an impressive array of features including the use of SC-FDMA for uplink transmission, thus combining a new hybrid modulation scheme that cleverly combines the low PAR of single-carrier systems with the multipath resistance and flexible subcarrier frequency allocation offered by OFDM, which is used by Mobile WiMAX.

Furthermore, as decision time draws near for which technology standards successfully meet the IMT-Advanced requirements as stipulated by ITU-R, a part of this thesis was also devoted to explaining what exactly are the requirements for IMT-Advanced and how the two main candidates mentioned earlier have scaled their features to meet these requirements. With particular attention paid to backward compatibility, the expectation that LTE-Advanced and IEEE 802.16m would merge into one as they target IMT-Advanced status is quelled because they are coming from different backgrounds. Despite some differences in their approach towards 4G certification, both these standards share a great deal of similar technological aspects and will certainly both qualify for 4G status.

Finally, as the "battle" moves from the labs to the street, it will be very interesting to see the market reaction when these two 4G technologies start being deployed. This may take up to a decade to happen but one lesson which can be learnt already today is the current status and deployment strategies of legacy systems LTE and Mobile WiMAX. This has also been discussed extensively in the closing parts of this thesis. What was observed is that while Mobile WiMAX has a time to market advantage and is very popular with operators who have deployed non-3GPP-standard networks, especially in developing countries concerned about initial CAPEX, LTE will enjoy a significant growth in the coming years mainly in developed countries and will also enjoy backing from the existing GSM-standard operators. This will consequently push down the price of LTE-supported devices and hence prepare the way for LTE-Advanced to make a grand entrance. However, only time will tell for sure what the stakes really will be.

In future, it will be interesting to know how all these developments in the mobile communications industry takes account of other related public issues like global warming. In particular, it would be interesting to know how the design and implementation of the new 4G standards can reduce power consumption at the level of BS or mobile devices which will be carried and used by millions of people worldwide.

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