

LTE and WiMAX Comparison

Tejas Bhandare

tbhandare@scu.edu

tbhandare@yahoo.com

Santa Clara University

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Audience

The target audiences of this paper are technical personnel from Telecommunications and Networking industry, especially engineers working on the development of next-generation wireless technologies, students from Electrical and Computer Science background, and anyone interested in a comparative study of the two leading contenders for 4G broadband wireless access technology: LTE and WiMAX.

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Overview

Over the last few years, there has been increasing demands for accessing the Internet over the mobile devices. To address this, the wireless telecommunication industry has been striving hard to define a new air interface for mobile communications to provide a framework for high mobility broadband services and increase the overall system capacity; reducing latency; and improving spectral efficiency and cell-edge performance.

Two emerging technologies, the IEEE 802.16 WiMAX (Worldwide Interoperability for Microwave Access) and the 3GPP LTE (Third Generation Partnership Project Long Term Evolution) aim to provide mobile voice, video and data services by promoting low cost deployment and service models through Internet friendly architectures and protocols. Both these technologies are being considered as candidates for the fourth generation (4G) of mobile networks.

This paper performs a detailed comparison of the LTE and WiMAX standards and delves into the intricacies of each of them. The paper begins with a brief history and technology overview of WiMAX and LTE. It then performs a detailed comparison of the System Architecture for each and also discusses the seamless integration of LTE and WiMAX technologies into the evolved 3GPP networks. It performs a detailed study of the Air Interface Radio Aspects such as access modes, transmission bandwidths, supported frequency bands, antenna techniques; the protocol aspects and various other features including control mechanisms, Quality of Service (QoS) and security for each of them.

Towards the end, the paper provides an overview of the competition in the wireless market and challenges and roadmap for each of these next-generation wireless standards.

Introduction

The communication industry has been formulating new standards to efficiently deliver high speed broadband mobile access in a single air interface and network architecture at low cost to operators and end users. Two standards, IEEE 802.16 (WiMAX) and 3GPP LTE are leading the pack towards forming the next-generation of mobile network standards.

The WiMAX (IEEE 802.16 standard) comes from IEEE family of protocols and extends the wireless access from the Local Area Network (typically based on the IEEE 802.11 standard) to Metropolitan Area Networks (MAN) and Wide Area Networks (WAN). It uses a new physical layer radio access technology called OFDMA (Orthogonal Frequency Division Multiple Access) for uplink and downlink. While the initial versions 802.16-2004 focused on fixed and nomadic access, the later version 802.16-2005, an amendment to 802.16-2004 include many new features and functionalities needed to support enhanced QoS and high mobility broadband services at speeds greater than 120 Km/h. The 802.16-2004 is also called 802.16d and is referred to as fixed WiMAX while the 802.16-2005 is referred to as 802.16e or Mobile WiMAX. The Mobile WiMAX uses an all IP backbone with uplink and downlink peak data rate capabilities of upto 75 Mbps depending on the antenna configuration and modulation, practicable to 10 Mbps within a 6 miles (10 Km) radius. The earliest iterations of WiMAX was approved with the TDMA TDD and FDD with line of sight (LOS) propagation across the 10 to 66 GHz frequency range which was later expanded to include operation in the 2 to 11 GHz range with non line of sight (NLOS) capability using the robust OFDMA PHY layer with sub-channelization allowing dynamic allocation of time and frequency resources to multiple users. The 802.16m (Mobile WiMAX Release 2) Task-force is currently working on the next-generation systems with an aim for optimizations for improved interworking and coexistence with other access technologies such as 3G cellular systems, WiFi and Bluetooth and enhance the peak rates to 4G standards set by the ITU under 'IMT-Advanced' umbrella which calls for data rates of 100 Mbps for high mobility and 1 Gbps for fixed/nomadic wireless access.

The LTE, on the other hand evolves from the Third-generation technology which is based on WCDMA and defines the long term evolution of the 3GPP UMTS/HSPA cellular technology. The specifications of these efforts are formally known as the evolved UMTS terrestrial radio access (E-UTRA) and evolved UMTS terrestrial radio access network (E-UTRAN), commonly referred to by the 3GPP project LTE. The first version of LTE is documented in Release 8 of the 3GPP specifications. It defines a new physical layer radio access technology based on Orthogonal Frequency Division Multiple Access (OFDMA) for the downlink, similar in concept to the PHY layer of Mobile WiMAX, and uses SC-FDMA (single Carrier Frequency Division Multiple Access) for the uplink. LTE supports high performance mobile access functional upto

350Km/h with 500Km/h under consideration. Peak data rates range from 100 to 326.4Mbps on the downlink and 50 to 86.4 Mbps on the uplink depending on the antenna configuration and modulation depth. The LTE also targets to achieve the data rates set by the 4G ‘IMT-Advanced’ standard. The development of LTE interface is linked closely with the 3GPP system architecture evolution (SAE) which defines the overall system architecture and Evolved Packet Core (EPC). The LTE aims to provide an all IP backbone with reduction in cost per bit, better service provisioning, flexibility in use of new and existing frequency bands, simple network architecture with open interfaces, and lower power consumption.

The figure below shows the wireless technology evolution path for WiMAX and LTE towards the ITU defined ‘IMT-Advanced’ 4G standard.

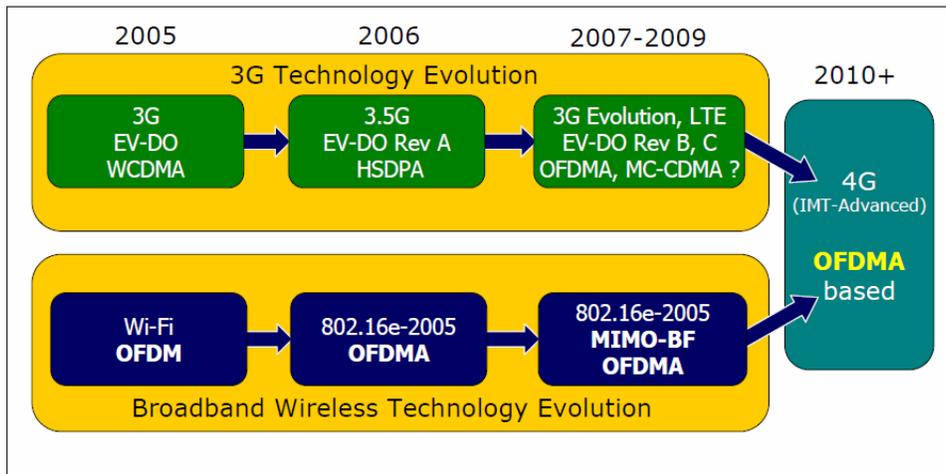


Figure-1: Evolution path of Mobile wireless technologies towards 4G [12]

System Architecture

The LTE and WiMAX System Architecture aims to improve latency, capacity, and throughput while simplifying the core network and optimizing the IP traffic and services. Both the architectures ensure seamless integration into the existing 3GPP cellular wireless networks and provide simplified support and handover to 3GPP and non-3GPP access technologies.

The LTE Architecture

Evolving from the 3GPP family, the LTE takes the 3G UMTS architecture as the baseline to define a simplified model in tandem with the 3GPP SAE (System Architecture Evolution) and Evolved Packet Core (EPC).

Baseline

A 3G-cellular logical baseline architecture is shown in the figure below.

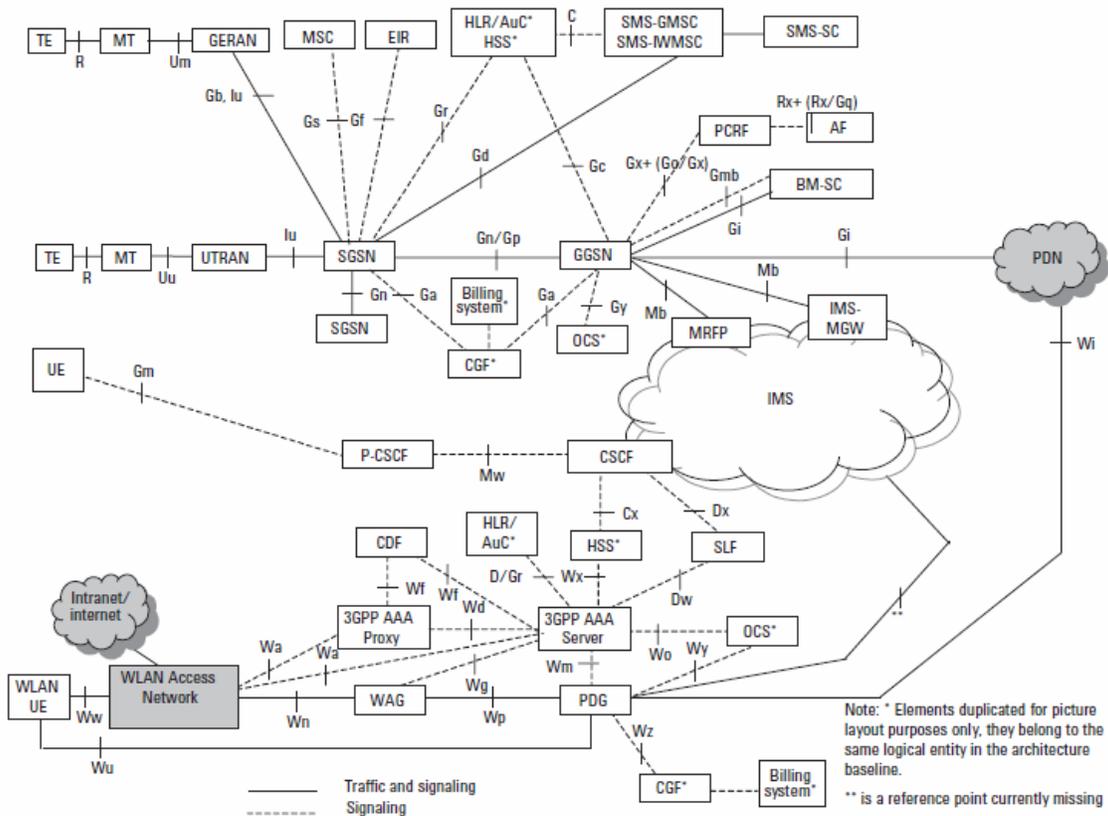


Figure-2: 3G-Cellular Logical Baseline Architecture [14]

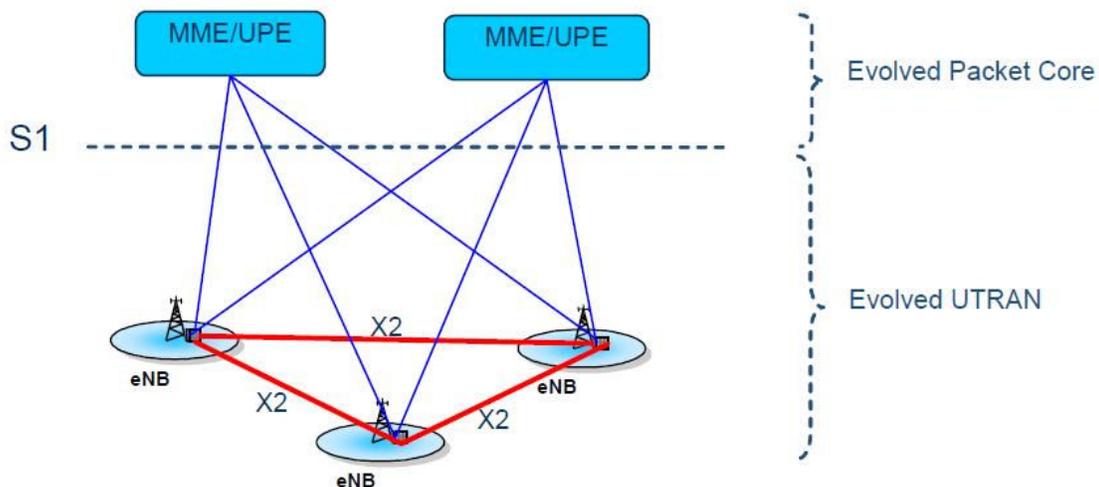
The LTE focuses on enhancing and optimizing this baseline architecture, specifically simplifying the UTRAN (Universal Terrestrial Radio Access Network) and UTRA and deliver services utilizing an Evolved Packet Core.

Towards LTE

The aim of the LTE Architecture is to:

- Provide open interfaces to support multi-vendor deployments.
- Provide robustness – no single point of failure.
- Support multi-RAT (Radio Access Technology) with resources controlled from the network.
- Support of seamless mobility to legacy systems as well as to other emerging systems including inter RAT Handovers and Service based RAT Selection.
- Maintain appropriate level of security.

Based on the higher goals, the LTE model gets rid of the RNC (Radio Network Controller). In the 3G UMTS network the RNC is located in the UTRAN and controls one or more NODE-Bs which are the Base Transceiver Stations. The LTE E-UTRAN (Evolved-UTRAN) is greatly simplified and has a new network element called eNB (evolved Node-B) that provides the E-UTRA user plane and control plane terminations towards the UE (User Equipment). The figure below shows the LTE architecture with E-UTRAN.



MME: Mobility Management Entity
 UPE: User Plane Entity
 eNB: evolved Node-B
 UTRAN: Universal Terrestrial Radio Access Network

Figure-3: LTE Architecture with E-UTRAN [13]

The eNBs are connected together through a new interface called X2, enabling direct communication between the elements and eliminating the need to channel data back and forth through the RNC. The E-UTRAN is connected to the EPC (Evolved Packet Core) through the S1 interface, which connects the eNBs to the mobility management entity (MME/UPE) and serving gateway (S-GW) elements residing at the EPC (not shown in figure) through a many-to-many relationship.

This new architecture pushes more signaling down to the eNBs by splitting the user plane and mobility management entities as depicted in the figure below.

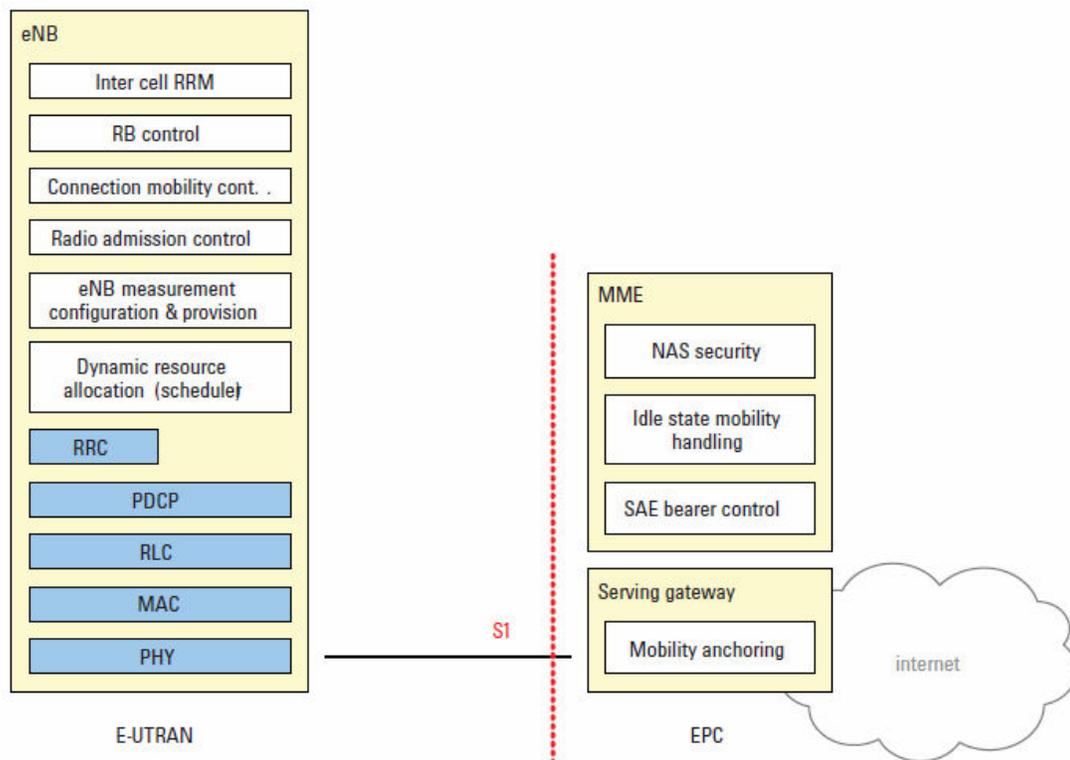


Figure-4: Functional split between E-UTRAN and EPC [17]

The eNB performs the following functions:

- Radio resource Management
- IP header compression and encryption
- Selection of MME at UE attachment
- Routing of user plane data towards S-GW
- Scheduling and transmission of paging and broadcast information
- Mobility measurement and configuration reporting

The MME functions include:

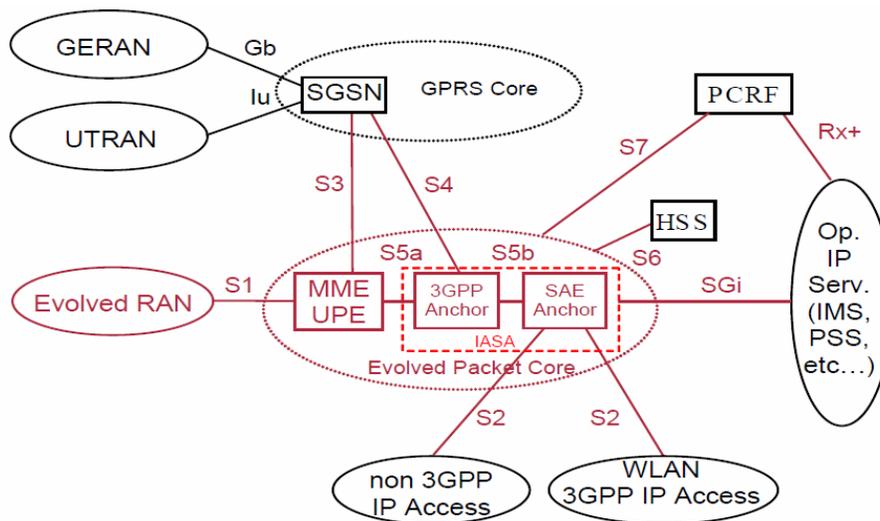
- Paging message distribution to eNBs
- Security control
- Idle state mobility control
- SAE bearer control
- Ciphering and integrity protection of non-access stratum (NAS) signaling

The functions performed by S-GW are:

- Termination of user-plane packets for paging reasons
- Switching of user plane for UE mobility

System Architecture Evolution (SAE)

Concurrent to the LTE architecture is the SAE architecture which forms the fundamental baseline for the LTE and Evolved Packet Core. The System Architecture Evolution (SAE) ensures future competitiveness of 3GPP systems while optimizing the network for IP traffic towards an All-IP network. The figure below shows the SAE approach that LTE uses.



MME: Mobility Management Entity
 UPE: User Plane Entity
 IASA = Inter-Access System Anchor

Figure-5: Baseline of SAE Architecture [14]

The SAE Anchor is the Mobility anchor between 3GPP access systems (2G/3G/LTE) and non-3GPP access systems (e.g. WLAN, WiMAX). The 3GPP Anchor is the Mobility anchor between 2G/3G and LTE access systems (based on GTP). This architecture

supports high throughput, low latency LTE access. All services are only through the Packet Switched domain and SAE does not support Circuit Switched domain.

Seamless migration

In order to ensure smooth migration to LTE, the MME, UPE, Inter AS Anchor and GSN function entities are combined in one node called ACGW (Access Control GateWay) which enables inter-working with UTRAN via Iu interface and GPRS core network via Gn interface. The figure below shows the ACGW way towards seamless migration to LTE.

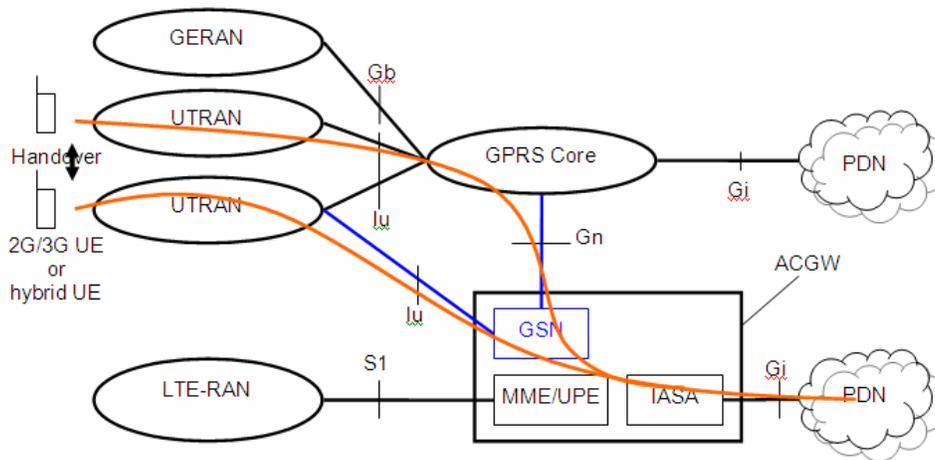


Figure-6: Seamless migration to LTE using ACGW [15]

The S3, S4 and S5 become internal interfaces in ACGW. From UTRAN's perspective, ASGW is a SGSN and thus provides complete Iu interface functionalities including Iu-Flex, which breaks the hierarchical mapping of RNCs to SGSNs (MSCs) and allows many-to-many relation of RNCs and SGSNs (and MSCs) enabling load sharing between SGSN and ACGW. Depending on the UE (2G/3G/hybrid), the RNC selects SGSN or ACGW for the UE. The Gn interface between GPRS and ACGW is only used during inter-RNC handover, in which case the source/target RNC has Iu interface to ACGW while the target/source RNC doesn't have Iu interface to ACGW and there is no Iur interface between these two RNCs. This is depicted in the figure above.

The GSN function entity is not required if the operator has no pre-SAE/LTE system or the pre-SAE/LTE system is withdrawn.

The WiMAX Architecture

The WiMAX (IEEE 802.16) standard comes from the IEEE family of protocols and extends and enhances the coverage of Wireless LAN (defined under IEEE 802.11) to MANs and WANs. The WiMAX network architecture is designed to provide an IP friendly framework with scalable data capacity, open access to innovative applications and services, enhanced QoS and mobility. The IEEE 802.16 standards define the structure of the PHY (Physical) and Link Layer operations that occur between mobile stations and base stations (BSs). The over-the-air upper layer signaling as well as network architecture and protocols behind the base stations required for an e2e (end-to-end) specifications are outside the scope of the IEEE 802.16 standard. Therefore, in order to ensure proper co-ordination and interoperability of various implementations of WiMAX products, the WiMAX forum established in 2003 initiated several technical specification efforts in co-ordination with the IETF, 3GPP, 3GPP2, DSL Forum and OMA (Open Mobile Alliance) to complement the IEEE 802.16 standards by defining minimum product interoperability requirements and e2e network architectures and protocol specifications. The WiMAX Forum defines a basic architecture for IP-based connectivity and services while supporting all levels of mobility.

Network Reference Model

The WiMAX Network Reference Model (NRM) logically representing a WiMAX network architecture is shown in the figure below.

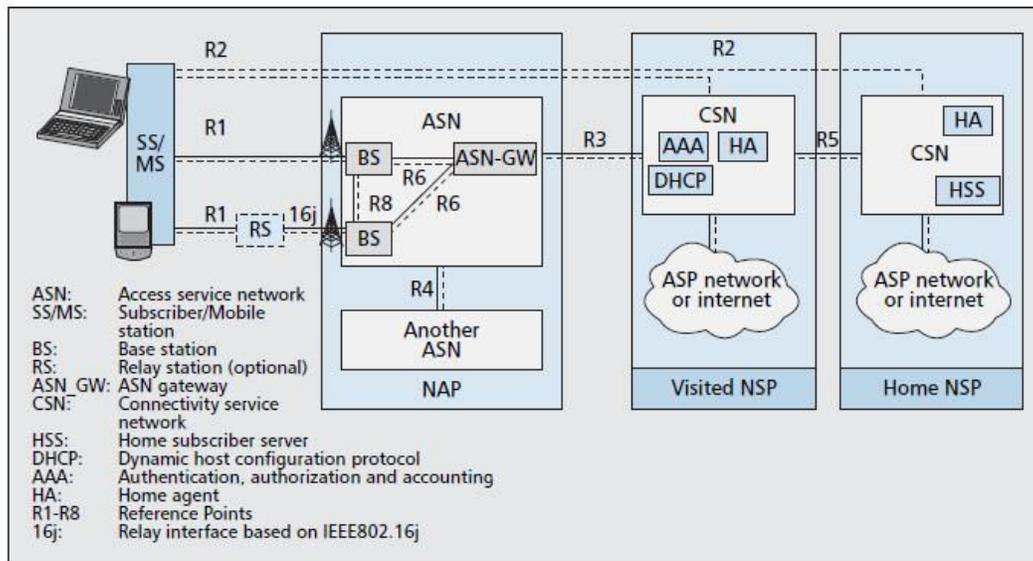


Figure-7: WiMAX Network Reference Model [1]

The WiMAX network can be deployed as a green field network (no legacy support) or as an overlay to existing fixed legacy circuit switched systems or mobile access networks such as 2G/3G cellular systems or cable/digital subscriber line (DSL). It can also be used on wireless backhaul to WiFi hot spots, fixed/nomadic access to customer premises equipment (CPE) and residential gateways (RGs), and mobile access to notebooks, smart phones, and next generation WiMAX embedded mobile Internet devices.

The Network Reference Model identifies the key functional entities and reference points for network interoperability. The network access provider (NAP) is a business entity that provides WiMAX radio access infrastructure while the Network Service Provider (NSP) is the business entity that provides IP connectivity and WiMAX services to the subscribers according to negotiated SLAs (Service Level Agreements) with one or more NAPs. The WiMAX NRM has several logical entities such as MSs (Mobile Stations) /SS (Subscriber Stations), ASN (Access Service Network), CSN (Connectivity Service Network) which represent logical grouping of functions they perform. The interaction between various elements of these entities takes place through the reference points R1-R8.

Mobile Station (MS)

The MS generically refer to both fixed and mobile device terminals providing wireless connectivity between single or multiple hosts and a WiMAX network.

Access Service Network (ASN)

The ASN performs various network functions required to provide radio access to the MS. These include:

- Layer 2 connectivity with the MS
- Transfer of AAA (Authentication, Authorization and Accounting) messages to the H-NSP (Home NSP)
- Preferred NSP discovery and selection
- Relay functionality for establishing layer 3 (L3) connectivity with MS
- Radio Resource Management (RRM)
- ASN and CSN anchored mobility
- Paging and location management
- ASN-CSN tunneling

The ASN may be implemented as an integrated ASN where all functions are collated in a single logical entity, or it may have a decomposed configuration in which the ASN

functions are selectively mapped into two separate nodes, a BS (Base Station) and an ASN-GW (ASN Gateway)

Base Station (BS)

The BS is a logical entity that primarily performs the radio related functions of an ASN interface with the MS. Each BS is associated with one sector with one frequency assignment and may incorporate a Down Link/Up Link scheduler.

ASN Gateway (ASN-GW)

ASN-GW is a logical entity that represents an aggregation of centralized functions related to QoS, security, and mobility management for all the data connections served by its association with the BSs through the R6 interface. It also performs IP layer interactions with the CSN through R3 interface and with other ASNs through R4 interface for mobility.

The BS and ASN-GW can have many-to-many relationship enabling load balancing and redundancy.

Connectivity Service Network (CSN)

The CSN provides IP connectivity services to WiMAX subscribers and may comprise of network elements such as routers, AAA proxy/servers, home agent, and user databases as well as interworking gateways or enhanced network servers to support multicast, broadcast and location based services. Some of the key functions of CSN include:

- IP address management
- AAA proxy or server
- QoS policy and admission control based on user subscription profiles
- ASN-CSN tunneling support
- Subscriber billing and inter-operator settlement
- Inter-CSN tunneling for roaming
- CSN-anchored inter-ASN mobility
- Connectivity to IMS, location based services, peer-to-peer services, and broadcast and multicast services
- Over-the-air activation and provisioning

The protocol layers used in the elements connected through various interfaces of the Network Reference Model is depicted in the figure below.

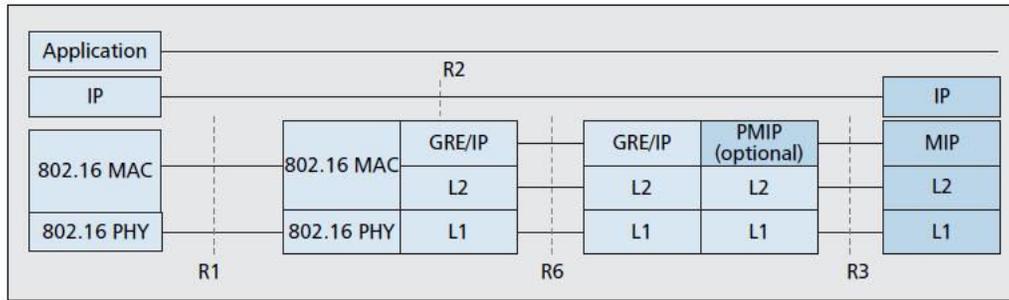


Figure-8: WiMAX simple IP based protocol structure [1]

The architecture uses a simple IP based protocol structure. The layers defined in the MS/SS, BS, ASN-GW, CSN are logically connected through the R1, R6 and R3 interfaces respectively. The R2 interface is a logical interface between the IP layers of the MS and the CSNs of Visited NSP/Home NSP.

In addition to the entities used in the NRM baseline architecture, a few optional elements could be incorporated for future 802.16m standard which is based on next-generation ITU ‘IMT-Advanced’ specifications to support enhanced roaming, seamless WiFi-WiMAX handover, 3GPP2 interworking, multimedia session continuity, support for femto-cells and network optimization.

Seamless integration with 3GPP networks

For the WiMAX technology to be globally successful, it is necessary to have seamless interoperability with existing wireless technologies specifically with the 3GPP cellular-networks. The 3GPP networks are also evolving towards an EPC (Evolved Packet Core) with an air-interface based on OFDMA technology similar to one used for WiMAX. Architecturally it is therefore possible to integrate the 3GPP networks to WiMAX networks and allow seamless handovers between them. The main requirement for achieving seamless integration with 3GPP access networks is to provide an appropriate authentication infrastructure, optimize the handover, preserve QoS between technologies, and enable inter-operator roaming. The figure below shows architecture for integrating the mobile WiMAX within the 3GPP evolved packet network.

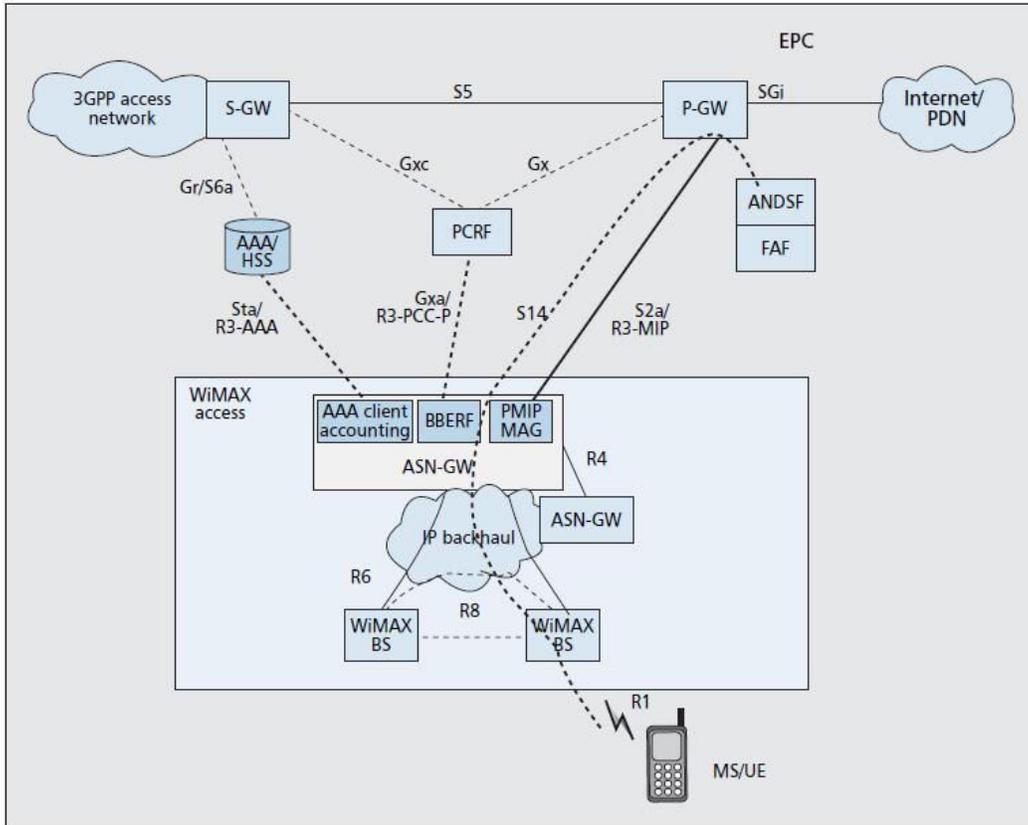


Figure-9: Architecture for integrating mobile WiMAX within 3GPP EPC network [11]

All 3GPP access technologies are connected to the EPC through the S-GW (Serving Gateway) while the WiMAX is typically connected through the packet data network gateway (P-GW). The WiMAX ASN is directly connected to the P-GW through the S2a interface as a trusted access through the (PMIP MAG) Proxy Mobile IP Mobility Access Gateway. The EPC has the HSS (Home Subscriber Server) which stores the user subscriber information, a AAA server which provides the authentication, authorization and accounting services for the user, and a PCC (Policy and Charging Control) architecture for enforcing charging and QoS policies. The WiMAX PCC uses the PCRF (Policy and Charging Rules Function) to receive the authorization envelope for associated QoS parameters that are enforced in the ASN-GW. The BBERF (Bearer Binding and Event Reporting Function) is used for reporting events for charging performed in the EPC. The ANDSF (Access Network Discovery and Selection Function) facilitates the handover process by assisting in the discovery of WiMAX cells and provide neighboring cell information such as QoS and service capabilities, charging rate et al. when requested by the UE (User Equipment). The FAF (Forward Authentication Function) is used to authorize access to 3GPP and prepare appropriate 3GPP resources on its behalf while the UE is still on the WiMAX network.

Four major logical interfaces are deployed in the architecture to achieve the seamless integration.

- **3GPP STa**
This is equivalent to the WiMAX R3-AAA interface and is used for AAA-based authentication of user equipment (UE) and enforcement of preconfigured QoS.
- **3GPP Gxa**
This is equivalent to the WiMAX R3-PCC-P and is used for enforcement of dynamic QoS and charging rules.
- **3GPP S2a**
This is equivalent to WiMAX R3-MIP interface and is used for layer 3 mobility and bearer establishment towards the core network.
- **3GPP S14**
The S14 interface is used for inter-technology network discovery and selection and for facilitating seamless handover between the two technologies using the ANDSF and FAF elements.

The architecture limits changes to the standard 3GPP interfaces/components to a minimum and defines new functionalities and interfaces in the WiMAX architecture wherever necessary.

Air Interface Radio Aspects

The air interface radio aspects accounts for various radio transmission and reception specifications.

Frequency bands

The LTE inherits all the frequency bands defined for UMTS, spectrum which typically consists of the 800 MHz, 900 MHz, 1800 MHz and 1900 MHz. Depending on regional and local variables LTE deployments can be undertaken in the any of the band range of 800 MHz to 2.62 GHz.

WiMAX was first designed for Line-of-Sight (LOS) environments (IEEE 802.16c) at high frequency bands of 10-66 GHz. Later versions (IEEE 802.16a, d, e) support Non-Line-of-Sight (NLOS) modes in radio bands between 2-11 GHz.

Radio Access Modes

Both the LTE and WiMAX air Interface support FDD and TDD modes. The earlier versions of WiMAX, prior to IEEE 802.16e (prior to WiMAX Forum Release 1.5) only supported the TDD mode. The FDD mode in WiMAX defines a half duplex FDD mode to support lower complexity terminals which time shares the hardware resources between the uplink and downlink. This mode is in consideration for LTE.

Data rates

Peak data rates for LTE range from 100 to 326.4Mbps on the downlink and 50 to 86.4 Mbps on the uplink depending on the antenna configuration and modulation depth. The WiMAX systems have peak data rate capabilities of 75 Mbps in the downlink and 25 Mbps in the uplink.

Multiple Access Technology

Downlink and uplink transmissions in LTE and WiMAX are based on the multiple access technologies. A technology called Orthogonal Frequency Division Multiple Access (OFDMA) is used for downlink transmission of LTE and for uplink and downlink transmission of WiMAX. The uplink transmission for LTE uses a new technology called SC-FDMA (Single Carrier Frequency Division Multiple Access). The SC-FDMA is superior to OFDMA, however is restricted to LTE uplink because the increased time domain processing of SC-FDMA would entail considerable burden on

base stations. Both OFDMA and SC-FDMA physical layer technologies are detailed further.

OFDMA (WiMAX Uplink/Downlink and LTE Downlink)

OFDMA is derived from OFDM (Orthogonal Frequency Division Multiplexing), a digital multi-carrier modulation scheme which uses the principle that information can be transmitted on a radio channel through variations of a carrier signal's frequency, phase or magnitude. Instead of transmitting all the information on to a single RF carrier signal, the high data rate input stream is multiplexed into parallel combination of low data rate streams. The parallel streams are modulated onto separate subcarriers in the frequency domain through the use of inverse fast Fourier transform (IFFT) and transmitted through the channel. At the receiver, the signal is demodulated using an FFT process to convert a time varying complex waveform back to its spectral components, recovering the initial subcarriers with their modulation and thus the original digital bit stream. The figure below shows frequency and time domain representation of an OFDM signal.

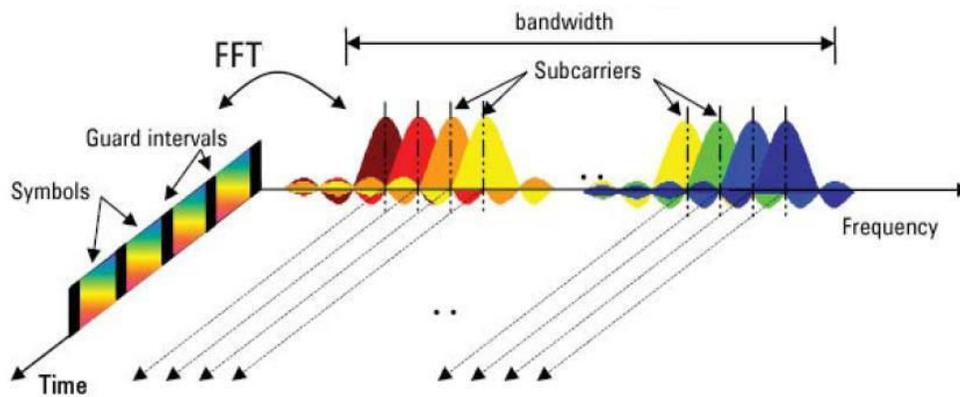


Figure-10: OFDM signal representation in frequency and time domain [18]

In OFDM, the subcarriers are spaced closely together without any guard bands in frequency domain and use the FFT to convert the digital signals from time domain into a spectrum of frequency domain signals that are mathematically orthogonal to each other. The frequency domain null of one subcarrier corresponds to the maximum value of the adjacent subcarrier which allows subcarriers to overlap without interference and thus conserve bandwidth. By using TDMA with basic OFDM, OFDMA is achieved thus allowing dynamic allocation of subcarriers among different users on the channel. OFDMA provides a robust system with increased capacity and resistance to multipath fading. The figure below shows the OFDM and OFDMA subcarrier allocation.

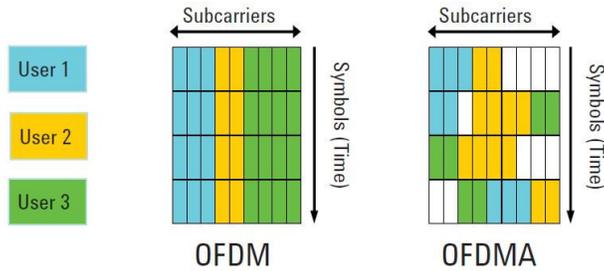


Figure-11: OFDM and OFDMA subcarrier allocation [2]

In LTE and WiMAX, each subcarrier is modulated with a conventional modulation scheme depending on the channel condition. LTE uses QPSK, 16QAM, or 64QAM while WiMAX uses BPSK, QPSK, 16QAM, or 64QAM for modulation at a low symbol rate. The FFT sizes of 128, 256, 512, 1024 and 2048, corresponding to WiMAX and LTE channel bandwidth of 1.25, 2.5, 5, 10 and 20MHz are used. In time domain, guard intervals known as cyclic prefix (CP) are inserted between each of the symbols to prevent inter-symbol interference at the receiver caused by multi-path delay spread in the radio channel. The normal CP for LTE is 4.69 μ s while for WiMAX it is 1/8 the length of OFDMA symbol time, typically 11.43 μ s for OFDMA symbol duration of 102.86 μ s. The detailed values and configurations are listed further in the comparison of Modulation Parameters. The CP is a copy of the end of the symbol inserted at the beginning. The figure below shows OFDMA transmitting a series of QPSK data symbols.

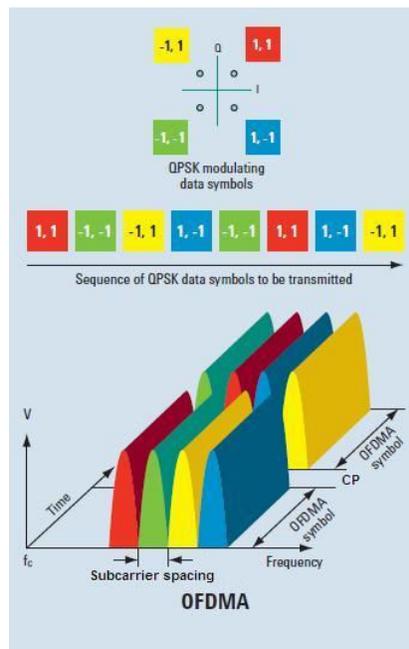


Figure-12: OFDMA transmitting a series of QPSK data symbols [4]

SC-FDMA (LTE uplink)

The LTE uses a new modulation technique called Single Carrier Frequency Division Multiple Access which in essence creates a single carrier waveform and shift it to the desired part of the frequency domain. This new technique provides robust resistance to multipath without the problem of high PAR (Peak-to-average ratio) Gaussian noise which occurs in OFDMA as the number of subcarriers increase. The figure below provides a comparison in time and frequency domain between SC-FDMA and OFDMA transmitting a sequence of four (M) QPSK data symbols. In real, LTE signals are allocated in units of 12 adjacent subcarriers.

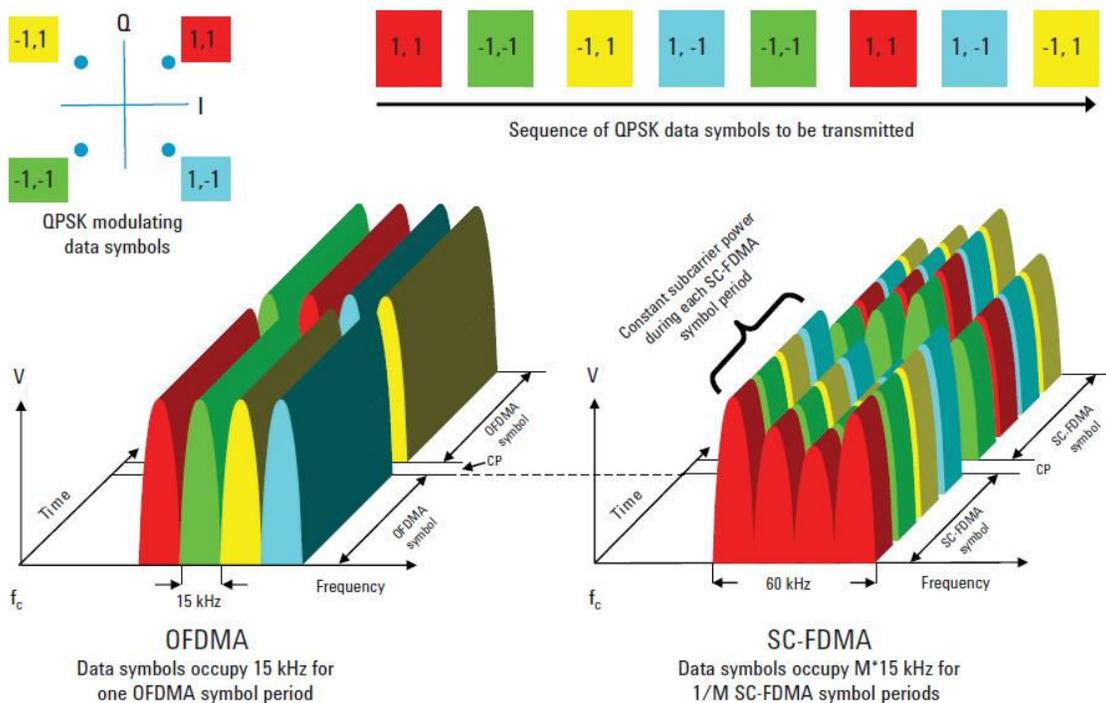


Figure-13: Comparison of OFDMA and SC-FDMA transmitting a series of QPSK data symbols [2]

The SC-FDMA transmits the data symbols in series at four (M) times the rate; with each data symbol occupying $M \times 15$ KHz; as against OFDMA which transmits the symbols in parallel, one per subcarrier. The SC-FDMA signal appears to be more like a Single Carrier (hence the name ‘SC’) with each data being represented by one wide signal. The SC-FDMA symbol contains M ‘sub-symbols’ that represent the modulating data.

By transmitting M data symbols at M times the rate, the SC-FDMA occupied bandwidth is the same as multicarrier OFDMA, but the PAR (Peak-to-Average Ratio) remains the same as used in the original data symbols and does not approach the Gaussian noise as in OFDMA.

Modulation Parameters

The modulation parameters such as system bandwidth, sampling frequency, FFT size, subcarrier spacing, symbol duration, cyclic prefix et al. for LTE and WiMAX are compared below.

LTE

The LTE has a scalable channel bandwidth selectable from 1.25 to 20 MHz with available system profiles of 1.25, 1.4, 2.5, 3, 5, 10, 15, and 20 MHz with both FDD and TDD. It uses a subcarrier spacing of 15 KHz. If eMBMS (evolved Multimedia Broadcast Multicast system), a technique to combine multi-cell transmissions in the UE is used, the subcarrier spacing of 7.5 KHz is deployed. The subcarrier spacing in LTE is constant and is independent of channel bandwidth. The OFDMA and SC-FDMA symbol length is the same at 66.7 μ s over which the subcarriers of 15 KHz (downlink OFDMA) and 60 KHz (uplink SC-FDMA) are each modulated by one QPSK data symbol. The smallest amount of allocated resource in both the downlink and uplink is called a resource block (RB) which is 180 KHz wide and lasts for 0.5 ms. An RB consists of 12 subcarriers at 15 KHz subcarrier spacing while for eMBMS the RB is 24 subcarriers at 7.5 KHz spacing. The maximum number of RBs supported by the given channel bandwidth is given in the table below.

Channel bandwidth (MHz)	1.4	3.0	5	10	15	20
Nominal transmission bandwidth configuration (MHz)	1.08	2.7	4.5	9	13.5	18
Nominal transmission bandwidth configuration (resource blocks)	6	15	25	50	75	100

Table-1: Channel bandwidth Configurations [4]

The length of the Cyclic Prefix (CP) used in LTE depends on the channel delay spread and accordingly either short or long CP is used. When short CP is used, the first OFDM

symbol in a slot has slightly longer CP than the remaining six symbols to preserve slot timing (0.5 msec). The table below lists the LTE modulation parameters.

Transmission BW	1.25 MHz	2.5 MHz	5 MHz	10 MHz	15 MHz	20 MHz	
Sub-frame duration	0.5 ms						
Sub-carrier spacing	15 kHz						
Sampling frequency	192 MHz (1/2 x 3.84 MHz)	3.84 MHz	7.68 MHz (2 x 3.84 MHz)	15.36 MHz (4 x 3.84 MHz)	23.04 MHz (6 x 3.84 MHz)	30.72 MHz (8 x 3.84 MHz)	
FFT size	128	256	512	1024	1536	2048	
OFDM sym per slot (short/long CP)	7/6						
OFDM Data Symbol	66.7 us						
CP length (usec/samples)	Short	(4.69/9) x 6, (5.21/10) x 1	(4.69/18) x 6, (5.21/20) x 1	(4.69/36) x 6, (5.21/40) x 1	(4.69/72) x 6, (5.21/80) x 1	(4.69/108) x 6, (5.21/120) x 1	(4.69/144) x 6, (5.21/160) x 1
	Long	(16.67/32)	(16.67/64)	(16.67/128)	(16.67/256)	(16.67/384)	(16.67/512)
Configuration		Cyclic Prefix Length					
			T_s	μsec			
Normal CP	$\Delta f = 15 \text{ kHz}$	160 for $l = 0$	5.21 for $l = 0$				
		144 for $l = 1, 2 \dots 5$	4.69 for $l = 1, 2 \dots 5$				
Extended CP	$\Delta f = 15 \text{ kHz}$	512	16.67				
	$\Delta f = 15 \text{ kHz}$	1024	33.33				

$T_s = 1 / (15000 \times 2048)$ seconds, which corresponds to the 30.72 MHz sample clock for the 2048 point FFT used with the 20 MHz system bandwidth.

Table-2: LTE modulation parameters [19]

WiMAX

The WiMAX also has variable channel bandwidth and ranges from 1.25 to 20MHz with available system profiles of 1.25, 2.5, 5, 10 and 20 MHz. The WiMAX however uses a subcarrier spacing which for a given channel bandwidth is inversely proportional to the number of subcarriers. The time duration of the OFDMA symbol is set by the inverse of the subcarrier spacing. The inverse relationship between the subcarrier spacing and symbol duration is a necessary and sufficient condition to ensure that the subcarriers are orthogonal. The table below lists the LTE modulation parameters as specified for mobile WiMAX 802.16e.

System bandwidth (MHz)	1.25	2.5	5	10	20
Sampling frequency (MHz)	1.4	2.8	5.6	11.2	22.4
FFT size	128	256	512	1024	2048
Subcarrier spacing (kHz)	10.94				
OFDM symbol duration (μ s)	102.86				
Useful symbol time ¹ (μ s)	91.43				
Cyclic prefix ¹ (μ s)	11.43				
¹ Cyclic prefix is 1/8 of useful symbol time according to the mobile WiMAX profile.					

Table-3: WiMAX 802.16e Modulation Parameters [5]

Multiple Antenna Techniques

The Antenna technologies play a very important role in any radio transmission. Multiple antenna techniques intent to improve the signal robustness and increase the system capacity and user data rates by taking advantage of the spatial diversity of the radio channel. LTE and WiMAX use appropriate Multiple Antenna Techniques to provide signal robustness and improve its system performance. The figure below illustrates various antenna techniques from simplest to more complex.

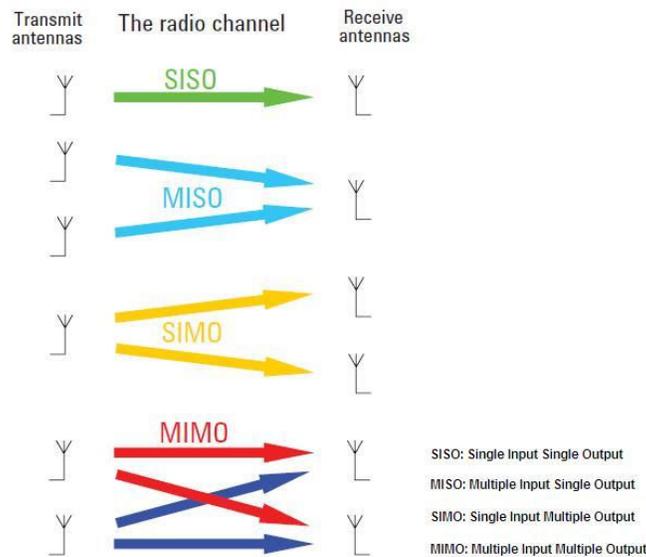


Figure-14: Antenna Techniques [2]

LTE

- **LTE Downlink**

For LTE downlink, three multiple antenna schemes are supported viz. Tx diversity (MISO), Rx diversity (SIMO) and Spatial Multiplexing (MIMO).

In the Tx diversity, the open-loop configuration is used while the more complex closed-loop Tx diversity is not supported. It supports either two or four antennas for Tx diversity.

The Rx diversity is mandatory for LTE User Equipment (UE) and forms the baseline receiver capability. By maximum ratio combining of received streams, the SNR (Signal-to-Noise-Ratio) is improved.

For the MIMO, LTE uses the two or four antenna configurations. A two channel UE receiver allows 2x2 or 4x2 MIMO, common being the 2x2 Single-User MIMO (SU-MIMO) for LTE. In SU-MIMO, the payload data is divided into two code word streams with each code-word being represented at different powers and phases on both antennas. It uses the closed-loop form of MIMO with pre-coding of streams where channel information is obtained from the UE on the uplink control channel.

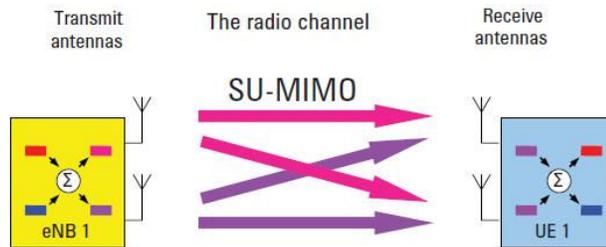


Figure-15: Single-User-Multiple Input Multiple Output in LTE [2]

In addition, a technique called cyclic delay diversity (CDD) is used which adds antenna-specific cyclic time shifts to artificially create multi-path on the received signal and prevent signal cancellation caused by the close spacing of transmit antennas.

- **LTE Uplink**

The LTE User Equipment (UE) uses only one transmitter in order to save cost and battery power. This configuration allows MU-MIMO (Multiple-User Multiple Input Multiple Output) in which two different UE transmit in the same frequency and time to the eNB. Under ideal conditions, this

configuration has the potential to double the uplink capacity without extra costs to UE.

In addition to the above configuration, a second transmit antenna can be used by the UE to allow uplink Tx diversity and SU-MIMO thus enabling higher data rates depending on channel conditions.

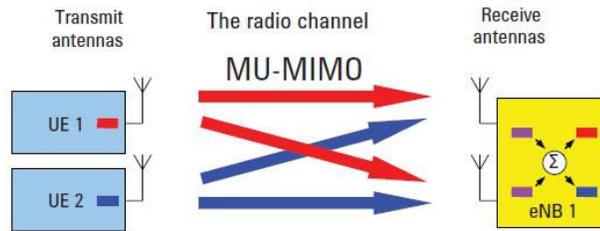


Figure-16: Multiple-User-Multiple Input Multiple Output in LTE [2]

For the eNB, Rx diversity is the baseline capability and LTE supports two or four receive antennas.

WiMAX

The WiMAX supports various Multiple Antenna System (MAS) technologies. WiMAX supports both open-loop MIMO as well as closed-loop MIMO. Open Loop MIMO includes Space-Time Block Coding (STBC or Matrix-A), open-loop Spatial Multiplexing (SM-MIMO or Matrix-B) and adaptive mode selection between the two. In closed-loop MIMO (Spatial Beamforming/Transmitter Adaptive Antenna), transmitter forms antenna beams adaptively based on the channel side information to enhance the system coverage and capacity.

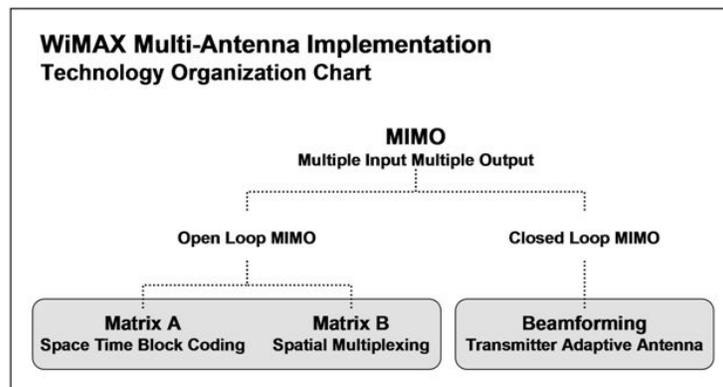


Figure-17: WiMAX Multi-Antenna Schemes [16]

- **WiMAX Downlink**

Both STBC and SM-MIMO are downlink open-loop MIMO schemes. The criterion to switch between Matrix-A (STBC) and Matrix-B (SM-MIMO) is based on which one gives high spectral efficiency. This task is called the Adaptive Mode Selection.

The STBC encoding is also known as the Alamouti scheme and transmits each symbol twice, once per antenna. WiMAX defines a number of space-time block coding schemes that can be used to provide transmit diversity in the downlink. For transmit diversity, there could be two or more transmit antennas and one or more receive antennas. The space-time block code (STBC) used for the 2 x 1 antenna case is the Alamouti codes, which are orthogonal and amenable to maximum likelihood detection. In addition to the 2 x 1 case, WiMAX also defines STBCs for the three- and four-antenna cases.

The Mobile WiMAX scheme SM-MIMO also known as Matrix-B supports two downlink data streams on the same frequency resource to one mobile receiver. It encodes a single stream of data and then splitting each pair of modulation symbols between the two antennas. It doubles the peak data rate and improves the system performance when the system is bandwidth limited.

Space-time coding cannot be used for the downlink common channel. In this case, the Cyclic Shift Transmit Diversity (CSTD) technology can be used to obtain diversity gains. CSTD technology allows different delayed copies of the same data stream to be transmitted through different antennas. Multi-path diversity is realized, and the common channel coverage is enlarged. For data channels, CSTD can be used in conjunction with Matrix A or Matrix B to further enhance diversity performance or diversity and multiplexing performance ^[6].

- **WiMAX Uplink**

Similar to SM-MIMO, WiMAX supports a scheme called uplink coordinated Space Division Multiple Access (SDMA) for uplink. In this scheme, an access point scheduler allows two uplink data streams on the same time frequency resource from two mobile transmitters. Using the receiver antenna array, the access point receiver separates the two data streams. SDMA too doubles the peak data rate and improves the system performance when the system is bandwidth limited.

The WiMAX Uplink also supports Collaborative Spatial Multiplexing (CSM) technology in which the terminals that correspond to two single transmission antennas are scheduled on the same time-frequency resources thus increasing

uplink capacity through multiplexing. The signal channels of different terminals are orthogonal to each other^[6].

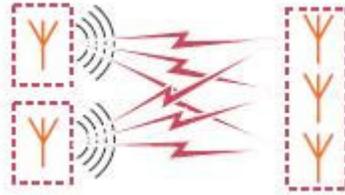


Figure-18: Collaborative spatial multiplexing

Spatial Beamforming (Closed-loop MIMO)

To further increase system coverage and capacity, WiMAX systems support beamforming by using Adaptive Antenna System (AAS). By using arrays of transmit and receive antennas, beamforming antennas control the directionality and shape of the radiation pattern. In the ‘MIMO domain’ closed-loop MIMO is beamforming of signal processed OFDM symbols or groups of symbols, so does not consider any geographical beam pattern, while in the ‘AAS domain’ beamforming is realized by directing the adaptive beams in space. The figure below depicts spatial beamforming.

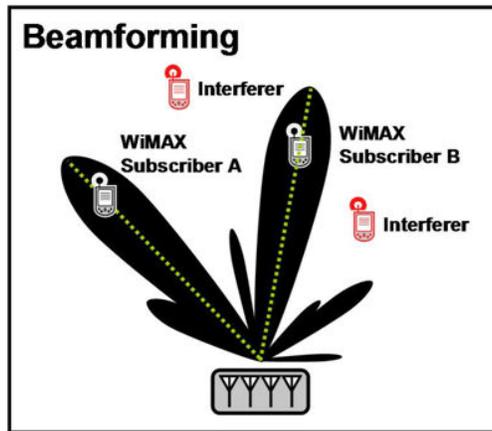


Figure-19: Spatial Beamforming in WiMAX [16]

There are two types of closed-loop MIMO or beamforming techniques. In the first, known as Maximum Ratio Transmission (MRT), an antenna beam is formed on each OFDM subcarrier. In the second scheme, called Statistical Eigen Beamforming (EBF) only one antenna beam is formed across multiple allocated subcarriers. These beamforming techniques are however optional features in the 802.16e WiMAX standard.

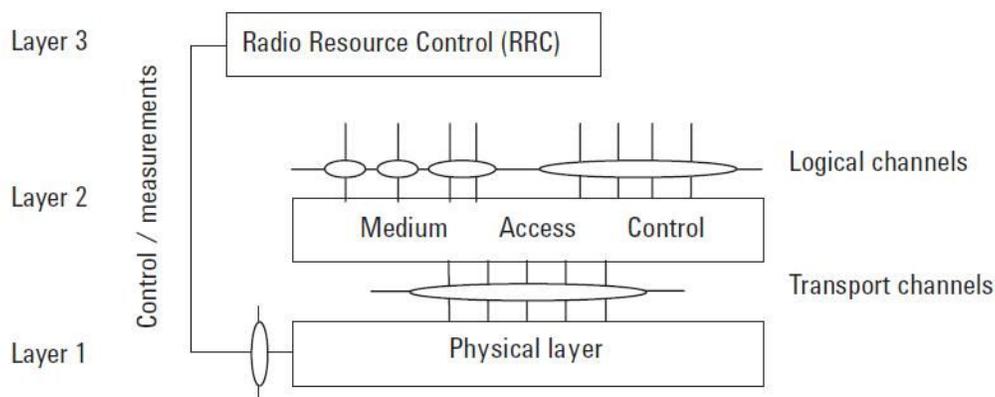
Air Interface Protocol Aspects

The Air Interface Protocol aspects detail the communication protocol layers and their functionalities defined in the 3GPP LTE and IEEE 802.16 WiMAX standards. A distinction based on protocol architecture, frame structure, physical channelization, modulation, channel coding and mapping, and various physical layer control mechanisms for each LTE and WiMAX is presented below.

Protocol Architecture

LTE

The figure below shows the radio interface protocol architecture defined for the LTE system.



Circles between different layers or sub-layers indicate Service Access Points (SAPs)

Figure-20: LTE Radio interface protocol architecture around the physical layer [2]

The LTE Physical Layer provides the data transport services to the higher layers which are accessed through the transport channels via the Layer 2 MAC sub-layer. The MAC layer provides the logical channels to the Layer 2 RLC (Radio Link Control) sub-layer. The Physical layer also has an interface with the Layer 3 RRC (Radio Resource Control) layer.

A detailed Protocol Stack for Control Plane and User Plane defined for LTE are depicted and illustrated below.

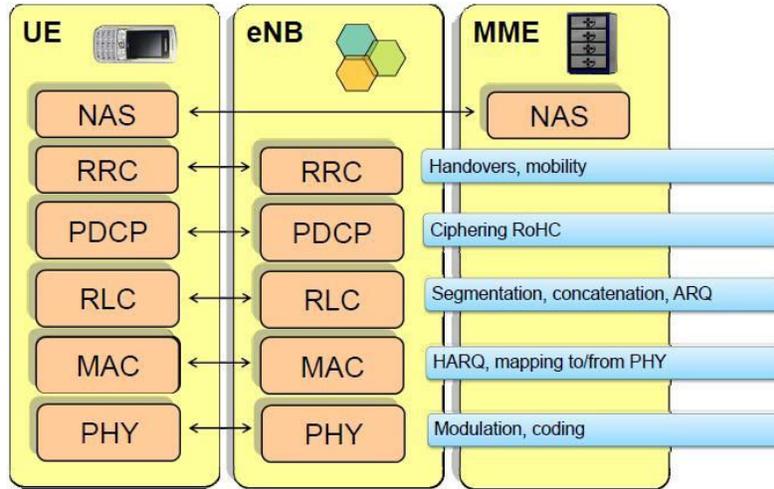


Figure-21: LTE Control Plane Protocol Stack [20]

The Physical layer is concerned with the modulation and encoding/decoding of the transport channels. The MAC layer handles the Hybrid Automatic Repeat Request (HARQ) and mapping functions. The RLC (Radio Link Control) layer provides segmentation, concatenation and ARQ services. In the control plane, the PDCP (Packet Data Convergence Protocol) performs ciphering and Integrity protection and transfer of control plane data between RRC and RLC layers. In the user plane it performs header compression and decompression, ciphering and transfer of user data between RRC and RLC layers. The RRC (Radio Resource control) layer handles the mobility and handover control tasks. The protocols of the Non-Access Stratum (NAS) in the control plane terminate in the wireless device and in the Mobility Management Entity (MME) of the core network.

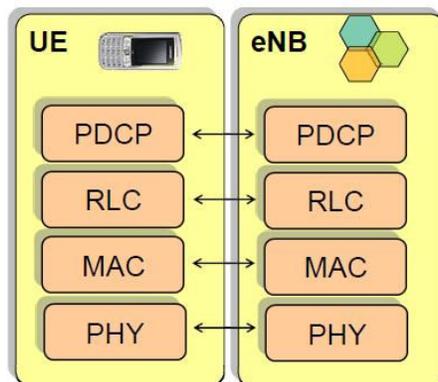


Figure-22: LTE User Plane Protocol Stack [20]

WiMAX

The WiMAX protocol structure defined in the IEEE 802.16e is shown in the figure below.

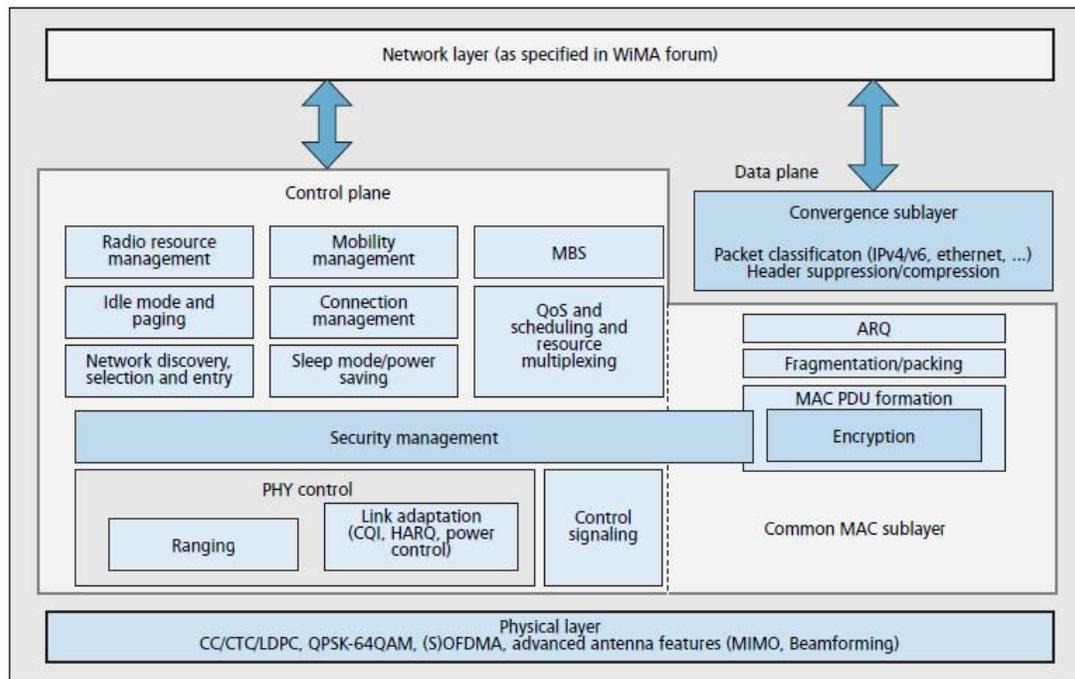


Figure-23: WiMAX MAC/PHY protocol structure in Control and Data Plane [1]

The protocol structure of WiMAX is built on a OFDMA-based physical layer and a MAC layer. The MAC layer is composed of two sub layers: MAC Common Part Sublayer (MAC CPS) and Convergence Sublayer (CS).

The CS multiplexes various types of network traffic into the MAC CPS. The functional blocks in CPS are logically classified into upper MAC and lower MAC functions. It may also be classified based on control plane and data plane functions. The upper MAC functional group includes protocol procedures related to radio resource control and mobility related functions such as:

- Network discovery, selection and entry
- Paging and idle mode management
- Radio resource management
- Layer 2 mobility management and handover
- QoS, scheduling, and connection management
- Multicast and Broadcast Services (MBS)

On the control plane, the lower MAC functional group perform sleep management, link control, resource allocation, multiplexing and provide layer 2 security [1].

The PHY control block in the MAC CPS handles physical signaling such as ranging, measurement/feedback using Channel Quality Indicator (CQI), HARQ acknowledgement (ACK), and negative ACK (NACK). The Control signaling block generates resource allocation messages [1].

On the data plane, the ARQ block handles the MAC ARQ function. The Fragmentation/packing block performs fragmentation or packing MSDUs (MAC Service Data Units) based on scheduling results from the scheduler block [1].

Frame Structure

The frame structures used in the LTE and WiMAX systems are presented in the comparison below.

LTE

LTE uses two radio frame structures: frame structure type 1 (FS1) for full duplex and half duplex FDD, and frame structure type 2 (FS2) for TDD. The FS1 frame structure is shown in figure below.

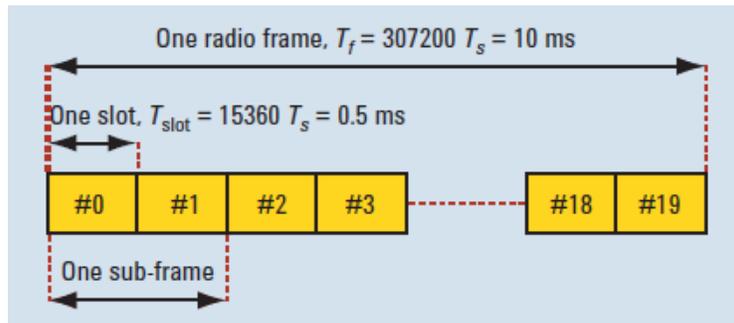


Figure-24: LTE FS1 frame structure [4]

FS1 is optimized to co-exist with the 3.84 Mbps UMTS systems. This structure consists of ten 1 ms sub-frames, each composed of two 0.5 ms slots, for a total duration of 10 ms. The FS1 is identical in the uplink and downlink in terms of frame, sub-frame, and slot duration however the allocation in terms of physical signals and channels is different. The uplink and downlink transmissions are separated in the frequency domain [2].

The FS2 has a more flexible structure than FS1. The FS2 frame structure is shown in the figure below.

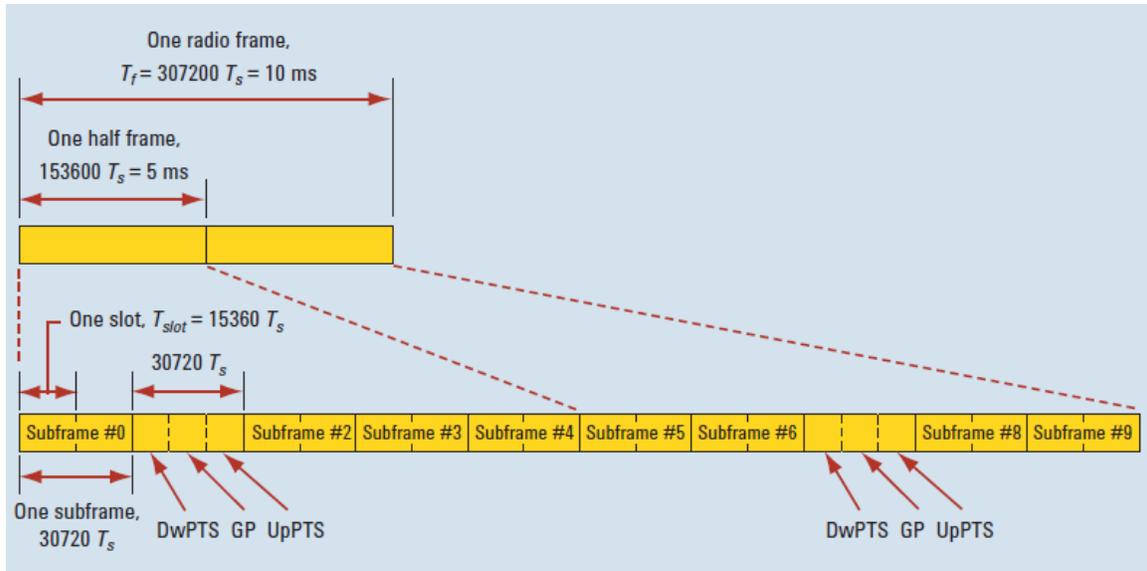


Figure-25: LTE FS2 frame structure for 5 ms Switch-point periodicity [4]

The example of FS2 above consists of two 5 ms half-frames for a total duration of 10 ms for a 5 ms switch-point periodicity. Sub-frames consist of either an uplink or downlink transmission, or a special sub-frame containing the downlink and uplink pilot timeslots (DwPTS and UpPTS) separated by a transmission gap (GP). The allocation of sub-frames for the uplink, downlink and special sub-frames is determined by one of the seven different configurations. Sub-frames 0 and 5 are always used for downlink transmissions, while sub-frame 1 is always a special sub-frame. The composition of other sub-frames varies based on the configuration.

WiMAX

The WiMAX 802.16e physical layer supports both TDD and FDD operation. The WiMAX IEEE 802.16e Release 1.0 includes only TDD profile while the FDD profile was added in Release 1.5.

The figure below shows the TDD frame structure used in WiMAX 802.16e Release 1.0.

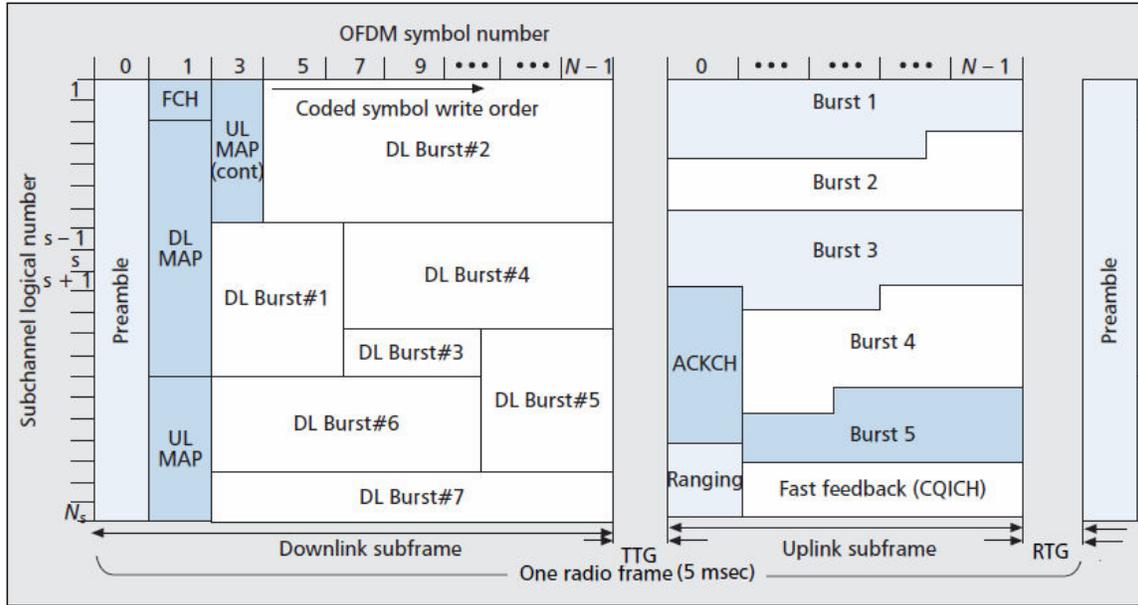


Figure-26: Mobile WiMAX frame structure and channelization for TDD system [5]

Each frame is configured to be 5 ms long and is time-division duplexed into downlink (DL) and uplink (UL) sub-frames. To avoid interference between downlink and uplink signals, they are separated by small time gaps called Transmit Time Gap (TTG) for the transition from downlink sub-frame to uplink sub-frame and Receive Time Gap (RTG) for the transition from uplink sub-frame to downlink sub-frame.

At the beginning of each frame, downlink control information is transmitted and has a preamble, a Frame Control Header (FCH) and a Media Access Protocol (MAP) message. The physical channels defined in the WiMAX frame and their functionalities are detailed below:

- **Preamble**
It is broadcast in the first OFDM multiplexed symbol of the frame in DL and used by the MS for BS identification, timing synchronization and channel estimation. There are no preambles in the UL except for systems using AAS.
- **Frame Control Header (FCH)**
It follows the preamble and provides the frame configuration information, such as MAP message length and coding scheme and usable sub-channels.
- **DL-MAP and UL-MAP**
The DL-MAP and UL-MAP provide resource allocation and other control information for the DL and UL sub-frames, respectively. To reduce the MAP overhead, the system supports multicast sub-MAPs that can carry traffic

allocation messages at higher Modulation and coding Scheme (MCS) levels for users closer to the BS and with higher CINR conditions. Each MAP message includes several information elements (IEs), and has a fixed part and a variable part. The size of variable part is proportional to the number of downlink and uplink users scheduled in that frame. The MAP contains the information such as 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, the number of sub-channels, number of symbols, power level, and repetition coding^[3].

- **UL Ranging**
The UL ranging sub-channel is allocated for an MS to perform closed-loop time, frequency and power adjustment, and bandwidth requests.
- **UL CQICH (Uplink Channel Quality Indicator Channel)**
The UL CQICH is allocated for the MS to provide feedback of channel state information.
- **UL ACK (Uplink Acknowledgement)**
The UL ACK is allocated for the MS to feedback DL HARQ ACKs.

Physical Channelization and Mapping

The physical signals and physical channels are appropriately mapped on to the frame structure for uplink and downlink transmission. The physical signals are generated in the Layer 1 and used for system synchronization, cell identification and radio channel estimation. Physical channels provide a means of carrying data from higher layers including control, scheduling and user payload. The channels and mapping details of LTE and WiMAX are discussed below.

LTE

The Physical signals defined in the LTE system for DL and UL are listed below:

DL Signals	Full name	Function
P-SCH	Primary Synchronization signal	Used for cell search and identification by UE. Carries part of cell ID (One of three orthogonal sequences)

S-SCH	Secondary Synchronization signal	Used for cell search and identification by UE. Carries remainder of Cell ID (one of 168 binary sequences)
RS	Reference Signal (Pilot)	Used for DL channel estimation. Exact sequence derived from cell ID (One of 3 x 168 = 504 pseudo random sequences)
UL Signals	Full name	Function
RS	Reference signal (Demodulation and sounding)	Used for synchronization to the UE and UL channel estimation

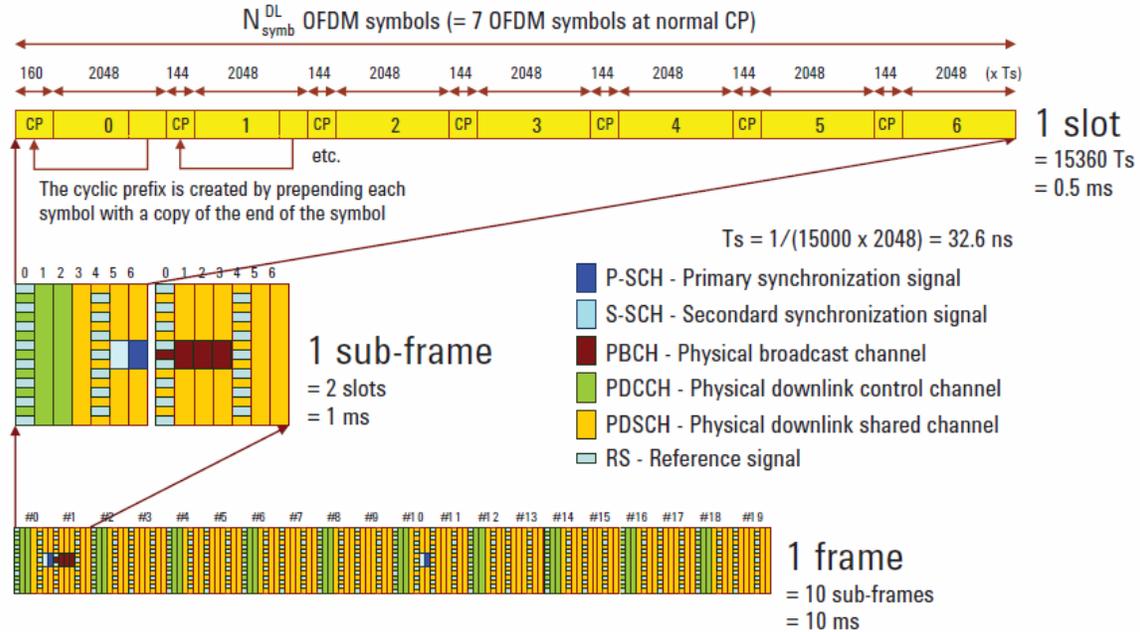
Table-4: LTE Uplink and Downlink Physical Signals

The LTE physical channels which carry the user and system information are listed in the table below. The LTE has no dedicated channels which is a characteristic of a packet-only system and is a deviation from the earlier circuit switched supporting systems.

DL Channels	Full name	Function
PBCH	Physical broadcast channel	Carries cell-specific information
PMCH	Physical multicast channel	Carries the MCH transport channel
PDCCH	Physical downlink control channel	Scheduling, ACK/NACK
PDSCH	Physical downlink shared channel	Payload
PCFICH	Physical control format indicator channel	Defines number of PDCCH OFDMA symbols per sub-frame (1, 2, or 3)
PHICH	Physical hybrid ARQ indicator channel	Carries HARQ ACK/NACK
DL Channels	Full name	Function
PRACH	Physical random access channel	Call setup
PUCCH	Physical uplink control channel	Scheduling, ACK/NACK
PUSCH	Physical uplink shared channel	Payload

Table-5: LTE Uplink and Downlink Physical Channels

These signals and channels are mapped on to the downlink and uplink frame structures for transmission. The mapping of physical signals and channels on to the FS1 frame structure for downlink is detailed in the figure below.



PMCH, PCFICH, PHICH not shown.

Figure-27: FS1 frame mapping for downlink [2]

The frame structure is defined in units of T_s , which is the shortest time interval of the system defined as $1/(15000 \times 2048)$ seconds or 32.552 ns. The physical mapping of the downlink physical signals and channels depicted in the above figure is as follows:

- Reference Signal (RS) pilot are transmitted at OFDMA symbol 0 of the first subcarrier and symbol 4 of the fourth subcarrier of each slot and its position varies with the antenna port number and CP length.
- P-SCH is transmitted on symbol 6 of slots 0 and 10 of each radio frame. It occupies 62 subcarriers centered around the DC subcarrier.
- S-SCH is transmitted on symbol 5 of slots 0 and 10 of each radio frame. It occupies 62 subcarriers centered around the DC subcarrier.
- PBCH is transmitted on symbols 0 to 3 of slot 1. It occupies 72 subcarriers centered around the DC subcarrier [2].

Similar to the downlink is the uplink frame mapping for FS1 in terms of frame, slot and sub-frame length. The mapping of PUSCH and PUCCH uplink channels on to the FS1 frame structure for uplink are depicted in the figures below.

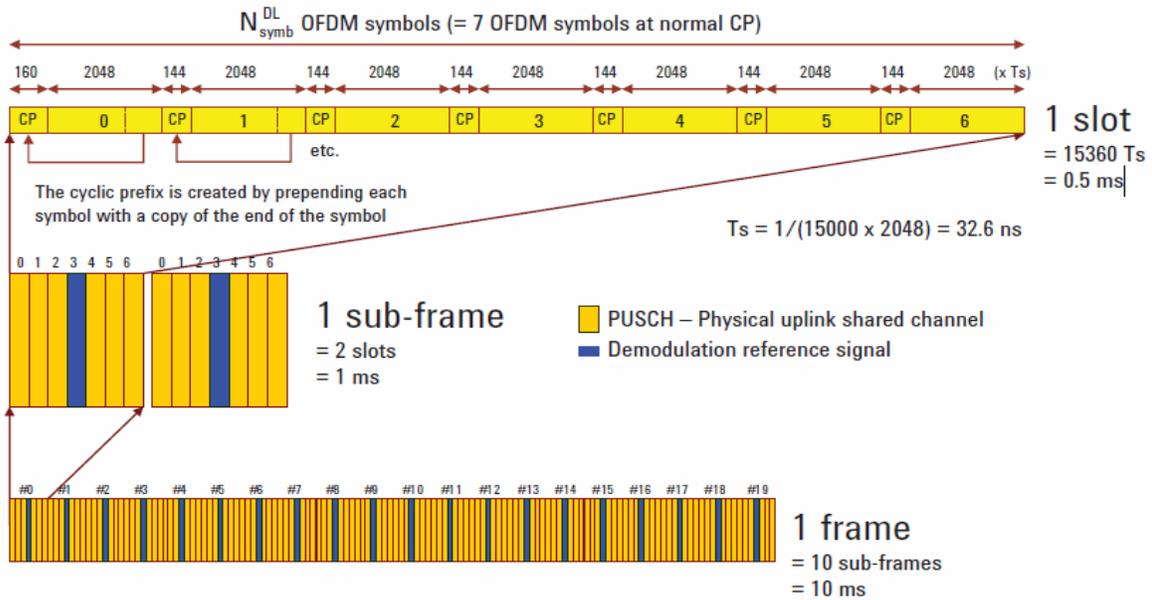


Figure-28: FS1 frame mapping for uplink for PUSCH [2]

The reference signals (RS) for demodulation are transmitted in the fourth symbol of the slot on all subcarriers of allocated PUSCH resource blocks to enable the eNB to demodulate the signal by uplink channel estimation.

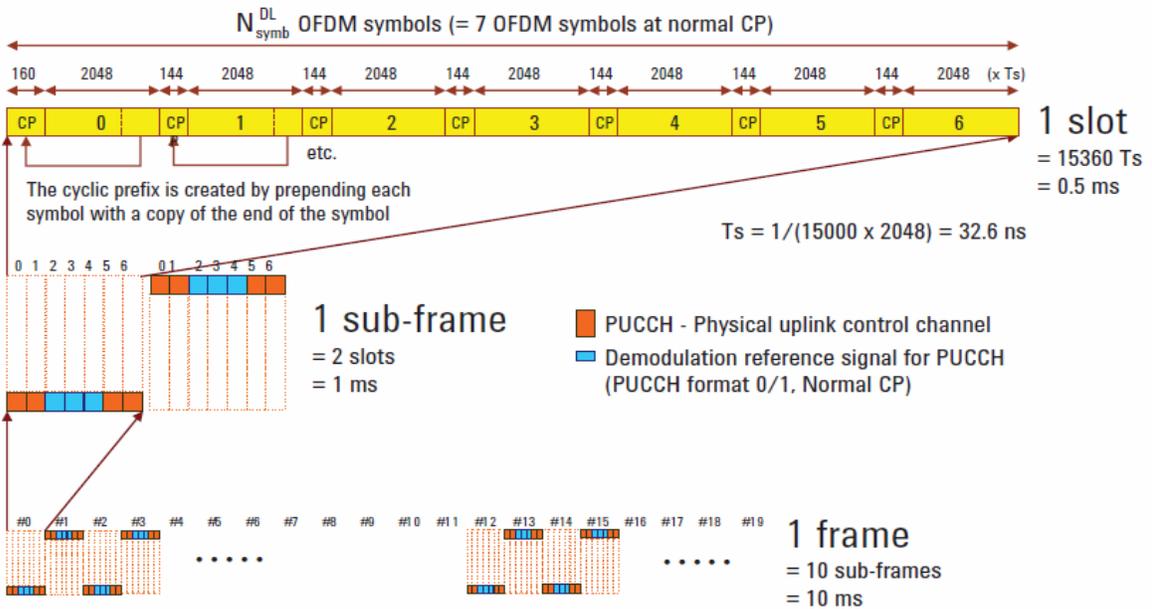


Figure-29: FS1 frame mapping for uplink for PUCCH format 0 or 1 [2]

The number of symbols in a slot depends on the CP length. There are 7 SC-FDMA symbols per slot for a normal CP while for an extended CP there are 6 SC-FDMA

symbols per slot. When no PUCCH or PUSCH is scheduled in the uplink, the eNB can request transmission of the sounding reference signal (SRS) for uplink channel estimation.

The physical channels mapped on to the frame structure for transmission requires to be transported between the physical, MAC and higher layers. For this purpose corresponding traffic and control channels are defined. The list below shows the downlink and uplink traffic and control channels and their respective mappings to the physical channels.

Downlink

TrCH (Traffic Channel)	Full name	Physical channel mapping
DL-SCH	Downlink Shared Channel	PDSCH
BCH	Broadcast Channel	PBCH
PCH	Paging Channel	PDSCH
MCH	Multicast Channel	PMCH
Control Information		
CFI	Control Format Indicator	PCFICH
HI	HARQ Indicator	PHICH
DCI	Downlink Control Indicator	PDCCH

Uplink

TrCH (Traffic Channel)	Full name	Physical channel mapping
UL-SCH	Uplink Shared Channel	PUSCH
RACH	Random Access Channel	PRACH
Control Information		
UCI	Uplink Control Information	PUCCH

Table-6: Physical channel mapping to Traffic channels and Control Information

WiMAX

In WiMAX, the data to be transmitted is mapped to physical subcarriers in two steps:

For the first step, data is mapped to one or more logical sub-channels called slots. This is controlled by the scheduler. A slot is a basic unit of allocation in the frequency-time grid. It is 1 sub-channel in frequency by 1, 2, or 3 symbols in time. The slots may

be further grouped and assigned to segments based on the application and can be used by the BS for different sectors in a cellular network.

For the second step, the logical sub-channels are mapped to physical subcarriers. The physical data and pilot subcarriers are uniquely assigned based on the type of sub-channelization used. Sub-channelization is an advanced form of FDMA in which multiple subcarriers are grouped into sub-channels to improve system performance. These sub-channels are formed by two types of subcarrier allocations:

- **Distributed allocation**
This allocation pseudo-randomly distributes the subcarriers over the available bandwidth thus providing frequency diversity in frequency selective fading channels and inter-cell interference averaging.
- **Adjacent allocation**
This allocation groups subcarriers adjacent to each other in the frequency domain. It is useful for frequency nonselective and slowly fading channels, implementing Adaptive Modulation and Coding (AMC), and assignment of the sub-channel with the best frequency response to the user.

Contiguous symbols that use specific type of sub-channel assignment are called permutation zones, or zones. There are seven zone types: FUSC, OFUSC, PUSC, OPUSC, AMC, TUSC₁, and TUSC₂ each of which is described in detail ahead. A single frame may contain one or more zones. The DL sub-frame requires at least one zone and it always starts with PUSC. The exact number of zones used in the frame depends on the network conditions. Antenna techniques such as Matrix-A and Matrix-B can be used for the PUSC and AMC zones. The zone types used for downlink and uplink are as follows:

- **Downlink Partial Usage of Sub-channels (DL PUSC)**
This zone marks the start of all DL frames following the preamble. In this zone, pairs of pilots swap positions on alternate symbols, averaging one in seven of the subcarriers. Dedicated pilots are only transmitted when corresponding data is available. Subcarriers are grouped into clusters of 14 contiguous subcarriers per symbol. A group of two clusters forms a sub-channel and one sub-channel over two OFDM symbols forms a slot. The sub-channels in a DL PUSC zone can also be mapped into larger groups called segments and up to three segments can be created from the larger groupings. The first PUSC zone is always SISO while further PUSC zones can be specified for MIMO.

- **Uplink Partial Usage of Sub-channels (UL PUSC)**
In this zone, four contiguous subcarriers are grouped over three symbols to form a tile. Six tiles form a sub-channel, and one sub-channel over three symbols forms a slot. Over the duration of one tile, one in three subcarriers is a pilot with its position changing with each symbol.
- **Adaptive Modulation and Coding (AMC)**
The structure of this zone is same for DL and UL and has a slightly wider bandwidth than the PUSC and FUSC. A contiguous block of subcarriers form a sub-channel. A slot is one sub-channel wide in logical frequency allocation and its length changes according to the zone. The position of the pilots in the DL changes in a rotating pattern that repeats every fourth symbol.
- **Downlink Full Usage of Sub-channels (DL FUSC)**
This zone uses all subcarriers thus providing a high degree of frequency diversity. The subcarriers are divided into 48 groups of 16 subcarriers. A sub-channel is formed by taking one subcarrier from each group. One sub-channel over one OFDMA symbol forms a slot. The pilots are regularly distributed with their position alternating with each symbol^[3].
- **Downlink Optional FUSC (DL OFUSC)**
This zone is a slight variation of FUSC where pilot subcarriers are evenly spaced by eight data subcarriers^[3].
- **Uplink Optional PUSC (UL OPUSC)**
This zone is same as UL PUSC except that it uses a tile size that is three subcarriers wide by three symbols long^[3].
- **Tile Usage of Sub-channels (TUSC₁ and TUSC₂)**
These optional zones are only available in the DL using AAS. They are similar to DL PUSC and OPUSC but use a different equation for assigning the subcarriers within the sub-channel. With the exception of the DL PUSC, which is assigned after the DL preamble, all other zones can be assigned in any order within the frame. The DL MAP provides the switching points between zone types.

The Figure below shows an OFDMA frame mapping with the various zones.

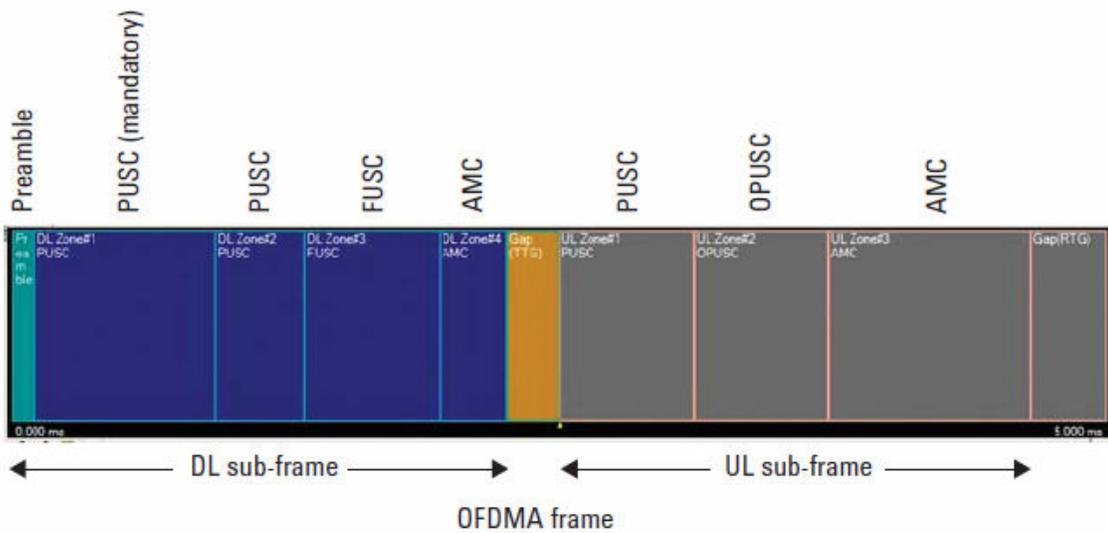


Figure-30: Zone mapping on WiMAX OFDMA frame [3]

As shown in the figure, the DL PUSC zone follows the preamble and is the only mandatory zone in the frame. The DL sub-frame also shows a second PUSC zone, a FUSC zone, and an AMC zone. The UL sub-frame follows the TTG and contains a PUSC, OPUSC, and AMC [3].

Modulation

Various Modulation schemes are deployed in LTE and WiMAX on the downlink and uplink signals and physical channels.

LTE

On the downlink, the channels PBCH, PDCCH, PCFICH use QPSK modulation. Channel PDSCH and PMCH use QPSK, 16QAM, or 64QAM. The PHICH uses BPSK modulated on I and Q with spreading factor of 2 or 4 Walsh codes.

The downlink physical signal RS use a complex (I+jQ) pseudo random sequence (length-31 Gold sequence) for modulation which is derived from the cell ID. The physical signal P-SCH use one of three Zadoff-Chu sequences while the physical signal S-SCH uses Two 31-bit BPSK M-sequence for modulation.

On the uplink, the physical channel PUCCH use BPSK or QPSK for modulation. The PUSCH use QPSK, 16QAM, or 64 QAM while the physical channel PRACH uses u^{th} root Zadoff-Chu for modulation.

The uplink physical signal 'Demodulation RS' use Zadoff-Chu for modulation while 'Sounding RS' use another modulation scheme based on Zadoff-Chu.

WiMAX

The data can be modulated using one of the three modulation types: QPSK, 16QAM, or 64QAM. In the uplink, the 64QAM is not mandatory. The BPSK modulation scheme is used for the preamble, pilots, and for modulating subcarriers in the ranging channel.

The FCH uses a robust QPSK rate $\frac{1}{2}$ modulation with four data repetitions. The bursts also use QPSK $\frac{1}{2}$ dummy symbols per need.

Physical Layer Control Mechanisms

Several physical layer control procedures are associated with LTE and WiMAX which are specified in each of the standards.

LTE

LTE uses Adaptive Modulation and Coding (AMC) as a mechanism for link adaptation to improve data throughput in a fading channel.

Cell search is used by UE to acquire time and frequency synchronization with a cell and detect its cell ID.

Power control is used for uplink power control and downlink power allocation. It determines the energy per resource element (EPRE). For the uplink, upwards of nine parameters cover the PUSCH, PUCCH, and SRS. Special procedures are also used for allocation of RB to UE at cell edges.

Random access procedures are used for transmission of random access preamble (carried on the PRACH) and random access response. There are also procedures related to PDSCH, PUSCH, PDCCH and PUCCH.

To achieve seamless mobility within the LTE network, LTE specifies intra-LTE handover which is a network controlled handover scheme. In this scheme, the decision to handover is taken by the source eNB.

The Radio Resource Management (RRM) in LTE covers the procedures and performance requirements that are used to make effective use of the radio resources.

Initial cell selection and cell reselection procedures between various Radio Access Technologies (RAT), handover and measurement performance are some of the RRM requirements for LTE.

WiMAX

WiMAX control procedures include ranging, fast feedback and Hybrid Automatic Repeat Request.

Ranging is used for several functions such as bandwidth requests, timing and power control, periodic maintenance, and handover.

Fast feedback slots are used by the MSs when the BS urgently requires information from the MS. A part of the beginning of UL sub-frame is allocated for this function. Information such as CINR, MIMO, antenna, and spatial multiplexing can use this channel.

The HARQ is used by the receiver to provide acknowledgement on successfully receiving data or notifying missing blocks of data. It combines the previous and retransmitted data to gain time diversity. With HARQ, Mobile WiMAX can deliver high performance with speeds in excess of 120 Km/h.

For seamless mobility within the WiMAX network, the Mobile WiMAX profile specifies hard and soft handover techniques, by means of which a MS can switch the user to another BS in order to improve its QoS. Hard handover uses a break-before-make approach while Soft handover uses a make-before-break approach. In soft handover, the connection to next BS is established before the user leaves an ongoing connection to a BS. This technique is suitable to handle low latency voice services. For data traffic (e.g. web browsing, e-mail), hard handover is used as soft handover results in lower spectral efficiency due to the bursty nature of the traffic which does not require continuous handover.

Radio Resource Management (RRM) in WiMAX is used to manage radio resources in the air interface. RRM is supported between the RRA (Radio Resource Agent) and RRC (Radio Resource Controller), located in the Base Station and ASN Gateway respectively.

Quality of Service (QoS)

LTE supports "End-to-End" QoS, meaning that bearer characteristics are defined and controlled throughout the duration of a session between the mobile device (UE) and the P-GW. QoS is characterized by an index, QCI (QoS Class Identifier), and the parameter ARP (Allocation and Retention Priority). Bearer types belong to two main classes with guaranteed and non-guaranteed rates and LABELs specify in more detail what values of packet delay and loss can be tolerated for any given bearer ^[7].

The WiMAX MAC layer has a connection-oriented architecture that is designed to support a variety of applications, including voice and multimedia services. WiMAX supports five types of QoS: UGS (Unsolicited Grant Service), rtPS (Real time polling Service), ertPS (Extended Real-time Polling Service), nrtPS (Non-real-time Polling Service) and BE (Best effort service). The Unsolicited Grant Service (UGS) is designed to support real-time service flows that generate fixed-size data packets on a periodic basis, such as T1/E1 and Voice over IP without silence suppression. WiMAX MAC is designed to support a large number of users, with multiple connections per terminal, each with its own QoS requirement ^[8].

Security

LTE specifies a new layering of security and the enforcement of a clearer separation of control plane security and user plane security providing strong security features. LTE has support for UEA1, UIA1, UEA2 (SNOW algorithm supporting 256 bits of keys) and UIA2. Signaling at UPE and MME relocation allows the transfer of algorithm information to target UPE, MME and UE ^[9].

WiMAX supports strong encryption, using Advanced Encryption Standard (AES), and has a robust privacy and key-management protocol. It supports Privacy and Key Management - PKMv1 RSA, HMAC, AES-CCM and PKMv2 – EAP, CMAC, AES-CTR, MBS Security. The AES and the 3DES are mandatory features and new high-performance coding schemes, such as TC and Low Density Parity Check (LDPC) are included. The system also offers very flexible authentication architecture based on Extensible Authentication Protocol (EAP), which allows for a variety of user credentials, including username/password, digital certificates, and smart cards ^[8].

Comparison Summary

The key highlights of the comparison between the two next generation broadband wireless access technologies: 3GPP LTE and WiMAX IEEE 802.16e is presented in the table below.

Aspect	3GPP-LTE	Mobile WiMAX (IEEE 802.16e)
Legacy	GSM/GPRS/EDGE/UMTS/HSPA	IEEE 802.16 a through d
Core Network	UTRAN moving towards All-IP Evolved-UTRA (E-UTRA) core network with IMS with SAE Architecture	WiMAX forum All-IP network
Access technology: Download (DL) Uplink (UL)	OFDMA SC-FDMA	OFDMA OFDMA
FFT Sizes	64, 128, 256, 512, 1024, 2048	128, 256, 512, 1024, 2048
Radio Access Modes	TDD and FDD	TDD and FDD
Frequency Band	Existing (800, 900, 1800, 1900 MHz) and new frequency bands (Range 800 MHz – 2.62 GHz)	NLOS: 2-11 GHz
Peak Data rate: DL UL	100 to 326.4Mbps 50 to 86.4 Mbps	75 Mbps 25 Mbps
Channel bandwidth	Scalable from 1.25 to 20 MHz with system profiles 1.25, 1.4, 2.5, 3, 5, 10, 15, and 20 MHz	Scalable from 1.25 to 20 MHz with system profiles 1.25, 2.5, 5, 10, 20 MHz
Cell radius	5 Km	~20.7 km for 3.5 or 7MHz BW ~8.4 km for 5 or 10 MHz BW
Cell Capacity	>200 users @ 5MHz >400 users for larger BW	100-200 users
Mobility: Speed Handover	Up to 350 Km/h Inter-cell soft handovers supported	Up to 120 Km/h Optimized hard handovers supported
Antenna Scheme: Downlink Uplink No. of code words	MIMO 2Tx X 2Rx 2Tx X 2Rx 2	MIMO 2Tx X 2Rx 1Tx X NRx (Collaborative) 1

Aspect	3GPP-LTE	Mobile WiMAX (IEEE 802.16e)
Roaming	New	Auto through existing GSM/UMTS
Security Algorithms	UEA1, UIA1, UEA2 (SNOW algorithm supporting 256 bits of keys) and UIA2	PKMv1 RSA, HMAC, AES-CCM and PKMv2 – EAP, CMAC, AES-CTR, MBS security

Table-7: Highlights of LTE and WiMAX comparison

Market Analysis and challenges

The demand for higher data rates for broadband mobile access has been increasing in the recent years with more and more bandwidth hogging applications being developed and operators desiring to bundle and deliver voice, video and data services on mobile platform. For the telecommunication service providers worldwide, the most pressing issue at hand is to decide which next-generation technology to deploy to satisfy these demands. The leading contenders for the 4G broadband wireless access technology are the 3GPP Long Term Evolution (LTE) and the Mobile WiMAX IEEE 802.16m with both moving strongly to fulfill the bandwidth and mobility demand.

Currently, the IEEE 802.16d (fixed) and 802.16e (mobile) WiMAX technology has reached various markets throughout the world with trials and commercial deployments while the WiMAX 802.16m and 3GPP LTE are currently in the development and testing stages. The LTE is aggressively evolving from its 3GPP predecessors UMTS /HSPA networks. The Mobile WiMAX being deployed throughout the world is aimed to provide low-cost service models with an All-IP Internet friendly architecture and multivendor plug and play support. The technology utilizes advanced radio techniques to provide high spectrum efficiency and QoS features. The LTE development is progressing in conjunction with the development of 3GPP SAE (System Architecture Evolution) architecture for an All-IP network. Some of the challenges in product development of WiMAX and LTE include design of UE to support high data rates using multiple antenna techniques. Also the successful implementation of new modulation scheme SC-FDMA for LTE is one of the challenges for optimized LTE system development. Also, challenges in seamless integration of LTE and WiMAX with each other as well as with the legacy and other access technologies are being addressed and configurations for handover between them are being defined and developed. Critical parts of transmit and receive chain are systematically designed and developed to solve impairments such as non-linearities and effective noise figure in an RF up-converter or down-converter, phase and amplitude distortion from power amplifier, channel impairments such as multi-path and fading, and impairments associated with the fixed bit-width of baseband hardware. The number of simultaneous frequency bands the system supports adds to the overall complexity of the system design. In Addition, time-to-market goals and system performance are key to the success of LTE and WiMAX products. For WiMAX, the WiMAX Forum assists the certification and standardization of the WiMAX products and introduces Releases which include mandatory IEEE features and optional features required for enhanced mobility QoS et al.

Although the LTE is still in development, it has won support of three large mobile operators worldwide, including Vodafone, Verizon, and AT&T. On the other hand

Intel has been a main force behind WiMAX which has also won support of various CPE (Customer Premises Equipment) and data card manufacturers and plans large incorporation with the existing PC products^[10].

As regards to market availability, the WiMAX service is already rolled out, and US Sprint has launched its Xohm WiMAX service by end of September 2008, whereas the LTE is currently in the development phase and earliest LTE-related service will not be available until the end of 2010. This is an advantage for WiMAX with respect to accumulation of customer base and coverage with more compatible UE being seen at the dawn and existing 3G cellular services failing to provide high speed broadband mobile Internet services.

For existing non-3GPP DSL and cable operators WiMAX seems to be the effective solution to provide broadband wireless mobile access to the users by deploying a green field network, whereas for existing 3GPP cellular service providers LTE may be a choice of convenience. This may however change with WiMAX evolving rapidly to integrate itself seamlessly with existing 3GPP networks and IMS. Thus, both LTE and WiMAX expect to co-exist and major telecom vendors have already invested resources in both technologies.

Except for Ericsson which has concentrated on LTE since the very start, other major vendors have invested considerable R&D manpower in the development of WiMAX equipment^[10]. Samsung and Motorola's WiMAX devices are among the first of the 2.5 GHz certified products and expect to benefit the Sprint and Clearwire's WiMAX deployment in the United States^[10]. Companies enrolled in LTE initiative include Alcatel-Lucent, Ericsson, Orange, NXP, Samsung, Nokia, Nokia Siemens Networks, Qualcomm, Nortel, T-Mobile, Vodafone, ZTE, Agilent, China Mobile, Huawei, LG Electronics, Motorola, NTT DoCoMo, Rohde & Schwarz, Singalio, Telecom Italia, and Telefonica^[10].

The equipment vendors supporting LTE have accelerated the development of LTE technology, and the WiMAX 802.16m group is also aggressively working to satisfy 4G requirements with seamless integration with 3GPP and non-3GPP networks. It is therefore evident that the competition between WiMAX and LTE is very ripe and the market is ready to accept both technologies for their next-generation deployment.

Conclusion

The increasing demand for high speed broadband wireless access supporting high data rate delivering capabilities for triple play (Voice, video, data) with mobility has created an interest in the telecom circles to formulate new technologies and architectures to offer such services at low cost and high efficiency to the operators and end users.

With the ITU defining the requirements for 4G under the 'IMT Advanced' tag, two technologies viz. WiMAX and 3GPP Long Term Evolution (LTE) are the major contenders for attaining the '4G' crown. The comparative study revealed that LTE and WiMAX are technically very alike providing similar access technologies, radio access modes, FFT sizes, channel bandwidth, cell radius, antenna configurations, QoS, and mobility in an All-IP network. However, in terms of market perspective, the two technologies differ in terms of legacy and time-to-market. WiMAX deployments have already begun throughout the world while LTE is still in the development phase. Efforts are being made in the telecom circles to provide seamless integration, roaming and mobility among these two technologies and also with their legacy and non-3GPP WiFi and other wireless access technologies.

New service providers, cable operators and non-3GPP DSL service providers wishing to instantly deliver their customers with a mobile broadband access may select Mobile WiMAX as their broadband wireless access system. On the other hand, the existing 3GPP UMTS/HSPA cellular service providers may use LTE as a convenient and natural way to upgrade their systems to the 4G standard. For the GSM/EDGE and cdma2000 cellular service providers, either WiMAX or LTE route can be employed to upgrade their technology while providing support for their legacy systems. As both the WiMAX and LTE Systems have similar technical profiles, the choice of the next-generation technology will more depend on the timeline benefit of the technology and the legacy platform of the service provider.

Acronyms

2G – Second Generation
3DES - Triple Data Encryption Standard
3G – Third Generation
3GPP – Third Generation Partnership Project
3GPP2 - Third Generation Partnership Project 2
4G – Fourth Generation
AAA – Authentication Authorization and Accounting
AAS – Adaptive Antenna System
ACGW - Access Control GateWay
ACK - Acknowledgement
AES - Advanced Encryption Standard
AES-CTR - Advanced Encryption Standard - Counter
AF - Assured Forwarding
AMC – Adaptive Modulation and Coding
AND-SF – Access Network Discovery And Selection Function
ARP – Allocation and Retention Priority
ARQ – Automatic Repeat Request
AS – Access System
ASN - Access Service Network
ASN-GW - Access Service Network Gateway
AuC – Authentication Center
BBERF – Bearer Binding and Event Reporting Function
BCH – Broadcast Channel
BE - Best Effort service
BM-SC - Broadcast/Multicast Service Centre
BPSK – Binary Phase Shift Keying
BS – Base Station
CC – Convolutional coding
CCM - Counter mode, Cipher block chaining, Message authentication code
CDD – Cyclic Delay Diversity
CDF - Charging Data Function
CDMA - Code Division Multiple Access
CFI – Control format Indicator
CGF - Charging Gateway Function
CINR – Carrier to Interference Noise Ratio
CMAC - Cipher-based Message Authentication Code
CP – Cyclic Prefix
CPE – Customer Premises Equipment
CPS - Common Part Sublayer
CQI – Channel Quality Indicator

CQICH – Channel Quality Indicator Channel
CS – Convergence Sublayer
CSCF - Call Session Control Function
CSM – Collaborative Spatial Multiplexing
CSN – Connectivity Service Network
CSTD – Cyclic Shift Transmit Diversity
CTC – Convolutional Turbo Coding
DC - Direct Current
DCI – Downlink Control Indicator
DHCP - Dynamic Host Configuration Protocol
DL - Downlink
DL – Downlink Media Access Protocol
DL-SCH – Downlink Shared Channel
DSL – Digital Subscriber Line
DwPTS - Downlink Pilot Time Slots
e2e – End-to-End
EAP – Extensible Authentication Protocol
EBF – Eigen Beam Forming
EDGE – Enhanced Data Rate for GSM Evolution
EIR - Equipment Identity Register
eMBMS – Evolved Multimedia Broadcast Multicast System
eNB – Evolved Node-B
EPC – Evolved Packet Core
EPRE – Energy per Resource Element
ertPS - Extended Real-time Polling Service
E-UTRA - Evolved Universal Terrestrial Radio Access
E-UTRAN – Evolved Universal Terrestrial Radio Access Network
EV-DO – Evolution Data Optimized
FAF – Forward Authentication Function
FCH – Frame Control Header
FDD – Frequency Division Duplexing
FFT - Fast Fourier Transform
FS1 – Frame Structure Type 1
FS2 - Frame Structure Type 2
FUSC – Full Usage of Sub-Channels
GERAN - GSM EDGE Radio Access Network
GGSN - Gateway GPRS Support Node
GP – Transmission Gap
GPRS - General Packet Radio Service
GRE - Generic Route Encapsulation
GSM - Global System for Mobile communications
GSN - GPRS Support Node

GTP - GPRS Tunneling Protocol
HA – Home Agent
HARQ – Hybrid Automatic Repeat Request
HI – Hybrid Automatic Repeat Request Indicator
HLR – Home Location Register
HMAC - Hash Message Authentication Code
H-NSP – Home Network Access Provider
HSDPA - High-Speed Downlink Packet Access
HSPA - High Speed Packet Access
HSS - Home Subscriber Server
IASA – Inter-Access System Anchor
IE – Information Element
IEEE - Institute of Electrical and Electronics Engineers
IETF - Internet Engineering Task Force
IFFT – Inverse Fast Fourier Transform
IMS - IP Multimedia Subsystem
IMS-MGW - IP Multimedia Subsystem Media Gateway
IMT - International Mobile Telecommunications
IP – Internet Protocol
IPV4 – Internet Protocol Version 4
IPV6 - Internet Protocol Version 6
ITU – International Telecommunication Union
L1 – Layer 1
L2 – Layer 2
L3 – Layer 3
LAN – Local Area Network
LDPC - Low-Density Parity-Check
LOS – Line of Sight
LTE – Long Term Evolution
MAC – Media Access Control
MAG – Mobility Access Gateway
MAN – Metropolitan Area Network
MAP – Media Access Protocol
MAS – Multiple Antenna System
MBS - Multicast Broadcast Services
MC-CDMA - Multi Carrier Code Division Multiple Access
MCH – Multicast Channel
MIMO – Multiple Input Multiple Output
MIMO-BF – Multiple Input Multiple Output- Beam Forming
MIP – Mobile Internet Protocol
MME – Mobility Management Entity
MRFP - Multimedia Resource Function Processor

MRT – Maximum Ratio Transmission
MS – Mobile Station
MSC - Mobile Switching Center
MSDU – Media Access Control Service Data Unit
MT – Mobile Terminal
MU-MIMO – Multiple User Multiple Input Multiple Output
NACK - Negative Acknowledgement
NAP – Network Access Provider
NAS - Non-Access Stratum
NLOS – Non Line of Sight
NRM – Network Reference Model
nrtPS - Non-real-time Polling Service
NSP - Network Service Provider
OCS - Online Charging Server
OFDMA – Orthogonal Frequency Division Multiple Access
OMA – Open Mobile Alliance
OPUSC – Optional Partial Usage of Sub-Channels
PAR – Peak-to-Average Ratio
PBCM – Physical Broadcast Channel
PCC – Policy and Charging Control
PCH – Paging Channel
PCRF - Policy Control and Charging Rules Function
P-CSCF – Proxy-Call Session Control Function
PDCCH – Physical Downlink Control Channel
PDCP - Packet Data Convergence Protocol
PDFICH – Physical Control Format Indicator Channel
PDG - Packet Data Gateway
PDN - Packet Data Network
PDSCH - Physical Downlink Shared Channel
PDU – Protocol Data Unit
P-GW – Packet data network Gateway
PHICH – Physical Hybrid ARQ Indicator Channel
PHY - Physical
PKM - Privacy Key Management
PMCH – Physical Multicast Channel
PMIP – Proxy Mobile Internet Protocol
PRACH – Physical Random Access Channel
P-SCH – Primary Synchronization Channel
PSS - Packet Switched Streaming
PUCCH – Physical Uplink Control Channel
PUSC – Partial Usage of Sub-Channels
PUSCH – Physical Uplink Shared Channel

QAM – Quadrature Amplitude Modulation
QCI – Quality-of-Service Class Indicator
QoS – Quality of Service
QPSK - Quadrature Phase Shift Keying
RACH – Random Access Channel
RAT – Radio Access Technology
RB –Resource Block
RF – Radio Frequency
RG – Residential Gateway
RLC - Radio Link Control
RNC – Radio Network Controller
RoHC – Robust Header Compression
RRA – Radio Resource Agent
RRC - Radio Resource Control
RRM – Radio Resource Management
RS – Reference Signal
RS – Relay atation
RSA - Rivest- Shamir- Adleman
rtPS - Real-time Polling Service
RX - Receiver
SAE - System Architecture Evolution
SC-FDMA – Single Carrier – Frequency Division Multiple Access
SDMA – Space Division Multiple Access
SGSN - Serving GPRS Support Node
S-GW – Serving Gateway
SGW- Serving Gateway
SISO – Single Input Single Output
SLA – Service Level Agreement
SLF - Subscriber Locator Function
SM-MIMO – Spatial Multiplexing Multiple Input Multiple Output
SMS-GMSC - Short Message Service Gateway Mobile Switching Centre
SMS-IWMSC - Short Message Service Interworking Mobile Switching Centre
SMS-SC - Short Message Service - Service Centre
SNR – Signal to Noise Ratio
SS – Subscriber Station
S-SCH – Secondary Synchronization channel
STBC – Space Time Block coding
SU-MIMO – Single User Multiple Input Multiple Output
TDD – Time Division Duplexing
TDMA – Time Division Multiple Access
TE – Terminal Equipment
TrCH – Traffic Channel

TTG – Transmit Time Gap
TUSC – Tile Usage of Sub-Channels
TX - Transmitter
UCI – Uplink Control Information
UE – User Equipment
UEA1 – UMTS Encryption Algorithm 1
UEA2 - UMTS Encryption Algorithm 2
UGS - Unsolicited Grant Service
UIA1 - UMTS Integrity Algorithm 1
UIA2 - UMTS Integrity Algorithm 2
UL - Uplink
UL – Uplink Media Access Protocol
UL-SCH – Uplink Shared Channel
UMTS - Universal Mobile Telecommunications System
UPE – User Plane Entity
UpPTS – Uplink Pilot Time Slots
UTRA - Universal Terrestrial Radio Access
UTRAN - Universal Terrestrial Radio Access Network
WAG - Wireless Access Gateway
WAN – Wide Area Network
WCDMA - Wideband Code Division Multiple Access
Wi-Fi – Wireless Fidelity
WiMAX – Worldwide Interoperability for Microwave Access
WLAN – Wireless Local Area Network

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