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COMPARISON BETWEEN WiMAX AND 3GPP LTE

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ABSTRACT

Mobile communication technology evolved rapidly over the last few years due to increasing demands such as accessing Internet services on mobile phones with a better quality of the offered services. In order to fulfil this, wireless telecommunication industry worked hard and defined a new air interface for mobile communications which enhances the overall system performance by increasing the capacity of the system along with improving spectral efficiencies while reducing latencies.

For this, two technologies, called Worldwide Interoperability for Microwave Access (WiMAX) and Third Generation Partnership Project Long Term Evolution (3GPP LTE), emerged with an aim of providing voice, data, video and multimedia services on mobile phones at high speeds and cheap rates.

In this thesis, we have conducted a detailed comparative study between WiMAX and 3GPP LTE by focusing on their first two layers, i.e. Physical and MAC layer. The comparison specifically includes system architecture, radio aspects of the air interface (such as frequency band, radio access modes, multiple access technologies, multiple antenna technologies and modulation), protocol aspects of the air interface (in terms of protocol architecture, modulation and frame structure), mobility and Quality of Service (QoS). We have also given a brief comparative summary of both technologies in our thesis.

In the thesis, we investigated the LTE uplink and performed link level simulations of Single Carrier Frequency Domain Equalization (SC-FDE) and Single Carrier Frequency Division Multiple Access (SC-FDMA) in comparison with Orthogonal Frequency Division Multiplexing (OFDM). The comparison has been in terms of Signal-to-Noise Ratio (SNR) and Symbol Error Rate (SER). In order to verify the theoretical results, we simulated the Peak to Average Power Ratio (PAPR) of SC-FDMA system in comparison with OFDMA. We also simulated the capacity of Multiple Input Multiple Output (MIMO) systems in comparison with Single Input Single Output (SISO) systems.

The simulation was performed on a PC running MATLAB 7.40 (R2007a). The operating system used in the simulation was Microsoft Windows Vista.

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DEDICATION

I, Syed Hamid Ali Shah dedicate my thesis work to my parents, siblings and my beloved nephew Syed Ajmal Ali Shah.

I, Tassadaq Hussain would like to dedicate my thesis to my family, especially my nephews and nieces.

I, Mudasar Iqbal dedicate my thesis project and degree to my parents.

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List of Acronyms

3GPP	3rd Generation Partnership Project
16-QAM	16-Quadrature Amplitude Modulation
64-QAM	64-Quadrature Amplitude Modulation
AAS	Adaptive Antenna System
AP	Access Point
ARQ	Automatic Repeat reQuest
AS	Access Stratum
ASN	Access Service Network
ASN GW	Access Service Network Gateway
ATM	Asynchronous Transmission Mode
AuC	Authentication Centre
AWGN	Additive White Gaussian Noise
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BPSK	Binary Phase Shift Keying
BSN	Block Sequence Number
BWA	Broadband Wireless Access
CCCH	Common Control Channel
CCDF	Complementary Cumulative Distribution Function
CDD	Cyclic Delay Diversity
CDMA	Code Division Multiple Access
CI	Cyclic Redundancy Indicator
CID	Connection Identifier
CIR	Channel Impulse Response
CN	Core Network
CPS	Common Part Sublayer
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
CS	Convergence Sublayer
CSN	Connectivity Service Network
DAC	Digital to Analog Convertor
DC	Direct Current
DCCH	Dedicated Control Channel
DFDMA	Distributed Frequency Division Multiple Access
DHCP	Dynamic Host Control Protocol
DRX	Discontinuous Reception
DSL	Direct Subscriber Line
DTCH	Dedicated Traffic Channel
EC	Encryption Control
EKS	Encryption Key Sequence

EPC	Evolved Packet Core
ErtPS	Extended Real Time Polling Service
E-UTRA	Evolved UMTS Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FBSS	Fast Base Station Switching
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FSN	Fragment Sequence Number
FTP	File Transfer Protocol
GMH	Generic MAC Header
GT	Guard Time
HARQ	Hybrid Automatic Repeat reQuest
HCS	Header Check Sequence
HHO	Hard Handover
HLR	Home Location Register
HSDPA	High Speed Downlink Packet Access
HSS	Home Subscriber Station
HT	Header Type
ICI	Inter Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fourier Transform
IP	Internet Protocol
IRC	Interference Rejection Combining
ISI	Inter Symbol Interference
ISP	Internet Service Provider
ITU	International Telecommunication Union
LFDMA	Localized Frequency Division Multiple Access
LLC	Logical Link Control
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MAN	Metropolitan Area Network
MBMS	Multimedia Broadcast Multimedia Service
MBSFN	Mobile Broadcast Single Frequency Network
MCCH	Multicast Control Channel
MCH	Multicast Channel
MCM	Multicarrier Modulation
MDHO	Macro Diversity Handover
MIMO	Multiple Input Multiple Output
MIP-HA	Mobile IP Home Agent
MMSE	Minimum Mean Square Error
MME	Mobility Management Entity

MPDU	MAC Packet Data Unit
MRT	Maximum Ratio Transmission
MS	Mobile Station
MSDU	MAC Single Data Unit
MTCH	Multicast Traffic Channel
MU-MIMO	Multi User-Multiple Input Multiple Output
MTCH	Multicast Traffic Channel
NAS	Non Access Stratum
NLOS	Non Line Of Sight
NSP	Network Service Provider
nrtPS	Non Real Time Polling Service
N-WEST	National Wireless Electronics Systems Testbed
NWG	Network Working Group
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open System Interface
OSS	Operation Supports System
PAPR	Peak-To-Average Power Ratio
PBCH	Physical Broadcast Channel
PBFICH	Physical Control Format Indicator Channel
PCCH	Paging Control Channel
PCEF	Policy Control Enforcement Function
PCMCIA	Personal Computer Memory Cards International Association
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PDCP	Packet Data Convergence Protocol
PDU	Packet Data Unit
P-GW	Packet Data Network Gateway
PHICH	Physical HARQ Indicator Channel
PHY	Physical Layer
PMCH	Physical Multicast Channel
PMP	Point-to-Multipoint
PRACH	Physical Random Access Channel
PRN	Pseudo Random Numerical
P-SCH	Primary Synchronous Channel
PSTN	Public Switch Telephone Network
PTP	Point-to-Point
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
QPP	Quadratic Polynomial Permutation
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
RE	Resource Element
RLC	Radio Link control

RP	Reference Point
RRC	Radio Resource Control
RRM	Radio Resource Management
rtPS	Real Time Polling Service
SAS	Smart Antenna System
SAE	System Architecture Evolution
SAP	Service Access Point
SC-FDE	Single Carrier with Frequency Domain Equalization
SER	Symbol Error Rate
S-GW	Serving Gateway
SM	Spatial Multiplexing
SNR	Signal-to-Noise Ratio
SOFDMA	Scalable Orthogonal Frequency Division Multiple Access
SS	Subscriber Station
S-SCH	Secondary Synchronous Channel
STBC	Space Time Block coding
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
UE	User Equipment
UL-SCH	Uplink Shared Channel
UMTS	Universal Mobile Telecommunication System
VoIP	Voice over Internet Protocol
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WiMAX	WiMAX
WMAN	Wireless Metropolitan Area Network
ZF	Zero Forcing

Chapter 1: Introduction

Worldwide Interoperability for Microwave Access (WiMAX) technology, also known as the IEEE 802.16 standard, is based on WMAN (Wireless Metropolitan Area Network). It provides data rates up to 75 Mbps over the distance of 50 km. WiMAX uses frequency bands of 10-66 GHz, covering long geographical areas using licensed or unlicensed spectrum. WiMAX uses OFDMA (Orthogonal Frequency Division Multiple Access) as multiplexing technique in uplink and downlink directions. The mode of operation used for communication between multiple subscriber stations and base station is Point-to-Multipoint (PMP), whereas the mode of operation used between two base stations is Point-to-Point (PTP).

Other versions of WiMAX include IEEE 802.16-2004 and IEEE 802.16-2005. IEEE 802.16-2004 is known as fixed WiMAX, has no mobility and is used for fixed and nomadic access. Since fixed WiMAX has no mobility it does not support handovers. IEEE 802.16-2005 is known as mobile WiMAX, which is an extension of fixed WiMAX, introducing many new features to support enhanced Quality of Service (QoS) to provide high mobility. The mobile WiMAX supports data rate of up to 75 Mbps.

The Long Term Evolution (LTE) is an evolution of the third generation technology based on Wideband Code Division Multiple Access (WCDMA). LTE uses OFDM for downlink, i.e. from base station to the terminal. There are three physical channels such as Physical Downlink Shared Channel (PDSCH), Physical Multicast Channel (PMCH), Physical Broadcast Channel (PBCH) in the downlink used for data transmission, broadcast transmission and system information within a cell. The modulation schemes used are Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (16-QAM) and 64-QAM.

LTE uses a precoded version of Orthogonal Frequency Division Multiplexing (OFDM) using a single carrier for uplink called Single Carrier Frequency Division Multiplexing (SC-FDMA). SC-FDMA is used to minimize Peak-to-Average Power Ratio (PAPR) caused by OFDM. PAPR is the ratio of peak signal power to the average signal power. There are two physical channels, Physical Random Access Channel (PRACH) and Physical Uplink Synchronization Channel (PUSCH), used in the LTE uplink. For initial access PRACH is used whereas when the User Equipment (UE) is not synchronized the data is send on PUSCH. The modulations schemes used for LTE uplink are QPSK, 16-QAM, 64-QAM.

The Figure 1.1 shows the wireless technology evolution of WiMAX and LTE.

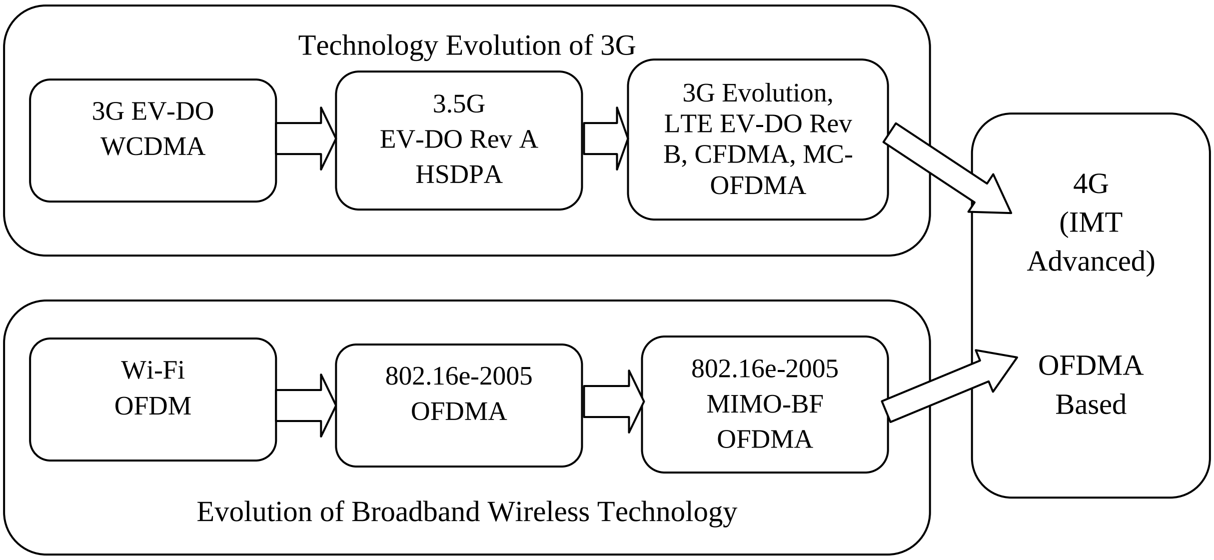


Figure 1.1: Evolution Path of Mobile Technologies towards 4G [1]

1.1 Objective

The objective of this thesis is to conduct a brief comparison between WiMAX and 3GPP LTE. The comparison is performed by discussing the physical and MAC layers of WiMAX and LTE including their multiplexing schemes. Link level simulations of the LTE uplink correspond to the main part of our thesis. Link level simulation of OFDM by using equalization schemes as Minimum Mean Square Error (MMSE) and Zero Forcing (ZF) in ITU Pedestrian A, ITU vehicular A and AWGN channels in comparison with SC-FDE and SCFDMA is also included in our thesis. The comparison is taken in terms of Symbol Error Rates (SER) and Signal-to-Noise Ratio (SNR). In addition, the Peak-to-Average Power Ratio (PAPR) is calculated for both the SC-FDMA and the OFDMA systems.

1.2 Thesis Outline

Chapter 2 gives a technical overview of the WiMAX technology including its different standards and air interfaces. This chapter also discusses Physical and MAC layers of WiMAX.

Chapter 3 gives a brief description of 3GPP LTE including its architectures, air interfaces, uplink, downlink, multiple antenna techniques and layers (Physical and MAC layer).

Chapter 4 underlines the main differences between WiMAX and LTE. The comparison is conducted in terms of system architecture, radio and protocol aspects of air interfaces, mobility and QoS.

Chapter 5 includes our simulation results. It also includes the link level simulation of LTE uplink in comparison with an OFDM system. In addition to this, the capacity of MIMO system is in comparison with a SISO system also discussed.

Chapter 6 concludes the thesis and provides some suggestions for future work.

Chapter 2: Introduction to WiMAX

2.1 Overview of WiMAX

WiMAX, also known as IEEE 802.16, provides wireless data services by using the 10-66 GHz frequency bands and provides data rates up to 70 Mbps over distance of 50 km. WiMAX covers large geographical areas using licensed or unlicensed spectrum in order to provide wireless Internet services to users with high data rates. It is based on WMAN which is not only an alternative to wired T1 and Digital Subscriber Lines (DSL) but it also provides wireless broadband services within a building from an Internet Service Provider (ISP) and can be used to connect many Wi-Fi networks across different campuses or cities.

WiMAX works like any other cellular technology and uses a base station to establish the wireless connection to the subscriber such as Universal Mobile Telecommunication Systems (UMTS). The communication between two or more WiMAX base stations could be Point to Point/ Line of Sight (LOS) whereas between the base station and the subscriber can be Point to Multi Point/ Non Line of Sight (NLOS).

2.2 IEEE 802.16 Standards

Telecommunication equipment manufacturers started introducing products for Broadband Wireless Access (BWA) at the end of the 90’s. But they were still looking for interoperable standard. The National Wireless Electronics Systems Testbed (N-WEST) called a meeting in 1998, about the need of an interoperable standard which resulted in the IEEE 802 standard. A lot of efforts were made in this regard which resulted later in the formation of IEEE 802.16 standard. Initially, the main focus of this group was to develop the radio interface for BWA which used the radio spectrum from the 10-66 GHz range. It also supports the LOS based Point to Multipoint (PMP) broadband wireless system.

2.2.1 IEEE 802.16-2001

The standard was developed in December 2001. It uses the spectrum range of 10-66 GHz to provide fixed broadband wireless connectivity and single carrier modulation techniques such as 16-QAM, 64-QAM and QPSK in physical layer and Time division Multiplexed (TDM) techniques in MAC layer. The standard includes Differential QoS techniques for the improvement of LOS based conditions. The standard uses Time Division Duplex (TDD) and Frequency Division Duplex (FDD) as duplexing techniques.

2.2.2 IEEE 802.16a-2003

The standard amended the basic IEEE 802.16 by using a frequency range of 2-11 GHz which includes both licensed and license free frequency bands. Due to inclusion of the low frequencies, below 11 GHz, NLOS communication is possible. The NLOS operations introduced the multipath propagation effects which have been overcome through the adaptation of multicarrier modulation techniques in the physical layer. OFDM was chosen as modulation technique. The standard improved also security issues by making the features of privacy layer mandatory.

2.2.3 IEEE 802.16c

The standard developed the profile details of 10-66 GHz frequency band and corrected the inconsistencies involved in the previous standard.

2.2.4 IEEE 802.16d-2004

Is the amendment of IEEE 802.16a. It was initially considered as the revision of IEEE 802.16 standard and was named IEEE 802.16 REVd. But in September 2004, due to the credibility of the amendments, it was named IEEE.802.16d. The standard was designed for fixed, nomadic and portable users so as to provide fixed BWA. It supports both TDD and FDD transmission modes. The most important feature of this standard is the provision of support for advance antenna systems and adaptive modulation and coding techniques.

2.2.5 IEEE 802.16e-2005

Is the amendment of IEEE 802.16d-2004 and provides support for mobility of subscribers, who can move at vehicular speeds and provides services such as high speed handoffs due to its technological advances. It enhances the overall system performance due to support of Adaptive Antenna Systems (AAS) and MIMO. It facilitates mobile, fixed and portable users. The standard updated the security feature included privacy sub-layer.

2.3 Fixed vs. Mobile WiMAX

IEEE 802.16-2004 is known as fixed WiMAX. The standard was originally developed as a wireless extension of the wired infrastructure. It uses OFDM to mitigate the effects of multipath and improves the propagation of signals in NLOS. Fixed WiMAX has no mobility and this is also the reason why it does not support handovers. The IEEE 802.16-2005, also known as mobile WiMAX, uses Scalable Orthogonal Frequency Division Multiplexing Access (SOFDMA), which divides the carrier up to 2048 subcarriers. This division of the carrier signal makes it possible to improve the signal penetration into the buildings and should enable cheaper products for the end subscriber such as PC and USB cards.

The basic difference between fixed and mobile variants of WiMAX is their mobility. Mobile WiMAX supports users moving at speeds of 120 km/h and enables the handoff mechanism when a user moves from one Base Station (BS) to another. A comparison between Fixed and Mobile WiMAX is shown in Table 2.1 [2].

Standard	IEEE 802.16-2004	IEEE 802.16-2005
Release	June 2004	December 2005
Spectrum	2 to 11 GHz	Fixed:2 to 11 GHz Mobile: 2 to 6 GHZ
Modulation Techniques	16-QAM, 64-QAM and QPSK	16-QAM, 64-QAM and QPSK
Propagation Schemes	NLOS	NLOS
PHY Layer	Single Carrier 256-OFDM 2048-OFDM	Single carrier Scalable OFDMA with 128, 256,512,1024 and 2048 subcarriers
Duplex Method	TDD/FDD	TDD/FDD
Data Rate	Maximum 70 Mbps for (20 MHz Channel)	Maximum 15 Mbps for (5MHz Channel)
Applications	Voice over IP (VoIP)	Mobile VoIP
Supported Services	Fixed, Nomadic and Portable	Mobile, Fixed and Portable
Targeted Groups	Service Providers Wired ISP Wireless ISP	Digital Subscriber Line (DSL) Wired and wireless ISP Modem Service Providers
User Equipment	PCMCIA card for Laptops	PCMCIA card Smart Phones
Mobility	NO	Yes
Coverage	Up to 50 km maximum	2-5 km approximately

Table 2.1: Fixed vs. Mobile WiMAX [2]

2.4 IEEE 802.16 Protocol Layers

The IEEE 802.16 uses the first two layers of the Open System Interconnection (OSI) model. The PHY layer uses OFDM and Orthogonal Frequency Division Multiple Access (OFDMA) as transmission techniques whereas data link layer is divided into MAC and Logical Link Control (LLC) sub-layers. The MAC layer is further divided into three sub-layers called Security Sublayer, MAC Common Part Sublayer (MAC CPS) and Convergence Sublayer (CS). The protocol stack of WiMAX is shown in Figure 2.1, and consists of the first two layers (PHY and Data link) of OSI reference model. The upper layers include network, transport, session, presentation and application layers of OSI model.

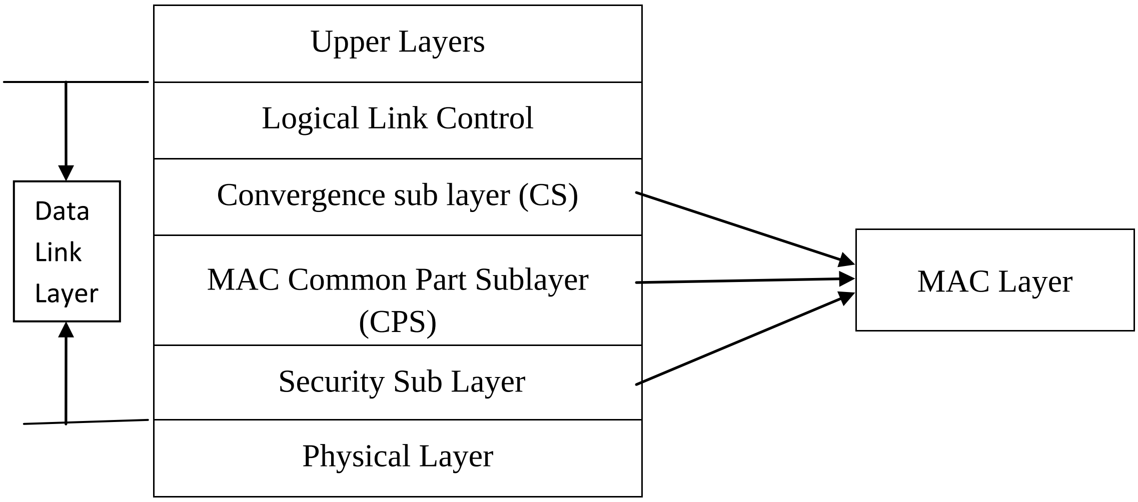


Figure 2.1 Protocol Stack of IEEE 802.16 [3]

PHY layer of WiMAX not only establishes the connection between communicating devices but is also responsible for defining the modulation/demodulation type for transmission of the incoming bit sequence. It uses OFDM and OFDMA as transmission schemes, which uses the frequency band between 2-11 GHz. The frequency band below 11 GHz makes possible NLOS wireless communication and the use of OFDM reduces multipath effects and Inter Symbol Interference (ISI). PHY layer uses FDD and TDD as duplexing techniques.

MAC provides the interface between PHY layer and the transport. From a transmission prospective, MAC layer takes the packets from the upper layers and organizes them in Protocol Data Units (PDU’s) for transmission over the air. The CS of the MAC layer can interface with the protocols of upper layers. Consequently, WiMAX supports both IP and Ethernet protocol. The MAC CPS is the core part of the MAC layer and is responsible for connection maintenance, bandwidth allocation, PDU framing, duplexing and channelization. The security sublayer connects the MAC CPS and the PHY layer and provides the necessary methods for encryption and decryption of data. Security sublayer is also used for authentication and the secure exchange of keys.

2.5 Physical Layer of IEEE 802.16

WiMAX supports five types of physical interfaces due to the use of various types of modulation techniques. In this section, we will first define each type of PHY layer interface and then will give a detailed description of the OFDM techniques used at the PHY layer.

- **WirelessMAN-SC:** The WirelessMAN-SC PHY uses single carrier modulation technique for LOS transmission within 10-66 GHz frequency band.
- **WirelessMAN-SCa**: The WirelessMAN-SCa PHY uses single carrier modulation techniques for the NLOS transmission in the frequency band of 2-11 GHz.
- **WirelessMAN-OFDM**: It is based on OFDM and is providing the NLOS transmission in the frequency band of 2-11 GHz.
- **WirelessMAN-OFDMA**: The WirelessMAN-OFDMA PHY uses the licensed frequency band of 2-11 GHz and supports the NLOS operation by using the 2048 subcarrier OFDM scheme.
- **WirelessHUMAN**: Is based on license free frequency band below 11 GHz. It can use any of the air interfaces that use the 2-11 GHz frequency band. It uses TDD as duplexing technique [4].

The description of physical layer interfaces is described in Table 2.2 [4].

PHY Interface	Duplexing	Modulation	Frequency Bands	Propagation Modes
WirelessMAN-SC	FDD and TDD	Single carrier	10-66 GHz	LOS
WirelessMAN-SCa	FDD and TDD	Single carrier	2-11 GHz	NLOS
WirelessMAN-OFDM	FDD and TDD	OFDM	2-11 GHz	NLOS
WirelessMAN-OFDMA	FDD and TDD	2048 subcarrier OFDM Scheme.	2-11 GHz	NLOS
WirelessHUMAN	TDD	SC, OFDM, OFDMA	License free frequency band below 11 GHz	NLOS

Table 2.2: Physical Layer Interfaces of IEEE 802.16 [4]

2.5.1 WirelessMAN OFDM PHY

It uses OFDM which enables high speed data services and multimedia communication in NLOS environment. It can reduce multipath effects in NLOS and provides efficient data rates for transmission.

2.5.2 Overview of OFDM

OFDM is based on a multicarrier modulation technique which, in turn, is based on the concept of dividing incoming data streams of high bit rates into several data streams of lower bit rates. OFDM modulates each stream onto separate carrier frequencies, known as subcarriers. Multicarrier Modulation (MCM) techniques use guard band to in order eliminate or reduce the ISI. The idea of OFDM is slightly different from that of MCM. In OFDM, subcarriers are placed in such a manner that they are orthogonal to each other. Consequently, the Inter Carrier Interference (ICI) is reduced and the available bandwidth is used more efficiently.

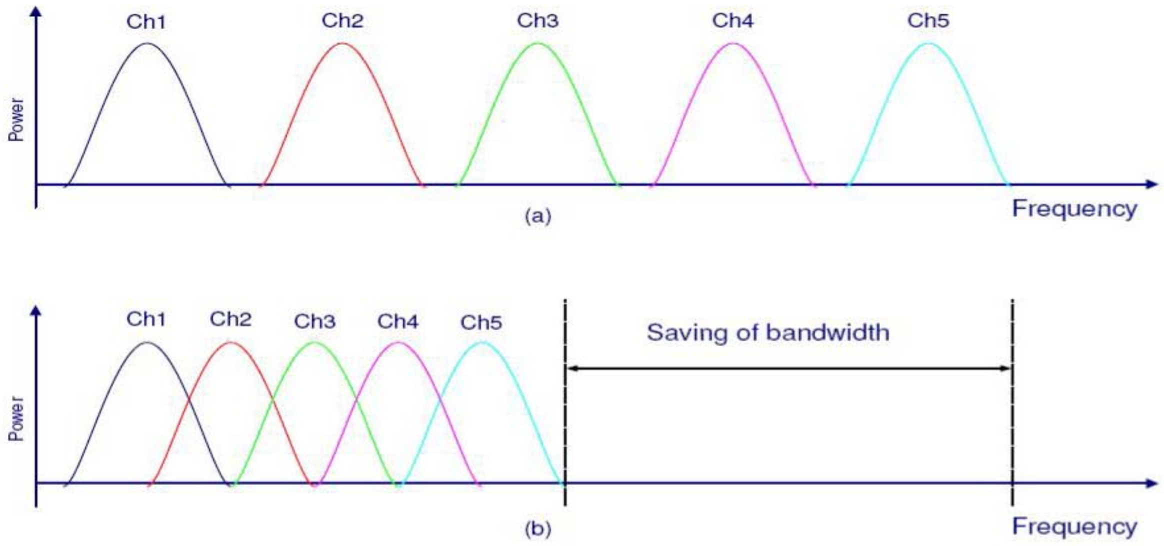


Figure 2.2: Comparison between Conventional FDM and OFDM [5]

The use of OFDM saves bandwidth as compared to the Frequency Division Multiplexing (FDM) as shown in Figure 2.2. The orthogonal overlapping nature of OFDM subcarriers not only reduces the ISI but also saves the bandwidth of system which is different from FDM where ISI is reduced by the introduction of guard bands. The addition of guard band is the wastage of power and bandwidth.

2.5.3 Time Domain OFDM

The Cyclic Prefix (CP) could be added at the beginning of the OFDM symbol before transmission. The addition of CP maintains orthogonality and reduces the delay spread introduced by multipath. The time occupied by CP is called Guard Time (T_G) and is used in computations of various data rates. The time occupied by data is called $T_{d.}$ In WiMAX the ratio of T_G/T_d is known as Guard Interval (G). The choice of G depends upon the conditions of radio channel. The values of G are 1/4, 1/8, 1/16, 1/32. The time domain description of CP is shown in Figure 2.3.

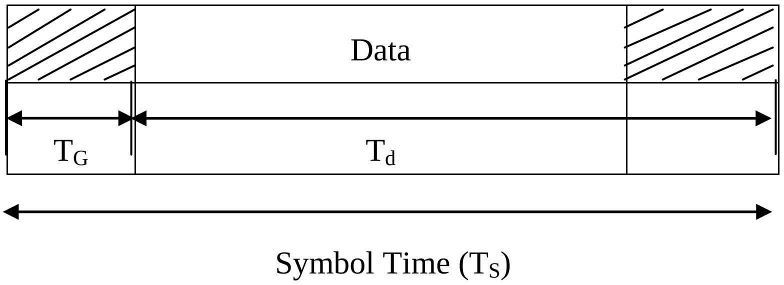


Figure 2.3: Cyclic Prefix in Time Domain

2.5.4 Frequency Domain OFDM

Useful data is not carried by all the subcarriers of an OFDM symbol. Four types of subcarriers are used in WiMAX OFDM:

- Data Subcarriers: Carries useful data for transmission.
- Pilot Subcarriers: Used for synchronization and channel estimation.
- Null Subcarrier: Having no data for transmission, known as frequency guard bands.
- Direct Current Subcarrier: DC subcarrier is called Null subcarrier as it corresponds to the zero frequency if the Fast Fourier Transform (FFT) signal is not modulated. The FFT signal is obtained by taking the transformation of discrete signal into discrete frequency domain. Normally, the DC subcarrier has a frequency equal to the RF centre of frequency of the transmitting station.

The OFDM symbol of WiMAX in frequency domain is shown in Figure 2.4.

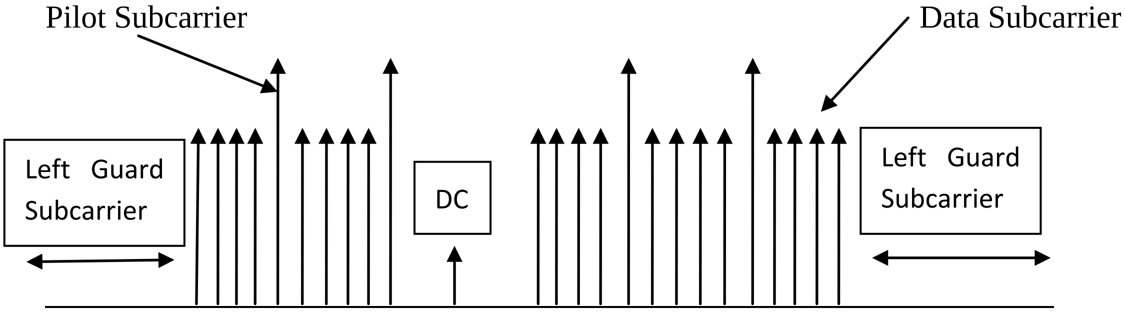


Figure 2.4: WiMAX OFDM Symbol in Frequency Domain

2.5.5 Parameters of OFDM

As mentioned previously, WiMAX has five different implementations of the physical layer. Here we will discuss the parameters of PHY for fixed and mobile WiMAX, based on OFDM and OFDMA PHY layers respectively. In addition to different air interfaces, mobile WiMAX also uses variable FFT size.

2.5.5.1 OFDM PHY for Fixed WiMAX

Fixed WiMAX is based on IEEE 802.16-2004 and uses the OFDM PHY layer. It uses 256 point FFT, where the size of FFT is fixed. From 256 points (subcarriers), 192 subcarriers carry data, 8 are used for estimation and synchronization, while the remaining 56 subcarriers are used as a guard band. Due to the fixed size of FFT, subcarrier spacing increases as the bandwidth increases which in turn decreases the symbol time. The reduction in symbol time increases the delay spread which is undesirable. Consequently, in order to reduce the delay spread, a large fraction of time needs to be allocated as guard time. For 3.5 MHz channel bandwidth, the maximum delay spread is 16us.

2.5.5.2 OFDMA PHY for Mobile WiMAX

Mobile WiMAX uses a scalable size of FFT that varies between 128 to 2048 points. In mobile WiMAX, when the bandwidth increases, the size of FFT increases such that the subcarrier spacing is 10.94 kHz. The spacing of 10.94 kHz keeps the balance between Doppler spread and delay spread requirements for both fixed and mobile WiMAX environments. Doppler spread occurs in the signal by movement of communicating devices (mobile phones) or other objects in the environment. The effect of Doppler spreading creates ICI by destroying the orthogonality of the subcarriers. In addition, the subcarrier spacing of 10.94 kHz supports delay spread values up to 20us and vehicular speed up to 125 km/h when operating in 3.5 GHz spectrum band. A scalable version of FFT also reduces cost due to support of various transmission bandwidths (3.5 MHz, 5 MHz, 10 MHz and 20 MHz) without any change in equipment. The OFDM parameters for OFDM PHY and OFDMA PHY layers are shown in Table 2.3.

OFDM Parameter	OFDM PHY for Fixed WiMAX	OFDMA PHY for Mobile WiMAX		
FFT Size	256	512	1024	2048
Number of Data Subcarrier	192	360	720	1440
Number of Pilot Subcarrier	8	60	120	240
Number of Null subcarrier	56	92	184	368
Cyclic Prefix (Guard Time)	1/32	1/8	1/4	1/4
Channel Bandwidth (MHz)	3.5	5	10	20
Subcarrier spacing (KHz)	15.625	10.94		
OFDM symbol duration (µs)	72	102.9		
Useful symbol time (µs)	64	91.4		

Table 2.3: OFDM Parameters used in Fixed and Mobile WiMAX [2]

2.5.6 Advantages and disadvantages of OFDM

OFDM has many advantages when compared with a single carrier modulation scheme.

Advantages of OFDM:

- OFDM is simple to implement due to the use of FFT.
- OFDM is spectral efficient due to overlapping spectra and orthogonality.
- It is robust in NLOS transmissions.
- OFDM reduces the effects of ISI through the use of a cyclic prefix in a transmitted symbol.
- In OFDM each subcarrier is modulated by different modulation techniques such as BPSK, QAM and QPSK.
- It is robust against narrow band interference.
- It is useful for coherent demodulation because pilot based channel estimations are easy to implement in OFDM systems.

Disadvantages of OFDM:

Here are some drawbacks of OFDM.

- OFDM has Peak to Average Power Ratio (PAPR) that causes nonlinearities and clipping distortions.
- It is sensitive to phase noise which is acute at higher frequencies.
- It is sensitive to timing and frequency offset [6].

2.5.7 Features of WirelessMAN OFDM PHY

Flexible Channel Bandwidth

WiMAX IEEE 802.16-2004 standard allows flexible channel bandwidth to provide compatibility with wireless technologies. It uses the channel bandwidth from 1.25 MHz to 20 MHz.

Adaptive Modulation and coding

WiMAX uses adaptive modulation techniques and allows the technique to be changed on burst by burst basis per link, depending on channel conditions [7]. On basis of channel quality, the base station scheduler assigns the modulation scheme that maximizes the throughput within available Signal to Noise Ratio (SNR). The downlink and uplink of WiMAX supports various modulation schemes including 16-QAM, QPSK and 64-QAM. The use of 64-QAM is optional in the uplink direction. Table 2.4 [2] shows various types of modulation and coding schemes used in the downlink and uplink of WiMAX.

	Downlink	**Uplink**
Modulation	BPSK, QPSK, 16-QAM, 64-QAM.	BPSK, QPSK, 16-QAM, 64-QAM (optional)
Coding	**Mandatory:** Convolutional codes at rate: 1/2.2/3,3/4,5/6 **Optional:** Convolutional Turbo codes at rate: 1/2.2/3,3/4,5/6 Repetition codes at rate: 1/2.1/3,1/6, LDPC, RS-Codes for OFDM PHY	**Mandatory:** Convolutional codes at rate: 1/2.2/3,3/4,5/6 **Optional:** Convolutional Turbo codes at rate: 1/2.2/3,3/4,5/6 Repetition codes at rate: 1/2.1/3,1/6, LDPC

Table 2.4: Modulation and Coding Schemes Supported by WiMAX [2]

Error Correction Mechanism

The WirelessMAN OFDM PHY provides robust error correction by using the Forward Error Correction (FEC) control mechanism. It uses a two stages FEC. In the first stage, FEC uses Reed Solomon Encoder that corrects burst errors at byte level and improves the OFDM link in multipath propagations. In the second stage, FEC uses convolutional coder that corrects independent bit errors. Convolutional coding reduces the overall number of bits needed to be sent on the channel due to puncturing functionality [2]. Puncturing is the process of removing certain bits before transmission and replacing the deleted bits with fixed values upon reception.

2.6 MAC Layer of IEEE 802.16

MAC layer provides the interface between the physical layer and upper layers. It takes MAC Service Data Units (MSDU) from the upper transport layers and organizes them in form of MAC Packet Data Units (MPDU) for transmission over the air. MAC layer supports variable length frames for transmission. In IEEE 802.16 MAC layer is divided in to three sub-layers:

- Service Specific Convergence Sublayer (SSCS)
- Common Part Sublayer (CPS)
- Security Sublayer (SS)

The CS accommodates upper layer protocols. The IEEE 802.16 MAC layer supports Asynchronous Transmission Mode (ATM) and Ethernet (IEEE.802.3) which specifies two types of traffic supported by CS; IP and ATM. CS takes the MSDU’s from upper layers and do key processing such as payload compression. After payload compression the MSDU’s are sent to CPS through Service Access Point (SAP). CS can accept data frames from the CPS.

The CPS of IEEE 802.16 takes MSDU's from the CS and organizes them in form of MPDU by performing fragmentation and segmentation. CPS is the core part of the MAC layer and it provides functions related to bandwidth allocations, connection initialization and maintenance, QoS, duplexing and framing. CPS provides the connection identifier to identify the serving MPDU, when MAC layer is connected to Subscriber Stations (SSs). The main goal of the SS is to ensure privacy services to the subscribers across the wireless network and give protection from theft of services to the operators. It provides encryption, authentication and secure key exchange functions on MPDUs and sends them to the PHY layer for further processing.

The data, control and management plane of WiMAX are shown in Figure 2.5.

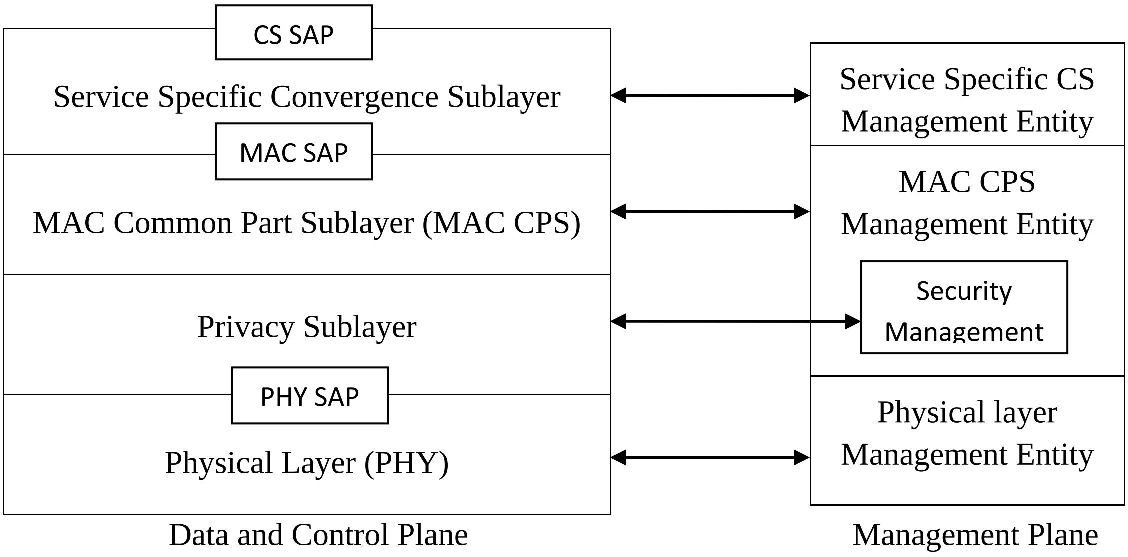


Figure 2.5: Architecture of WiMAX [8]

2.6.1 MAC Frame Format

WiMAX supports two types of generic MAC frame formats. The first contains the management information while the second has transport information.

Generic MAC Header (GMH)	Subheader	MAC Management Information	Forward Error Correction (FEC)

Figure 2.6(a): Generic MAC Frame Having Management Payload

Generic MAC Header (GMH)	Subheader	MAC Transport Information	Forward Error Correction (FEC)

Figure 2.6(b): Generic MAC Frame Having Transport Payload

Figures 2.6(a) and 2.6(b) show the generic MPDU frame format. A generic MPDU contains the GMH, subheader which is optional, payload information and error correction mechanisms, in the form either CRC or FEC. The header of GMH is shown in Figure 2.7.

HT	EC	Type	Reserved	CI	EKS	Reserved	LEN	CID	HCS
1bit	1bit	6 bits	1bit	1bit	2bits	1bit	11 bits	16 bits	8 bits

6 Bytes

Figure 2.7: Generic MAC Header (GMH)

From Figure 2.7, GMH consists of Header Type (HT), Encryption Control (EC), Type, Reserved bits, Cyclic Redundancy Indicator (CI), Encryption Key Sequence (EKS), Length of Number of bytes of MPDU (LEN), Connection Identifier (CI) and Header Check Sequence (HCS). Each field of GMH has its specific function which is described below.

The GMH contains information about MPDU details. The 1 bit HT indicates the type of header. The MAC layer supports two types of MPDUs, Generic MPDU and the Bandwidth Request PDU. For Generic MPDU the “HT” contains the “0” value. The 1 bit “EC” indicates the encryption of the payload. The “0” value in EC indicates the payload is not encrypted while “1” indicates the payload is encrypted. The “Type” field indicates the type of payload contents used. The payload content can be fragmentation, Automatic Repeat Request (ARQ), mesh and Aggregation. The “CI” field indicates the status of CRC, whether it is present or not. Value “0” indicates the absence of CRC while 1 indicates its presence. The “EKS” field indicates the key used to encrypt the frame payload. The “LEN” field indicates the number of bytes of MPDU. The “LEN” field is 11 bits allowing thus a maximum frame length of 2047 bytes. The “CID” indicates the connection where the MPDU has to be sent. The “HCS” performs error check for the GMH. The second field of “Generic MPDU” is Subheader (SH) which is optional. The “SH” defines the bits for aggregation, ARQ, fragmentation and mesh feature of the MAC. The “Payload” field of MPDU contains fragments of MSDUs, single MSDU, aggregates of fragments of MSDUs and aggregates of MSDUs, which depend on aggregation or fragmentation rules for MAC.

2.6.2 Aggregation

The CPS of MAC layer is capable of packing one or more MSDUs in a single MPDU due to the variable size of MSDU. The size of the payload is determined by on-air timing slots and feedback from SS. Figure 2.8 shows two complete MSDUs, where one partial MSDU is packed to form the payload of MPDU. The concatenations of this type of MSDUs safe the resources of the MPDU from wastage. The aggregation used in payload is indicated by the "Type" field of GMH of MPDU. To indicate aggregation, the "type" bit is set and the subheaders are used accordingly. Figure 2.8 shows multiple "SH" fields each followed by fragmented MSDU and MSDU. The "SH" field is 1 byte long having three sub fields. The "Fragmented Control (FC)" field indicates whether the MSDU is fragmented or not. The "00" indicates the packet is not fragments while "01", "10", and "11" indicates the packet is fragmented. The "Fragment Sequence Number (FSN)" indicates the sequence number of fragmented MSDU. The "length field" indicates the start of next subheader in the payload.

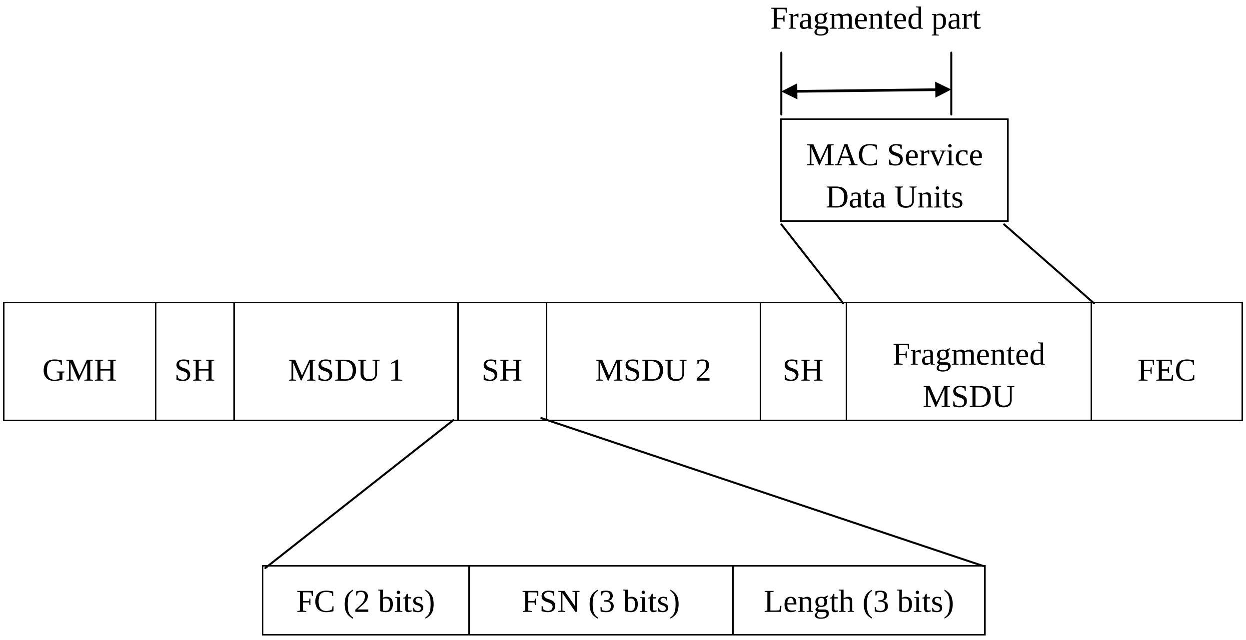


Figure 2.8 Multiple MSDUs Packed into MPDU

2.6.3 Fragmentation

The CPS can fragment the single MSDU into multiple MPDUs. In this case, the payload of MPDU is small to accommodate the complete MAC service data unit. Hence single MSDU is fragmented and packed into multiple MPDUs for transmission.

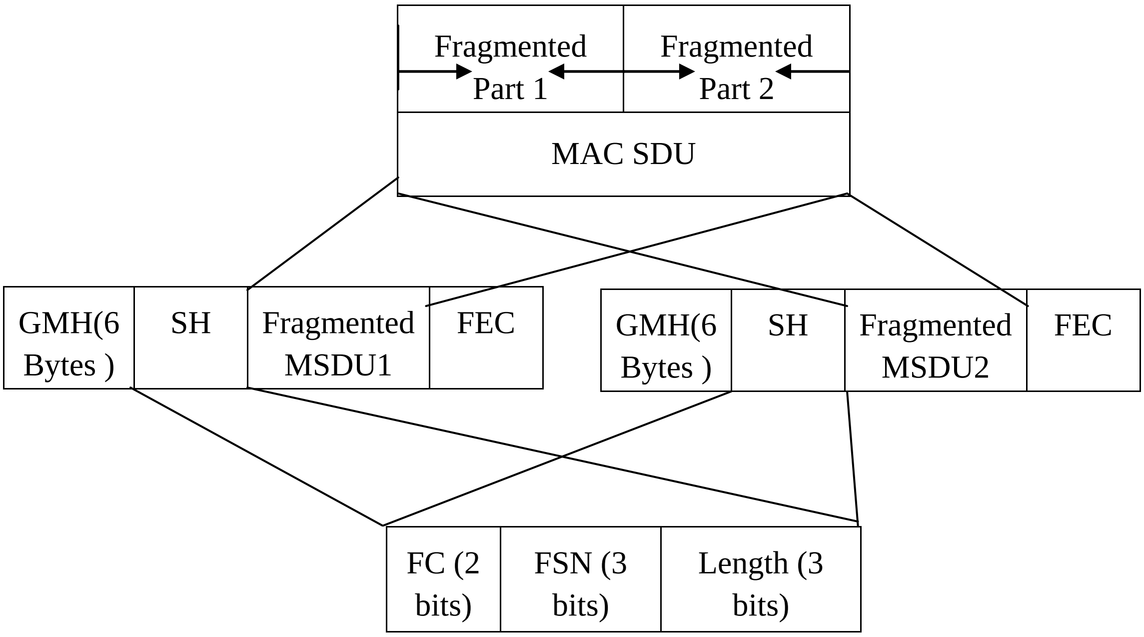


Figure 2.9: Single MSDU Packed into Multiple MAC Packets Data Units (MPDUs)

Figure 2.9 shows the fragmentation of a single MSDU into multiple MPDUs. The “FC” field indicates the fragment number in case of Fragmentation. The “10” in “FC” indicates the first fragment, “01” indicates the last fragment and the “11” indicates the fragments in between first and last. The “FSN” has the sequence number of the fragmented MSDU.

2.6.4 Transmission and Connection setup

The connection setup between SSs and the BS is established in three phases.

Phase 1: SS sends connection request

SS sends the ranging request packet to the BS which enables the timing, initial ranging and power parameters of the BS. The request for service flow parameters is sent next to the ranging packet request and turn on the variable size MSDUs. The service flow parameters include bandwidth, frequency and peak services.

Phase 2: BS confirmation

When the ranging request packet is received, the BS transmits the ranging response to SS with initial ranging, timing and power adjustment parameters. The service flow parameters are agreed on this stage and CID is given to the subscriber station.

Phase 3: Transmission of MPDUs

The MSDUs provided by the MAC convergence layer are organized in MPDUs. The MSDUs are either fragmented or packed into one or several MPDUs depending on the need. At the start of transmission there is no feedback received from the receiver. When feedback is received, the next MPDU is ready to transmit but it depends upon the type of feedback response. If the response is positive the next MPDU is transmitted over the air while in case of negative feedback the packets are retransmitted.

2.6.5 Automatic Repeat Request (ARQ)

The mechanism of sending feedback use ARQ to check whether the packet is received correctly or not. In WiMAX, ARQ is optional and used when needed. The header format of ARQ is shown in Figure 2.10.

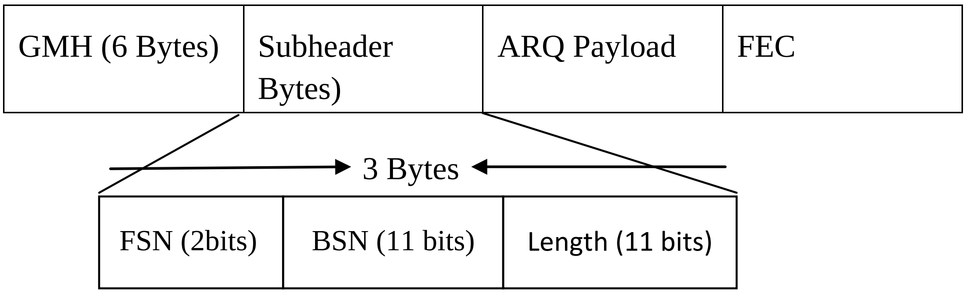


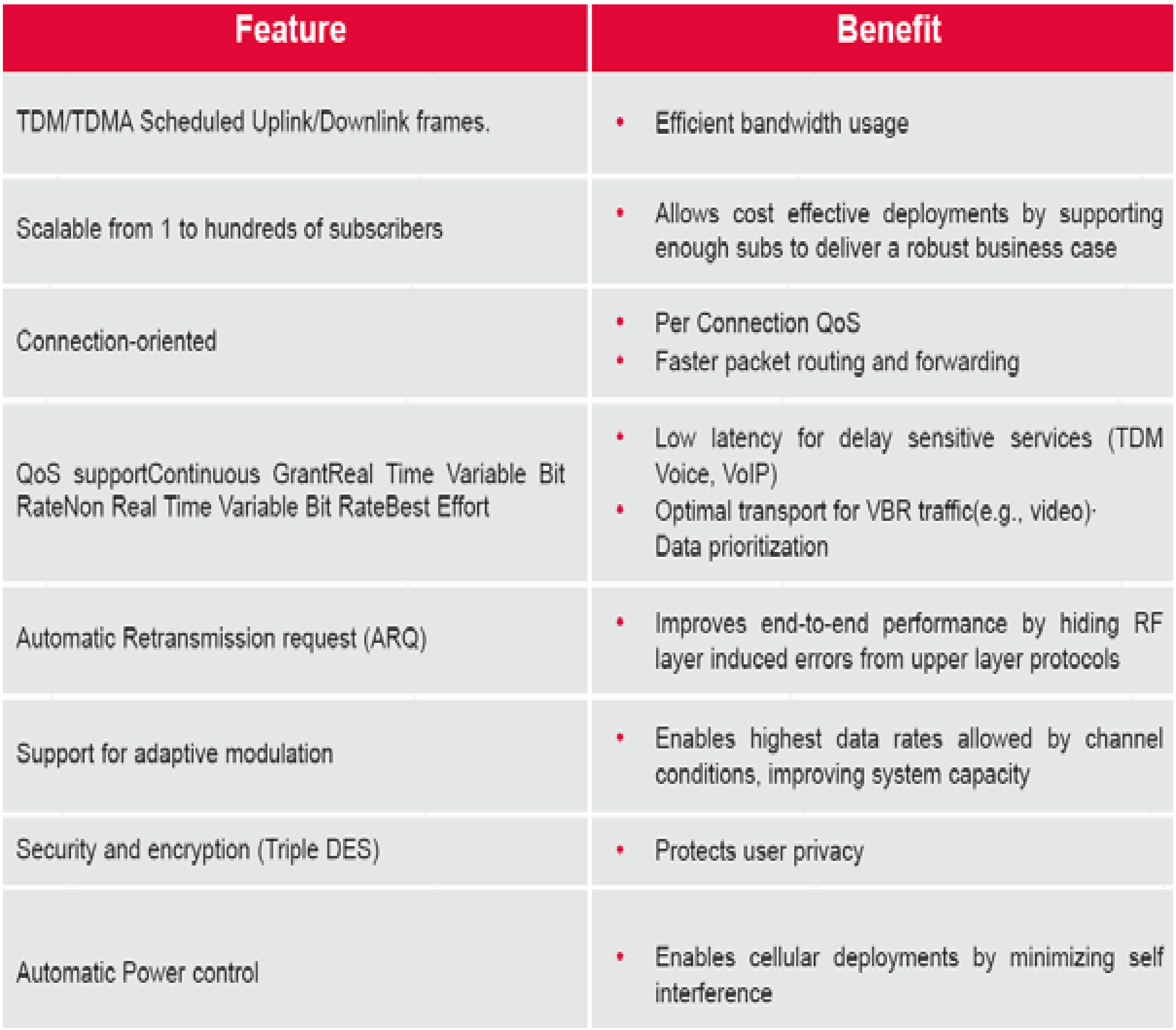
Figure 2.10: ARQ MAC Frame Format

To indicate ARQ, the "Type" field of the GMH has a specific value and the subheader is extended. The ARQ MAC frame uses 11 bits Block Sequence Number (BSN) instead of using FSN to store the sequence number of the block.

2.6.7 Features of MAC Layer

MAC layer is designed to support large amounts of traffic including voice and video services by providing peak data rates over the channel. MAC layer is developed to sustain the PMP frame with centralized BS. TDM is used as multiplexing technique in the downlink while the uplink is shared between subscriber stations with TDMA.

The key features of MAC layer are summarized in Table 2.5 [9].



Feature	Benefit
TDM/TDMA Scheduled Uplink/Downlink frames.	• Efficient bandwidth usage
Scalable from 1 to hundreds of subscribers	• Allows cost effective deployments by supporting enough subs to deliver a robust business case
Connection-oriented	• Per Connection QoS • Faster packet routing and forwarding
QoS supportContinuous GrantReal Time Variable Bit RateNon Real Time Variable Bit RateBest Effort	• Low latency for delay sensitive services (TDM Voice, VoIP) • Optimal transport for VBR traffic(e.g., video)· Data prioritization
Automatic Retransmission request (ARQ)	• Improves end-to-end performance by hiding RF layer induced errors from upper layer protocols
Support for adaptive modulation	• Enables highest data rates allowed by channel conditions, improving system capacity
Security and encryption (Triple DES)	• Protects user privacy
Automatic Power control	• Enables cellular deployments by minimizing self interference

Table 2.5: WiMAX MAC Layer Features [9]

2.7 Multi Antenna Technologies

WiMAX supports multi antenna technologies in order to provide data rates and spectral efficiencies, which distinguish it from wireless technologies such as High Speed Downlink Packet Access (HSDPA) and 1x EV-DO. WiMAX has two standards IEEE 802.16-2004 and IEEE 802.16-2005, based on OFDM and OFDMA, respectively. Multiple antenna technologies are easy to implement in WIMAX due to the simplicity of OFDM and OFDMA based physical layers in the sense of orthogonality between subcarriers and support of flexible bandwidths. These implementations increase the range, capacity, diversity, data rates and efficiency of the system as compared to a single antenna system.

Multiple antenna technologies are normally divided into three types:

- Smart Antenna System (SAS)
- Diversity Techniques
- Multiple Input Multiple Output (MIMO)

2.7.1 Smart Antenna System

SAS is known as Adaptive Antenna System (AAS). SAS constructs the channel model and attains channel knowledge by using signal processing techniques in order to steer the beam towards the desired subscriber while transmitting null steering towards the interferer [10]**.** The null steering cancels out undesired portion of the signal and reduces the gain of radiation pattern obtained from adaptive array antenna in the direction of interference source. This is achieved by using beamforming and null steering towards desired user and interferer respectively. The process of combining the radiated signal and focusing it in the desired direction is called Beamforming [10]. SAS is divided as follows.

2.7.1.1 Switch Beam Antennas

Switch beam antenna forms several fixed beams to cover the coverage area. It selects the beam pattern which has strong power towards the direction of intended user. As the mobile moves, the beam switching algorithm determines when a particular beam should be selected to enhance the quality of the mobile user. Switched beam antennas continuously scan the output of each beam and select the beam having strongest output power. Figure 2.11 shows the Switch beam antenna.

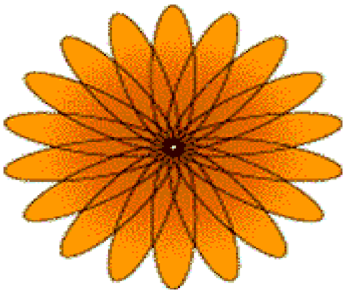


Figure 2.11: Switched Beam Antenna [11]

2.7.1.2 Adaptive Array Antenna

Adaptive array antenna has an infinite number of beam patterns that can be adjusted according to real time scenarios. The adaptive array utilizes advanced signal processing techniques to distinguish between the interferer, multipath and the desired subscriber. It continuously monitors the changes between interfering desired signal locations, and maximizes the link budget (estimation and determination of all gains and losses of transmitted signal upon arrival at the receiver) due to its ability to track the interferer with null and users with main lobes. Figure 2.13 shows the adaptive array antenna.

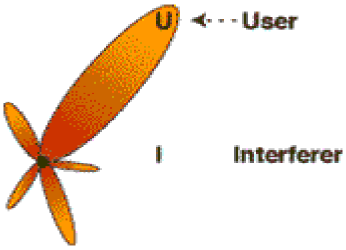


Figure 2.12: Adaptive Array System [11]

2.7.2 Diversity Techniques

Diversity techniques enhance the performance of the wireless system by reducing the fading a signal faces during its transmission. Time diversity, frequency diversity and space diversity are common types of diversity.

2.7.3 Multiple Input Multiple Output (MIMO)

MIMO refers to a system having minimum two antennas at the base station as well as at the mobile station. MIMO system enhances the performance of WiMAX including spatial multiplexing, diversity and interference reduction. WiMAX supports two forms of MIMO systems, Open loop MIMO and Closed loop MIMO systems. A general MIMO system is shown in Figure 2.13.

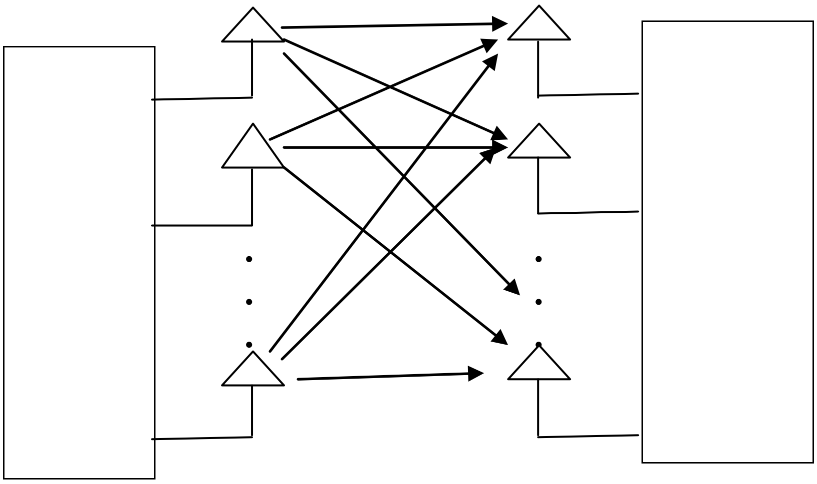


Figure 2.13: General MIMO System

2.7.3.1 Open loop MIMO System

Open loop MIMO techniques are subdivided into Matrix A and Matrix B. Open loop MIMO does not utilize the information of the channel. Matrix A refers to the Space Time Block Coding (STBC) whereas Matrix B refers to the spatial multiplexing in WiMAX. Open loop techniques increase the range and capacity of WiMAX.

2.7.3.2 Closed loop MIMO System

The transmitter collects information about the propagation channel in the closed loop MIMO to further enhance coverage and capacity of WiMAX. Closed loop MIMO utilizes the beamforming or Maximum Ratio Transmission (MRT).

The Multiple antenna organization chart for WiMAX is shown in Figure 2.14.

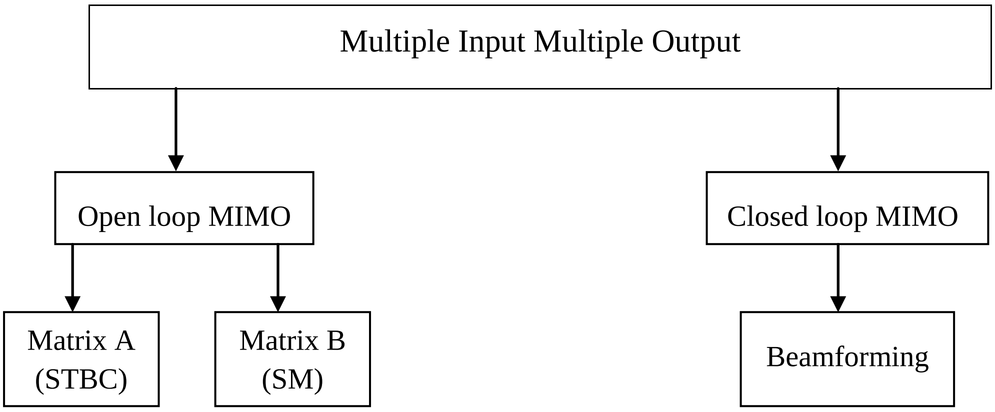


Figure 2.14: WiMAX Multiple Antenna Implementation Organization Chart

2.8 Network Architecture of WiMAX

IEEE 802.16e specifies the air interface but it does not define the end-to-end network architecture for WiMAX. The Network Working Group (NWG) has developed a reference network architecture used for the deployment of WiMAX. Interoperability between various WiMAX equipments and operators can be ensured by this framework. The network architecture is based on IP services and can be divided logically into three parts: Mobile Station (MS), Connectivity Service Network (CSN) and Access Service Network (ASN). Reference network architecture is shown in Figure 2.15 [12].

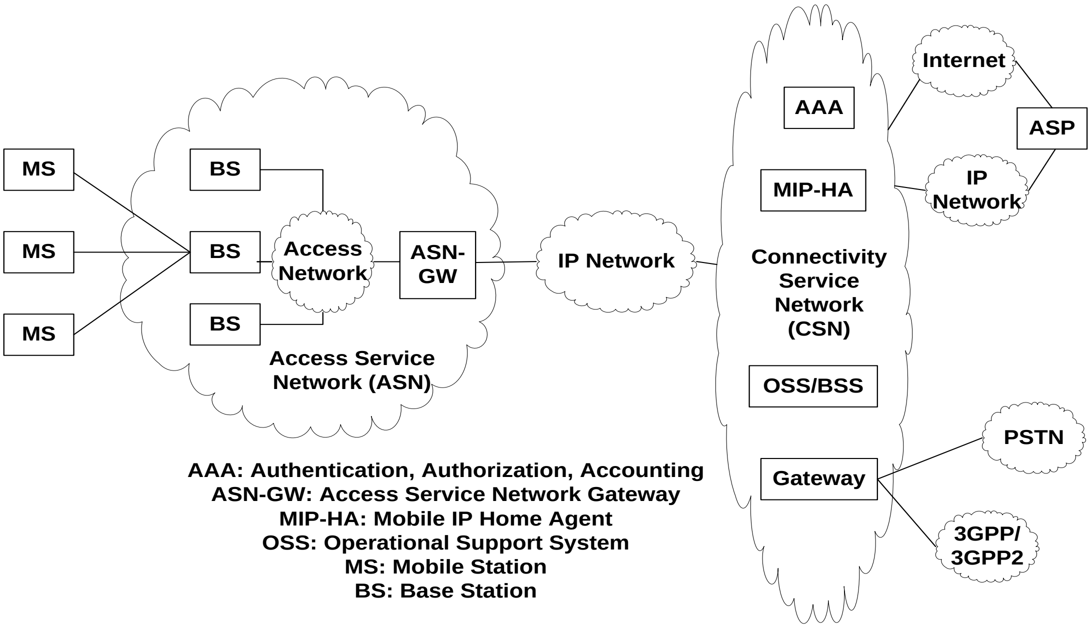


Figure 2.15: WiMAX Network Architecture [12].

Chapter 3: Long Term Evolution

3.1 Overview of 3GPP Long Term Evolution

The 3rd Generation Partnership Project (3GPP) started working on 3G cellular system evolution in November, 2004. The 3GPP is the collaboration agreement for promotion of mobile standards in order to cope future needs (high data rates, spectral efficiencies, etc.). The 3GPP LTE (Long Term Evolution) was developed to provide higher data rates, lower latencies, wider spectrum and packet optimized radio technology.

Like other cellular technologies LTE uses OFDM as multiplexing technique. LTE uses OFDMA as downlink and Single Carrier FDMA (SC FDMA) as uplink transmission technique. The use of SC FDMA in LTE reduces the Peak to Average Power Ratio (PAPR) which is the main drawback of OFDM.

LTE uses wider spectrum, up to 20 MHz, to provide compatibility with existing cellular technologies such as UMTS and HSPA+, and increases the capacity of the system. LTE uses flexible spectrum which makes it possible to be deployed in any bandwidth combinations. This makes LTE suitable for various sizes of spectrum resources.

LTE uses both FDD and TDD as duplexing techniques to accommodate all types of spectrum resources.

3.2 LTE Performance Targets

The LTE performance targets are shown in Table 3.1.

		Requirements	**Comment**
Downlink	Peak data transmission rate	> 100 Mbps	LTE Bandwidth = 20 MHz Duplexing Mode = FDD Spatial Multiplexing = 2x2
	Peak Spectral Efficiency	> 5 b/s/Hz	
	Spectral Efficiency of cell Edge	> 0.04 – 0.06 bps/Hz/user	Assumed 10 Users/Cell
	Average Cell Spectral Efficiency	> 1.6 – 2.1 bps/Hz/cell	Spatial Multiplexing = 2x2 Receiver = IRC (Interference Rejection Combining)
	Broadcost Specral Efficiency	1 bps/Hz	Carrier dedicated for Broadcast mode

		Requirements	Comments
Uplink	Peak Data Transmission Rate	> 50 Mbps	LTE Bandwidth = 20 MHz Duplexing Mode = FDD Transmission = Single Antenna
	Peak Spectral Efficiency	> 2.5 bps/Hz	
	Spectral Efficiency of Cell Edge	> 0.02 – 0.03 Bps/Hz/user	Single Antenna transmission Receiver =IRC
	Average Spectral Efficiency	> 0.66 – 1.0 bps/Hz/cell	Assumed 10 Users/Cell
System	Operating Bandwidth	1.4 MHz to 20 MHz	Initially starts at 1.25 MHz
	User Plane Latency	< 10 ms	
	Connection set up Latency	< 100 ms	From Idle mode to Active

Table 3.1: Performance Targets for Long Term Evolution

3.3 LTE Physical Layer

The physical layer of LTE conveys data and control information between E-UTRAN NodeB (eNodeB) and user equipment (UE) in an efficient way. It employs advanced technologies such as OFDM and MIMO for data transmission. In addition, LTE uses OFDMA and SC-FDMA for downlink and uplink data transmissions. The use of SC-FDMA in the uplink reduces PAPR. A detail description of LTE physical layer is provided below.

3.3.1 Generic Frame Structure

The generic frame of LTE has a length of 10ms and is subdivided into ten sub-frames of 1ms length. Each sub-frame is further divided into two slots of 0.5ms having six or seven OFDM symbols depending upon the length of CP. Each slot uses 7 OFDM symbols in case of normal CP whereas 6 OFDM symbols in case of extended CP. Sub-frames can be assigned for either uplink or downlink. The generic frame structure of LTE downlink and uplink is shown in Figure 3.1.

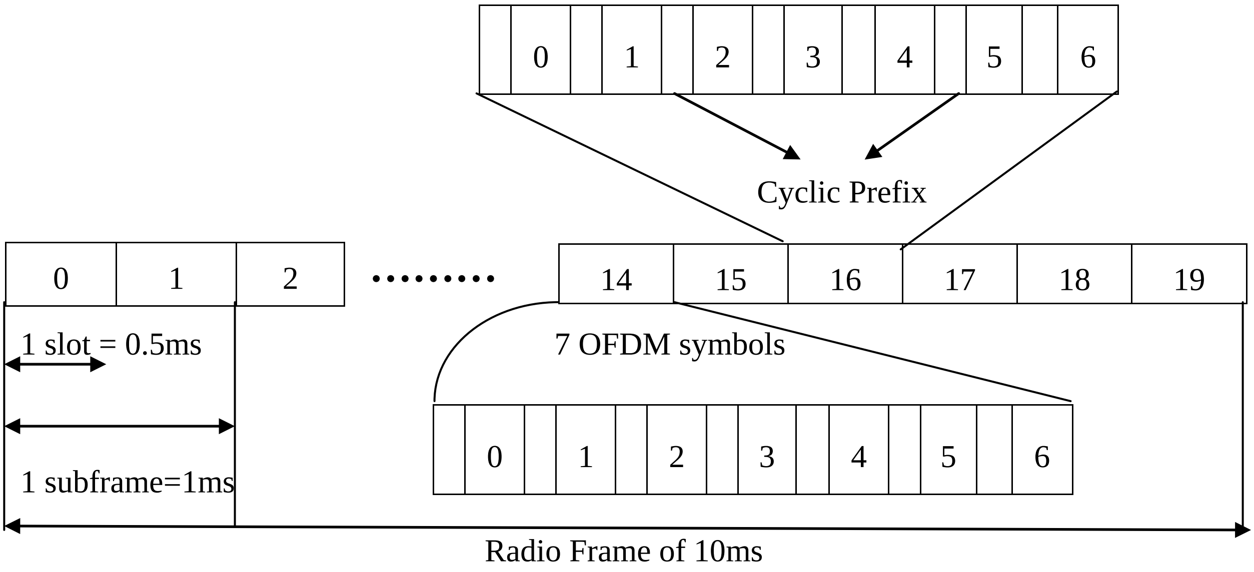


Figure 3.1: Generic Frame Structure for Downlink and Uplink of LTE

In case of FDD, all subframes are used either for downlink or for uplink data transmissions. For TDD, subframe 1 and 6 are used for downlink transmission whereas the rest of the frames are used either for uplink or downlink. Subframes 1 and 6 contain synchronization signals for downlink. Figure 3.2 shows downlink and uplink subframe assignments for FDD.

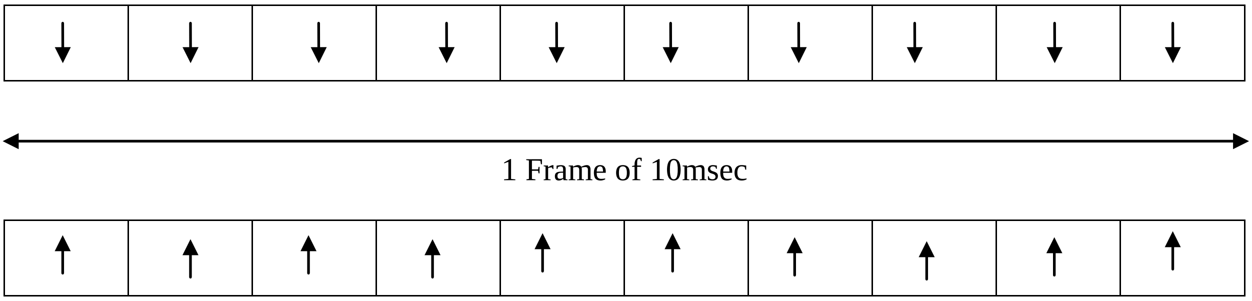


Figure 3.2: Downlink and Uplink Subframe Assignment for FDD

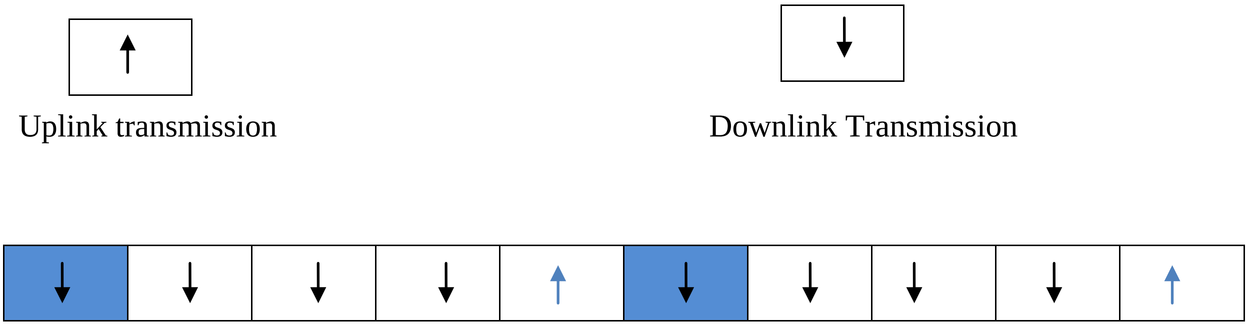


Figure 3.3(a): Downlink Subframe Assignment for TDD

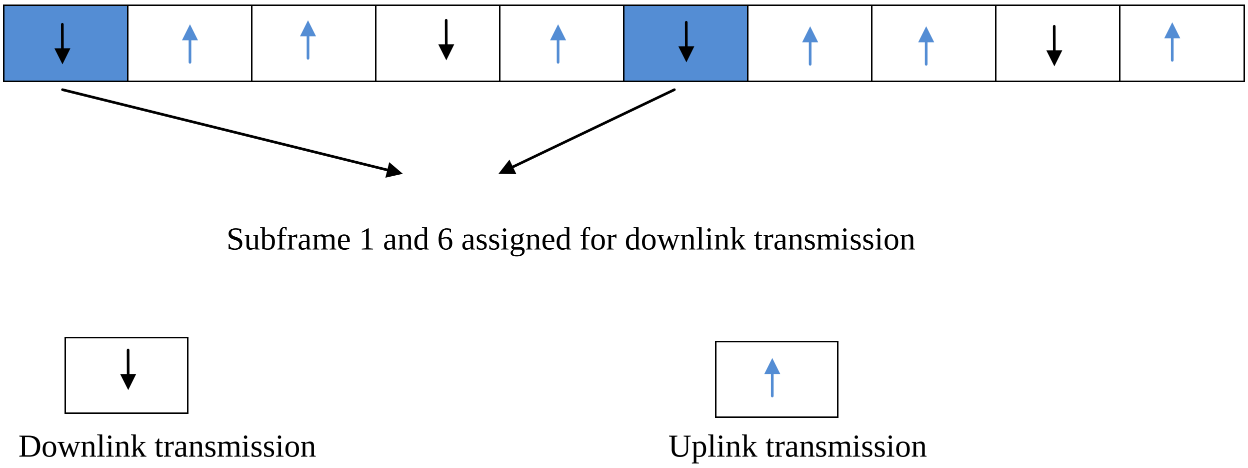


Figure 3.3(b): Uplink Subframe Assignment for TDD

Figure 3.3(a) and Figure 3.3(b) show the uplink subframe assignments for FDD and TDD.

3.3.2 LTE Physical Layer for downlink Transmission

3.3.2.1 Modulation Parameters

The transmission scheme used in downlink is OFDM using a cyclic prefix. The basic subcarrier spacing is 15 kHz with OFDM symbol duration of 66.67us. The downlink uses a subcarrier spacing of 7.5 kHz with OFDM symbol duration of 133us in case of Mobile Broadcast Single Frequency Network (MBSFN). MBSFN refers to a mobile network using a single band on which broadcasted and dedicated signals are sharing single frequency [13]**.** Two types of cyclic prefixes are used, depending on the delay dispersion characteristics of the radio cell (channel delay spread). The normal CP is used in urban or high frequency areas whereas extended CP is used in rural and low frequency areas.

The modulation parameters for various transmission bandwidth configurations for LTE are shown in Table 3.2.

Parameters	**Values**					
Transmission Bandwidth (MHz)	1.25	2.5	5	10	15	20
Subcarrier Spacing	15 kHz					
Sampling Frequency	1.92 MHz (1/2x3.84 MHz)	3.84 MHz	7.68 MHz (2x3.84 MHz)	15.36 MHz (4x3.84 MHz)	23.04 MHz	30.72 MHz
FFT Size	128	256	512	1024	1536	2048
No. of occupied subcarrier	76	151	301	601	901	1201

Parameters		Values					
Number of OFDM symbols/slot		7 for Normal CP and 6 for Extended CP					
CP lengths (us/sample)	Normal	(4.69/9) x 6, (5.21/10) x 1	(4.69/18)x6 (5.21/10) 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)x6 (5.21/120)x1	(4.69/144) x 6 (5.21/160)x1
	Extended	(16.67/32)	(16.67/64)	(16.67/128)	(16.67/256)	(16.67/512)	(16.67/1024)

Table 3.2: Modulation Parameters for Downlink [13]

3.2.2.2 Downlink Physical Resource

The downlink physical resource consists of Physical Resource Blocks (PRBs) where a PRB consists of 12 consecutive subcarriers for one slot (1 slot = 0.5msec). The bandwidth of PRB is 180 kHz. A resource element corresponds to one subcarrier for the duration of one OFDM symbol. Thus depending on the cyclic prefix length, a PRB comprises 84 OFDM symbols in case of normal CP and 72 OFDM symbol in case of extended CP. The number of resource blocks depends upon the transmission bandwidth of LTE i.e. 1.25 MHz to 20 MHz. Table 3.3 shows the number of PRBs for various transmission bandwidths.

Transmission Bandwidth (MHZ)	1.25	2.5	5	10	15	20
Subcarrier BW (kHz)	15					
PRB BW (kHz)	180					
Number of available PRB	6	12	25	50	75	100

Table 3.3: Number of Physical Resource Blocks (PRB) for Various Transmission Bandwidths [14]

The Downlink physical resource in time frequency grid is shown in Figure 3.4 [15].

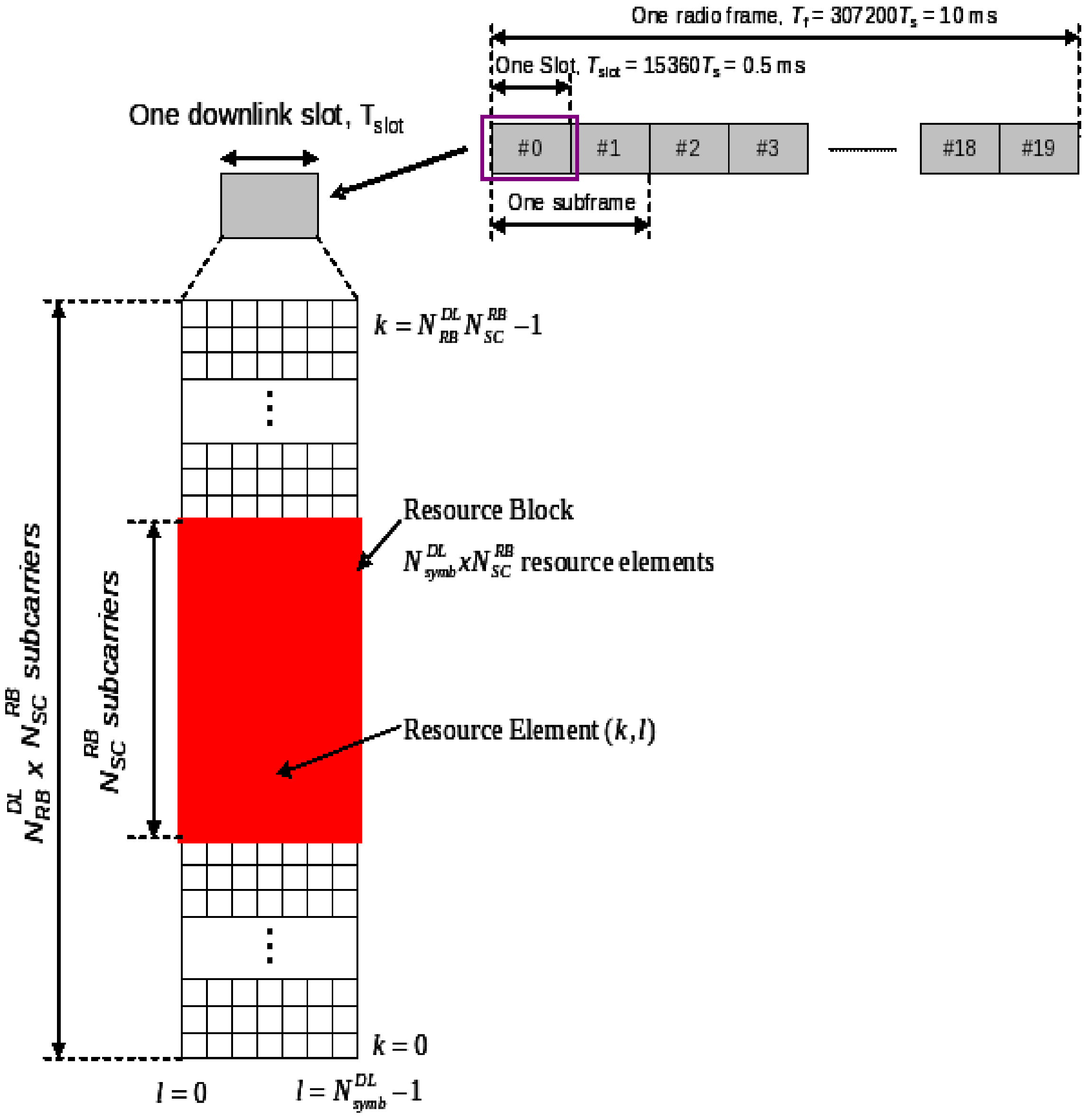


Figure 3.4: LTE Downlink Physical Resource [15]

Figure 3.4 shows that, a PRB is comprised of 12 consecutive subcarriers with a subcarrier spacing of 15 kHz and 7 OFDM symbols for the duration of 0.5ms in case of normal cyclic prefix. Thus a PRB of 84 resource elements (12 x7 = 84) corresponds to one slot in the time domain whereas a PRB of 180 kHz (15 kHz x 12 = 180 kHz) corresponds to the frequency domain.

3.2.2.3 LTE Physical Channels for Downlink

Physical channels convey information from upper layers of the LTE stack. Physical channels are mapped onto transport channels. The transport channels act as an interface or Service Access Points (SAPs) between the MAC and physical layer. Every physical channel has defined the algorithms for bit scrambling, modulation, layer mapping, Cyclic Delay Diversity

(CDD) precoding and resource elements. LTE supports various types of physical channels in the downlink.

Physical Broadcast Channel (PBCH)

It carries paging and control signaling information. The coded broadcast channel transport block is mapped on four subframes within 40ms interval, blindly detected (no explicit signaling) [16]. The subframes are assumed to be self decodable. QPSK is used as modulation technique in this channel [14].

Physical Control Format Indicator Channel (PBFICH)

PBFICH contains the number of OFDM symbols used for Physical Downlink Control Channel (PDCCH) and it informs the UE about this. PBFICH is transmitted in every subframe.

Physical Downlink Control Channel (PDCCH)

PDCCH is used to carry out the control signaling information to UE. PDCCH is used by the eNodeB. It carries ACK/NACK response to the uplink channel, resource allocation information for UE and scheduling grant for UL [16]. Multiple PDCCH can be transmitted in one subframe. PDCCH is mapped onto resource elements in up to the first three OFDM symbols in the first slot of a subframe. It uses QPSK as a modulation technique.

Physical Hybrid ARQ Indicator Channel (PHICH)

It carries the ACK/NAK responses of Hybrid ARQ. It uses QPSK as modulation technique.

Physical Downlink Shared Channel (PDSCH)

It is utilized for transportation of data and multimedia services. Due to requirement of high data rates, it uses modulation techniques such as QPSK, 16 and 64-QAM. Spatial multiplexing is implemented in PDSCH.

Physical Multicast Channel (PMCH)

It carries multicast data. It uses QPSK, 16-QAM and 64-QAM as modulation techniques.

3.2.2.4 LTE Downlink Physical Signals

Physical signals use assigned resource elements in the physical resource. They do not convey information to (or from) upper layers of the LTE stack.

There are two types of physical signals used in LTE:

Reference Signals

Reference signals are generated as a combination of Pseudo Random Numerical (PRN) sequence and an orthogonal sequence. They are used to determine the Channel Impulse Response (CIR). Reference signals consist of known reference symbols that are inserted in the first and third OFDM symbol of every slot. There are 510 unique reference signals. Reference signals are of three types:

- Cell specific reference signals.
- User equipment specific reference signals.
- Mobile Broadcast Single Frequency Network (MBSFN) reference signals.

Cell specific reference signals are associated with non MBSFN transmission. They use 1, 2 or 4 antenna ports for the transmission.

MBSFN reference signals are associated with MBSFN transmission. They are transmitted on antenna port.

UE reference signals support single antenna port transmissions of PDSCH in the frame structure of type 2.

Figure 3.5 [17] shows the cell specific reference signals.

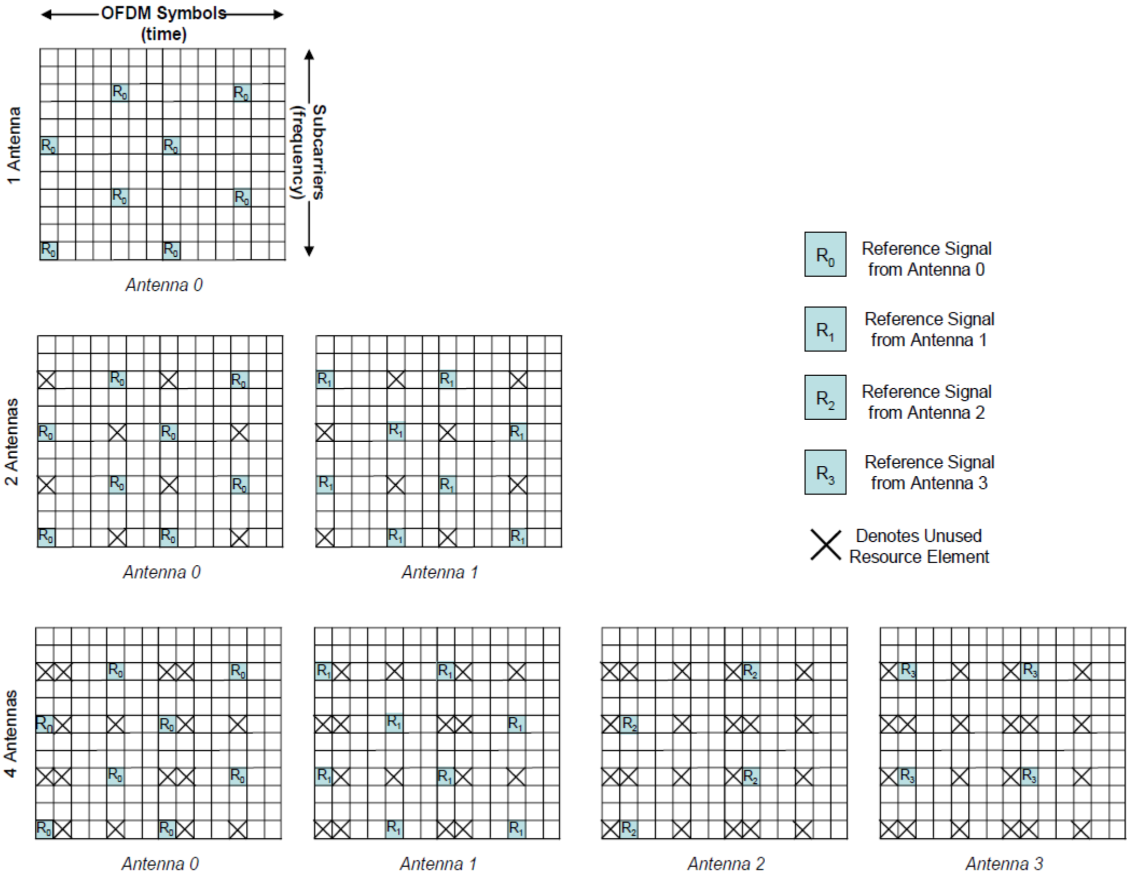


Figure 3.5: Cell Specific Reference Signals [17]

Figure 3.5 shows that reference signals are transmitted on first and fourth OFDM symbol of every slot, which depend on the antenna port and type of the frame structure.

Synchronization Signals

Synchronization signals are used for cell identification and slot synchronization. For this purpose they use Primary Synchronization Channel (P-SCH) and Secondary Synchronization Channel (S-SCH). Synchronization signals are transmitted on 72 subcarriers centered around the DC subcarrier during every 0 and 10 frame slot [14]. The modulation schemes used in physical signals are shown in Table 3.4.

Physical Signals	Modulation Scheme
Reference Signals	Orthogonal Sequence of binary PN sequence
Primary Synchronization Channel (P-SCH)	Cycle of 3 Zadoff-Chu sequence
Secondary Synchronization Channel (S-SCH)	Two 31 bit BPSK M sequences

Table 3.4: Modulation Schemes for Downlink Physical Signals

3.2.2.5 LTE Downlink Transport Channel

Transport channels act as an interface between MAC and the physical layer [18]. They transfer the information to MAC and upper layers. The description of downlink transport channel is described below.

Broadcast Channel (BCH)

Broadcast channel is used to broadcast the system parameters (such as random access related parameters) to enable the devices accessing the system.

- Fixed transport format
- Broadcast the information in the entire cell coverage area.

Downlink Shared Channel (DL-SCH)

It carries user data information for point to point connection in the downlink. DL-SCH is characterized as:

- Dynamic link adaptations supported by varying the coding, modulation and transmit power.
- Suitable to use with beamforming.
- Hybrid ARQ.
- Can be broadcasted in the entire cell coverage area.
- Support for semi static and dynamic resource allocation.
- MBMS transmission.

Paging Channels

Paging channels are used to carry paging information to move the device from RRC_IDLE state to RRC_CONNECTED state. In RRC_CONNECTED state a mobile has established RRC connection with SGSN (Serving GPRS Support Node) and Radio Access Network (RAN). Paging channels are characterized as follows:

- Requirement for broadcast over whole cell coverage area.
- Mapped to physical resources which can be allocated dynamically for traffic channels.

Multicast Channel (MCH)

Multicast channel is used to transfer multicast data to the UE in the downlink.

- Requirement for broadcast over whole cell coverage area.
- Provides support for MBSFN.
- Semi static resource allocation.

3.2.2.6 Mapping of Downlink Transport channels to Downlink Physical Channels

Figure 3.6 shows the mapping of downlink transport channel to physical channel. The PCH and DL-SCH are mapped on PDSCH. BCH is mapped on PBCH and MCH is mapped on his related downlink PMCH physical channel.

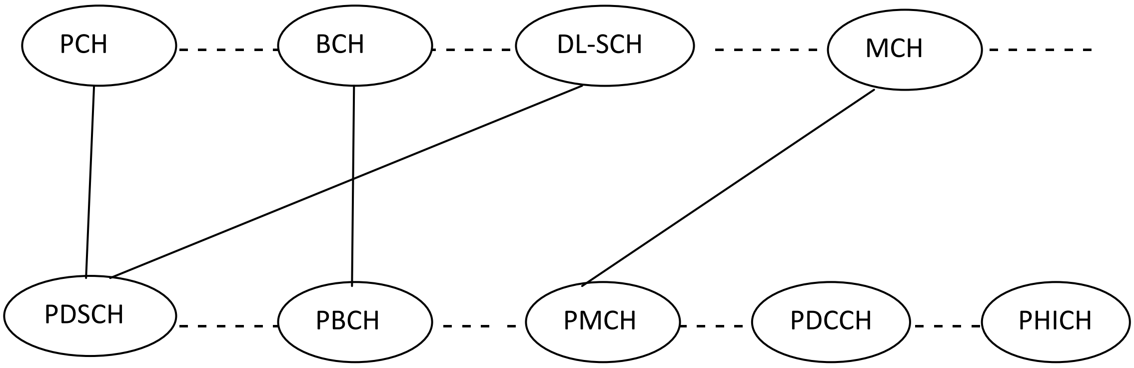


Figure 3.6: Mapping of Downlink Transport Channels to Physical Channels [16]

Transport channels provide the structure for transferring data to or from upper layers, the mechanism for configuring the physical layer, peer to peer signaling for upper layers and status indicators (Channel-Quality Indicator (CQI), packet errors) to upper layers.

3.2.2.7 OFDMA Basics

OFDMA is an extension of OFDM and is used in the downlink of LTE. OFDMA distributes subcarriers to different users at the same time so that multiple users can receive data simultaneously while in OFDM, a single user can receive data on all subcarriers at any given time. Subcarriers are allocated in contiguous groups with a subcarrier spacing of 15 kHz in order to reduce the overhead of indicating which subcarriers have been allocated to each user [19].

OFDMA is based on Discrete Fourier Transform (DFT) and Inverse Discrete Fourier Transform (IDFT) to switch between time and frequency domain. The time domain representation of various inputs applied to FFT are shown in Figure 3.7 [20].

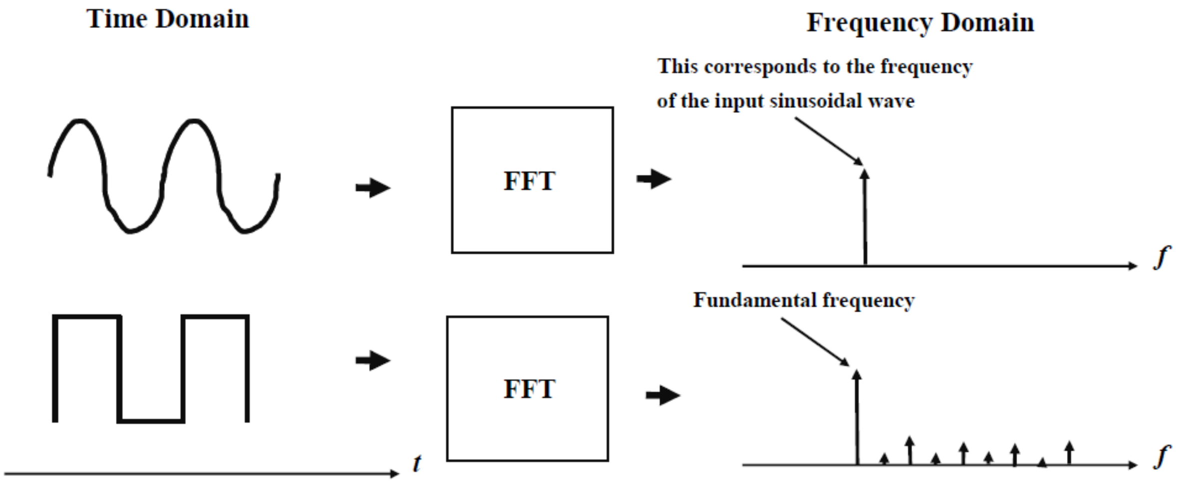


Figure 3.7: FFT Operation Applied to Various Inputs in Time Domain [20]

FFT converts the time domain signal to frequency domain. For a sinusoidal wave, FFT operation results in a peak at the corresponding frequency and zeros elsewhere, while in case of square wave FFT the operation results in having multiple peaks on various frequencies. The bigger peak of square wave corresponds to the fundamental frequency (f = 1 / T) while rests are the odd harmonics of it.

OFDMA Transmitter and Receiver

OFDMA transmitter uses narrow and orthogonal subcarriers such that at the sampling instant of one subcarrier, the remaining subcarriers have zero value. In LTE, OFDMA uses fixed 15 kHz frequency spacing between the subcarriers regardless of the transmission bandwidth. In the OFDMA transmitter, first high data rate bit stream is passed through the modulator. The modulator uses various coding schemes such as QAM. The modulated bits are converted from serial to parallel which becomes the input of IFFT block. The inputs to the IFFT block are the subcarriers converted into the time domain signal. CP is added in the signal by copying the part of the symbol at the end and inserted in the beginning. The advantage of adding cyclic prefix is to avoid the ISI. The length of CP should be larger than the channel delay spread or channel impulse response in order to avoid the ISI at the receiver.

The receiver does the inverse procedure by first removing the CP extension followed by serial to parallel conversion. The subcarriers are then passed to FFT block which converts them into a frequency domain signal. The frequency domain signal is equalized and demodulated.

The Transmitter-Receiver block diagram of OFDMA is shown in Figure 3.8 [21].

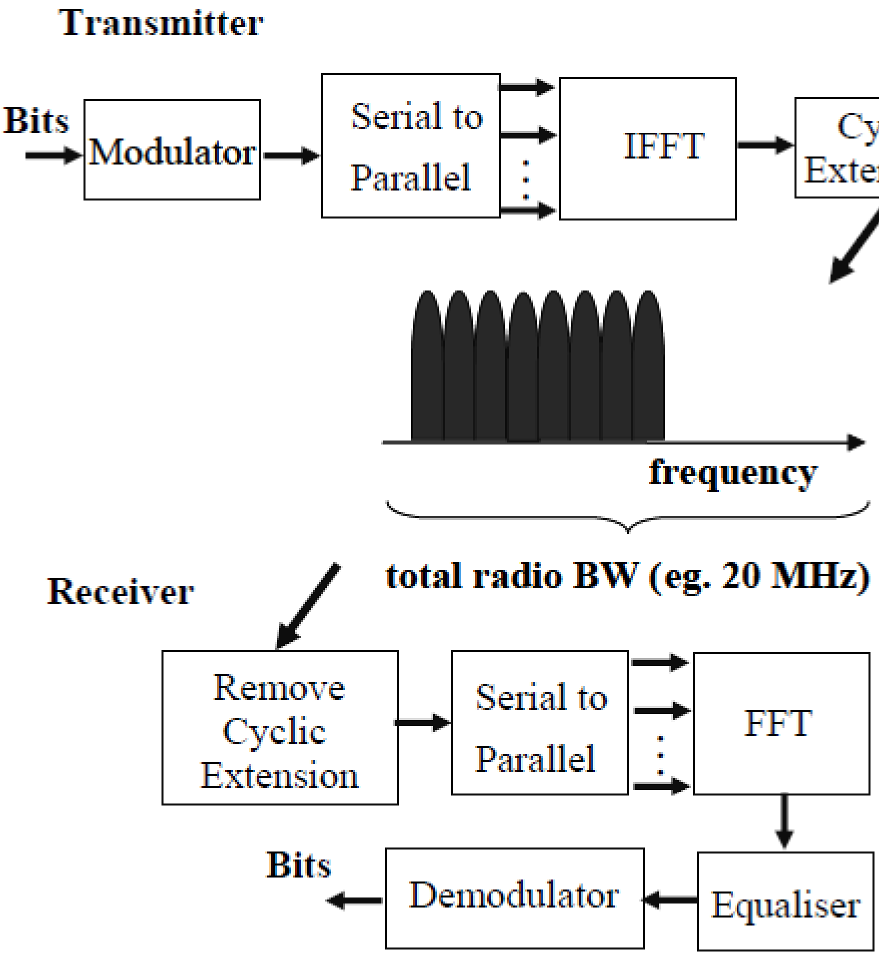


Figure 3.8: Transmitter-Receiver Block Diagram for OFDMA [21]

OFDMA arranges the subcarrier on the basis of resource blocks instead of individual subcarriers. A resource block is comprised of 12 consecutive subcarriers with 15 kHz frequency spacing in the frequency domain for a duration of 0.5ms in time domain. The size of RB is 180 kHz in the frequency domain while having 84 OFDM symbols (12 x 7 = 84) in the time domain as in the case of normal CP. One OFDM symbol corresponds to a Resource Element (RE). The OFDMA resource blocks in LTE are shown in Figure 3.9 [21].

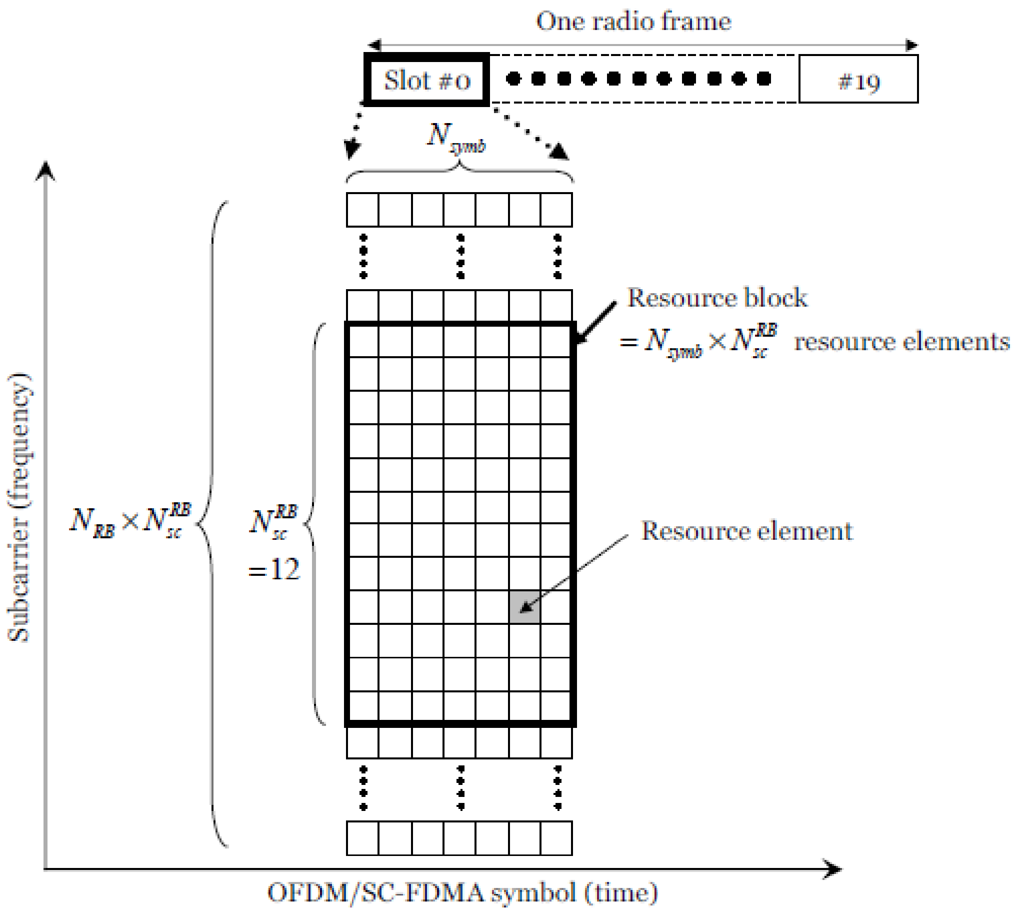


Figure 3.9: Structure of OFDMA Resource Blocks [21]

3.2.2.8 Downlink Physical Layer Processing

Physical layer interfaces to MAC layer by mean of transport channels. The LTE physical layer receives data in the form of transport blocks of a certain size. The downlink transport channel processing consists of the steps depicted in Figure 3.10.

CRC Insertion
Channel coding
Hybrid ARQ Processing
Channel Interleaving
Scrambling
Modulation
Layer mapping and Pre-coding
Antenna Mapping
Resource Management

Figure 3.10: LTE Physical Layer Processing in Downlink [22]

CRC Insertion: A 24 bits CRC is inserted in the beginning of the transport blocks. CRC detects residual errors at the receiver by decoding the transport blocks.

Channel Coding: It uses turbo coding based on Quadratic Polynomial Permutation (QPP) inner interleaving with trellis termination [23].

Hybrid ARQ (HARQ) processing: The functionality of downlink hybrid ARQ is to extract the bits from the blocks of code bits delivered by the channel encoder and to transmit the exact set of bits within a given Transmission Time Interval (TTI). The number of extracted bits depends on the modulation scheme, assigned resource size and spatial multiplexing order.

If the number of coded bits from the channel encoder is larger than the number of bits to be transmitted, the hybrid ARQ will extract the subsets of code bits with an effective rate $R_{eff} > 1/3$.

If the number of encoded bits from the channel is smaller than the number of bits that have to be transmitted, the hybrid ARQ will repeat the subset of bits or total bits with an effective rate of $R_{eff} < 1/3$.

Hybrid AQR transmits the various code bits set in case of a retransmission.

Scrambling: "Scrambling of coded data ensures that the receiver side decoding can utilize the processing gain provided by the channel code" [24]. In LTE, scrambling is applied on the bits delivered from the HARQ by multiplying with the scrambling sequence. The downlink scrambling is shown in Figure 3.11.

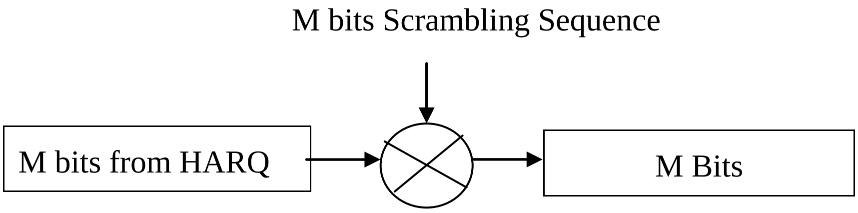


Figure 3.11: Downlink Scrambling

Scrambling is applied to DL-SCH, PCH, and BCH while MCH uses cell common scrambling.

Modulation: The LTE downlink supports 16-QAM, 64-QAM and QPSK as modulation schemes. Modulation is performed on the scrambled bits and results in the M/L modulation symbols where L = 2, 4, 6 for QPSK, 16-QAM and 64-QAM respectively. BCH uses QPSK as modulation scheme. The block diagram for downlink modulation is shown in Figure 3.12.

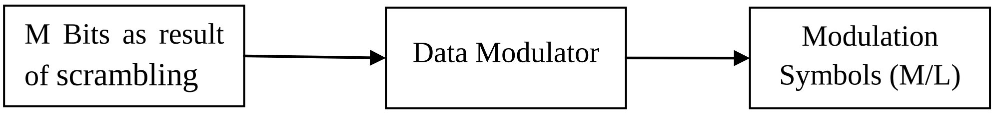


Figure 3.12 Downlink Modulation

Antenna Mapping: Antenna mapping jointly processes the modulation symbols, corresponding to two transport blocks in general and maps the output to various antenna ports.

In LTE, antenna mapping can be configured to support spatial multiplexing, transmit diversity and multi-antenna schemes.

Resource Block Mapping: It maps the symbols which are the outputs of the antenna port to the resource elements of the resource blocks. The resource blocks are assigned by the MAC scheduler for the transport block(s) transmission to terminal.

3.3.3 Uplink Physical Layer

3.3.3.1 Modulation Parameters

Uplink uses a frequency spacing of 15 kHz between subcarriers. The subcarriers are grouped in the form of RBs comprised of 12 consecutive SCFDMA subcarriers for the duration of one slot (0.5ms) using normal or extended cyclic prefixes. A slot uses 7 and 6 SC-FDMA symbols in the case of normal and extended CPs respectively. The duration of normal and extended CPs are as

Normal CP: T_{CP} = 160×Ts = 5.2 us (SC-FDMA symbol #0), T_{CP} = 144×Ts = 4.7 us (SC-FDMA symbol #1 to #6).

Extended CP: $T_{CP\text{-}e}$ = 512×Ts = 16.67 us (OFDM symbol #0 to OFDM symbol #5)

Due to the fixed size of RBs in LTE, uplink supports a number of resource blocks ranging from $N_{RB\text{-}min}$ = 6 to $N_{RB\text{-}max}$ = 110 in frequency domain, where $Ts = 1/2048x\Delta f$ and Δf is subcarrier spacing.

$$N_{RB}(Number\ of\ RB) = \frac{Transmission\ Bandwidth\ of\ LTE}{Bandwidth\ of\ Resource\ Block}$$

$$N_{RB-min} = \frac{Minimum\ Transmission\ Bandwidth\ of\ LTE}{Bandwidth\ of\ Resource\ Block} = \frac{1.25\ MHz}{180\ kHz} = 6$$

$$N_{RB-max} = \frac{Maximum\ Transmission\ Bandwidth\ of\ LTE}{Bandwidth\ of\ Resource\ Block} = \frac{20\ MHz}{180\ kHz} = 110$$

Data is mapped onto the QPSK, 16-QAM and 64-QAM in the LTE uplink. The modulated symbols are fed into a serial-to-parallel convertor instead of modulating the QPSK/QAM symbols directly in the LTE downlink OFDM. The FFT block takes the parallel modulated symbols as an input and transforms them into discrete frequency domain sequences. The discrete Fourier terms are mapped to the subcarriers and converted back into the time domain by using IFFT. The CP is added and the signal is sent for transmission.

The use of SC-FDMA in the uplink minimizes the PAPR as compared to OFDM and is bandwidth efficient.

3.3.3.2 Uplink Physical Resource

The uplink physical resources can be shown in form of time-frequency resource grids. Uplink supports two frame structures similar to the downlink LTE. We consider a generic frame structure of LTE and discuss the resources according to it. The generic frame structure is comprised of 10 subframes with a duration of 10msec. The subframes are further divided into slots of 0.5msec per slot. Every slot consists of 7 or 6 SC-FDMA symbols depending on the type of cyclic prefix. A slot is comprised of 7 SC-FDMA symbols in case of normal CP and 6 for extended CP.

The slot structure for normal CP and extended CP for LTE uplink is shown in Figure 3.13 (a) and 3.13 (b).

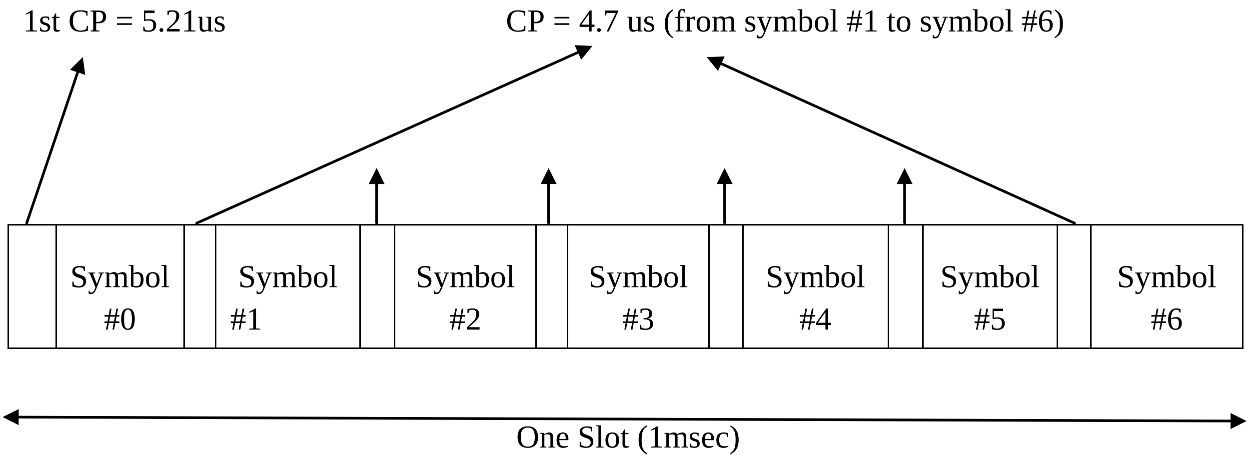


Figure 3.13(a): Uplink Slot Structure in Case of Normal CP

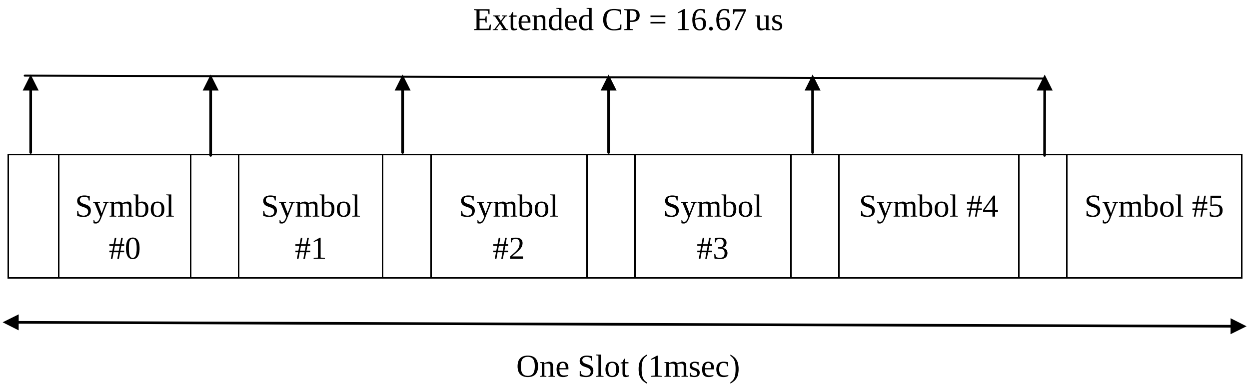


Figure 3.13(b): Uplink Slot Structure in Case of Extended CP

The uplink resources are grouped in RBs where every RB consists of 12 consecutive subcarriers for the duration of one slot in the LTE frame structure. Hence a RB consists of (12x7 = 84 SCFDMA symbols) or (12x6 = 72 SCFDMA symbols) for the normal and extended CP, respectively. The frequency spacing is 15 kHz between the subcarriers.

The transmitted signal in every uplink slot is comprised of N_{RB}^{UL} x N_{SC}^{RB} subcarriers and N_{Symb}^{UL} SC-FDMA symbols as shown in Figure 3.14 [25]. The N_{RB}^{UL} depends on the transmission bandwidth due to its fixed size. The N_{RB}^{UL} ranges from 6 to 110 resource blocks while the transmission bandwidth ranges from 1.25 MHz to 20 MHz. The elements in the resource grid are called resource elements (REs). We can access specific RE by time-frequency coordinates (k, l) where k is subcarrier number and 'l' is the SC-FDMA symbol. The resource grid for LTE uplink is shown in Figure 3.14 [25].

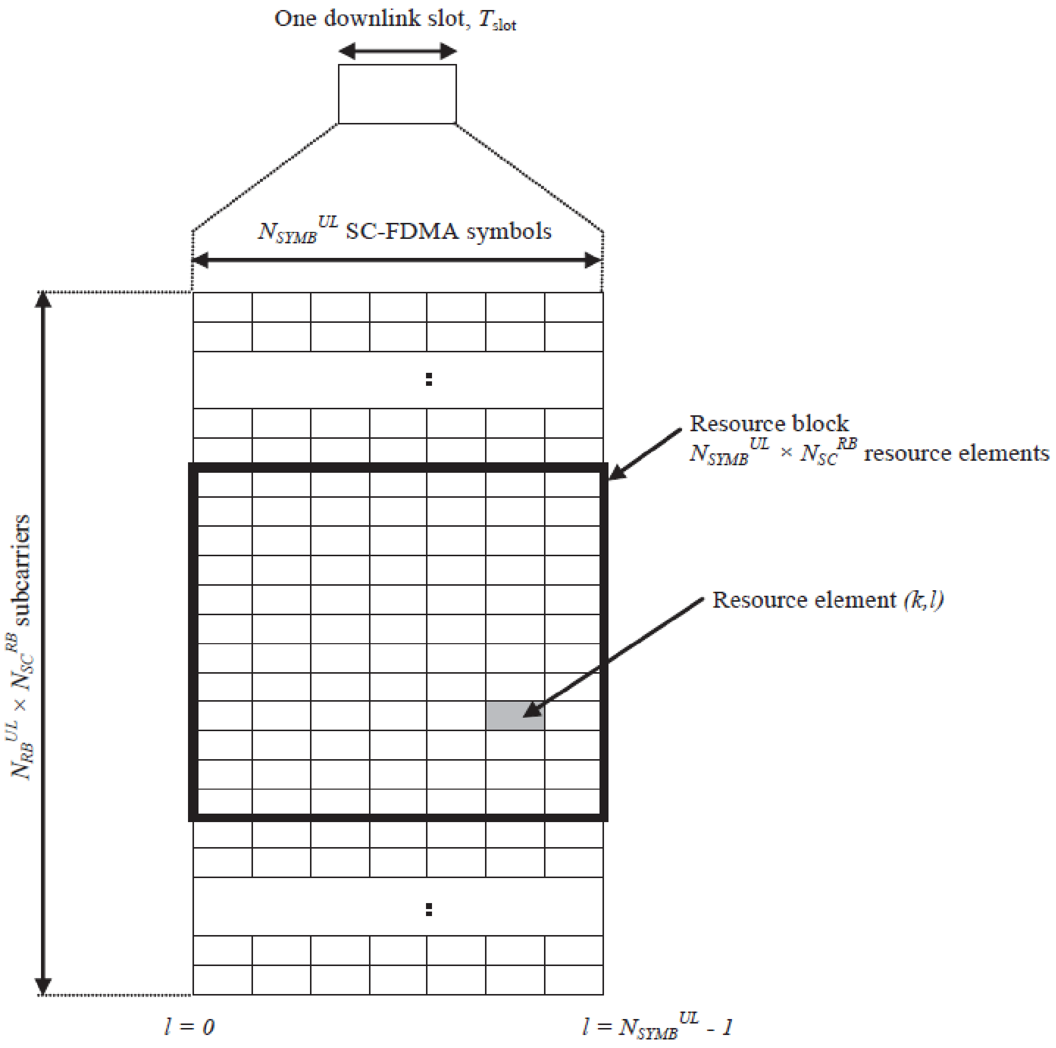


Figure 3.14: Resource Grid for LTE Uplink [25]

3.3.3.3 LTE Uplink Physical Channels:

LTE Uplink supports three types of physical channels:

- Physical Random Access Channel (PRACH).
- Physical Uplink Shared Channel (PUSCH).
- Physical Uplink Control Channel (PUCCH).

Physical Random Access Channel (PRACH)

The PRACH carries the random access preamble. The random access preamble consists of CP length and sequence length. There are four types of preamble formats. The random access preambles are generated from Zadoff-Chu sequences [26] with zero correlation zone generated from one or several root Zadoff-Chu sequences. Zadoff-Chu sequence is a complex mathematical sequence and it generates signals of constant amplitude. The use of Zadoff-Chu sequences reduces the PAPR and BER of LTE uplink. The format of Random Access Preamble is shown in Figure 3.15.

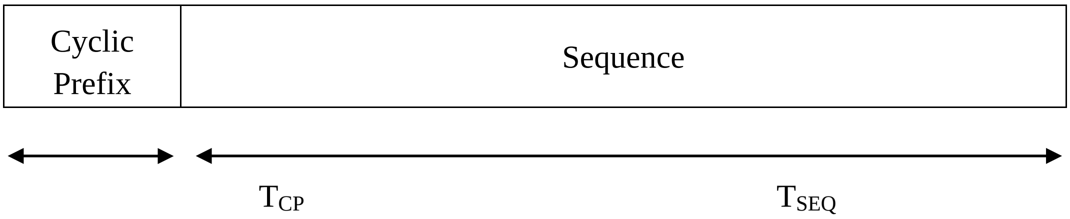


Figure 3.15 Random Access Preamble Format

Physical Uplink Shared Channel (PUSCH)

PUSCH carries user data for transmission (generates time domain SC-FDMA signals for every antenna port). Transmission time is 1msec which is similar to downlink transmission. PUSCH uses QPSK, 16-QAM and 64-QAM modulations.

Physical Uplink Control Channel (PUCCH)

PUCCH carries the uplink control information. It is not simultaneously transmitted with PUSCH for the UE. PUCCH will be mapped to the uplink control channel resource which is defined by a code and two resource blocks, consecutive in time, with hopping at slot boundary [26].

The signaling for uplink can differ depending on presence or absence of time synchronization. In case of time synchronization PUCCH performs the following duties:

- Carries Channel Quality Indicators (CQI) reports.
- Scheduling Request.
- Carries HARQ ACK/NACK responses in reaction of downlink transmission.
- It uses QPSK and BPSK modulation.

The CQI tells the scheduler about the channel conditions seen by UE. The HARQ consists of a single ACK/NACK bit per HAQR process.

3.3.3.4 Uplink Physical Signals

Uplink physical signals are used by the physical layer but they do not carry data from upper layers of LTE. There are two types of uplink physical signals:

- Reference Signals.
- Random Access Preamble.

Reference Signals

In case of normal CP, uplink reference signals are transmitted in the fourth block in every slot in order to facilitate coherent demodulation [27]. There are two types of reference signals:

- Demodulation reference signals: Transmitted in the fourth SC-FDMA symbol in every slot and facilitate coherent demodulation. They are based on Zadoff-Chu sequences.
- Sounding reference signals: Based on Zadoff-Chu sequences and facilitate frequency selective scheduling.

Random Access Preamble

Random access procedure includes upper layers and physical layer of the LTE stack. As the transmission of random access preamble starts, the UE initiates the cell search procedure. If it is successful, a random access sequence is received from the eNodeB. Zadoff-Chu sequences are used to derive the random access preambles. Random access preambles are grouped in 72 contiguous subcarriers for transmission.

The random access preamble shown in Figure 3.16 consists of CP, preamble and a guard period.

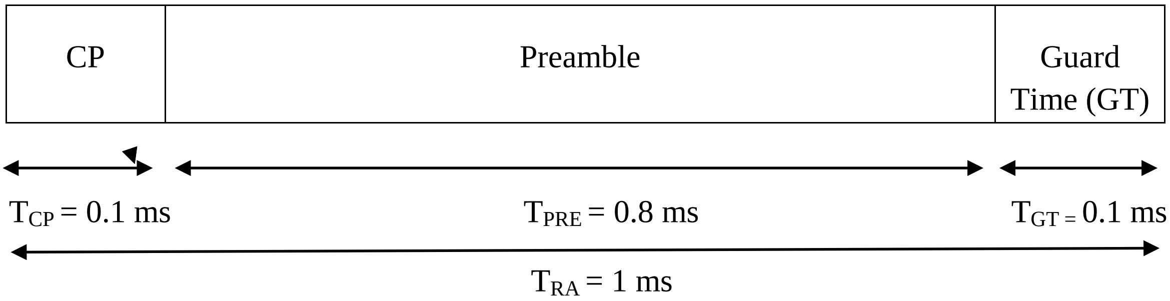


Figure 3.16: Format of Random Access Preamble [14]

Random access preamble is 1ms in duration and comprised of T_{CP} of 0.1 ms, preamble of 0.8 ms and T_{GT} of 0.1 ms. In GT no transmission takes place. Upper layers provide preamble sequences, initial transmission power, available random access channels and maximum number of retries to the PHY. The basic functionality of random access preamble is shown in Figure 3.17 [17].

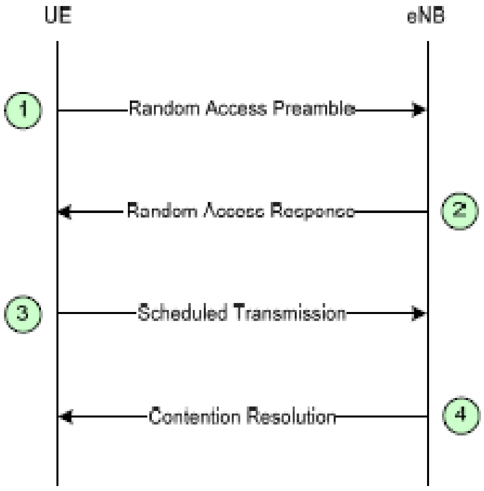


Figure 3.17: Random Access Preamble Functionality [17]

3.3.3.5 LTE Uplink Transport Channels

Uplink transport channels act as an interface between physical and upper layers of LTE stack.

The description of uplink transport channels are as follows:

Uplink Shared Channel (UL-SCH)

- Support for beamforming (optional).
- Hybrid ARQ.
- Dynamic link adaptations are supported by varying coding and modulation.
- Semi-static and dynamic resource allocation.

Random Access Channel (RACH)

- Carries minimal control information.
- Transmission may be lost due to collision.

3.3.3.6 Mapping of Uplink Transport Channels to Uplink Physical Channels

Uplink transport channels are mapped to their respective uplink physical channel as shown in Figure 3.18. UL-SCH is mapped on PUSCH and RACH is mapped on PRACH.

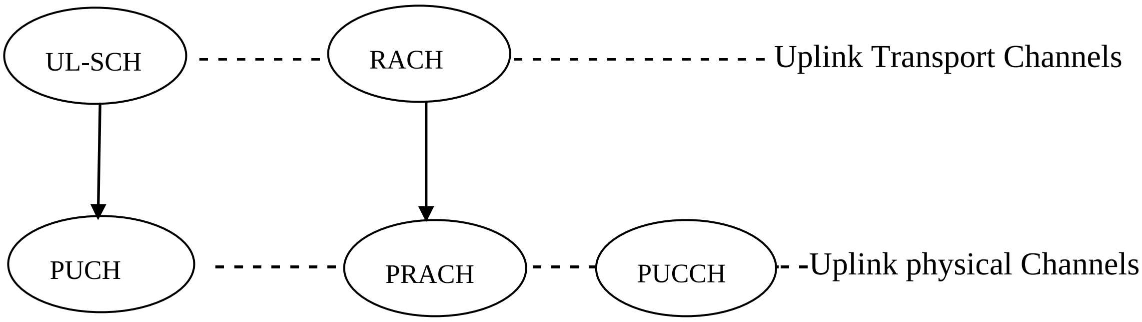


Figure 3.18: Mapping of Uplink Transport and Physical Channels

3.3.3.7 Single Carrier FDMA Basics

Single Carrier-FDMA (SC-FDMA) is an extension of OFDMA and is used in the uplink of LTE. Unlike OFDMA, SC-FDMA reduces the PAPR by adding additional blocks of DFT and IDFT at transmitter and receiver. The transmitter and receiver structure of SC-FDMA is as follows.

SC-FDMA Transmitter

The SC-FDMA transmitter consists of function blocks similar to OFDMA. The block diagram of SC-FDMA is shown in Figure 3.19. The input data stream is first modulated to single carrier symbols by using QPSK, 16-QAM or 64-QAM. The resultant modulated symbols become the inputs of the functional blocks of SC-FDMA. The description of every functional block is described below.

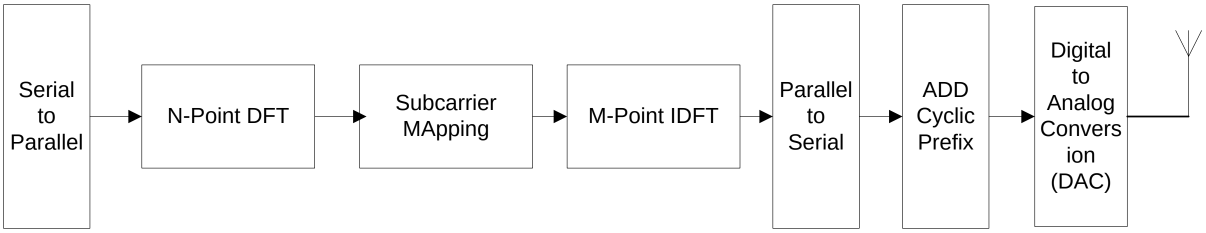


Figure 3.19: SC-FDMA Transmitter Structure

Serial to Parallel Convertor (S-to-P): The modulated symbols are converted into parallel symbols and organized into blocks.

N-Point DFT (Discrete Fourier Transform): Converts time domain single carrier blocks into N discrete frequency tones.

Subcarrier Mapping: Controls the frequency allocation, and maps N-discrete frequency tones to subcarriers for transmission. The mapping can be localized or distributed. In localized mapping, N-discrete frequency tones are mapped on N consecutive subcarriers where as in distributed mapping, N-discrete frequency tones are mapped on uniformly spaced subcarriers. Figures 3.20(a) and 3.20(b) show the localized and distributed mapping respectively. LTE uses localized mapping because it exploits frequency selective gain by channel dependent scheduling [28].

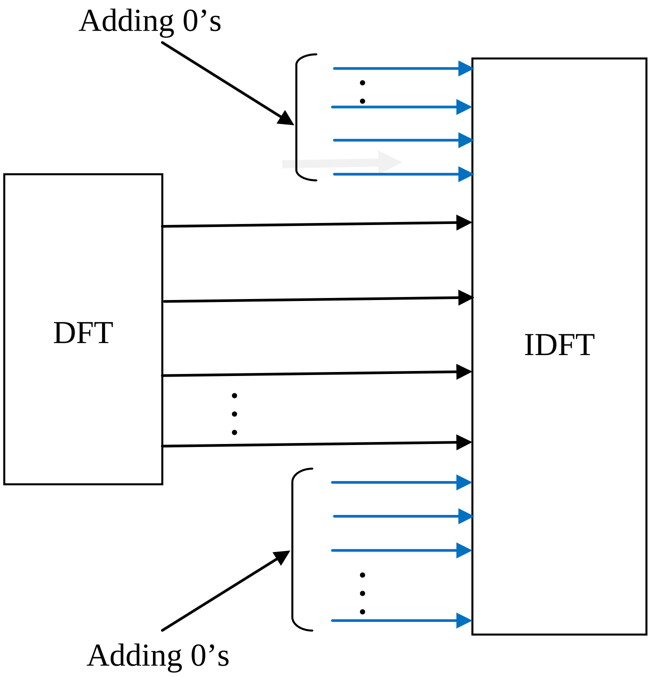


Figure 3.20(a): Localized FDMA

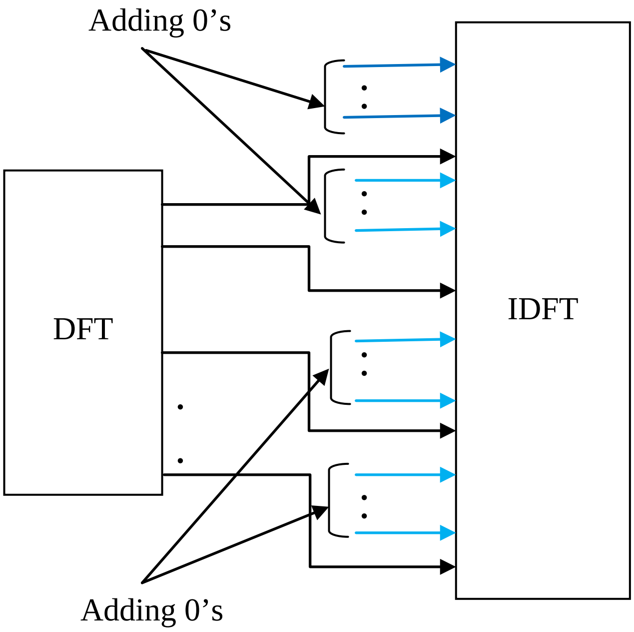


Figure 3.20(b): Distributed FDMA

M-Point IDFT: Converts the mapped subcarriers to time domain. For efficient computations of IDFT M>N.

Parallel to Serial Convertor (P-to-S): The time domain subcarriers are converted back from parallel to serial.

Add Cyclic Prefix: CP is added to avoid ISI. The length of CP is larger than the channel delay spread in order to avoid ISI at the receiver.

Digital to Analog Convertor (DAC): Converts the digital signal to analog signal and up convert (convert set of values to higher set of values) to RF for transmission over the channel.

SC-FDMA Receiver

The SC-FDMA receiver does the inverse of SC-FDMA transmitter. The block diagram of receiver is shown in Figure 3.21.

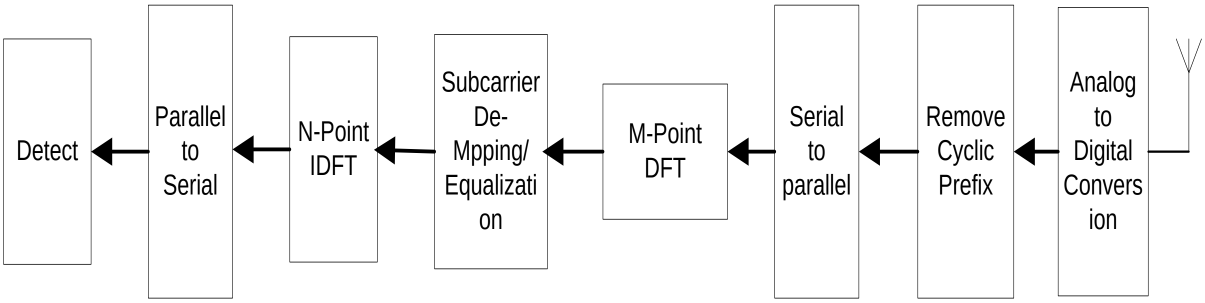


Figure 3.21: SC-FDMA Receiver

The receiver converts the analog signal to digital and removes the cyclic extension. The output of "Remove CP" block is converted serial to parallel and become the input to M point DFT, which results into M-mapped subcarriers in the frequency domain. The M-mapped subcarriers are de-mapped which results in N-discrete frequency tones. The N-frequency tones are converted back into time by using IDFT and passed to the PS convertor and converts parallel time domain symbols to serial data stream. The serial data stream is passed through detector which results in single carrier modulation symbols in the time domain. The single carrier symbols are demodulated in order to get the input bit stream.

SC-FDMA Resources

SC-FDMA arranges subcarriers in RBs similar to the downlink OFDMA. A RB is comprised of 12 consecutive subcarriers for the duration of one time slot of LTE frame (1slot = 0.5 ms). Two types of CP are used in uplink, the normal and extended CP having 7 and 6 SC-FDMA symbols respectively. Due to the fixed size of RB's, uplink supports flexible transmission bandwidths similar to downlink.

The SC-FDMA Resource Grid for LTE is shown in Figure 3.22 [29].

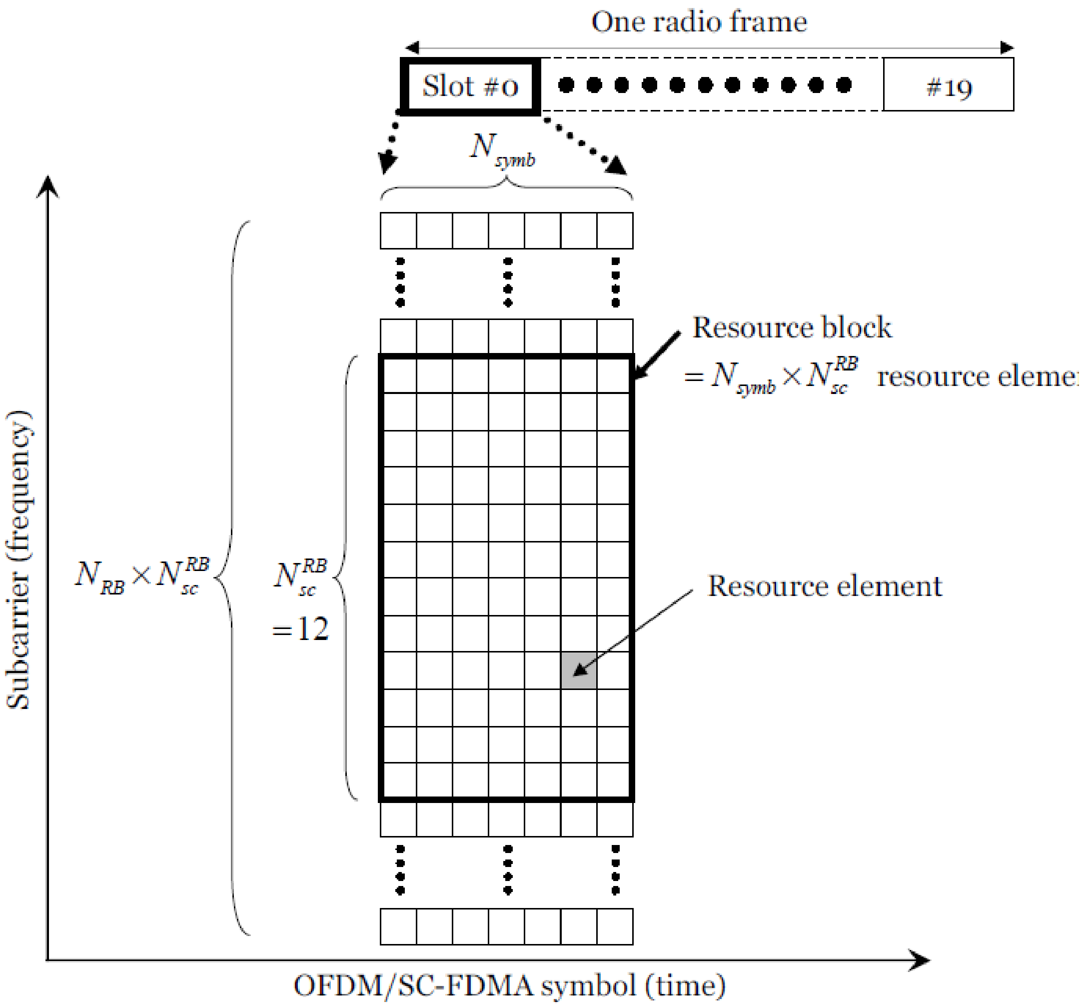


Figure 3.22: LTE Resource Grid for SC-FDMA [29]

Where N_{RB} = number of Resource Blocks

N_{sc}^{RB}= Number of subcarriers in a resource block

N_{RB} x N_{sc}^{RB} = Total transmission bandwidth (LTE supports bandwidth ranges from 1.4 MHz to 20 MHz).

N_{symb}= Number of SC-FDMA symbols in one slot.

N_{symb} x N_{sc}^{RB}= Number of REs in one RB.

The SC-FDMA parameters used in LTE are described in Table 3.5

	Transmission Bandwidth					
	1.4	**3**	**5**	**10**	**15**	**20**
FFT Size	128	256	512	1024	1536	2048
Sampling Rate: (N/M x 3.84 MHz)	½	1/1	2/1	4/1	6/1	8/1
Number of subcarriers	72	180	300	600	900	1200
Number of Resource blocks	6	15	25	50	75	100
Bandwidth Efficiency (%)	77.1	90	90	90	90	90

Table 3.5: SC-FDMA Parameters for LTE [29]

In Table 3.5, N>M in order to perform efficient computations of IDFT.

3.3.3.8 Uplink Physical layer Processing:

The LTE uplink transport channel for Uplink-Shared Channel (UL-SCH) is shown in Figure 3.23. The uplink transport channel processing is somewhat similar to downlink transport however, uplink transport channel processing did not define transmit diversity and spatial multiplexing for the LTE uplink. In addition, there is no explicit multi-antenna mapping functions defined for the processing of the uplink transport channel. In contrast to downlink, a single transport block of dynamic size is transmitted for every Transmission Time Interval (TTI).

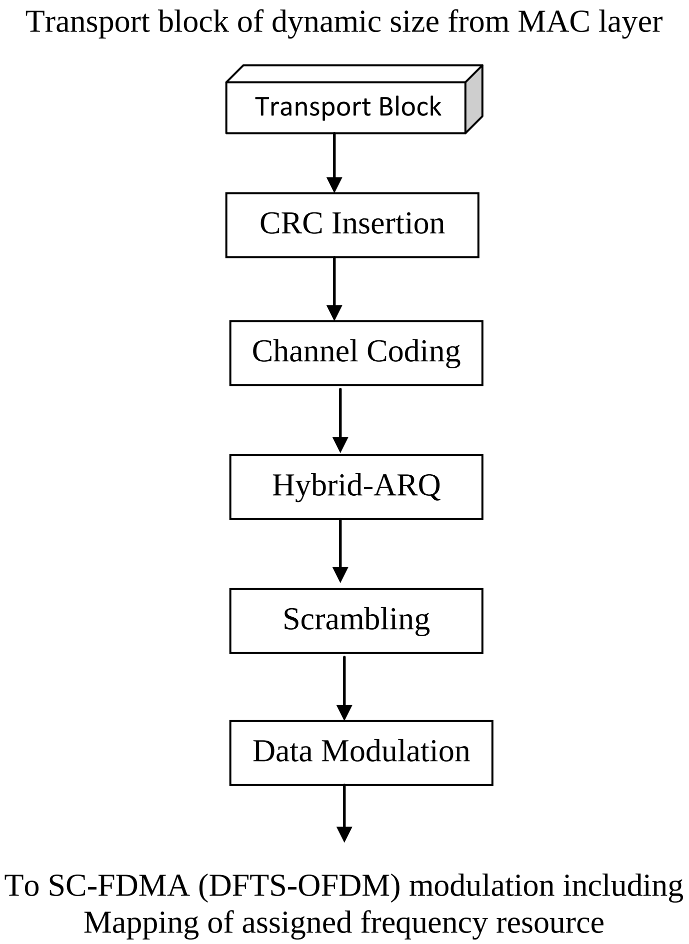


Figure 3.23: LTE Uplink Transport Channel Processing [30]

CRC Insertion: A 24-bits CRC is calculated and appended at the end of every transport block. CRC allows receiver to detect residual errors from the decoded transport block. The block diagram for CRC insertion is shown in Figure 3.24.

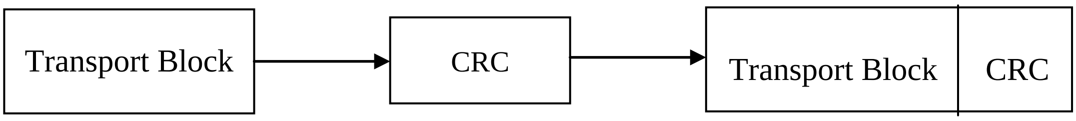


Figure 3.24: CRC Insertions per Transport Block

Channel Coding: Uplink channel coding uses turbo codes, including QPP based inner interleaver similar to downlink.

HARQ functionality: The task of physical layer hybrid ARQ is to extract the exact set of bits from the blocks of code bits delivered by the encoder. The extracted bits are transmitted within a given TTI. The uplink HARQ functionality is similar to downlink however the uplink and downlink have different HARQ protocols i.e. asynchronous vs. synchronous operation.

Scrambling: Uplink scrambling is applied to the code bits coming from the HARQ. The purpose of uplink scrambling is to randomize the interference which ensures fully utilization of processing gain provided by the channel code. The uplink scrambling is specific to mobile terminal where every terminal uses a unique scrambling sequence.

Data Modulation: Transforms the scrambled bits into complex modulation symbols. The UL-SCH uses 16-QAM, QPSK and 64-QAM for modulation in LTE uplink. UL-SCH supports a similar set of modulation techniques as the DL-SCH in the downlink.

The block of modulation symbols is applied to DFTS-OFDM for processing, which maps the complex modulation symbols to discrete frequency tones followed by the mapping of discrete tones to specific subcarriers. The subcarriers are converted back to time domain by IDFT and the cyclic prefix is inserted. The time domain signal with CP is converted from digital to analog and sent for transmission.

3.3.4 Multi- Antenna Techniques in LTE

LTE supports transmissions with 2 or 4 antennas in the downlink. LTE uses maximum two codewords for fixed mapping between codewords to layers. A codeword is formed by a sequence of bits.

LTE MIMO

MIMO is a technique used to increase data rates to fulfill the needs of next generation mobile networks. It also fulfills the needs of high capacity and extended coverage. In order to achieve high data rates, multiple antennas can be used such as 2x2 or 4x4 MIMO whereas to achieve extended coverage, beam-forming is used.

Downlink MIMO:

In LTE downlink, 2x2 and 4x4 configurations are used. Different MIMO modes i.e. spatial multiplexing and transmit diversity are dependent on the condition of the channels.

Spatial Multiplexing

Spatial multiplexing transmits different data streams on the same downlink block. These streams of data belong to a single user also called Single User MIMO (SU-MIMO) or to multiple users called Multi User MIMO (MU-MIMO). In SU-MIMO, data rate is increased whereas in MU-MIMO, overall capacity is increased. This is only possible if the mobile channel allows it. The basic spatial multiplexing principle can be seen in Figure 3.25.

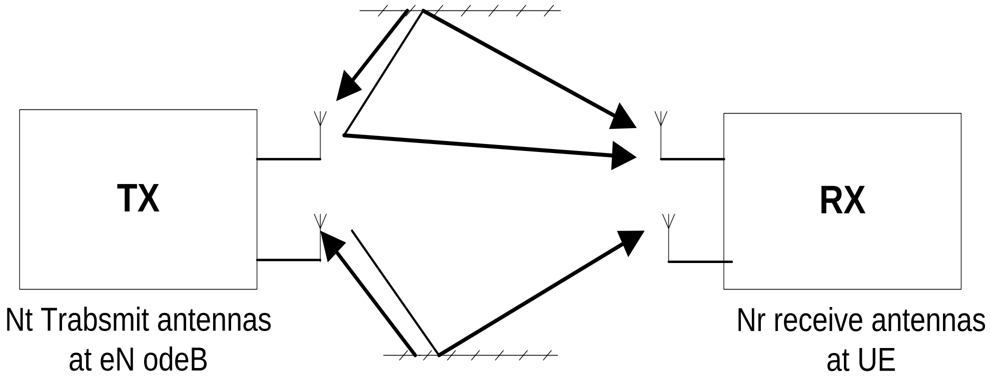


Figure 3.25: Spatial Multiplexing [31]

Figure 3.25 shows that each transmitter 'Tx', transmitting different streams of data and each antenna at the receiver 'Rx' is receiving data streams from all transmitters. The channel is specified by the following matrix H.

$$\mathrm{H} = \begin{array}{cc} N_t & \\ \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & & h_{2N_t} \\ \vdots & & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN_t} \end{bmatrix} & N_r \end{array}$$

Where N_t represents the number of antennas at transmitter and N_r represents the number of antennas at receiver. The h_{ij} are the coefficients of the channel from Tx j to Rx i.

The matrix rank H limits the data that can be sent over the MIMO channel and is given by min $\{N_t, N_r\}$. When the matrix H is singular , the quality of the transmission degrades significantly. This is possible when both the antennas i.e. Tx and Rx are too close.

3.3.4.2.2 Transmit Diversity

The transmit diversity scheme is used when the conditions of the channel do not allow spatial multiplexing. This means that in transmit diversity a single stream of data is transmitted, whereas in spatial multiplexing multiple streams are transmitted.

3.3.4.3 Uplink MIMO

The baseline used in the UL-MIMO is MU-MIMO. The MU-MIMO reception at eNodeB is supported by allocating the same time frequecy resources to multiple UEs, transmitting on single antenna [32]. The closed loop transmit diversity is only supported by FDD, and is optional for UE.

3.4 LTE MAC Layer

The MAC layer is the part of logical link layer (Layer 2) of the radio protocol stack of LTE as shown in Figure 3.26. MAC layer is connected to Radio Link Control (RLC) and physical layers through logical and transport channels respectively. MAC layer sends/receives the MAC PDUs to/from the physical layer through transport channels. The connection to RLC layer is through logical channels by means of RLC Service Data Units (SDUs).

MAC layer performs HARQ transmissions/retransmissions, multiplexing/de-multiplexing of logical channels and downlink/uplink scheduling.

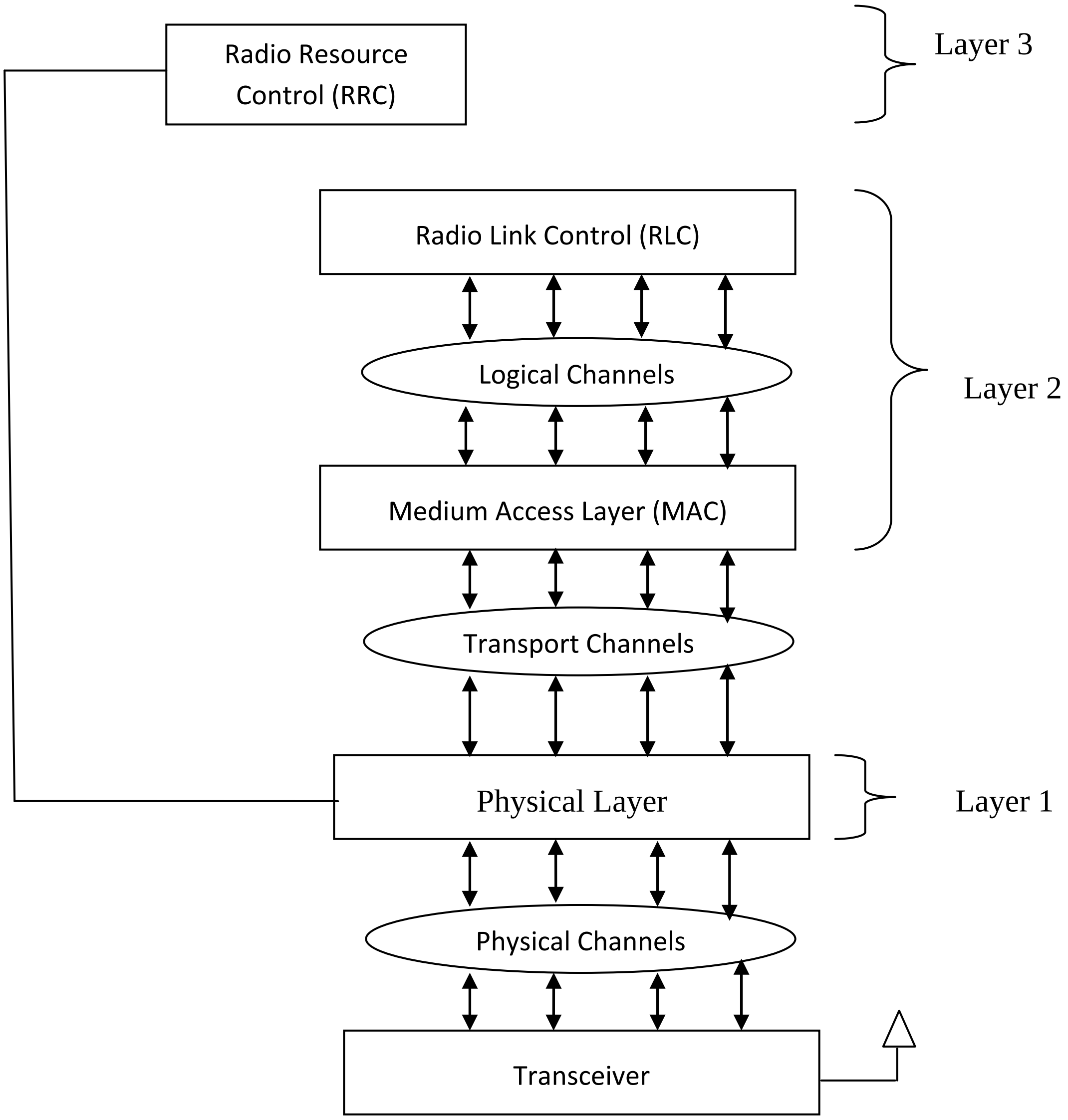


Figure 3.26: LTE Protocol Stack

3.4.1 Logical Channels

MAC layer transfers data to/from RLC layer through logical channels. Logical channels are categorized into control logical channels and traffic logical channels. Control logical channels carry control information whereas user plan information is carried out by traffic control channels. The control and traffic channels used in LTE are as follows:

Control Logical Channels

Carry the control data such as Radio Resource Control (RRC) signaling.

Dedicated Control Channel (DCCH)

Transmits dedicated control information to/from the specific UE. It configures the UEs individually such as handover massages. It is used when UE has a RRC connection with the eNodeB [33].

Broadcast Control Channel (BCCH)

Broadcast the system control information to the mobile terminals within a cell. It is necessary for every mobile terminal to have system control information prior to accessing it in order to have knowledge about system configuration and how to behave within a cell.

Paging Control Channel (PCCH)

Transmit the paging control information when the location cell of UE is unknown to the network.

Common Control Channel (CCCH)

Used for regular transmission of control information between UEs and eNodeB and it does not care whether the UEs have RRC connection with eNodeB or not.

Multicast Control Channel (MCCH)

Used for transmission of MBMS control information from network to UE for one or several multicast traffic channels. It is used by UEs that receive MBMS [16].

Traffic Logical Channels

Dedicated Traffic Channel (DTCH)

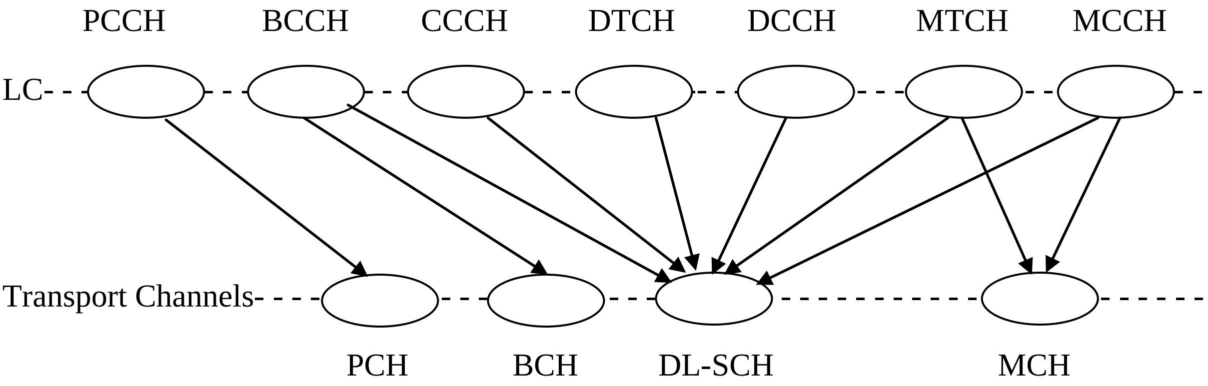
DTCH is used to transmit user information dedicated to one UE. Further it is used in uplink and non MBFSN downlink transmissions.

Multicast Traffic Channel (MTCH)

MTCH is used to transmit user data in the downlink MBMS services.

3.4.2 Mapping of Logical Channels to Transport Channels

The logical channels are mapped to specific transport channels in downlink and uplink direction. Figure 3.27 shows the mapping of downlink logical channels to downlink transport channels where PCCH is mapped on PCH transport channel, BCCH is mapped on BCH and DL-SCH. The CCCH, DCCH, DTCH, MCCH and MTCH are mapped on DL-SCH while MCCH and MTCH are mapped on MCH.



Where, “LC” stands for Logical Channels.

Figure 3.27: Downlink Mapping of Logical and Transport Channels [16]

Figure 3.28 shows the mapping of uplink logical channels to uplink transport channels.

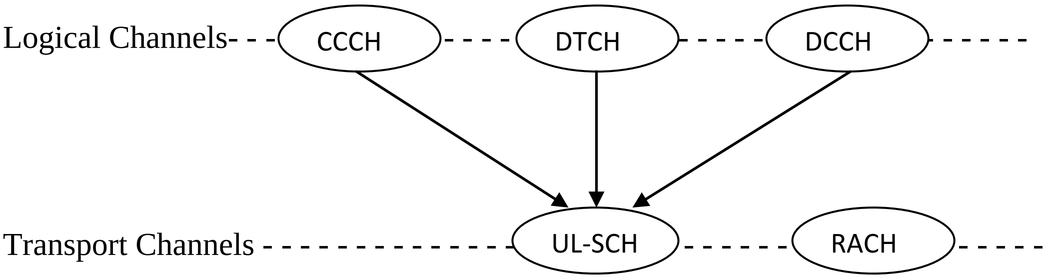


Figure 3.28: Uplink Mapping of Logical and Transport Channels [16]

3.4.3 Data Flow in MAC

MAC layer receives data as MAC SDUs from RLC layer. The MAC SDUs are combined along with the attachment of MAC header and MAC control elements to form MAC PDUs. The MAC header is further divided into subheaders where every subheader contains the Logical Control Identification (LCID) and length field. The LCID indicates which type of control elements are used in the MAC payload field or indicates the type of channel. The length field indicates the length of MAC SDUs or MAC control elements.

MAC control elements perform control functionalities in the uplink and downlink direction. In uplink related to UL-SCH, MAC payload contains control elements such as:

- Buffer Status Report: Contains information about data in the UE, waiting for transmission and information about the priority of data in the buffer.

- Power Headroom Report: Contains information about available power resources in the uplink direction.
- Contention Resolution Procedure Information (C-RNTI and CCCH).

In the downlink, the control elements related to DL-SCH are as follow:

- Timing advance commands: Used to adjust the timing of uplink.
- Contention resolution information.
- Used Discontinuous Reception (DRX) commands to control the DRX operation.

The general MAC PDU structure is described in Figure 3.29.

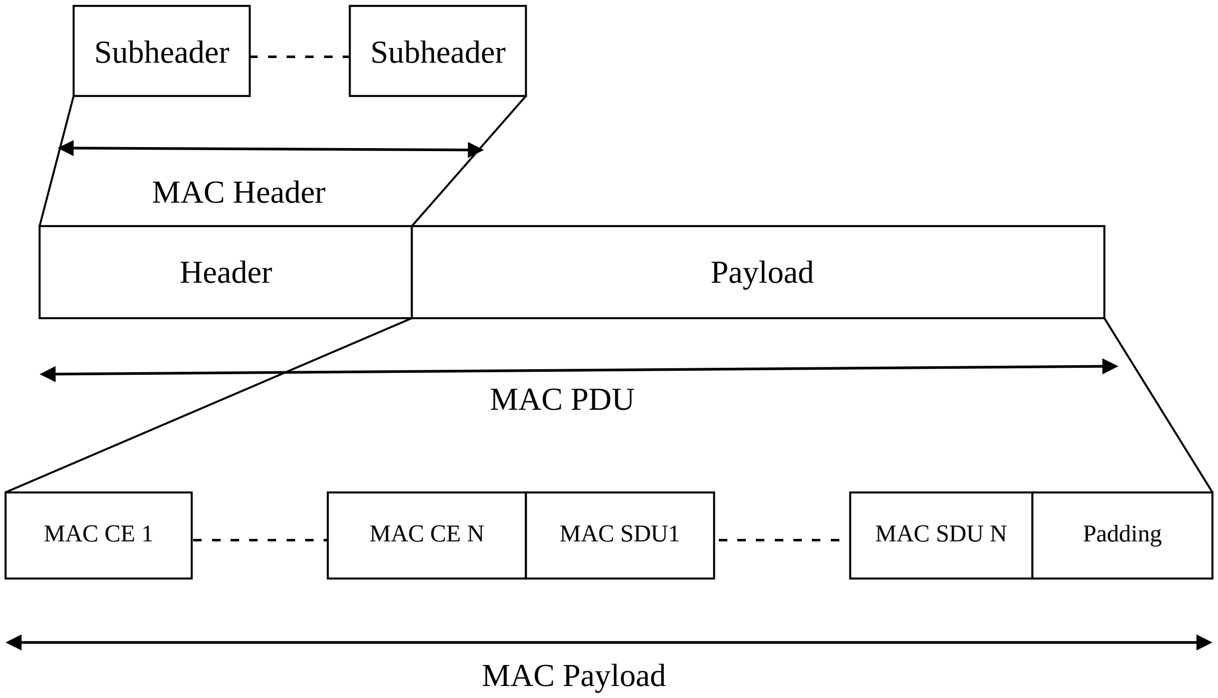


Figure 3.29: MAC PDU Format [34]

The "MAC CE" corresponds to a MAC control element. In case of PCCH and BCCH, the MAC header does not contain the LCID field because there is no multiplexing used in PCCH and BCCH. The format of MAC header in MAC PDU in case of UL-SCH and DL-SCH is shown in Figure 3.30.

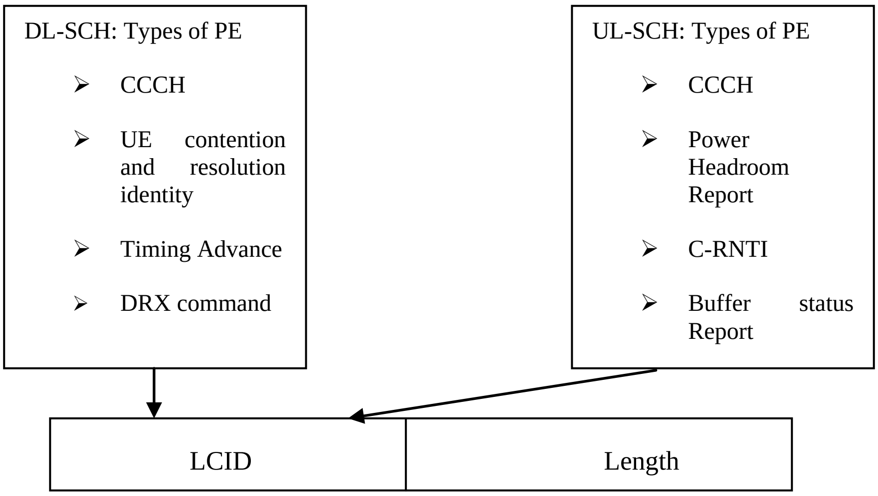


Figure 3.30: MAC Header Format

Chapter 4: Comparison between WiMAX and LTE

4.1 Introduction

In recent years, communication industry have been keen to develop and formulate new standards in order to provide high speed broadband mobile access in a single air interface and network architecture for reasonable cost for end-users and mobile operators [35]. WiMAX and LTE are two leading standards as the results of above efforts.

WiMAX belongs to the IEEE family of standards and refers to IEEE 802.16 standard. It enhances the WLAN (IEEE 802.11) by extending the wireless access to Wide Area Network (WAN) and Metropolitan Area Network (MAN). It uses OFDMA as physical layer radio access technology in the downlink and uplink. The initial versions of WiMAX, IEEE 802.16-2004 (fixed WiMAX) supports fixed and nomadic access, while IEEE 802.16-2005 (mobile WiMAX) supports enhanced QoS and mobility up to 120 km/h. Mobile WiMAX uses IP based services to provide downlink peak data rates up to 75 Mbps depending on the modulation technique and antenna configuration used. WiMAX supports LOS and NLOS propagations across 10 GHz to 66 GHz and 2 GHz to 11 GHz respectively.

LTE is the part of 3GPP and evolved from the evolution of UMTS/HSPA cellular technology to meet current user demands of high data rates and spectral efficiencies. LTE specifications are jointly based on E-UTRA and E-UTRAN. The version specification for LTE is released in 3GPP Release 8. LTE uses OFDMA radio access technology in downlink and SC-FDMA in the uplink. The use of SC-FDMA in the uplink reduces PAPR as compared to OFDMA. The downlink peak data rates range from 100 Mbps to 326.4 Mbps depending on the modulation technique and antenna configuration used. LTE aims at providing data rates, IP backbone services, flexible spectrum, lower power consumptions and simple network architecture with open interfaces.

In this chapter we do a comparative study of WiMAX and LTE in context of system architecture, air interfaces radio and protocol aspects (including multiple access techniques, access modes and modulation. Further, we provide a comparative summary that concludes this chapter.

4.2 System Architecture

In this section we will discuss system architecture in the context of WiMAX and LTE.

4.2.1 WiMAX Architecture

The WiMAX architecture is based on a network reference model to define end-to-end WiMAX network.

4.2.1.1 Network Reference Model (NRM)

The network reference model for WiMAX was developed by the WiMAX Network Working Group (NWG). The model defines the entire WiMAX network. The NRM ensures interoperability between various WiMAX enabled devices and operators. The network architecture is based on IP services and it can be logically divided into three parts; Mobile Station, Access Service Network and Connectivity Service Network. The network reference model is described in Figure 4.1 [37].

Mobile Station (MS): Used to access the network.

Access Service Network (ASN): Comprised of ASN GWs (Gateways) and BSs to form Radio Access Network (RAN) at the edge.

Base Station: Provides air interface to MS. In addition, BS is responsible for handoff triggering, radio resource management, enforcement of QoS policy, Dynamic Host Control Protocol (DHCP) proxy, session management, key management and multicast group management.

Access Service Network Gateway: Acts as layer 2 traffic aggregation point within an ASN [36]. In addition, ASN-GW performs AAA client functionality, establish and manage mobility tunnel with BSs, foreign agent functionality for mobile IP and outing towards selected Connectivity Service Network (CSN).

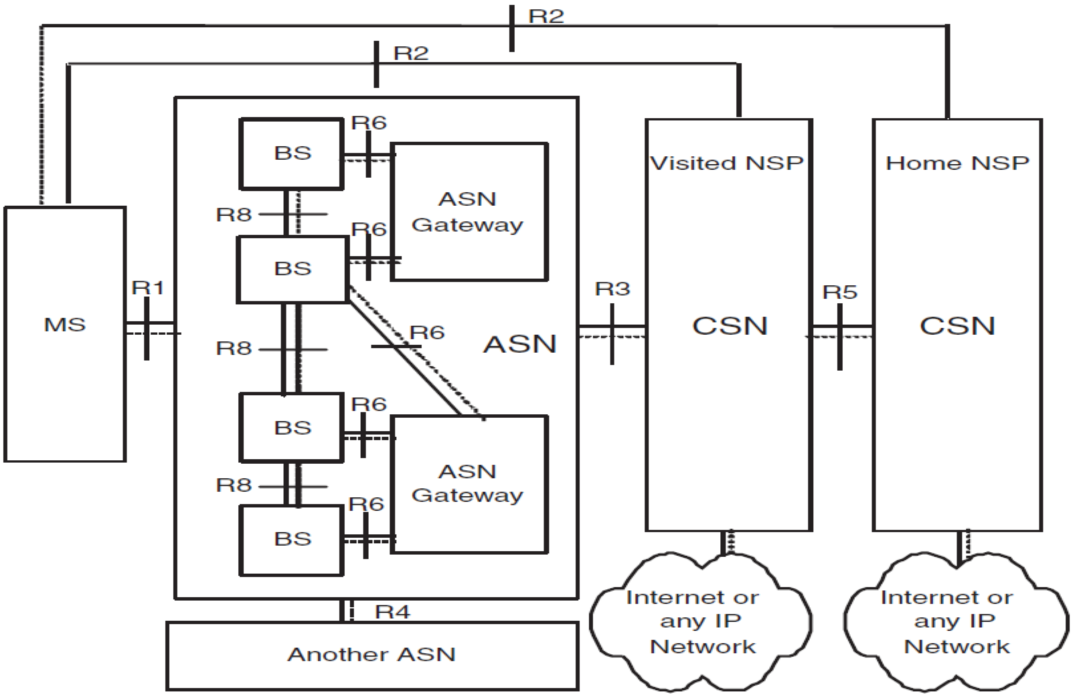


Figure 4.1 Network Reference Model for WiMAX [37]

Connectivity Service Network: Provides IP connectivity to internet, PSTN (Public Switched Telephone Network), ASP and corporate networks. In addition, it provides core IP functions. CSN is owned by the Network Service Provider (NSP), and is comprised of AAA servers, Mobile IP Home Agent (MIP-HA), Operation Supports Systems (OSS) and gateways. AAA servers are used to authenticate devices, users and specific services. CSN has following responsibilities:

- IP address Management.
- Mobility, roaming and location management between ASN's.
- Roaming between NSPs by Inter-CSN tunneling.

The logical link that connects two functional groups is called Reference Point (RP). The NRM shown in Figure 4.1 has 8 RPs ranges from R1 to R8. The description of RPs is given in Table 4.1.

Reference Points	**Description**
R1	Connect Mobile Station (MS) and ASN
R2	Connect MSN and CSN
R3	Connect ASN and CSN
R4	Connect two ASNs
R5	Connect two CSN
R6	Connect BS and ASN- GW
R7	Represents the internal communication within the gateway.
R8	Connect two Base Stations (BSs)

Table 4.1: Description of Reference Points

4.2.2 LTE Architecture

LTE supports packet data services unlike previous cellular systems that support circuit switched data model. In addition, LTE provides seamless IP connectivity between Packet Data Network (PDN) and UE. LTE architecture is comprised of Core Network (CN) and Access Network (AN), where CN corresponds to the Evolved Packet Core (EPC) which comes from System Architecture Evolution (SAE). The AN refers to E-UTRAN. The CN and AN together correspond to Evolved Packet System (EPS). EPS connects the users to PDN by IP address in order to access the internet and services like Voice over IP (VoIP). Typically, the EPS bearer is associated with QoS. Multiple bearers can be established for a user to provide connectivity to different PDNs or QoS streams. The overall network architecture including various EPS elements is shown in Figure 4.2 [38].

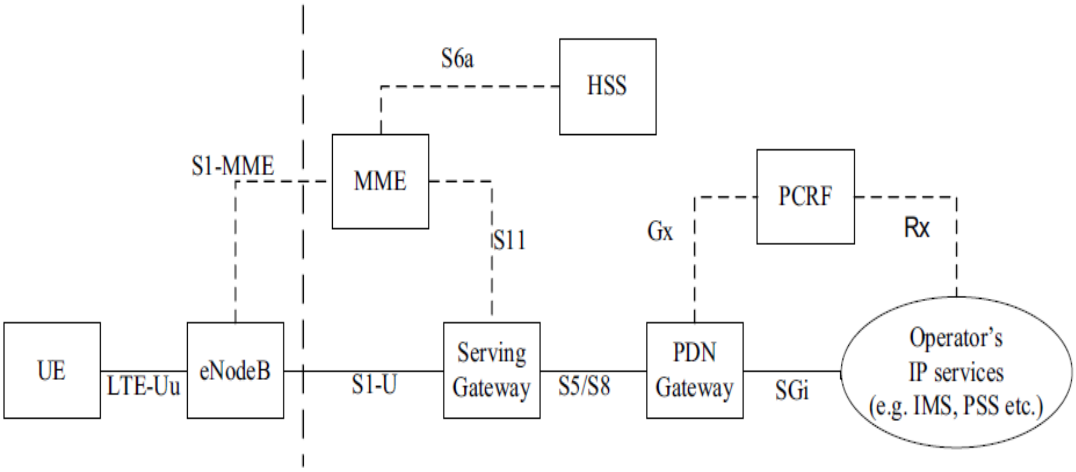


Figure 4.2: Evolved Packet System (EPS) Network Elements [38]

EPS elements are inter-linked with standard interfaces which allow the operators to source the network elements from various vendors.

4.2.2.1 Core Network

Core network is known as EPC in SAE. The key responsibilities of CN include bearer establishment and control of UE. EPC is made of various logical nodes.

- Mobility Management Entity (MME).
- Packet Data Network Gateway (P-GW).
- Serving Gateway (S-GW).
- Policy Control and Charging Rules Function (PCRF).
- Home Subscriber Server (HSS).

Mobility Management Entity

It is the control node used to process signaling information between CN and UE. The protocols running between CN and UE are called Non Access Stratum (NAS) protocols. The key functions of MME are:

- **Bearer Management Functions:** Handled by the session management layer in the NAS protocol and used to establish, maintain and release bearers.
- **Connection Management Functions:** Handled by the mobility management or the connection management layer in the NAS protocol. They are used to manage security and connection establishment between UE and network.

Packet Data Network Gateway

Used to allocate the IP address for UE as well as flow based charging and QoS enforcement. It filters the downlink user IP packets into the bearers typically based on QoS. This is based on traffic flow templates. In addition, P-GW acts as mobility anchor to work with Non-3GPP technologies i.e. WiMAX and CDMA2000.

Serving Gateway

S-GW is responsible for transferring user IP packets. It stores local mobility information for data bearers when UE runs between various eNodeBs. S-GW acts as mobility anchor to work with 3GPP technologies (UMTS, GPRS etc). In addition, it collects information about legal interception and charging, i.e. the volume of data sent to or received from the user is called charging.

Policy Control and Charging Rules Functions

PCRF controls flow based charging functions which are part of Policy Control Enforcement Function (PCEF) as well as it organize decision making control policy. PCEF is part of P-GW. The key responsibility of PCRF is to provide QoS authorization i.e. bit rate and QoS class identifier. QoS authorization decides the method of treating certain data flows in the PCEF and ensures that the data flow is in accordance with the subscription of the user profile.

Home Subscriber Server (HSS):

HSS is also called Home Location Register (HLR). It contains the SAE subscription data of users such as roaming restrictions and EPS subscribed QoS profiles. HSS contains the information of PDN in the form of AP or PDN address. In addition, HSS contains dynamic information i.e. identity of the MME to which an user is connected currently. The vectors for security keys and authentication are generated as the result of AuC (Authentication centre) integration.

4.2.2.2 Access Network

The Access Network (EUTRAN) is comprised of network of eNodeBs connected to each other through interfaces called X2. The Architecture of E-UTRAN is flat due to the absence of a centralized controller in the case of normal traffic (as opposed to broadcast). The eNodeB is connected to EPC via S1 interface and to MME through S1-MME interface. The eNodeB and S-GW are interlinked by means of S1-U interface. The S1-U interface carries user data between serving GW and eNodeB. The protocols which run between eNodeB and UE are known as Access Stratum (AS) Protocols. The Architecture of Access Network is shown in Figure 4.3 [39].

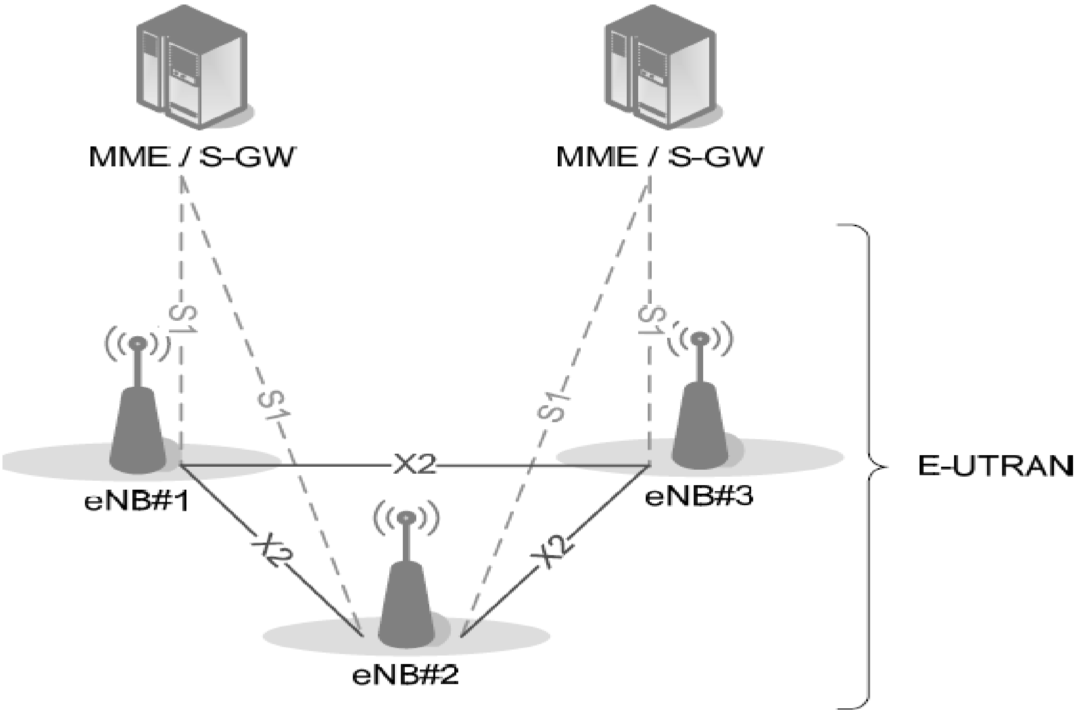


Figure 4.3: Architecture of LTE Access Network (E-UTRAN) [39]

The key responsibilities of E-UTRAN are as follows:

- **Radio Resource Management (RRM):** RRM includes radio bearers related functions such as radio admission control, radio bearer control, scheduling, radio mobility control and dynamic allocation of resources in downlink and uplink to UEs.
- **Header Compression:** Due to IP header compression, the radio interface can be utilized efficiently in case of small IP packets.
- **Security:** The data sent to the radio interface is secured by encryption.
- **Connectivity to the EPC:** Connectivity to the EPC consists of bearer path towards S-GW and signaling towards the MME.

The functions described above reside in the eNodeB for network prospective. In contrast to previous generation technologies, LTE embed radio controller functionalities into eNodeB which allows tight interaction between the protocol layers of AN. This distributed control eliminates the need for a processing intensive radio controller which in turn reduces the cost and avoids a “single point of failure”. In addition, due to absence of the radio controller improve the efficiency of the network by reducing the latency. There is no soft handover in LTE, which eliminates the need for a centralized data combining function.

4.3 Radio Aspects of Air Interface

4.3.1 Frequency Bands

Frequency bands play an important role for providing broadband wireless services. WiMAX uses license-exempt and licensed frequency bands for providing broadband wireless access. Every frequency band has unique characteristics which have significant impact on overall system performance.

Licensed Frequency bands: The licensed frequency bands used by WiMAX are: 2.3 GHz, 2.5 GHz, 3.3 GHz and 3.5 GHz.

License-Exempt Frequency Bands: WiMAX uses unlicensed frequency band of 5 GHz. The fixed profile of WiMAX created in 2004 used 5.8 GHz unlicensed frequency band. In addition, various frequency bands between 5 GHz and 6 GHz are under consideration for unlicensed WiMAX.

Table 4.2 summarizes the frequency bands used for WiMAX globally.

Regions	Frequency Bands for WiMAX (in GHz)	
	License Bands	License-Exempt Bands
USA	2.3 and 2.5	5.8
Europe	3.5 and 2.5	5.8
South East Asia	2.3, 2.5, 3.3 and 3.5	5.8
Middle East	3.5	5.8
Africa	3.5	5.8
South and Central America	2.5 and 3.5	5.8

Table 4.2: Reported Frequency Bands used for WiMAX

LTE can be deployed in paired and unpaired spectrum. For paired spectrum, uplink and downlink use separate frequency bands for transmissions. In addition, we can deploy FDD systems in paired spectrum. TDD systems are deployed in unpaired spectrum. In unpaired spectrum, uplink and downlink use same frequency band for transmissions. The summary of LTE FDD and LTE TDD frequency bands in various regions are shown in Table 4.2(a) and Table 4.2(b) respectively.

Operating Band	Regions	Downlink	Uplink
I	Europe, Asia	1920 - 1980 MHz	2110 -2170 MHz
II	America	1850 -1910 MHz	1930 -1990 MHz
III	Europe, Asia	1710-1785 MHz	1805-1880 MHz
IV	America	1710-1755 MHz	2110-2155 MHz
V	America	824 - 849 MHz	869-894 MHz
VI	Japan	830-840 MHz	875-885 MHz
VII	Europe, Asia	2500-2570 MHz	2620-2690 MHz
VIII	Europe, Asia	880 - 915 MHz	925 - 960 MHz
IX	Japan	1749.9-1784.9 MHz	1844.9-1879.9 MHz
X	America	1710-1770 MHz	2110-2170 MHz
XI	Japan	1427.9 - 1452.9 MHz	1475.9 - 1500.9 MHz
XII	America	698 – 716 MHz	728 – 746 MHz
XIII	America	777 - 787 MHz	746 - 756 MHz
XIV	America	788 – 798 MHz	758 – 768 MHz

Table 4.3(a): LTE FDD Frequency Bands [40]

Band	Regions	Downlink and Uplink (in MHz)
A	Asia (not Japan), Europe	1900-1920 (UL and DL transmission) 2010-2025 (UL and DL transmission)
B	-	1850-1910 (UL and DL transmission) 1930-1990 (UL and DL transmission)
C	-	1910-1930 (UL and DL transmission)
D	Europe	2570-2620 (UL and DL transmission)
E	Europe, Asia	2300-2400 (UL and DL transmission)

Table 4.3(b): LTE TDD Frequency Bands [40]

4.3.2 Radio Access Modes

LTE and WiMAX use FDD and TDD as radio access modes. In FDD, BS and mobile user transmit and receive simultaneously due to allocation of separate frequency bands. While in TDD, downlink and uplink transmit in different times due to sharing of same frequency. The radio mode currently specified by WiMAX is TDD whereas LTE is specified for FDD. The spectral holdings of operator's will be a key decision factor for selecting the technology (based on FDD or TDD).

4.3.3 Data Rates

The peak data rates of LTE and WiMAX depend upon multiple antenna configuration and modulation scheme used. The peak data rates of LTE and WiMAX in DL and UL are illustrated in Table 4.4.

	Downlink (DL)	**Uplink (UL)**
WiMAX	75 Mbps	25 Mbps
LTE	100 Mbps	50 Mbps

Table 4.4 Peak Data Rates of LTE and WiMAX

4.3.4 Multiple Access Technology

The multiple access technologies used by WiMAX and LTE are quite similar having modification in the uplink. The multiple access technology adopted in the downlink of LTE and uplink/downlink of WiMAX is OFDMA, whereas uplink of LTE is based on SC-FDMA. The benefit of SC-FDMA in the uplink is the reduction of the PAPR.

4.3.4.1 OFDMA

It is an extension OFDM and is used in downlink of LTE and uplink/downlink of WiMAX. In OFDMA, subcarriers are allocated dynamically to users in different time slots. OFDMA has various advantages as compared to OFDM where single user can transmit/receive in the entire time frame. Due to this, OFDM suffers from PAPR. OFDMA reduces PAPR by distributing the entire bandwidth to multiple mobile stations with low transmit power. In addition, OFDMA accommodates multiple users with widely varying applications, QoS requirements and data rates.

4.3.4.2 SC-FDMA

SC-FDMA is an extension of OFDMA and is used in the uplink of LTE. SC-FDMA significantly reduces PAPR as compared to OFDMA by adding additional blocks of DFT and IDFT at transmitter and receiver. However, due to existing similarities with OFDMA, parameterization of LTE in the uplink and downlink can be harmonized. The 3D visualization of OFDMA is shown in Figure 4.4.

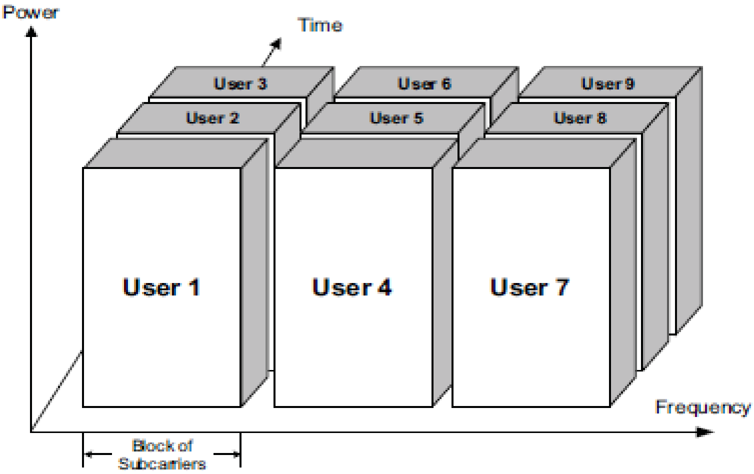


Figure 4.4: 3D Visualization of OFDMA

4.3.5 Modulation Parameters

WiMAX and LTE support flexible bandwidth ranges from 1.25 MHz to 20 MHz. Due to the flexible bandwidth of the two technologies, they use various modulation parameters (FFT size, subcarrier spacing etc). A detail comparison of modulation parameters used by LTE and WiMAX is described in Table 4.5.

Parameter	Fixed WiMAX	Mobile WiMAX				LTE					
Transmission B.W (in MHz)	3.5	1.25	5	10	20	1.25	2.5	5	10	15	20
FFT Size	256	128	512	1024	2048	128	256	512	1024	1536	2048
Subcarrier Spacing (in kHz)	15.625	10.94				15					
Subframe Duration (in ms)	5	2 to 20 but focus on 5				1					
Cyclic Prefix	1/32, 1/16, 1/8 (typically for mobile WiMAX) and 1/4					5us for Normal CP and 16.67us for extended CP					
Number of OFDM/SC-FDMA Symbols	69 OFDM Symbols	48 OFDM Symbols				DL: Normal CP = 14, Extended CP = 12 UL: Normal CP = 14, Extended CP = 12 DL uses OFDM symbol whereas UL uses SC-FDMA symbol.					
OFDM/SC-FDMA Symbol duration (in us)	72	102.9				DL: Normal CP = 71.8, Extended CP = 83.4, UL: Normal CP = 71.8, Extended CP = 83.4. DL uses OFDM symbol whereas UL uses SC-FDMA symbol.					

Table 4.5: Modulation parameters for LTE and WiMAX

4.3.6 Multiple Antenna Techniques

WiMAX and LTE use multiple antenna configurations in uplink and downlink in order to increase capacity, diversity, data rates and efficiency as compared to single antenna systems. As described in chapter 2, WiMAX uses three types of multiple antenna technologies such as SAS, diversity techniques and MIMO. The MIMO systems are further subdivided into open loop and closed loop systems. WiMAX support 1, 2, 4 antennas at the BS and 1, 2 antennas at the MS. LTE uses multiple antenna techniques and wider spectrum to provide data rates in the entire cell coverage area. The advanced antenna techniques used by LTE are beamforming, Spatial Division Multiple Access (SDMA) and MIMO. The antenna configuration supported by LTE DL is (2x2) and (4x4) having 2 or 4 antennas at eNodeB and 2 or 4 antennas at UE. The UL of LTE supports 2x2 MIMO having 2 antennas at UE as well as at eNodeB. In addition, the number of code words used by LTE is 2 which are independent of the antenna configuration. Table 4.6 describes the summary of MIMO antenna configurations used by WiMAX and LTE.

MIMO	WiMAX	LTE
Uplink	1Tx X NRx	2Tx X 2Rx
Downlink	2Tx X 2Rx	2Tx X 2Rx or 4Tx X 4Rx
Number of code words	1	2

Table 4.6: MIMO Aspects for WiMAX and LTE

4.4 Protocol Aspects of Air Interface

Protocol aspects of air interface include protocol architecture, frame structure, modulation and physical layer control mechanisms. The detail description of these aspects with reference to WiMAX and LTE are discussed below.

4.4.1 Protocol Architecture

Protocol architecture of WiMAX consists of physical and data link layer of the OSI model. Data link layer is further divided into LLC layer and MAC layer where MAC layer itself consists of three sublayers. The protocol architecture described in Figure 4.5 shows step by step collection of data from upper layers to physical layer. The MAC layer is responsible for assembling upper layer data into frames along with error detection and also attaches/detaches addresses to the fields upon transmission/reception. In addition, MAC layer governs the wireless transmission medium. The CS which is part of MAC layer takes IP or ATM packets from upper layers through CS SAP since WiMAX supports two types of transmission modes. In addition, CS does key processing on upper layer frames including frame compression, addressing frames according to IEEE 802.16, transforming the QoS parameters to IEEE 802.16 and sends the MSDUs to CPS. CPS is the core part of MAC layer and it performs functions related to channel access, QoS requirements, connection establishment and maintenance. Furthermore, it takes MSDUs from MAC SAP and organizes them in MAC PDUs by doing segmentation and fragmentation. The security sublayer performs encryption, authentication and secure key exchange functions on MPDUs and sends them to the PHY layer for further processing. The physical layer takes MPDUs from PHY SAP and convert them into signals in order transmit across the air interface. The protocol architecture of WiMAX is shown in Figure 4.5 [41].

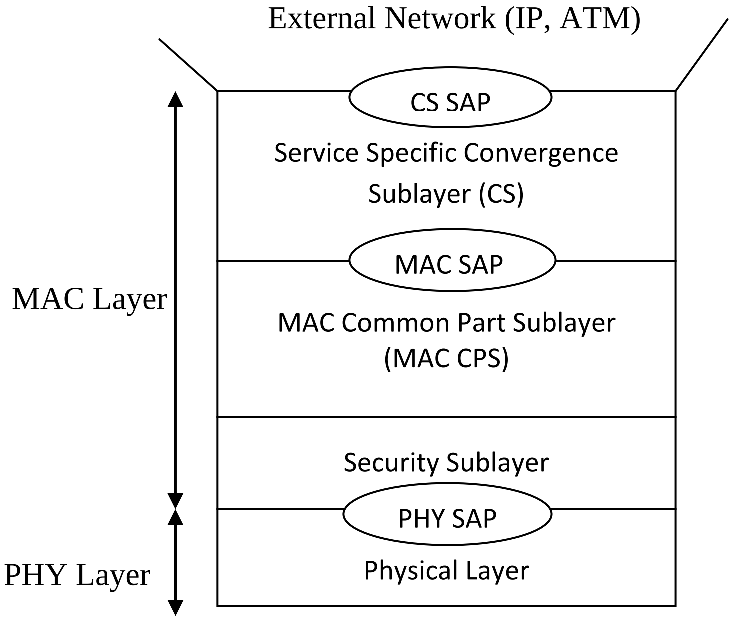


Figure 4.5 Protocol Architecture of WiMAX (IEEE 802.16) [41]

LTE protocol architecture is similar to the WiMAX but it uses the first three layers of OSI model. Data is coming in form of IP packets from the upper layers to the Packet Data Convergence Protocol (PDCP) which performs IP header compression along with ciphering. The data at this stage is called PDCP SDUs. PDCP attaches header information with PDCP SDUs, to form PDCP PDUs. The header contains information about deciphering. The PDCP PDUs are sent to the RLC for further processing. The RLC first assembles the PDCP PDUs in RLC SDUs and then performs segmentation (or concatenation) along with header attachment. The RLC header has information about identification of RLC PDUs in case of retransmissions and in-sequence delivery of data in the UE. The RLC PDUs are sent to MAC layer, which assembles them into MAC SDUs. The MAC SDUs are converted to MAC PDUs by adding the MAC header at every MSDU. The MPDUs are sent to the physical layer for further processing. The PHY performs encoding/decoding of data and organizes the MPDUs in transport blocks. In addition, physical layer attaches CRC with every transport block. The protocol architecture of LTE is shown in Figure 4.6. The logical and transport channels are used to offer services to RLC and MAC layers respectively.

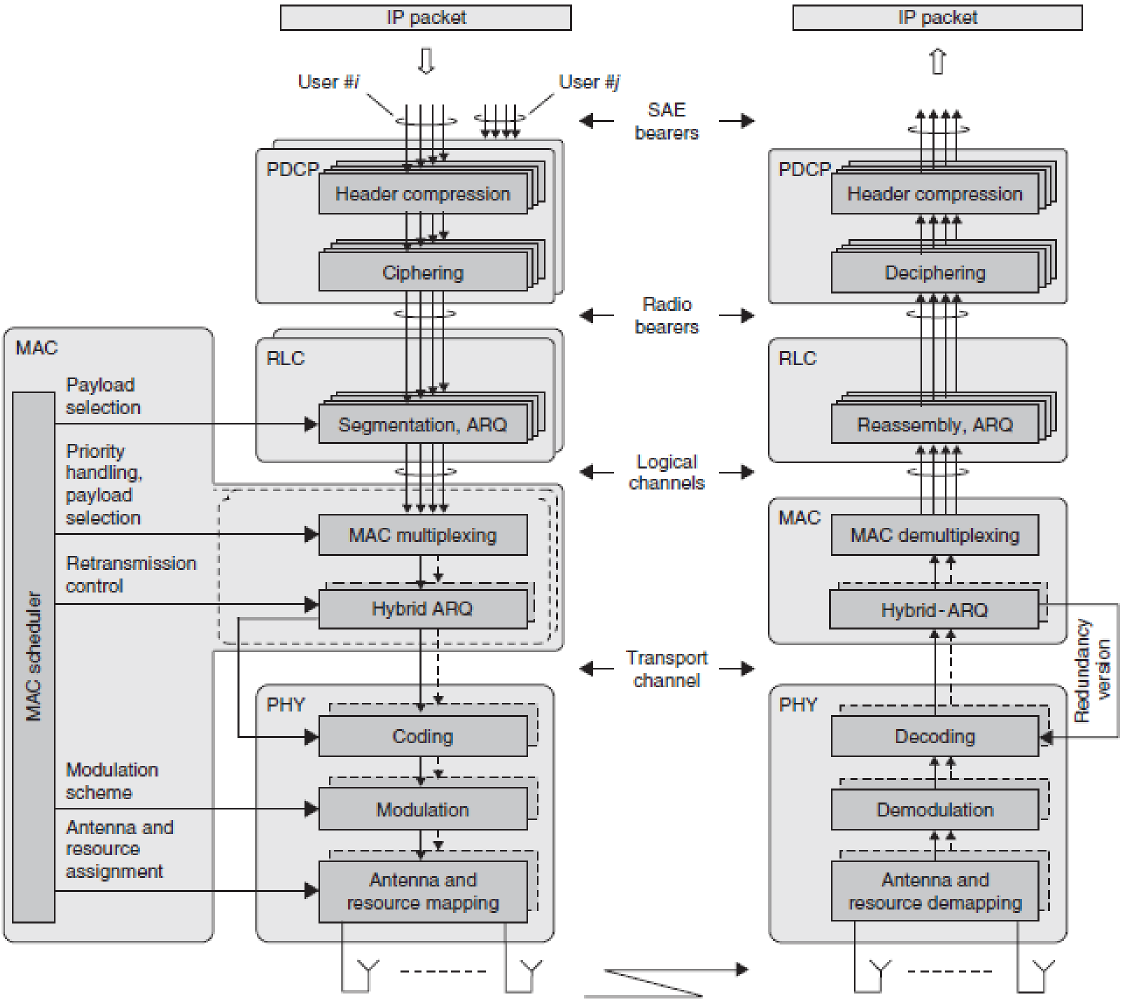


Figure 4.6: LTE Protocol Architecture [42]

4.4.2 Modulation

LTE and WiMAX use modulation schemes such as QPSK, 16-QAM or 64-QAM in uplink and downlink. However, the use of 64-QAM in the WiMAX uplink is optional.

4.4.3 Frame Structure

LTE uses two types of frames, the Generic Frame Structure (GFS) and Alternative Frame Structure (AFS). The GFS used by FDD is 10ms in duration and has 10 subframes. Every subframe is 1ms in length and divided into two equal slots of 0.5ms. Every slot comprises 7 OFDM/SC-FDMA symbols in case of normal CP and 6 OFDM/SC-FDMA symbols in case of extended CP. In contrast to GFS, an alternative frame structure is used by TDD. In this frame structure, there is a certain restriction for the allocation of subframes. Subframe #1 and subframe #6 are used for downlink synchronization. The GFS and alternative frame structure are described in Figure 4.7(a) and 4.7(b).

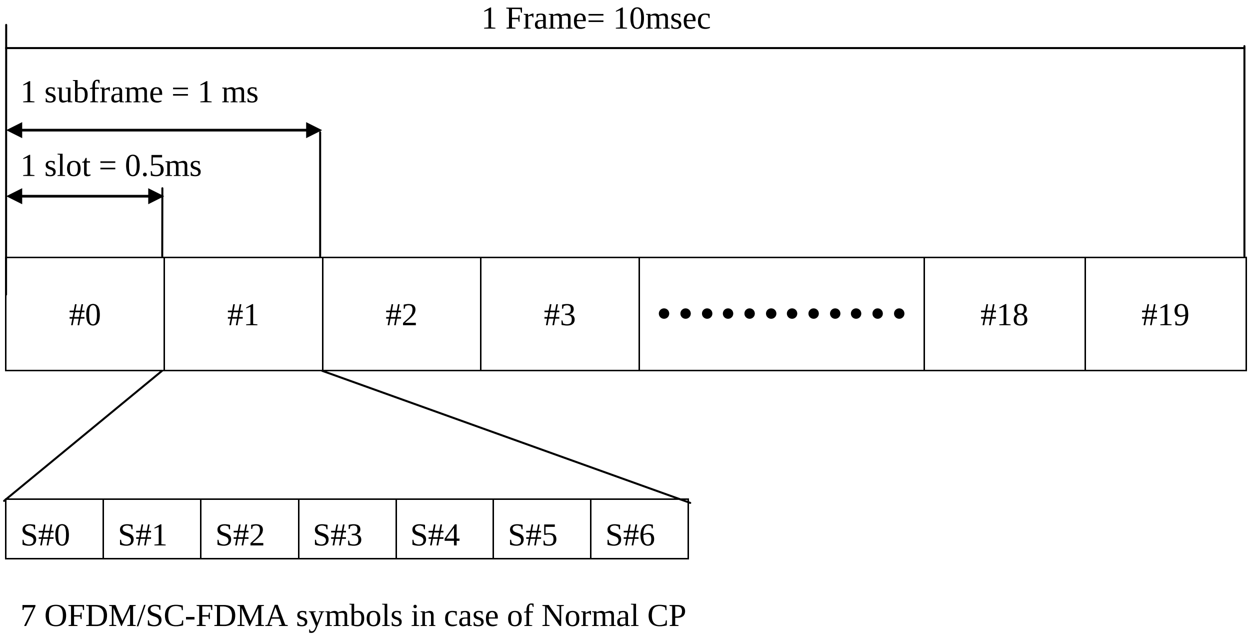


Figure 4.7(a): Generic Frame Structure for LTE (FDD)

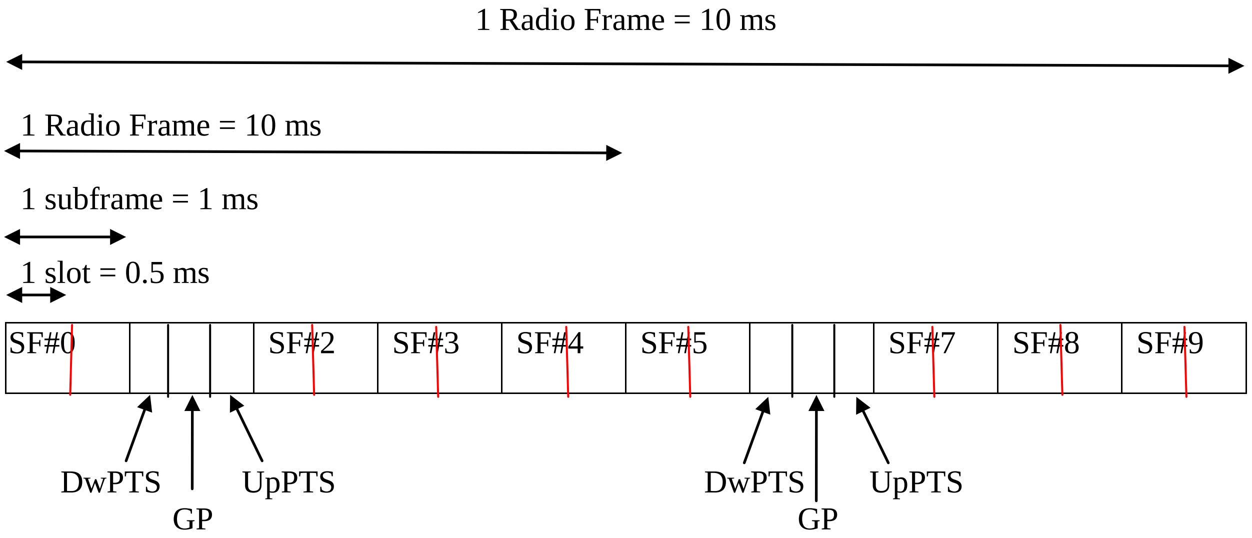


Figure 4.7(b): Alternative Frame Structure for LTE (TDD) [43]

WiMAX supports both TDD and FDD frame structures but adopted TDD frame structure due to its flexible nature. The TDD frame is comprised of downlink subframe along with uplink subframe. The DL subframe is further divided in to DL-PHY PDU, comprised of preamble information, FCH and DL bursts. The preamble contains information about downlink synchronization. Frame configurations such as modulation schemes, length of MAP messages and usable subcarriers are provided by the Frame Control Header (FCH). The DL-Burst consists of MAC PDU, DL-Map and UL-Map. The Map messages are used to provide user allocations to the BS. The uplink subframe contains information about contention region, contention bandwidth requests and UL PHY PDUs. The contention region provides contention based access which includes periodical closed loop frequency and power adjustments. The contention bandwidth request contains uplink bandwidth requests. The WiMAX frame structure is flexible in nature as it supports variable length frames ranging from 2ms to 20ms. However, most of the WiMAX products use 5ms frames. The WiMAX TDD frame is shown in Figure 4.8.

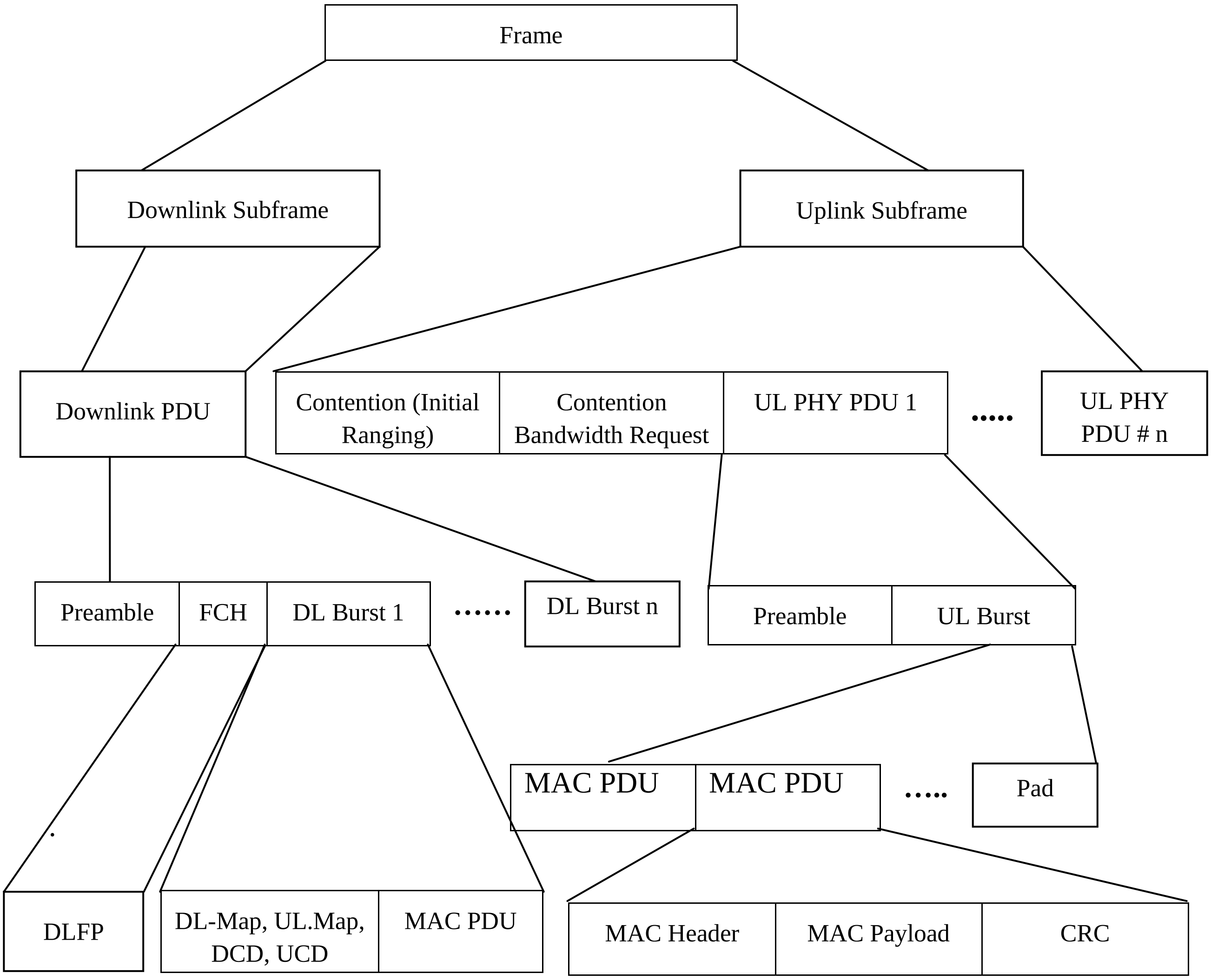


Figure 4.8: WiMAX TDD Frame Structure [44]

4.5 Quality of Service

WiMAX supports connection oriented QoS mechanisms which enable end-to-end QoS control. The QoS parameters are defined per Service Flow (SF). The SF provides multiple flows to or from the mobile station [45]. The QoS parameters are negotiated dynamically or statically through MAC messages and provide scheduling and transmission ordering on the air interface. In addition WiMAX QoS mechanism supports various applications such as:

- rtPS (Real Time Polling Service): Streaming applications (Audio/Video) .
- UGS (Unsolicited Grant Service): VoIP.
- ErtPS (Extended Real Time Polling Service): Voice with Activity.

- nrtPS (Non Real Time Polling Service): FTP (File Transfer Protocol).
- BE (Best Effort Service): Web browsing, Data Transfer.

LTE provides QoS as well as Quality of Experience (QoE). The QoS parameters defined for LTE are as follow:

- QCI: It is a scalar quantity which is preset by the operator. It determines the characteristics of packet forwarding.
- ARP (Allocation-Retention Priority): Contains allocation and retention priority for SDF (Service Data Flow).
- MBR: Stands for Maximum Bit Rate. It enforces the maximum bit rate to SDF.
- GBR (Guaranteed Bit Rate): Used for determining the allocation of resources.
- AMBR (Aggregate Maximum Bit Rate): Used by non GBR flows.

4.6 Mobility

Mobile WiMAX supports idle mode and sleep mode connectivity. In idle mode, UE is not registered with the BS whereas in sleep mode UE may scan neighboring base stations or may power down. Mobile WiMAX supports three types of handovers; Hard Handover (HHO), Macro Diversity Handover (MDHO) and Fast Base Station Switching (FBSS). HHOs are mandatory in mobile WiMAX whereas FBSS and MDHO are used optionally. Mobility speeds supported by mobile WiMAX are up to 120 km/h.

LTE supports RRC_IDLE and RRC-CONNECTED modes to provide mobility. In contrast to WiMAX, LTE supports Inter Cell Soft Handovers and Inter RAT handovers with mobility speeds up to 350 km/h.

4.7 Comparative Summary

The brief comparative summary of WiMAX and LTE is illustrated in Table 4.7.

	WiMAX	**LTE**
Network Architecture	IP based, Flat	IP based, Flat
Access Technology	DL: OFDMA (For Mobile WiMAX), UL: OFDMA (For Mobile WiMAX)	DL: OFDMA, UL:SC-FDMA
Channel Bandwidth (in MHz)	1.25, 3.5, 5, 10, 20	1.25, 2.5, 5, 10, 15, 20
FFT Size	128, 256, 512, 1024, 2048	128, 256, 512, 1024, 2048
Duplexing Mode	TDD and FDD; Focus: TDD	TDD and FDD; Focus: FDD

	WiMAX	LTE
Subcarrier Spacing (in kHz)	Support variable subcarrier spacing ranges from 7 to 20 kHz. Typically 10 kHz (For Mobile WiMAX)	15 kHz (Fixed)
Cyclic Prefix Length	Variable: 1/32, 1/16, 1/8 and 1/4.	Normal CP: 5.21 us Extended CP: 16.67 us
Frequency Bands or Spectrum (in GHz)	Licensed:2.3, 2.5, 3.5 Licensed Exempt: 5.8	Licensed, IMT 2000 bands (~2GHz)
Modulation	QPSK, 16-QAM and 64-QAM	QPSK, 16-QAM and 64-QAM
Coding	Turbo Encoder, Convolutional Encoder and LDPC	Turbo Encoder, Convolutional Encoder
Framing, TTI	Variable: 2 to 20 ms, Focus: 5 ms	Fixed: 1msec (2 slots of 0.5 ms)
Number of Symbols in Subchannel/Physical Resource Block	Number of symbols in a Subchannel: 24 x 2 in PUSC mode	Number of symbols in Physical Resource Block: 12x7 (Normal CP)
Peak Data Rate	DL: 75 Mbps, UL: 25 Mbps	DL: 100 Mbps, UL: 50 Mbps
Cell Radius	2-7 km	5 km
Cell Capacity	100-200 users	> 200 users (at 5 MHz), >400 users (for larger Bandwidth)
Spectral Efficiency (in bits/sec/Hz)	3.75	5
MIMO	DL: 2x2, 2x4, 4x2, 4x4 UL: 1x2, 1x4, Code Words: 1	DL: 2x2, 2x4, 4x2, 4x4 UL: 1x2, 1x4, 2x2, 2x4 Code Words:2
Mobility	120 km/h	350 km/h
Handovers	Mandatory: Optimized Hard Handover, Optional: FBSS and MDHO.	Inter frequency Soft Handovers are supported.
Roaming Framework	Work in process	Through existing GSM/UMTS network
Legacy Network	IEEE 802.16a to IEEE 802.16d (For Mobile WiMAX)	GSM, GPRS, EGPRS, UMTS, HSPA.

	WiMAX	LTE
Time Line	For Mobile WiMAX Standard Completed: 2005 Initial Deployment: 2007-08 Mass Market: 2009	Standard Completed: 2007 Initial Deployment: 2010 Mass Market: 2012

Table 4.7: Comparative Summary of WiMAX and LTE

Chapter 5: Simulation

5.1 Introduction

This chapter presents our simulation results along with underlying assumptions. In the first part, we investigated LTE uplink and performed link level simulations of Single Carrier Frequency Domain Equalization (SC-FDE) and SC-FDMA in comparison with OFDM. We have used two types of multipath channels, i.e. ITU Pedestrian A and ITU Vehicular A channels. In addition an Additive White Gaussian Noise (AWGN) channel is also used. Furthermore, the simulation of PAPR is performed for SC-FDMA and OFDMA systems. In the second part of this chapter, we analyzed the capacity of the MIMO system and performed a comparison with SISO.

All simulations are performed in MATLAB 7.40 (R2007a).

5.2 Link Level Simulation of SC-FDE

SC-FDE is a frequency domain equalization technique used to minimize the frequency selective fading effects in LTE uplink. SC-FDE has similar spectral efficiency and link level performance as OFDM. However, it has certain advantages upon OFDM due to usage of DFT and IDFT in the receiver. The block diagrams used in the link level simulation of SC-FDE and OFDM are shown in Figure 5.1 and 5.2 respectively. We can see the similarity between two block diagrams as they contain the same signal processing blocks.

The parameters used in simulation are described in Table 5.1. The parameters are chosen only for 5 MHz transmission bandwidth of LTE system. The number of iterations used in the Monte Carlo simulation are 10^4. A Monte Carlo simulation is a method which repeatedly counts the number of transmitted symbols and symbol errors on every iteration.

Parameters	Assumptions
System Bandwidth	5 MHz
Sampling Rate	5 Mega-samples per second
Pulse Shaping	None
Modulation Format	QPSK
Cyclic Prefix	4 µs or 20 samples
Subcarrier Spacing	5 MHz / 512 = 9.765 kHz
IFFT Size	512 Points
Input Block Size	16 Symbols
Input FFT size	16

Parameters	Assumptions
Channel coding	None
Number of iteration	10^4
Equalization	Minimum Mean Square Error (MMSE), Zero Forcing (ZF)
Channel	ITU Pedestrian A, ITU Vehicular A and AWGN.
Detection	Hard
Confidence Interval	32

Table 5.1: Simulation Parameters and Assumptions

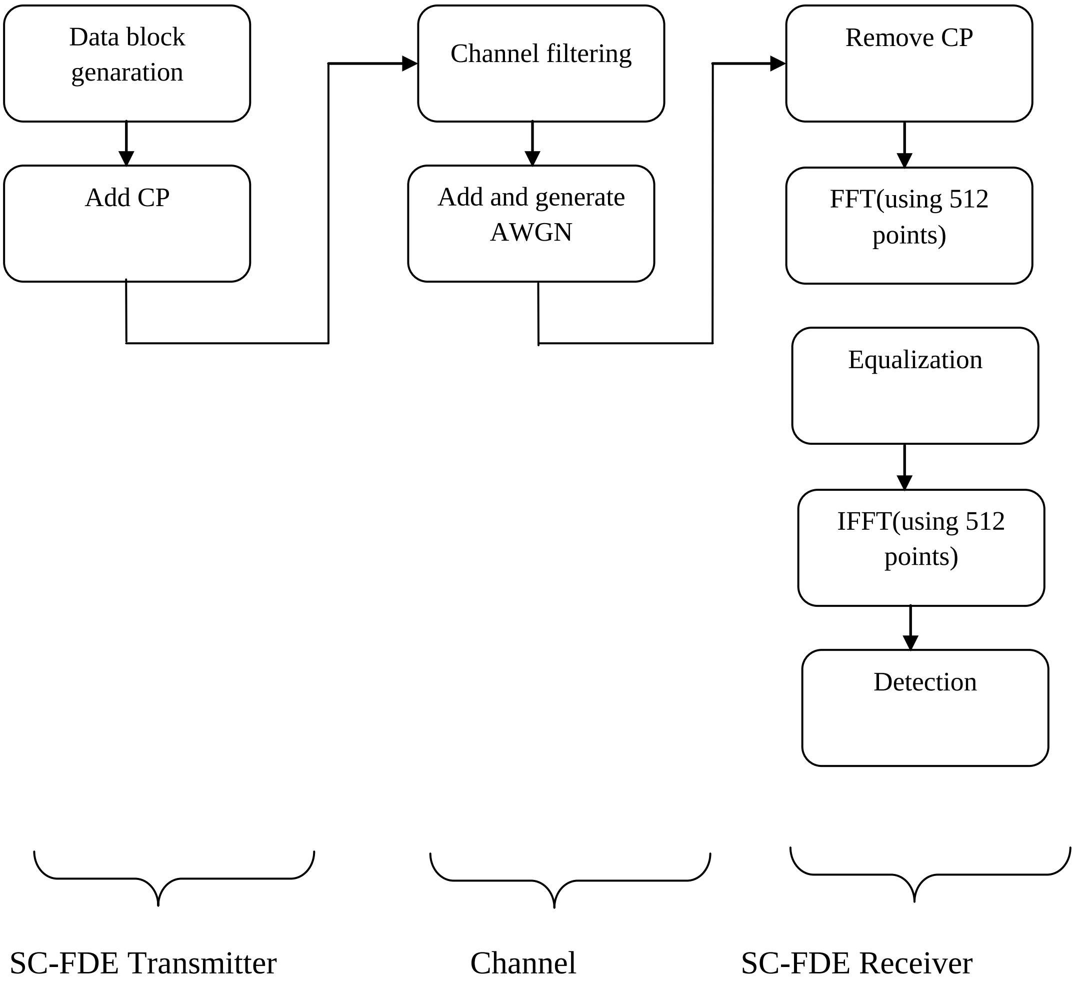


Figure 5.1: Block Diagram of SC-FDE Link Level Simulator

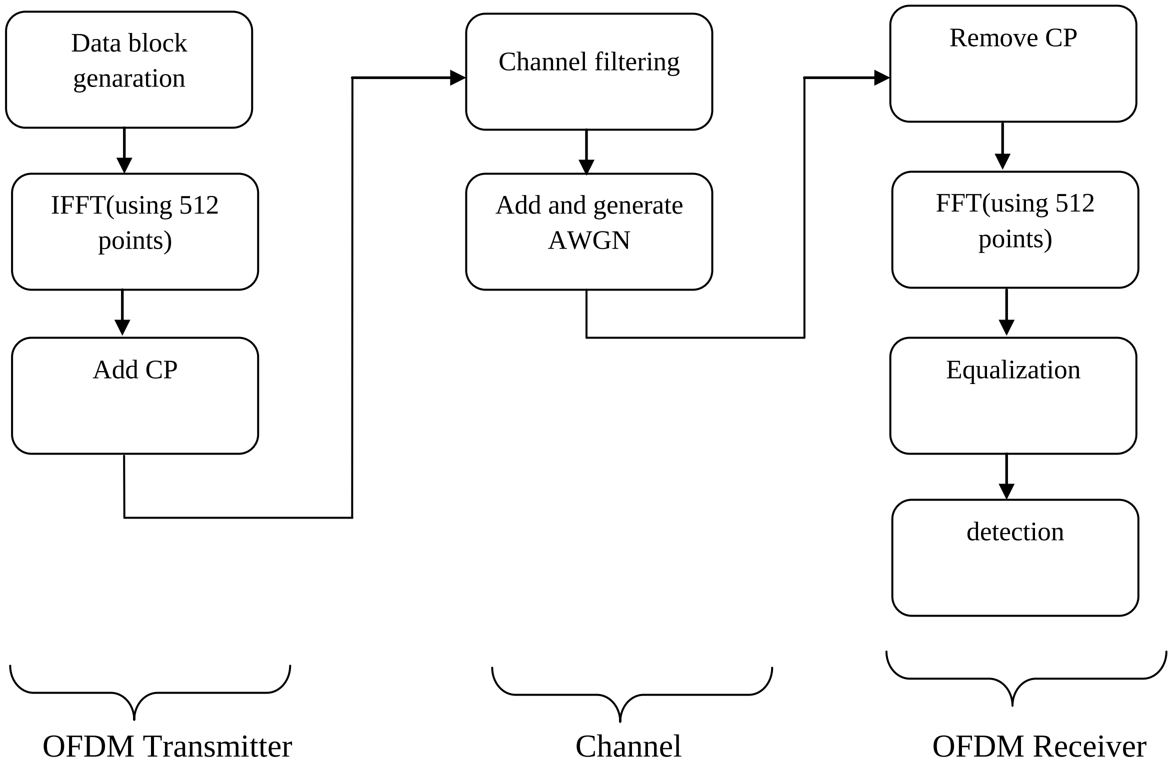


Figure 5.2: Block Diagram of OFDM Link Level Simulator

The simulation results compute Symbol Error Rate (SER) for the performance measurement of SC-FDE and OFDM in various scenarios.

5.2.1 SER for SC-FDE and OFDM using MMSE as Equalization Scheme

We have calculated SER measurement of SC-FDE and OFDM by using three types of channels, ITU Pedestrian A, ITU Vehicular A and AWGN channel. The equalization scheme used to obtain the SER curves is MMSE.

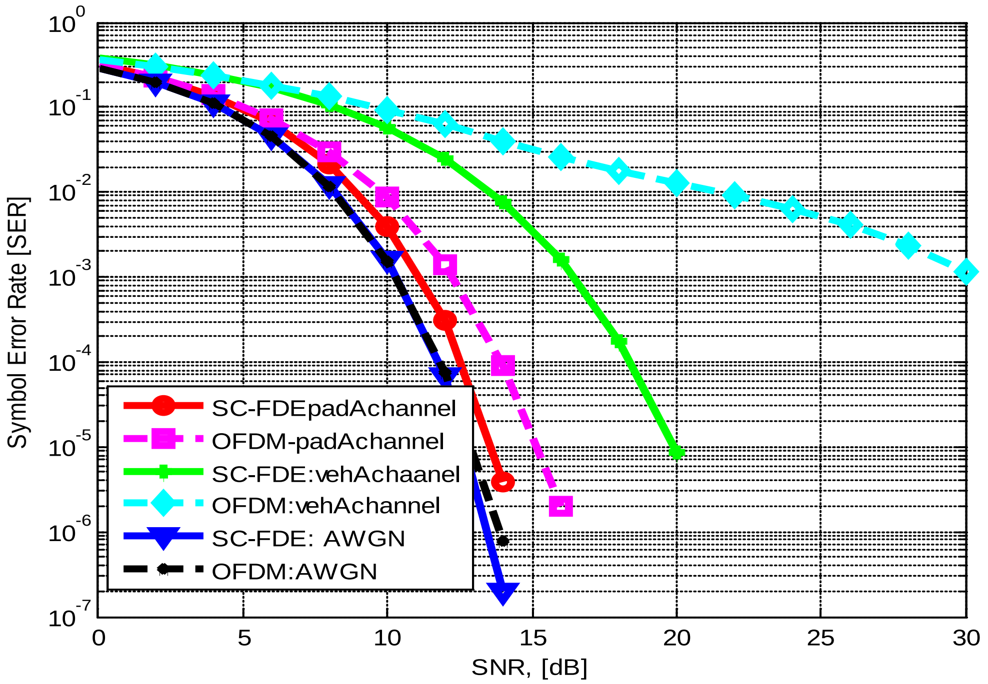


Figure 5.3: Comparison of SC-FDE and OFDM using MMSE Equalization in Pedestrian A, Vehicular A and AWGN Channels

Simulation results show that in case of AWGN channel SC-FDE and OFDM has similar SER performance. However, in case of Pedestrian A and Vehicular A channel, SC-FDE outperforms the OFDM. As we know OFDM needs additional channel coding to achieve this performance due to its sensitive nature to carrier frequency. The comparative summary obtained from Figure 5.3 is described in Table 5.2 and Table 5.3.

	Channels	**SNR (in dB)**	**SER**
SC-FDE	AWGN	10	0.001566
	Pedestrian A	10	0.004029
	Vehicular A	10	0.0577
OFDM	AWGN	10	0.001566
	Pedestrian A	10	0.008625
	Vehicular A	10	0.09313

Table 5.2: Comparison between SC-FDE and OFDM in Various Channels Using MMSE Equalization

The Table 5.2 clearly shows that SC-FDE significantly reduces SER as compared to OFDM in Vehicular A and Pedestrian A Channel.

	Channel	SNR (in dB)	SER
SC-FDE	Vehicular A	16	0.001578
		20	8.594e-006
OFDM	Vehicular A	16	0.02622
		20	0.013

Table 5.3: Comparison between SCFDE and OFDM in Vehicular A Channel using MMSE Equalization

Table 5.3 illustrates an important result i.e. as SNR increases the SC-FDE sharply reduces the Symbol error rate as compared to OFDM in case of vehicular channel.

5.2.2 SER for SC-FDE and OFDM using Zero Forcing

The calculation of SER is performed using Zero Forcing as equalization scheme for the comparison of SC-FDE and OFDM in AWGN, ITU Pedestrian A and ITU Vehicular A channel.

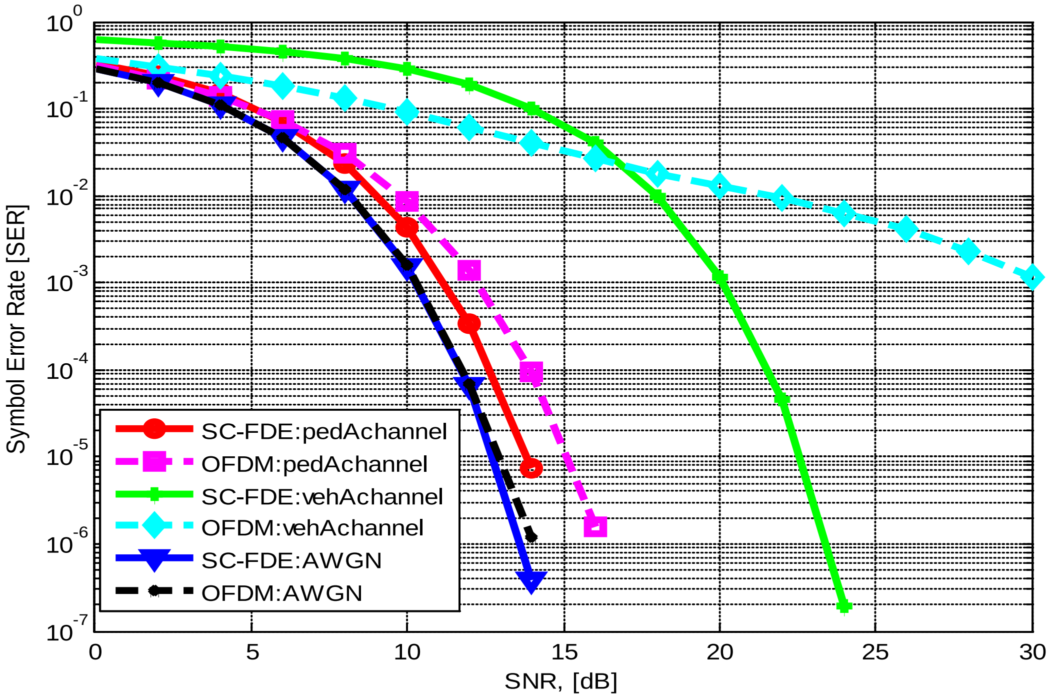


Figure 5.4: Comparison of SC-FDE and OFDM using Zero Forcing Equalization

Simulation results show that SC-FDE outperforms the OFDM in case of multipath channels i.e. ITU Pedestrian A and ITU Vehicular A channel. We see that in case of Vehicular A channel, OFDM has a continuous reduction of SER and it significantly minimizes the SER up to certain values of SNR as compared to SC-FDE. However, SC-FDE outperforms OFDM for higher values of SNR. The comparative summary of the results obtained from the simulation are shown in Figure 5.2 and described in Table 5.4 and 5.5.

	Channels	SNR (in dB)	SER
SC-FDE	AWGN	10	0.001578
	Pedestrian A	10	0.004428
	Vehicular A	10	0.2797
OFDM	AWGN	10	0.001578
	Pedestrian A	10	0.008546
	Vehicular A	10	0.0932

Table 5.4: Comparison of SCFDE and OFDM in various Channels using Zero Forcing

Table 5.4 shows that SCFDE has better performance in case of AWGN and Pedestrian channel while OFDM is better in case of vehicular channel.

	Channel	**SNR (in dB)**	**SER**
SC-FDE	Vehicular A	14	0.1004
		18	0.009742
		22	4.492e-005
OFDM	Vehicular A	14	0.04008
		18	0.01804
		22	0.009223

Table5.5: Performance of SCFDE and OFDM using Zero Forcing in Vehicular A Channel

Table 5.5 shows that OFDM gives better performance for smaller values of SNR but for higher values, the SC-FDE significantly reduces SER as compared to OFDM system which continuously reduces the error as the value of SNR is increased.

We observe from Figure 5.3 and 5.4 that MMSE gives better performance as compared to zero forcing.

5.2.3 Comparison of SC-FDE and OFDM with/without CP

The comparison of SCFDE and OFDM is performed in Vehicular channel with and without CP. The equalization scheme used in this simulation is MMSE.

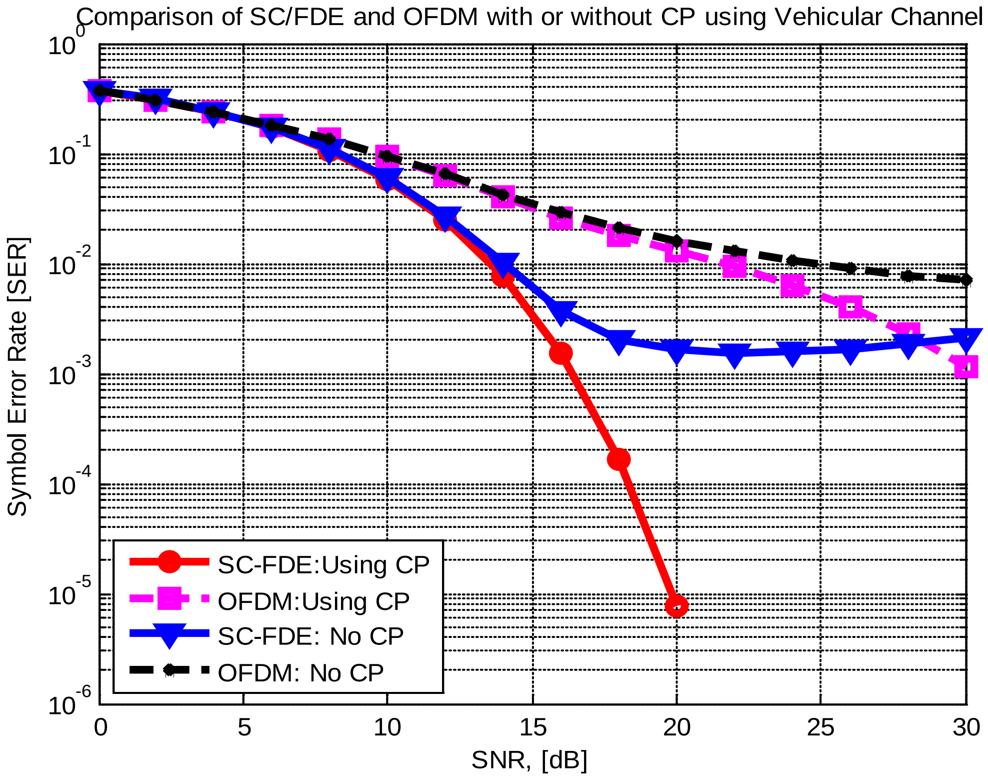


Figure 5.5: Comparison of SC/FDE and OFDM with or without CP using Vehicular Channel

Figure 5.5 shows that the use of CP reduces the SER as compared to the system having no CP. In addition, it is clearly shown that SC-FDE system gives low SER as compared to OFDM. Table 5.6 summarizes the comparison obtained from simulation.

	Channel	With CP		Without CP		Equalization
		SNR (in dB)	SER	SNR (in dB)	SER	
SC-FDE	Vehicular A	16	0.00155	16	0.003771	MMSE
		18	0.0001684	18	0.002033	
		20	7.813e-006	20	0.001675	
OFDM	Vehicular A	16	0.02626	16	0.02895	
		18	0.01823	18	0.02083	
		20	0.01292	20	0.01611	

Table 5.6: Comparison of SC-FDE and OFDM With and Without CP

5.3 Link Level Simulation of SCFDMA

The simulation flow for SCFDMA is shown in Figure 5.6. We have investigated two types of subcarrier mapping schemes for SCFDMA and compared their performance in terms of SER and SNR. The types of subcarrier mapping schemes are Interleaved FDMA (IFDMA) and Localized FDMA (LFDMA). Parameters used in simulation are given in Table 5.7.

Parameters	Assumptions
System Bandwidth	5 MHz
FFT Size	512
Block Size	16 symbols
CP Length	20 samples
Range of SNR	0 to 30 dB
Modulation	QPSK
Number of iteration	10^4
Channel	AWGN, Pedestrian A and Vehicular A.
Equalization	MMSE
Confidence Interval	32

Table 5.7: Simulation Parameters of SC-FDMA

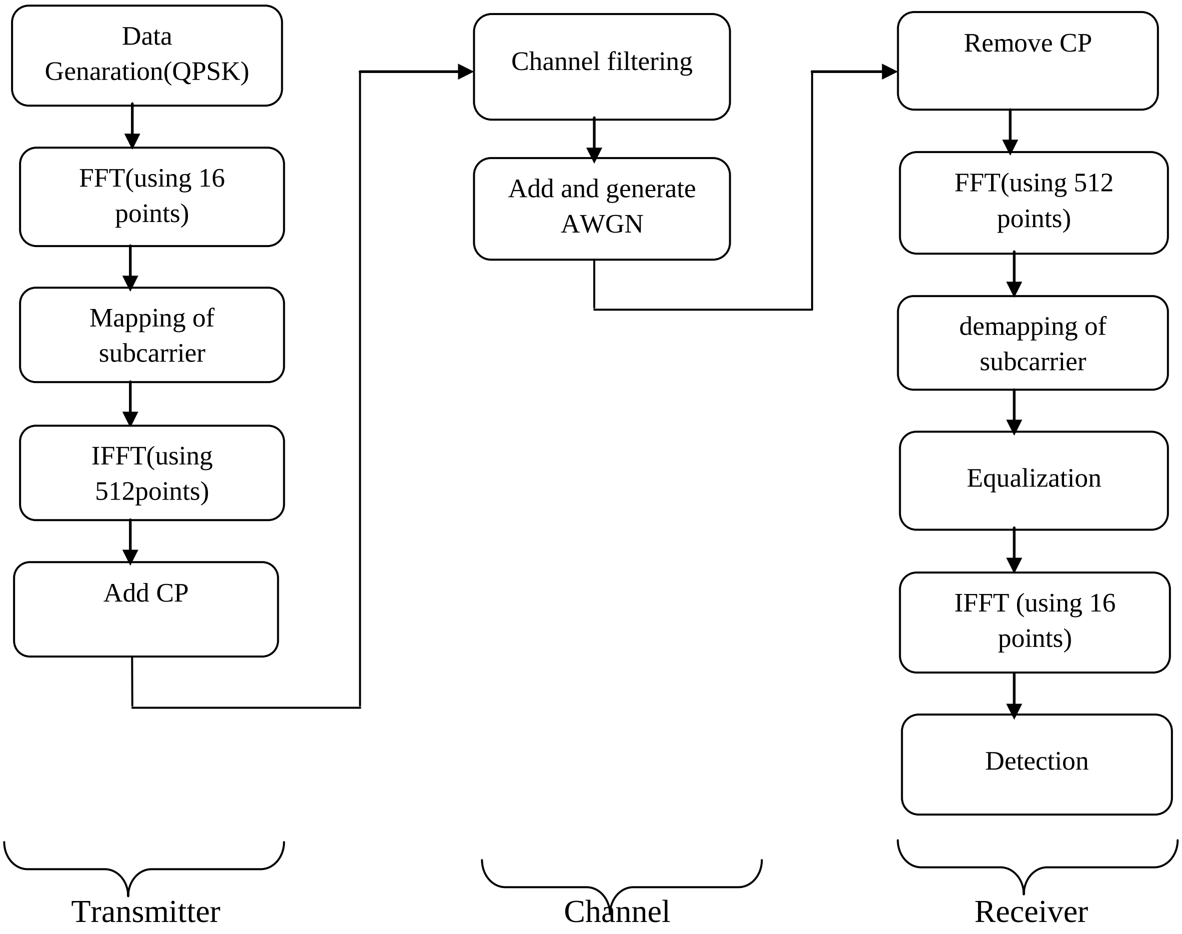


Figure 5.6: System Model of SC-FDMA

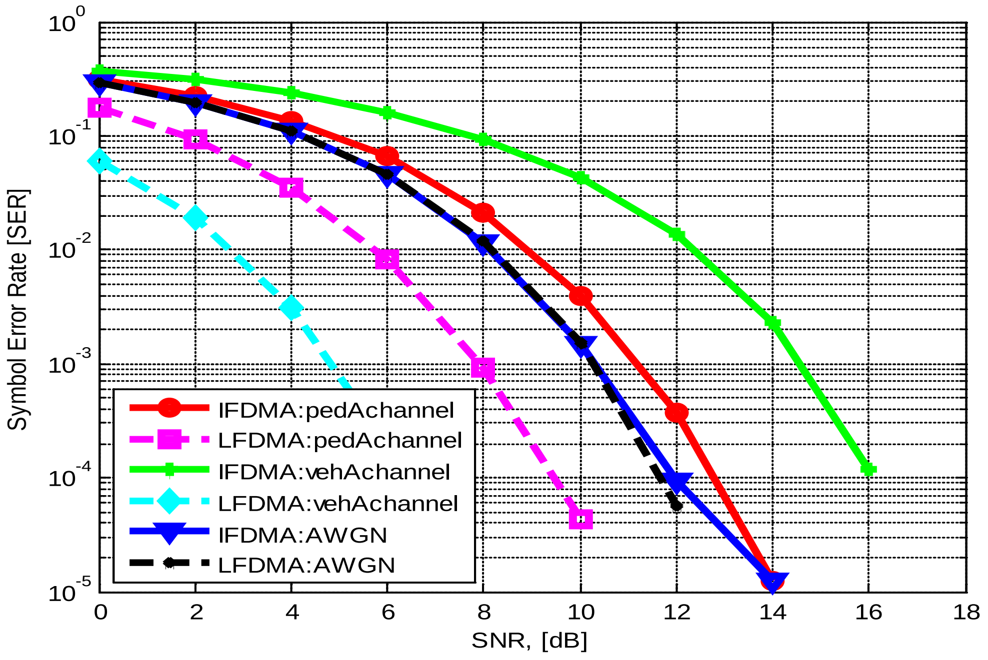


Figure 5.7: Comparison of SER with Various Subcarrier Mapping Schemes

Figure 5.7 presents the performance of SC-FDMA system using subcarrier mapping schemes IFDMA and LFDMA for various channels. It is clear from the simulation that LFDMA outperforms the IFDMA in all channel conditions and gives better performance.

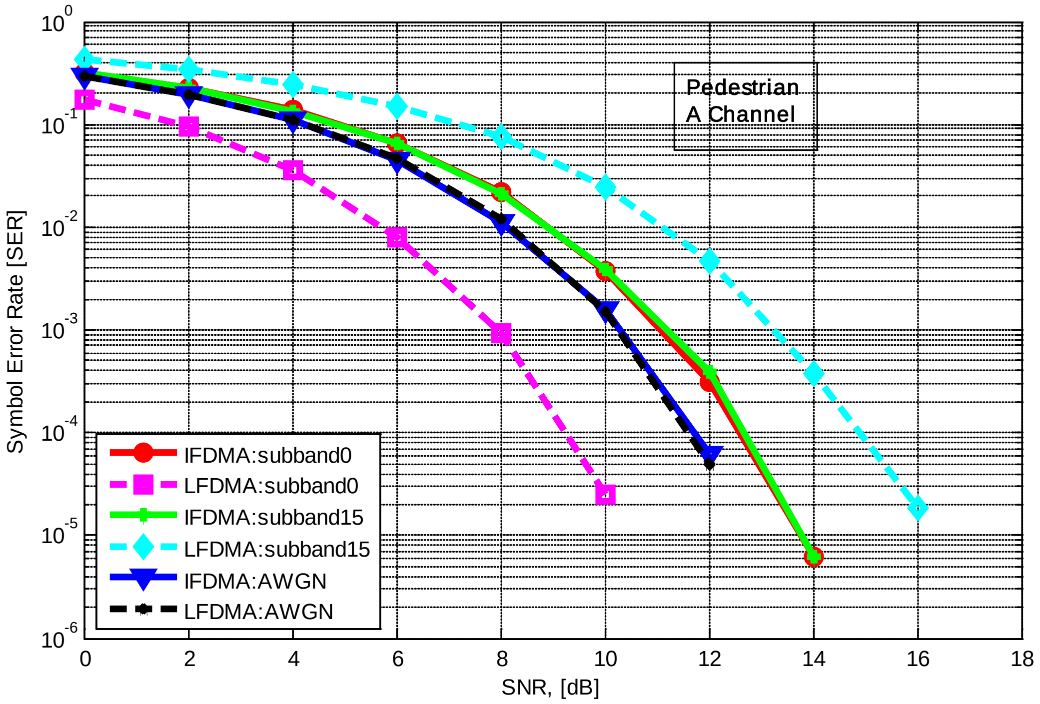


Figure 5.8: SER Performance of SC-FDMA System Using Various Subcarrier Mapping Schemes

Figure 5.8 presents the SER performance of SC-FDMA system in AWGN and Pedestrian A channel using two subcarrier mapping schemes. In case of AWGN channel, we see that IFDMA and LFDMA have similar performance whereas for Pedestrian A channel the two subcarrier schemes have different SER performance. In addition, it is clearly shown that the performance of IFDMA system does not depend on location of subband and gives approximately similar SER curves for subband 0 and subband 15. This is due to the inherent characteristic of frequency diversity of the IFDMA scheme. As for LFDMA, the performance of SC-FDMA is better in case of subband 0 and worst in case of subband 15. This is because of channel gain which is higher than average at subband 0 and below to average at subband 15.

5.4 Peak -to- Average Power Ratio

Peak to average power ratio is defined as “the ratio of peak signal power to the average signal power”.

$$PAPR = \frac{Peak\ Signal\ Power}{Average\ Signal\ Power}$$

Mathematically, PAPR can be written as

$$PAPR = \frac{\underset{0 \le t \le N\tilde{T}}{\max} \; |x(t)|^2}{\frac{1}{N\tilde{T}} \int_0^{N\tilde{T}} |x(t)|^2 \, dt}$$

Where

$$x(t) = e^{j w_c t} \sum_{n=0}^{N-1} \tilde{x}_n p(t - n\tilde{T}) \, a_n$$

$\tilde{x}_n$: n =0, 1, …, N-1 are the time domain symbols that come after the IDFT.

w_c = Carrier Frequency

$\tilde{T}$= $\tilde{x}_n$ symbol duration, and

p (t) = Baseband Pulse.

The simulation model for calculating PAPR of SC-FDMA system is shown in Figure 5.9.

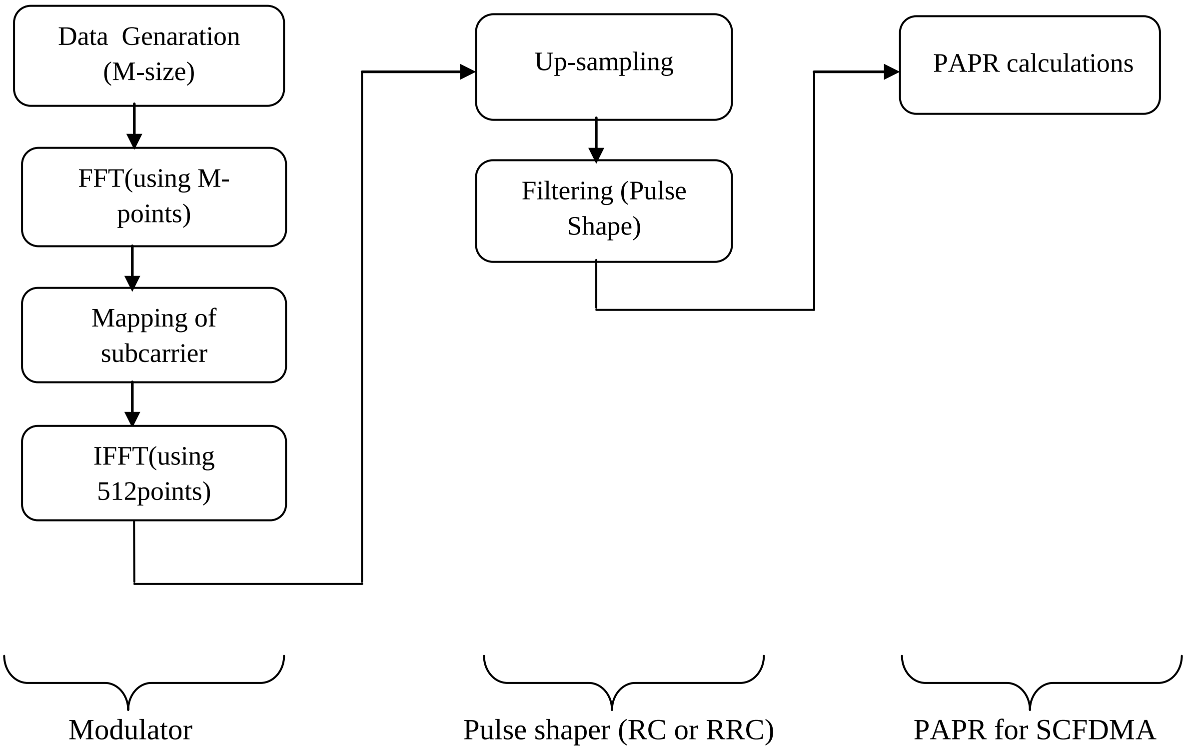


Figure 5.9: Simulation Model of PAPR Calculations for SCFDMA

For pulse shaping we used Raised Cosine (RC) and Square Root Raised Cosine (RRC) filters because they make the receiver robust against timing synchronization errors. The parameters used for the calculation of PAPR are illustrated in Table 5.8. For the calculation of PAPR we use Complementary Cumulative Distribution Function (CCDF). The CCDF is defined as the probability for which PAPR is greater than any PAPR value i.e. $PAPR_0$.

Parameters	Assumptions
System Bandwidth	10 MHz
Number of Subcarriers (N)	512
Number of Symbols (M)	128
Spreading Factor for IFDMA (Q)	Q= N/M=4
Spreading Factor for LFDMA	2
Roll of Factor	0.25
Over Sampling Factor	4
Number of iteration	10^4
Subcarrier Mapping Schemes	IFDMA,DFDMA,LFDMA
Confidence Interval	32
CCDF: Pr (PAPR >PAPR$_0$)	

Table 5.8: Parameters used in the simulation of PAPR calculation for SCFDMA

5.4.1 PAPR-SCFDMA Calculation Using QPSK

The PAPR calculation using various subcarrier mapping schemes for SCFDMA system is shown in Figure 5.10. The modulation scheme used for the calculation of PAPR is QPSK.

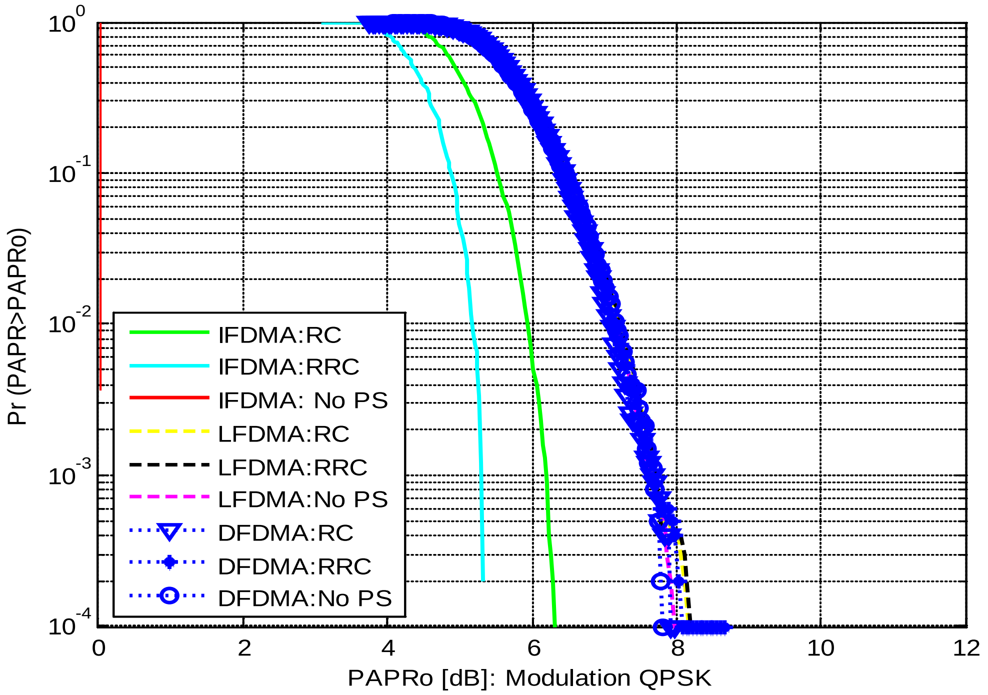


Figure 5.10: Comparison of CCDF of PAPR for DFDMA, IFDMA and LFDMA using QPSK

Figure 5.10 show that IFDMA gives lowest PAPR values as compared to other subcarrier mapping schemes (DFDMA and LFDMA).

5.4.2 PAPR-SCFDMA Calculation Using 16-QAM

The PAPR calculation using various subcarrier mapping schemes for SC-FDMA system is shown in Figure 5.11. The modulation scheme used for the calculation of PAPR is 16-QAM.

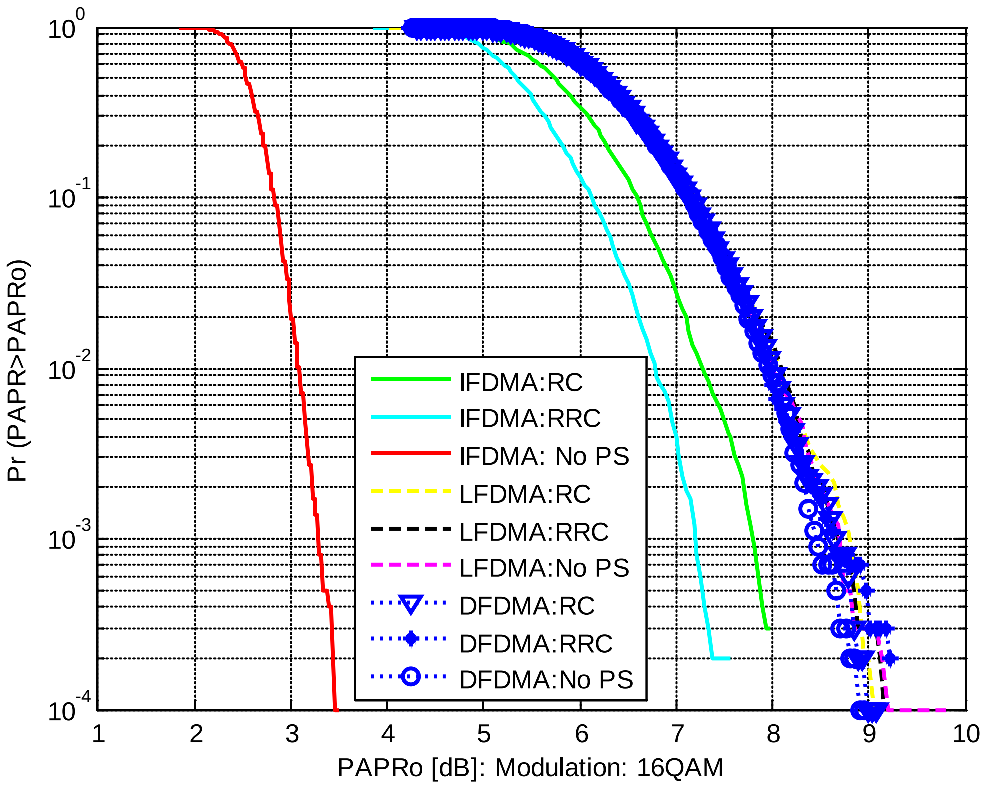


Figure 5.11: Comparison of CCDF of PAPR for IFDMA, DFDMA and LFDMA using 16-QAM

Figure 5.11 show that IFDMA has lowest value of PAPR at 3.2dB which is 0dB in case of QPSK as modulation technique. We can also observe from the figure that we get higher values of PAPR by using 16-QAM which is undesirable because they cause non linear distortions at the transmitter.

5.4.3 PAPR Calculation for OFDMA

We know theoretically that OFDMA gives higher PAPR values as compared to SCFDMA due to its multicarrier nature. In addition, there is no pulse shaping filter used in OFDMA. The simulation model for the calculation of PAPR for OFDMA system is shown in Figure 5.12.

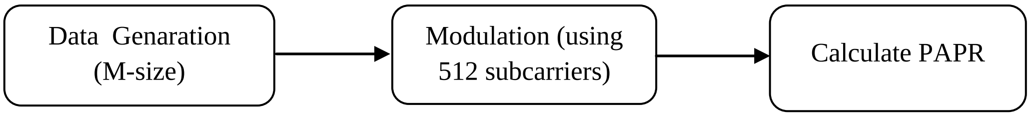


Figure 5.12: Simulation Model of PAPR Calculations for OFDMA

The simulation parameters used in the simulation are described in Table 5.9.

Parameters	Assumptions
System Bandwidth	5 MHz
Number of Subcarriers (N)	512
Number of Symbols (M)	128
Over Sampling Rate	4
Number of Iterations	10^4
Confidence Interval	32

Table 5.9: Parameters Used in the Simulation of PAPR-Calculation for OFDMA

Figure 5.13 shows the PAPR calculation of OFDMA system using QPSK and 16-QAM modulation techniques. The graph shows that the PAPR value of OFDMA system is much higher than SC-FDMA system. We can also observe that the behavior of CCDF is quite similar in case of QPSK and 16-QAM.

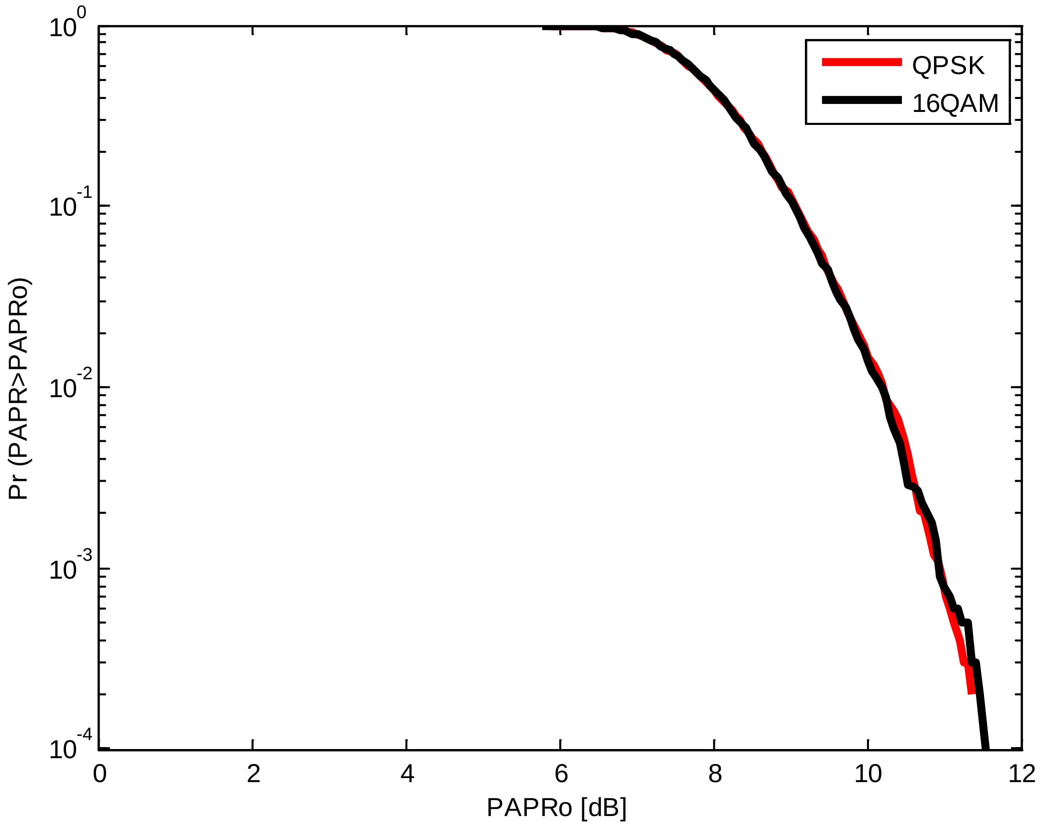


Figure 5.13: Comparison of CCDF of PAPR for OFDMA using QPSK and 16-QAM

5.5 Capacity of MIMO System

MIMO system consists of multiple transmit and receive antennas interconnected with multiple transmission paths. MIMO increases the capacity of system by utilizing multiple antennas both at transmitter and receiver without increasing the bandwidth.

$$\textit{Capacity of MIMO}= \sum_{i=1}^{r} log_2(1+\frac{\rho}{M}\,\lambda i)$$

Where,

r = rank of matrix
λ= Positive eigenvalues of HH^H (as H^H is the conjugate of H)
ρ= SNR

$$\textit{Capacity of SISO}= log_2\,(1+\rho h^2)$$

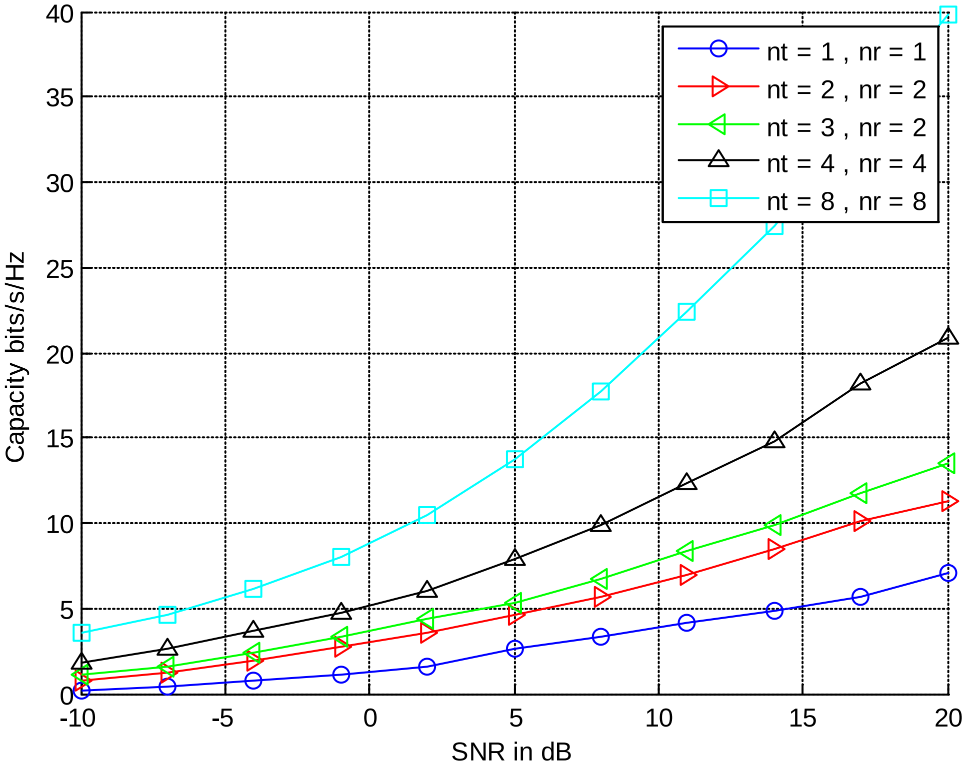


Figure 5.14: Comparison of MIMO and SISO system in terms of Capacity

Figure 5.14 shows the comparison between MIMO and SISO systems in terms of capacity. The graph depicts that the capacity of system can be increased by increasing the number of antennas at transmitter and receiver. The graph also show that 8x8 MIMO system has larger capacity whereas SISO system as lowest capacity.

Table 5.10 summarizes simulation results obtained from Figure 5.13.

For SNR= 5dB

Antenna Configuration	Capacity (bits/s/Hz)
SISO	2.589
MIMO (2x2)	4.589
MIMO (3x2)	5.325
MIMO (4x4)	7.907
MIMO (8x8)	13.7

Table 5.10: Comparison between MIMO and SISO System with SNR=5 dB

For SNR= 14dB

Antenna Configuration	Capacity (bits/s/Hz)
SISO	4.89
MIMO (2x2)	8.485
MIMO (3x2)	9.941
MIMO (4x4)	14.83
MIMO (8x8)	27.48

Table 5.11: Comparison between MIMO and SISO System with SNR=14 dB

Chapter 6: Conclusion and Future Work

6.1 Conclusion

We conclude that both WiMAX and LTE are technically similar standards. However, there are some differences present in the uplink access method used by both technologies. LTE uses SC-FDMA whereas WiMAX uses OFDMA as an access method. The adaptation of SC-FDMA in the uplink gives edge to LTE over WiMAX because it resolves the PAPR problem of OFDMA due to its single carrier nature.

We also conclude that, LTE gives better data rates in the uplink and downlink due to support of MIMO system as compared to WiMAX which only supports MIMO in the downlink direction.

From a market prospective, WiMAX has edge on LTE due to its early deployments. WiMAX was first deployed in 2007-08 whereas LTE is not yet deployed. Due to timeline advantages of WiMAX over LTE, we also conclude that new and existing service providers will go for mobile WiMAX in order to provide mobile services to subscribers. We also conclude that the service providers of GSM and CDMA 2000 in developing countries will naturally go for mobile WiMAX for broadband wireless services, whereas service providers of UMTS/HSPA will go for 3GPP-LTE.

We conclude from our simulations that SC-FDE has low SER as compared to OFDM in all channel conditions. Also, the use of LFDMA as a subcarrier mapping scheme in SC-FDMA gives better SER performance when compared to IFDMA in all channel conditions (ITU Pedestrian A, ITU Vehicular A, AWGN).

IFDMA gives lowest PAPR as compared to LFDMA and DFDMA subcarrier mapping schemes. The use of QPSK further reduces the PAPR as compared to 16-QAM.

We also conclude that OFDMA gives high PAPR values as compared to SC-FDMA due to the use of multiple subcarriers.

6.2 Future Work

In future, implementation of WiMAX and LTE on a single chip could be done to facilitate the advantages of the two technologies in one system. Practical implementation of multiple antenna techniques on LTE can be tested in future to verify our theoretical results.

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