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by

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Performance Evaluation of WiMAX/IEEE 802.16 Physical Layer

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Information and Communication Engineering

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Recommendation

The undersigned certify that they have read and recommended to the Department of Electronics and Computer Engineering for acceptance, a thesis entitled **“Performance Evaluation of WiMAX/IEEE 802.16 Physical Layer**”, submitted by **Min Prasad Aryal** in partial fulfillment of the requirement for the award of the degree of “**Master of Science in Information and Communication Engineering**”.

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The thesis entitled **"Performance Evaluation of WiMAX/IEEE 802.16 Physical Layer",** submitted by **Min Prasad Aryal** in partial fulfillment of the requirement for the award of the degree of "**Master of Science in Information and Communication Engineering**" has been accepted as a bonafide record of work independently carried out by him in the department.

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ABSTRACT

The advancements in broadband and mobile communication has given many privileges to the subscribers for instance high speed data connectivity, voice and video applications in economical rates with good quality of services. WiMAX is an eminent technology that provides broadband and IP connectivity on "last mile" scenario. Orthogonal frequency division multiple access uses adaptive modulation technique on the physical layer of WiMAX and it uses the concept of cyclic prefix that adds additional bits at the transmitter end. The signal is transmitted through the channel and it is received at the receiver end. Then the receiver removes these additional bits in order to minimize the inter symbol interference, to improve the bit error rate.

This report includes the study of the technological aspects of WiMAX standards and evaluate/analyze the performance of WiMAX physical layer in different perspectives. In this research work, I investigate the physical layer performance on the basis of bit error rate, signal to noise ratio etc. The performance would be analyzed in different aspects such as with the variation of different modulation techniques, cyclic prefix, coding, channel models etc. The different techniques employed are studied to know the impact of variations of different parameters causing the variation in the desired output thus maximizing the system throughput and improving BER performance.

There are also other different Broadband Wireless Technologies which provides broadband solutions to the customers such as 3G, WCDMA, HSPA, WiFi, LTE etc. In this thesis, I have studied in brief on different BWA technologies and also compare other BWA technologies with respect to WiMAX in the key dimensions.

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LIST OF SYMBOLS

τ_{max}	Maximum delay spread
N_{used}	Number of Used Subcarrier
G	Ratio of Guard time to useful symbol time
n	Sampling Factor
N_{FFT}	Smallest power of 2 greater than N_{used}
F_s	Sampling Frequency
Δf	Subcarrier Spacing
T_b	Useful Symbol Time
T_g	CP Time
T_s	OFDM Symbol Time
N	The number of overall bytes after encoding
K	The number of data bytes before encoding
T	The number of data bytes which can be corrected
N_{cbps}	Number of coded bits per allocated sub channels per OFDM symbol
N_{cpc}	The number of coded bits per sub carriers
M	The complex constant of the complex Gaussian set
σ^2	The variance of the complex Gaussian set
f_m	Doppler frequency

LIST OF ABBREVIATIONS

AAS	Adaptive Antenna System
ADC	Analog to Digital Conversion
ADSL	Asymmetric Digital Subscriber Line
AMC	Adaptive Modulation Coding
AMPS	Advanced Mobile Phone System
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
BSID	Base Station Identification
BWA	Broadband Wireless Access
BTC	Block Turbo Coding
CA	Collision Avoidance
CC	Convolutional Code
CD	Collision Detection
CP	Cyclic Prefix
CPE	Customer Premises Equipment
CPS	Common Part Sublayer

CS	Convergence Sublayer
CSMA	Carrier Sense Multiple Access
DAC	Digital to Analog Conversion
DFS	Dynamic Frequency Selection
DFT	Discrete Fourier Transform
DIUC	Downlink Interval Usage Code
DL	Downlink
DSL	Digital Subscriber Line
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
GPRS	General Packet Radio Service
HIPERMAN	High PERformance Metropolitan Area Network
HSPA	High Speed Packet Access
HSCSD	High Speed Circuit Switched Data
ICI	Inter Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications

IP	Internet Protocol
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
LAN	Local Area Network
LOS	Line of Sight
MAC	Medium Access Control
MCM	Multicarrier Modulation
MIMO	Multiple Input Multiple Output
MOIC	Ministry of Information and Communications
PCI	Peripheral Component Interconnect
PDA	Personal Digital Assistant
PTM	Point to Multipoint
MS	Mobile Station
NLOS	Non Line of Sight
NTA	Nepal Telecommunications Authority
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAR	Peak to Average Ratio
PAPR	Peak to Average Power Ratio
PCI	Peripheral Component Interconnect

PMP	Point to Multipoint
PSK	Phase Shift Keying
PTP	Point to Point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift keying
SCFDMA	Scalable Orthogonal Frequency Division Multiple Access
SNR	Signal to Noise Ratio
SS	Subscriber Stations
STBC	Space Time Block Code
SUI	Stanford University Interim
TDD	Time Division Duplexing
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
UL	Uplink
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications System
VOIP	Voice over Internet Protocol
VLAN	Virtual Local Area Network

WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WirelessMAN	Wireless Metropolitan Network
3GPP-LTE	Third Generation Partnership Project – Long Term Evolution

CHAPTER 1 INTRODUCTION

1.1 Background

In the last few years, the telecommunication industries' development has focused on an intensive use of broadband systems, which are characterized by high quality features. For this issue, new technologies with high transmission abilities have been designed. The broadband wireless access has become the best way to meet escalating business demand for rapid internet connection and other different multimedia applications. WiMAX is a promising technology which can offer high speed voice, video and data service up to the customers. Based on the IEEE 802.16 standard, WiMAX allows for an efficient use of bandwidth in a wide frequency range, and can be used as a last mile solution for broadband internet access.

WiMAX is a wireless broadband technology based on the IEEE 802.16 and ETSI HiperMAN standards. WiMAX uses OFDM technology with an all-IP core network – so called next generation technology. It delivers superior performance with high throughput, low latency, advanced security and QoS.

WiMAX is a standards-based technology enabling wireless broadband connections in fixed, nomadic and mobile usage modes for wireless broadband connectivity without the need for direct line-of-sight with a radio base station. As an alternative or complement to wired broadband access such as cable and DSL, WiMAX provides cell radii of up to ten kilometers. This provides enough bandwidth simultaneously to support hundreds of businesses with T-1 speed connectivity and thousands of residences with DSL speed connectivity.

1.2 Objective and Scope

The aim of this thesis is literature study and implementation with simulation the IEEE 802.16 OFDM physical layer in order to have better understanding of the standard and the system performance. The objective of this thesis is to study, evaluate and analyze the performance of IEEE 802.16 technology. The objective of the thesis deals the study and analysis of IEEE 802.16 physical layer and performance evaluation of the same with respect to different modulation techniques, Cyclic Prefix insertion, Channel models, nominal channel Bandwidth, coding .

The main objectives are:

1. To investigate the WiMAX physical layer performance on the basis of bit error rate, signal to noise ratio etc.
2. To know the impact of different parameters such as variation of modulation techniques, cyclic prefix, coding, channel models, nominal Bandwidth on the system performance.
3. To have comparative knowledge of other Broadband Wireless Access Technologies with respect to WiMAX.

This technology can be used for cellular backhaul applications, residential broadband customers, and in the underserved and unserved areas where there is no existence of wired infrastructure for fixed, nomadic and even mobile applications. The Quality of Service provided by WiMAX supports applications such as VoIP, streaming audio or video, file transfer protocol, data transfer, web browsing, etc. WiMAX can also be used as a wireless backhaul network that enables high speed internet access to residential, small, and medium business customers, as well as internet access for WiFi hotspots and cellular base stations thus providing cost-effective ubiquitous broadband coverage in various scenarios.

1.3 Statement of the Problem

The demand for broadband services continues to grow. Conventional high speed broadband solutions are based on wired-access technologies such as subscriber line. This type of solution is difficult to deploy in remote as well as hilly areas, and furthermore it lacks support for terminal mobility. WiMAX as a Broadband Wireless Access offers a flexible and cost effective solution to these problems. Because of its wireless nature, it can be faster to deploy, easier to scale and more flexible, thereby giving it the potential to serve customers not served or not satisfied by their wired broadband alternatives. BWA has emerged as a promising solution for last mile access technology to provide high speed internet access in the residential as well as small and medium sized enterprise sectors.

WiMAX is the first industry wide standard that can be used for wireless access with substantially higher bandwidth than most of cellular networks. Wireless broadband systems have been in use for many years, but the development of this standard enables economy of scale that can bring down the cost of equipment, ensure interoperability, and reduce investment risk for operators. Other BWA technologies (e.g. WiFi, 3G) have also drawbacks to provide the broadband service easily and quickly in reliable manner. Since the other BWA technologies are not effective and efficient to provide BWA, and have their own drawbacks, WiMAX is one of the best solutions in order to increase the broadband penetration in the country, it provides alternate and better solution.

1.3 Broadband

Broadband wireless is about bringing the broadband experience to a wireless context, which offers users certain unique benefits and convenience. There are wire line and wireless broadband solutions. In BWA, there are two fundamentally different types of broadband wireless services. The first type attempts to provide a set of services similar to that of the traditional fixed-line broadband but using wireless as the medium of transmission. This type, called fixed wireless broadband, can be thought of as a competitive alternative to DSL or cable modem. The second type of broadband wireless, called mobile broadband, offers the additional functionality of portability, nomadicity, and mobility. Mobile broadband attempts to bring broadband applications to new user experience scenarios and hence can offer the end user a very different value proposition. WiMAX technology is designed to accommodate both fixed and mobile broadband applications.

Broadband is defined as the high speed, reliable and on-demand internet connectivity. Broadband access not only gives the access to download files more quickly and provides faster web surfing but also enables multimedia applications like real-time audio, video streaming, multimedia conferencing and interactive gaming. The broadband connection is also used as voice telephony by using the VoIP technology [1].

Different organizations such as ITU or other international regulators specified that if the downloading speed is in the range of 256 Kbps to 2 Mbps or higher then it fall in the category of Broadband connections. By considering these points they formed the formal definition as:
“As an always-on the data connection side that is able to support various interactive services and that has the capability of a minimum download speed of 256 Kbps.”

In Nepal the broadband policy is not formulated till date. It is understood that the homework is being carried out by NTA and MOIC in order to formulate the broadband definition and the relevant national policy. The draft policy is recently developed which has defined broadband for always on connection having at least 64 Kbps upload and 256 Kbps download speed irrespective of the technology.

There are different fixed broadband access technologies such as DSL, Cable, Optical fiber, BPL etc. There are different wireless broadband technologies such as satellite broadband, wireless LAN, IMT – Advanced, 3GPP - LTE, UMB, iBurst, WCDMA, HSPA, WiMAX etc.

1.4 Generations of Mobile Phone

For nearly 100 years telecommunications provided mainly voice services and very low speed data (telegraph and telex). With the advent of the Internet several data services became the main stream in telecommunications to a point that voice is becoming an accessory to the IP centric data network [2]. Before 1977, wireless communication was only used in military applications and for research purposes in satellite communication. The evolution of AMPS was the starting and turning point in wireless communication by offering a two way communication (Full Duplex Mode). It uses analogue technology and also supports data streams up to 19.2 Kbps. AMPS is an example of first generation of wireless phones. Details of other generations of mobile phone are shown in below [1, 3]:

Different current 2.5G and 3G standards Data Communications Standards

Generation	Standard	Multiple Access	Channel BW	Duplex	Frequency Band	Throughput
2 G	GSM	TDMA/FDMA	200 KHz	FDD	890-960 (MHz) 1710-1880 (MHz)	9.6 Kbps
2.5 G	GPRS	TDMA/FDMA	200 KHz	FDD	890-960 (MHz) 1710-1880 (MHz)	171.2 Kbps
2.5 G	HSCSD	TDMA/FDMA	200 KHz	FDD	890-960 (MHz) 1710-1880 (MHz)	57.6 kbps
2.75 G	EDGE	TDMA/FDMA	200 KHz	FDD	890-960 (MHz) 1710-1880 (MHz)	384 Kbps
3G	UMTS	W-CDMA	5 MHz	FDD	1885-2025 (MHz) 2110-2200 (MHz)	2 Mbps
2.5G	IS-95B	CDMA	1.25 MHz	FDD	824-849 (MHz) 869-894 (MHz) 1850-1880 (MHz) 1930-1960 (MHz)	144 kbps
3G	CDMA 2000 1x RTT	CDMA	1.25 MHz	FDD	824-849 MHz/869-894 MHz	144 kbps
3G	CDMA 2000 1x EV (DO & DV)		3.75 MHz	FDD	824-849 MHz/869-894 MHz	2 Mbps

The 4^{th} Generation of mobile phone system is under research with an objective of fully IP based integrated system. The only difference with 3G is that it provides an IP based solution for data, voice and multimedia services to subscribers on the basis of two concepts i.e. "Anywhere" and "Anytime". In this scenario, the users are always connected to the network with good and reliable data connectivity, where ever they go and whatever the time is. The generations that came after the 2.5^{th} generation are also referred as the broadband generations because these generations have high data rates and provide multimedia services to their subscribers.

1.6 Brief Introduction on different BWA Technologies

There are different alternative broadband solutions such as 3G, WCDMA, Wi-Fi, and HSPA. The throughput capabilities of WiMAX depend on the channel bandwidth used. Unlike 3G systems, which have a fixed channel bandwidth, WiMAX defines a selectable channel bandwidth from 1.25 MHz to 28 MHz, which allows for a very flexible deployment. The reliance of Wi-Fi and WiMAX on OFDM modulation, as opposed to CDMA as in 3G, allows them to support very high peak rates. The need for spreading makes very high data rates more difficult in CDMA systems.

More important than peak data rate offered over an individual link is the average throughput and overall system capacity when deployed in a multicellular environment. From a capacity standpoint, the more pertinent measure of system performance is spectral efficiency. Therefore, when compared to 3G, WiMAX offers higher peak data rates, greater flexibility, and higher average throughput and system capacity. Another advantage of WiMAX is its ability to efficiently support more symmetric links-useful for fixed applications, such as T1 replacement-and support for flexible and dynamic adjustment of the downlink-to-uplink data rate ratios.

The WiMAX media access control layer is built from the ground up to support a variety of traffic mixes, including real-time and non-real-time constant bit rate and variable bit rate traffic, prioritized data, and best-effort data. Such 3G solutions as HSDPA and 1x

EV-DO were also designed for a variety of QoS levels. Brief Introduction on different BWATs is mentioned hereunder.

1.6.1 WCDMA

The UMTS is the European standard for the follower of GSM. The purpose has to deliver also data services to mobile users, but still carries the burden from 1G and 2G, system designed for mobile voice transmission. This results in not so excellent data capabilities. The UMTS reaches the data rate of only few hundreds of Kilobits in a second. However, it has a higher in terms of supported mobile speeds [4]. The first deployment of the UMTS is the release99 (R99) architecture. It is specified by 3GPP and is part of the global ITU IMT-2000 standard. The most common form of UMTS uses W-CDMA (IMT Direct Spread) as the underlying air interface but the system also covers TD-CDMA and TD-SCDMA.

Unlike EDGE (IMT Single-Carrier, based on GSM) and CDMA2000, UMTS requires new base stations and new frequency allocations. However, it is closely related to GSM/EDGE as it borrows and builds upon concepts from GSM. Further, most UMTS handsets also support GSM, allowing seamless dual-mode operation. Therefore, UMTS is sometimes marketed as 3GSM, emphasizing the close relationship with GSM and differentiating it from competing technologies.

Table 1.1 WCDMA Technical Specifications [5]

Multiple Access Scheme	DS-CDMA
Duplex Scheme	FDD/TDD
Max. user Data Rate	2 Mbps
Channel bit rate	5.76 Mbps
Chip Rate	3.84 Mcps
Carrier Spacing	4.4 -5.2 MHz
Channel raster	200 KHz
Channel coding Frame Length	Convolutional Coding, Turbo Code 10 ms (38400 chips)

The chip rate may be extended to two or three times the standard 3.84 Mcps to accommodate data rates higher than 2 Mbps. The 200 kHz carrier raster has been chosen to facilitate coexistence and interoperability with GSM.

1.6.2 Wi-Fi

Wi-Fi networks use radio technologies called IEEE 802.11a, 802.11b, 802.11g or 802.11n to provide secure, reliable, fast wireless connectivity. A Wi-Fi network can be used to connect computers to each other, to the Internet, and to wire networks (which use IEEE 802.3 or Ethernet). Wi-Fi networks operate in the unlicensed 2.4 and 5 GHz radio bands, with an 11 Mbps (802.11b) or 54 Mbps (802.11a) data rate or with products that contain both bands (dual band). WiFi has problems with distance, interference, and throughput and that is why triple play (voice, data, and video) technologies cannot be hosted on traditional WiFi. In contrast 802.16 use a scheduling algorithm. This algorithm allows the user to only compete once for the access point. This gives WiMAX inherent advantages in throughput, latency, spectral efficiency, and advanced antenna support [6]. Comparison of WiFi and WiMAX standards with respect to different parameters is shown in the table given below:

Table 1.2 Comparison of WiFi and WiMAX

S.N	Feature	WiFi	WiMAX
1.	IEEE Standards	802.11	802.16
2.	Primary Application	Wirless LAN	Broadband Wireless Access
3.	Frequency Band	2.4 GHz, 5 GHz ISM	Licensed/Unlicensed 2 to 11 GHz
4.	Channel BW/Scalability	20 MHz Fixed	Adjustable 1.25 to 28 MHz
5.	Radio Technology	OFDM	OFDM/DSSS
6.	BW Efficiency	<=2.7 bps/Hz	<= 5 bps/Hz
7.	FEC	Convolutional or none	CC and RS
8.	Encryption	Optional	Mandatory
9.	Mobility	In development	Mobile WiMAX
10.	Mesh	Yes	Vendor Propritory
11.	Access Protocol	CSMA/CA	Request/Grant
12.	Peak Data Rate	54 Mbps	70 Mbps
13.	Duplexing	TDD	TDD/FDD
14	QoS	Doesn’t guarantee any QoS	Provide several layer of QoS
15.	Modulation	BPSK, QPSK, 16-64 QAM	BPSK,QPSK,16QAM, 64 QAM

1.6.3 iBurst

iBurst system is mobile broadband internet access system that provides end users with:

- broadband internet access service comparable with DSL and Cable connection system
- mobility: internet at anywhere at any time with freedom to move
- high speed connectivity: Internet connection at the speed of 1 Mbps today and 2 Mbps in the coming system release with the protocol support upto 16 Mbps
- access of service through the standard devices: iBurst wireless modem connects to the standard IP-enabled devices like laptop, desktop PC and PDA
- simplicity: easy to obtain and use it-plug it in, turn it on

Air Interface:

- TDD/TDMA/SDMA, 625 KHz channel spacing
- Initial per user data rates up to 1 Mpbs downlink, 345 kbps uplink in fully loaded system (the next system will have 2 Mbps downlink, 700 Kbps uplink)
- 4bps/Hz/Cell spectral efficiency (20 Mbps in 5 MHz) , measuring net actual user throughput in a fully loaded, multi-cell network in real-world conditions
- 3:1 downlink/uplink throughput asymmetry
- Tiered modulation and channel coding for link quality adaptation
- FEC and ARQ for error free link within the coverage area
- Bandwidth on demand, dynamic resource allocation
- Fully Mobility and Handover support
- Built in air interface QOS system

The iBurst system spectral efficiency yields system capacity that allows the broadband experience to be delivered to many users simultaneously in the cell, reducing the cost of service delivery in the mass market of the broadband service.

1.6.4 CDMA 2000

The CDMA2000 family of standards includes core air interface, minimum performance, and service standards. The CDMA2000 air interface standards specify a spread spectrum radio interface that uses CDMA technology to meet the requirements for 3G wireless communication systems. In addition, the family includes a standard that specifies analog operation, to support dual-mode mobile stations and base stations. Throughout the remainder of this document, use of the term CDMA2000 refers to the CDMA2000 family.

The technical requirements contained in CDMA2000 form a compatibility standard for CDMA systems. They ensure that a mobile station can obtain service in a system manufactured in accordance with the CDMA2000 standards. The requirements do not address the quality or reliability of that service, nor do they cover equipment performance or measurement procedures. Compatibility, as used in connection with CDMA2000, is understood to mean: any CDMA2000 mobile station is able to place and receive calls in CDMA2000 or IS-95 systems. Conversely, any CDMA2000 system is able to place and receive calls for CDMA2000 and IS-95 mobile stations. In a subscriber’s home system, all call placements is automatic. The sequence of call processing steps that the mobile stations and base stations execute to establish calls is specified, along with the digital control messages and, for dual-mode systems, the analog signals that are exchanged between the two stations. The base station is subject to different compatibility requirements than the mobile station. Radiated power levels, both desired and undesired, are fully specified for mobile stations, in order to control the RF interference that one mobile station can cause another.

1.6.5 UMB

UMB is a breakthrough technology which will support the ITU's vision for next generation services. It combines the best aspects of CDMA, TDM, LS-OFDM, OFDM, and OFDMA into a single air interface using advanced and highly optimized control and signaling mechanisms. It also incorporates advanced antenna techniques such as MIMO and SDMA. The combination of these techniques enables UMB to achieve higher peak data rates, very low latency, and very high spectral efficiency. The technology has a flexible and dynamic mode of operation to combine and allocate spectrum as needed for the variety of user applications and activities.

The aims for UMB, Ultra-Mobile Broadband include making significant increases to the user data rates when compared to the existing CDMA2000 cellular technologies, there will be increases to the system capacity, a lowering the cost per bit of data transfer, enhancements to the existing services, possibility of new applications, and the ability to use new spectrum opportunities.

In order enable UMB to compete with other standards such as WiMAX and preventing them from gaining a foothold in the market, the timescales for UMB are very aggressive.

UMB salient features are mentioned hereunder [7]:

The UMB, Ultra cellular telecommunications system offers has many new features and techniques that enable it to fulfill the high expectations for it, and to enable it to compete with other new and emerging technologies.

- Data rates of over 275 Mbit/s in the downlink (base station to mobile) and over 75 Mbit/s in the uplink (mobile to base station)
- Uses an OFDM / OFDMA air interface
- Uses frequency division duplex (FDD)
- Possesses an IP network architecture
- Has a scalable bandwidth between 1.25 - 20 MHz (NB - OFDM / OFDMA systems are well suited for wide and scalable bandwidths)

- Supports flat, mixed and distributed network architectures
- Supports MIMO

It can be seen from the features and salient points, that the UMB cellular system will provide a significant leap in terms of capability when compared to the existing CDMA2000 based systems. However UMB will operate alongside cdam2000 1X and CDMA2000 1X-EVDO, and it will offer seamless handoff to and from these services. In this way a phased roll-out of the new UMB service can be offered.

1.6.6 WiMAX

WiMAX refers the Worldwide Interoperability for Microwave access. There are different standards developed in this technology such as IEEE 802.16d, 802.16e, 802.16m. This Broadband Wireless Access is a promising technology, which can offer high-speed voice, video and data service up to the customer end in fixed nomadic, and mobile in nature. Radio communication Sector of the International Telecommunications Sector has included the WiMAX technology in the IMT 2000 set of standards in 2007 AD [8]. A mobile WiMAX system is based on SCFDMA and includes other advanced concepts such as subchannelization, channel estimation techniques, AMC and use of MIMO [9].

1.7 Comparison of different BWATs

Table 1.2 Comparison of different BWATs

S. N.	Parameters/Technology	WiMAX	WCDMA (UMTS)	WiFi	iBurst	LTE	UMB	CDMA 2000
1	Frequency Spectrum	2 GHz-11GHz But commonly used are , 2.3GHz, 2.5GHz and 3.5GHz	1920 MHz - 1980 MHz and 2110 MHz - 2170 MHz	2.4 GHz and 5 GHz	1.8 GHz,1.9 GHz and 2.3 GHz	400 MHz, 800 MHz, 2300MHz, 2500 MHz	900 MHz, 1700 MHz, 1900 MHz, 2100 MHz	400, 800,900, 1700,1800 1900,2100 MHz
2	Spectrum Channel Width	1.25 to 28 MHz (Scalable)	5 MHz	20 MHz	5 MHz	1.5 MHz to 20MHz (Scalable)	1.25 MHz to 20MHz (Scalable)	1.25 MHz
3	Coverage	8 km	12 km	100 m	5 km	12 Km	3-5 km	12 km
4	Data Rate	Upto 70 Mbps	2 Mbps	11 Mbps or 54 Mbps	1 Mbps to 2 Mbps	50 Mbps to100 Mbps	75 Mbps to 275 Mbps	144 kbps to 2 Mbps
5	Spectral Efficiency	5 bps/sec/Hz	Max 0.51 bps/Hz	2.7 bps/Hz	4 bps/Hz	3.0 bps/Hz	7.4 bps/Hz	1.3 bps/Hz

1.8 WiMAX Overview

1.8.1 Introduction

BWA has emerged as a promising solution for last mile access technology to provide high-speed Internet access in the residential as well as small and medium sized enterprise sectors. At this moment, cable and DSL technologies are providing broadband service in this sector. But the practical difficulties in deployment have prevented them from reaching many potential broadband Internet customers. Many areas throughout the world currently are not under broadband access facilities. Even many urban and suburban locations may not be served by DSL connectivity as it can only reach about three miles from the central office switch. But with BWA this difficulties can be overcome. Because of its wireless nature, it can be faster to deploy, easier to scale and more flexible, thereby giving it the potential to serve customers not served or not satisfied by their wired broadband alternatives. IEEE 802.16 standard for BWA and its associated industry consortium, WiMAX forum promise to offer high data rate over large areas to a large number of users where broadband is unavailable.

Wireless broadband systems have been in use for many years, but the development of this standard enables economy of scale that can bring down the cost of equipment, ensure interoperability, and reduce investment risk for operators. Taking the advantage of OFDM technique the PHY is able to provide robust broadband service in hostile wireless channel. Mobile WiMAX technology therefore, is designed to be able to scale to work in different channelizations from 1.25 to 28 MHz to comply with varied worldwide requirements as efforts proceed to achieve spectrum harmonization in the longer term. Because of the combination of multiple low data rate subcarriers, OFDM provides a composite high data rate with long symbol duration. Depending on the channel coherence time, this reduces or completely eliminates the risk of ISI, which is a common phenomenon in multipath channel environment with short symbol duration. The use of Cyclic Prefix in OFDM symbol can reduce the effect of ISI even more, but it also introduces a loss in SNR and data rate. OFDM system requirements depend upon the required bit rate, available Bandwidth, tolerable delay spreads, and Doppler values. The design parameters are number of sub carriers, symbol duration and clock pulse length, subcarrier spacing, modulation type and FEC coding.

Salient Features of WiMAX

WiMAX is a wireless broadband solution that offers a rich set of features with a lot of flexibility in terms of deployment options and potential service offerings. Some of the more salient features that deserve highlighting are as follows [10]:

- OFDM-based physical layer
- Very high peak data rates
- Scalable bandwidth and data rate support
- Adaptive modulation and coding (AMC)
- Link-layer retransmissions
- Support for TDD and FDD
- Orthogonal frequency division multiple access (OFDMA)
- Flexible and dynamic per user resource allocation
- Support for advanced antenna techniques
- Quality-of-service support
- Robust security
- Support for mobility
- IP-based architecture

In order to evaluate the performance of the developed communication system, an accurate description of the wireless channel is required to address its propagation environment. The radio architecture of a communication system plays very significant role in the modeling of a channel. The wireless channel is characterized by path loss, multipath delay spread, fading characteristics, Doppler spread, co-channel and adjacent channel interference. The channel model would be selected to address three different terrain types. This kind model can be used for simulations, design, and development and testing of technologies suitable for fixed broadband wireless. The parameters for the model would be selected based upon some statistical models.

1.8.2 Evolution of IEEE family of standard for BWA

The IEEE 802.16 standard contains the specification of Physical (PHY) and MAC layer for BWA. The first version of the standard IEEE802.162001 was approved on December 2001 and it has gone through many amendments to accommodate new features and functionalities. The current version of the standard IEEE 802.162004, approved on September 2004, consolidates all the previous versions of the standards. This standard specifies the air interface for fixed BWA systems supporting multimedia services in licensee and licensed exempt spectrum. The Working Group approved the amendment IEEE 802.16e2005 to IEEE802.162004 on February 2006. Later the amendment was included in the applicable version of standard IEEE 802.162004 in December 2005 to develop 802.16e standard, which includes the PHY and MAC layer enhancement to enable combined fixed and mobile operation in licensed band. Unlike the CDMA-based 3G systems, which have evolved from voice-centric systems, WiMAX was designed to meet the requirements necessary for the delivery of broadband data services as well as voice. The Mobile WiMAX physical layer is based on Scalable OFDMA technology [11].

The comparison of three major standards along with the technical specifications is shown in the Table 1.4 given below.

		Fixed(802.16-2004)	**Mobile(802.16e-2005)**	**802.16m**
Frequency	Frequency Band	<11 GHz	<6 GHz	<6 GHz
	Bandwidth	1.25~28 MHz	1.25~28 MHz	1.25~28 MHz
Peak Data Rate Cell Radius		75 Mbps (UL+DL) 2-10 Km(max. 50 Km)	75 Mbps (UL+DL) 2-10 Km(max 50 Km)	>130 Mbps(DL) >56 Mbps(UL) Upto 5 Km
Modulation	Primary(AMC)	BPSK/QPSK/16QAM/64QAM	QPSK/16QAM/64QAM	QPSK/16QAM/64QAM
	Secondary	OFDM (SC/OFDMA)	OFDM (SC/OFDMA)	OFDM (SC/OFDMA)
Technology for Higher Data Speed		AAS,STC,MIMO	AAS,STC,MIMO	AAS,STC,MIMO
Mobility		Fix/Nomadic	Max. 120 Km/h	Max 250 Km/hr
Configuration		NLOS	NLOS	NLOS

Table 1.4 Comparison of different IEEE 802.16 standards

1.8.3 IEEE 802.16 Protocol Layers

The IEEE 802.16 standard is structured in the form of a protocol stack with well defined Interfaces. In this thesis, only the Physical layer is considered for performance analysis. The MAC layer is formed with the following three sublayers:

- Service Specific Convergence Sublayer (CS)
- MAC Common Part Sublayer (CPS) and
- Privacy Sublayer

1. 8. 4 Network Architecture and Deployment Topology

In fact, the IEEE 802.16 network is resembled to cellular phone network. Each cell consists of a BS and one or more SS, depending on the implementation of the topology. Therefore, the BS provides PTP service or PMP service in order to serve multiple SSs. BSs provide connectivity to core networks. The SS can be a roof mounted or wall mounted CPE or a stand alone hand held device like Mobile phone, PDA or peripheral component interconnect PCI card for PC or Laptop. In case of a outside CPE, the users inside the building are connected to a conventional network like Ethernet Local Area Network (IEEE 802.3 for LAN) or Wireless LAN

(IEEE 802.11b/g for WAN) which have access to the CPE. A group of cells can be grouped together to form a network, where BSs are connected through a core network, as shown in Figure 1.1. The IEEE 802.16 network also support mesh topology, where SSs are able to communicate among themselves without the need of a BS [11].

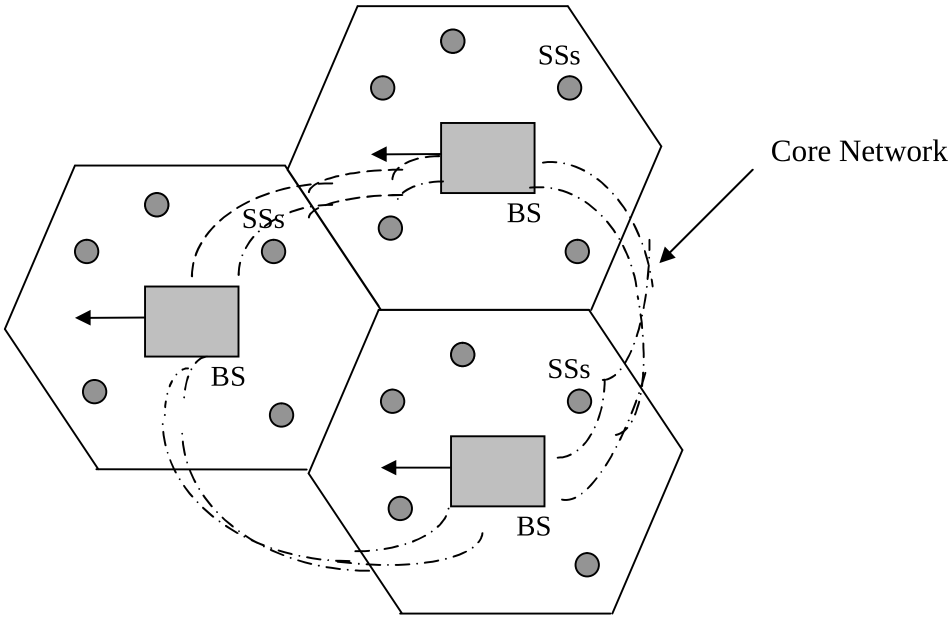

Figure 1.1 A typical IEEE 802.16 Network

BSs typically employ one or more wide beam antennas that may be partitioned into several smaller sectors, where all sectors sum to complete 360 degree coverage. CPEs typically employ highly directional antennas that are pointed towards the BS. Depending upon the need, IEEE 802.16 network can be deployed in different forms.

1.8.5 Application of IEEE 802.16 based network

IEEE 802.16 supports ATM, IPv4, IPv6, Ethernet and VLAN services. So, it can provide a rich choice of service possibilities to voice and data network service providers. It can be used for a wide selection of wireless broadband connection and solutions. Typical application scenario is shown in figure 1.2 below [1].

- **Cellular Backhaul**: IEEE 802.16 wireless technology can be an excellent choice for back haul for commercial enterprises such as hotspots as well as point to point back haul applications due to its robust bandwidth and long range.
- **Residential Broadband**: Practical limitations like long distance and lack off return channel prohibit many potential broadband customers reaching DSL and cable technologies. IEEE 802.16 can fill the gaps in cable and DSL coverage.
- **Underserved areas**: In many rural areas, especially in developing countries, there is no existence of wired infrastructure. IEEE 802.16 can be a better solution to provide communication services to those areas using fixed CPE and high gained antenna.
- **Always Best Connected**: As IEEE 802.16e supports mobility, so the mobile user in the business areas can access high speed services through their IEEE 802.16/WiMAX enabled handheld devices like PDA, Pocket PC and smart phone.

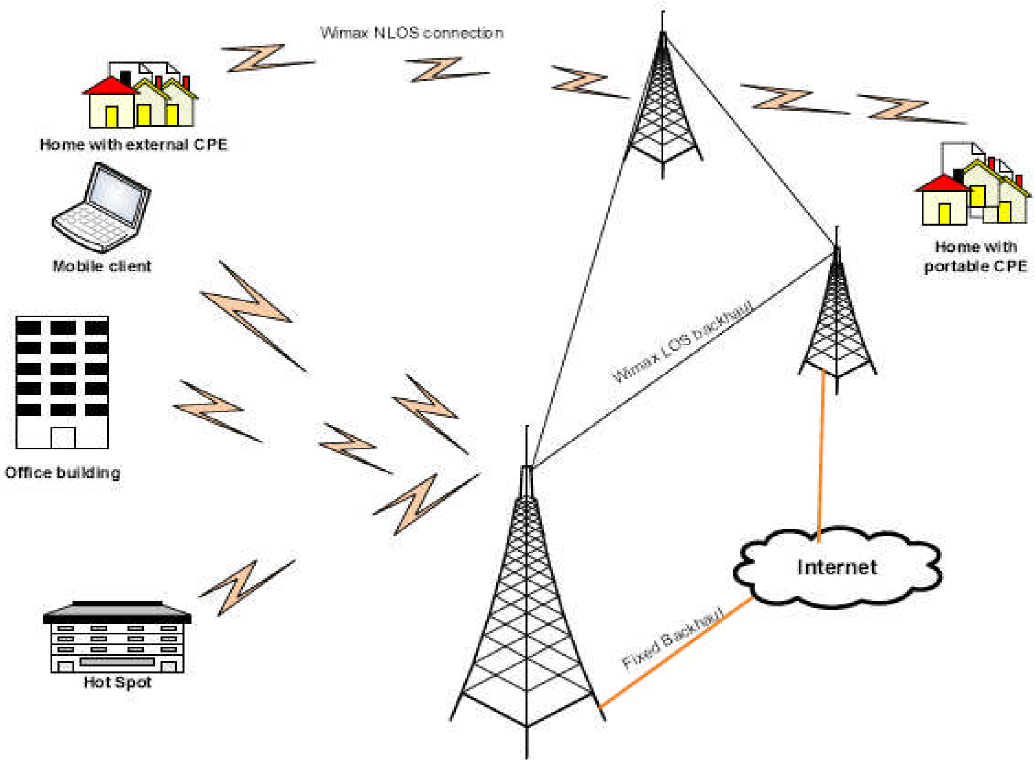

Figure 1. 2 Application scenarios

1.8.6 WiMAX forum and adaptation of IEEE 802.16

The WiMAX forum is an alliance of telecommunication equipments and components manufacturers and service providers, formed to promote and certify the compatibility and interoperability of BWA products employing the IEEE 802.16 specifications. WiMAX Forum Certified equipment is proven interoperable with other vendors' equipment that is also WiMAX Forum Certified. So far WiMAX forum has setup certification laboratories in Spain, Korea and China. Additionally, the WiMAX forum creates what it calls system profiles, which are specific implementations, selections of options within the standard, to suit particular ensembles of service offerings and subscriber populations. WiMAX forum has adopted two version of the IEEE 802.16 standard to provide different types of access:

- **Fixed/Nomadic access**: The WiMAX forum has adopted IEEE802.162004 and ETSI HyperMAN standard for fixed and nomadic access. This uses Orthogonal Frequency Division Multiplexing and able to provide supports in LOS and NLOS propagation environment. Both outdoor and indoor CPEs are available for fixed access. The main focus of the WiMAX forum profiles are on 3.5 GHz and 5.8 GHz frequency band.

- **Portable/Mobile Access**: The forum has adopted the IEEE 802.16e version of the standard, which has been optimized for mobile radio channels. This uses Scalable OFDM Access and provides support for handoffs and roaming. IEEE 802.16e based network is also capable to provide fixed access. The WiMAX Mobile WiMAX profiles will cover 5, 7, 8.75, and 10 MHz channel bandwidths for licensed worldwide spectrum allocations in the 2.3 GHz, 2.5 GHz, 3.3 GHz and 3.5 GHz frequency bands.

CHAPTER 2 LITERATURE REVIEW

2.1 IEEE 802.16 Physical Layer

The chapter two discusses about the different variants of the IEEE 802.16 PHY layer with their capabilities and conditions of operation. The OFDM based physical layer has been overviewed with its various mechanisms. Finally the chapter concludes with a discussion on OFDM technology and its design considerations.

The WiMAX physical layer is based on orthogonal frequency division multiplexing. OFDM is the transmission scheme of choice to enable high-speed data, video, and multimedia communications and is used by a variety of commercial broadband systems, including DSL, Wi-Fi, Digital Video Broadcast-Handheld, and MediaFLO, besides WiMAX. OFDM is an elegant and efficient scheme for high data rate transmission in a non-line-of-sight or multipath radio environment. In this section, we cover the basics of OFDM and provide an overview of the WiMAX physical layer.

The IEEE 802.16 standard supports multiple physical specifications due to its modular nature. The first version of the standard only supported single carrier modulation. Since that time, OFDM and scalable OFDMA have been included to operate in NLOS environment and to provide mobility. The standard has also been extended for use in below 11 GHz frequency bands along with initially supported 10 - 66 GHz bands.

2.1.1 Supported Band of Frequency

The IEEE 802.16 supported licensed and unlicensed bands of interest are as follows:

- 10-66 GHz licensed band**:** In this frequency band, due to shorter wave length**,** LOS operation is required and as a result the effect of multipath propagation is neglected. The standard promises to provide data rates up to 120 Mb/s in this frequency band. The abundant availability of bandwidth is also another reason to operate in this frequency range. Unlike the lower frequency ranges where frequency bands are often less than 100 MHz wide, most frequency bands above 20 GHz can provide several hundred megahertz of bandwidth. Additionally, channels within these bands are typically 25 or 28 MHz wide.

- 2-11 GHz licensed and licensed exempt: In this frequency bands, both licensed and licensed exempt bands are addressed. Additional physical functionality supports have been introduced to operate in Near LOS and NLOS environment and to mitigate the effect of multipath propagation. In fact, many of the IEEE 802.16 PHY's most advantageous capabilities are found in this frequency range. Operation in licensed exempt band experiences additional interference and coexistence issue. The PHY and MAC address mechanism like DFS to detect and avoid interference (for licensed exempt band). Though service provision in this frequency band is highly depends on design goals, vendors typically cite target aggregate data rates of up to 70 Mbps in a 14 MHz channel.

2.1.2 WirelessMAN OFDM PHY Layer

This version of the 256 - point OFDM based air interface specification seems to be favored by the WiMAX forum for reasons such as lower peak to average ratio, faster FFT calculation, and less stringent requirements for frequency synchronization compared to 2048-point WirelessMAN OFDMA. The size of the FFT point determines the number of subcarriers. Of these 256 subcarriers, 192 are used for user data, 56 are nulled for guard band and 8 are used as pilot subcarriers for various destination purposes. The PHY allows to accept variable CP length of 8, 16, 32 or 64 depending on the expected channel delay spread. This PHY specification is chosen for the simulation model.

2.1.3 Flexible Channel Bandwidth

The channel bandwidth can be of 1.25 MHz, 1.5 MHz, 1.75 MHz, 2MHz, 2.5MHz, 3 MHz, and 3.5, 5 MHz, 5.5 MHz, 6 MHz, 7 MHz, 10 MHz, 11 MHz, 12 MHz, 14 MHz, 15 MHz, 20 MHz, 24 MHz, and 28 MHz. But the WiMAX forum has initially narrowed down the large choice of possible bandwidth to a few possibilities to ensure interoperability between different vendor's products.

2.1.4 Robust Error Control Mechanism

Forward Error Correction is done on two phases through the outer Reed Solomon (RS) code and inner Convolutional code (CC). The RS coder corrects burst error at the byte level. It is particularly useful for OFDM links in the presence of multipath propagation. The CC corrects independent bit errors. The puncturing functionality in CC made the concatenated codes rate compatible as per specification. The support of Turbo coding is left as an optional feature to increase the coverage and/or capacity with the expense of increased decoding latency and complexity.

2.1.5 Adaptive Modulation and Coding

The growing demand of all types of services, not only voice and data but also multimedia services, aims for the design of increasingly more intelligent and agile communication systems, capable of providing spectrally efficient and flexible data rate access. These systems are able to adapt and adjust the transmission parameters based on the link quality, improving the spectrum efficiency of the system, and reaching, in this way, the capacity limits of the underlying wireless channel. Link adaptation techniques, often referred to as AMC, are a good way for reaching the cited requirements. They are designed to track the channel variations, thus changing the modulation and coding scheme to yield a higher throughput by transmitting with high information rates under favorable channel conditions and reducing the information rate in response to channel degradation.

Since the available radio spectrum for wireless communications is extremely scarce, there is a rapid growth in the demand of services for portable and wireless devices, and, as these services become more and more complex, the use of spectrally efficient transmission schemes supporting higher information rates is needed.

In traditional communication systems, the transmission is designed for a worst case" channel scenario thus coping with the channel variations and still delivering an error rate below a specific limit. Adaptive transmission schemes, however, are designed to track the channel quality by adapting the channel throughput to the actual channel state. These techniques take advantage of the time-varying nature of the wireless channel to vary the transmitted power level, symbol rate, coding scheme, constellation size, or any combination of these parameters, with the purpose of improving the link average spectral efficiency, i.e. the number of information bits transmitted per second per Hz bandwidth used.

Thus AMC is a promising tool for increasing the spectral efficiency of time-varying wireless channels while maintaining a predictable BER. In AMC, not only the modulation order but also the FEC schemes are varied by adjusting their code rate to the variations in the communication channel. For example, in periods of high fade when the channel is in a poor state, i.e. low SNR, the signal constellation size is reduced in order to improve fidelity, lowing the effective SNR to make transmission more robust. Conversely, in periods of low fade or high gain high SNR; the signal constellation size is increased in order to allow higher data rate modulation schemes to be employed with low probability of error, thus improving the instantaneous SNR. An example of utilization of the cited AMC scheme is illustrated in Figure 2.1[12]. It shows that as the range increases, the system steps down to a lower modulation, but as closer to the base station, higher order modulations can be used for increased throughput [10].

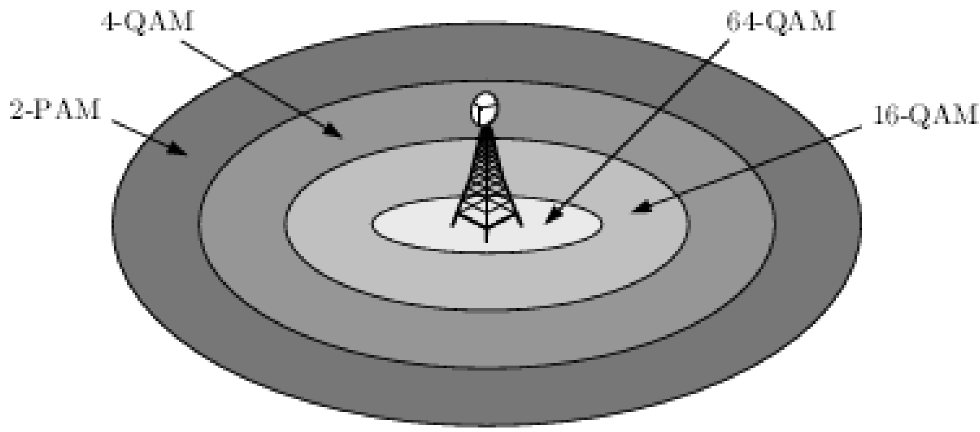

Figure 2.1 Scheme for the utilization of AMC

The specified modulation scheme in the downlink and uplink are BPSK, QPSK, 16 QAM and 64 QAM to modulate bits to the complex constellation points. The FEC options are paired with the modulation schemes to form burst profiles. The PHY specifies seven combinations of modulation and coding rate, which can be allocated selectively to each subscriber, in both UL and DL. There are tradeoffs between data rate and robustness, depending on the propagation conditions. Table 2.1 shows the combination of those modulation and coding rate [12].

Table 2.1 Mandatory channel coding per modulation

Modulation	**Uncoded Block Size(bytes)**	**Coded Block Size(bytes)**	**Overall Coding rate**	**RS Code**	**CC Code rate**
BPSK	12	24	½	(12,12,0)	½
QPSK	24	48	½	(32,24,4)	2/3
QPSK	36	48	¾	(40,36,2)	5/6
16-QAM	48	96	½	(64,48,8)	2/3
16-QAM	72	96	¾	(80,72,4)	5/6
64-QAM	96	144	2/3	(108,96,6)	¾
64-QAM	108	144	¾	(120,108,6)	5/6

2.1.6 Adaptive Antenna System

The PHY optionally supports and provides a signaling structure that enables the use of AAS. The features enables the transmission of DL and UL burst using directed beams, each intended for one or more SSs. In addition, the feature allows SS to deliver channel quality feedback to the BS.

2.1.7 Transmit Diversity

STBC can be implemented in the DL to provide transmit diversity. The feature is optional to implement. This has been proposed as a good candidate to implement this feature providing diversity in time and space.

2.2 OFDM

In this section, we will discuss about the OFDM method and its design consideration.

2.2.1 OFDM Basics

OFDM belongs to a family of transmission schemes called multicarrier modulation, which is based on the idea of dividing a given high-bit-rate data stream into several parallel lower bit-rate streams and modulating each stream on separate carriers—often called subcarriers, or tones. Multicarrier modulation schemes eliminate or minimize ISI by making the symbol time large enough so that the channel-induced delays — delay spread being a good measure of this in wireless channels —are an insignificant (typically, <10 percent) fraction of the symbol duration. Therefore, in high-data-rate systems in which the symbol duration is small, being inversely proportional to the data rate, splitting the data stream into many parallel streams increases the symbol duration of each stream such that the delay spread is only a small fraction of the symbol duration [10, 11].

OFDM is a spectrally efficient version of multicarrier modulation, where the subcarriers are selected such that they are all orthogonal to one another over the symbol duration.

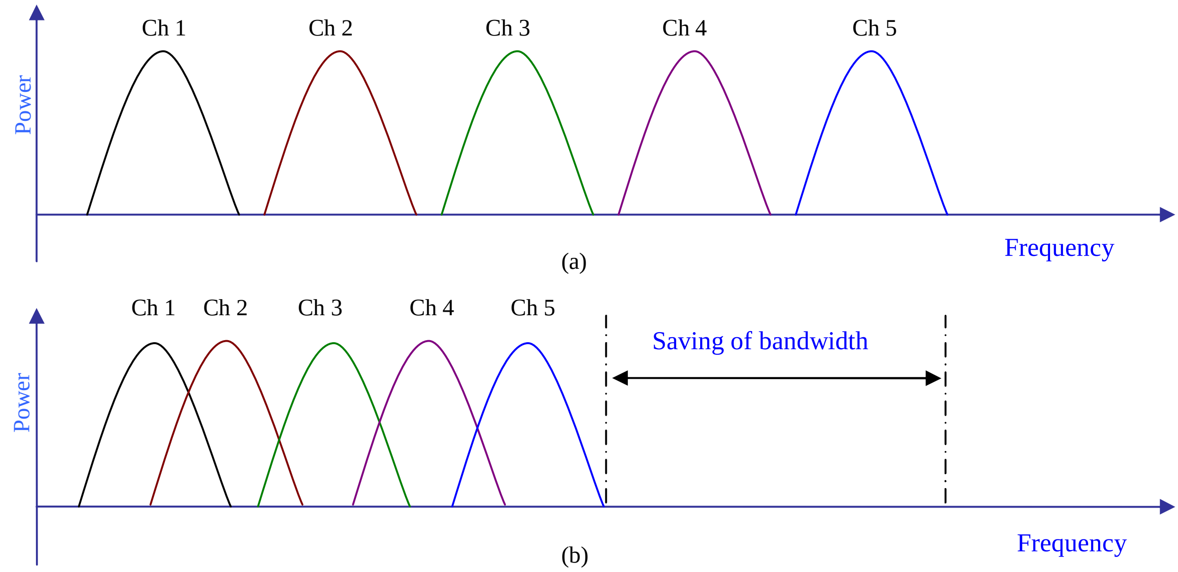

Figure 2.2 Comparison between conventional FDM and OFDM

OFDM has recently found wide adoption in a widespread variety of high-data-rate communication systems, including digital subscriber lines, wireless LANs (802.11a/g/n), digital video broadcasting, and now WiMAX and other emerging wireless broadband systems such as the proprietary Flash-OFDM developed by Flarion (now QUALCOMM), and 3G LTE and fourth generation cellular systems. OFDM's popularity for high-data-rate applications stems primarily from its efficient and flexible management of ISI in highly dispersive channels.

As the channel delay spread becomes an increasingly large multiple of the symbol time Ts, the ISI becomes very severe. By definition, a high-data-rate system will generally have $\tau \gg$ Ts, since the number of symbols sent per second is high. In a NLOS system, such as WiMAX, which must transmit over moderate to long distances, the delay spread will also frequently be large. In short, wireless broadband systems of all types will suffer from severe ISI and hence will require transmitter and/or receiver techniques that overcome the ISI. Although the 802.16 standards include single-carrier modulation techniques, the vast majority of, if not all, 802.16-

compliant systems will use the OFDM modes, which have also been selected as the preferred modes by the WiMAX Forum.

To develop an understanding of how to use OFDM in a wireless broadband system, the followings are included in the report:

- Elegance of multicarrier modulation and how it works in theory
- Practical understanding of OFDM system design, covering such key concepts as the cyclic prefix, frequency equalization, and synchronization
- Implementation issues for WiMAX systems, such as the peak-to-average ratio

2.2.2 Multicarrier Modulation

The basic motto of using the multicarrier modulation is to achieve good data rates with minimum or least ISI. To acquire a channel which has no ISI it is required that the symbol time Ts should be more or greater than the channel delay spread time τ and if the symbol time approaches or falls below the channel delay spread time then the BER becomes unacceptable and the system is intolerable .The basic idea of multicarrier modulation is quite simple and follows naturally from the competing desires for high data rates and ISI-free channels. Digital communication systems simply cannot function if ISI is presents; an error floor quickly develops, and as τ_s approaches or falls below τ, the bit error rate becomes intolerable. As noted previously, for wideband channels that provide the high data rates needed by today's applications, the desired symbol time is usually much smaller than the delay spread, so ISI is severe [10].

In order to overcome this problem, multicarrier modulation divides the high-rate transmit bit stream into L lower-rate substreams, each of which has $Ts/L >> \tau$, and is hence effectively ISI free. These individual substreams can then be sent over L parallel subchannels, maintaining the total desired data rate. Typically, the subchannels are orthogonal under ideal propagation conditions, in which case multicarrier modulation is often referred to as OFDM. The data rate on each of the subchannels is much less than the total data rate, so the corresponding subchannel bandwidth is much less than the total system bandwidth. The number of substreams is chosen to ensure that each subchannel has a bandwidth less than the coherence bandwidth of the channel, so the subchannels experience relatively flat fading. Thus, the ISI on each subchannel is small. Moreover, in the digital implementation of OFDM, the ISI can be completely eliminated through the use of a CP.

In its simplest form, multicarrier modulation divides the wideband incoming data stream into L narrowband substreams, each of which is then transmitted over a different orthogonal-frequency subchannel. The number of substreams L is chosen to make the symbol time on each substream much greater than the delay spread of the channel or, equivalently, to make the substream bandwidth less than the channel-coherence bandwidth. This ensures that the substreams will not experience significant ISI.A simple illustration of a multicarrier transmitter and receiver is given in Figure shown below [10, 11].

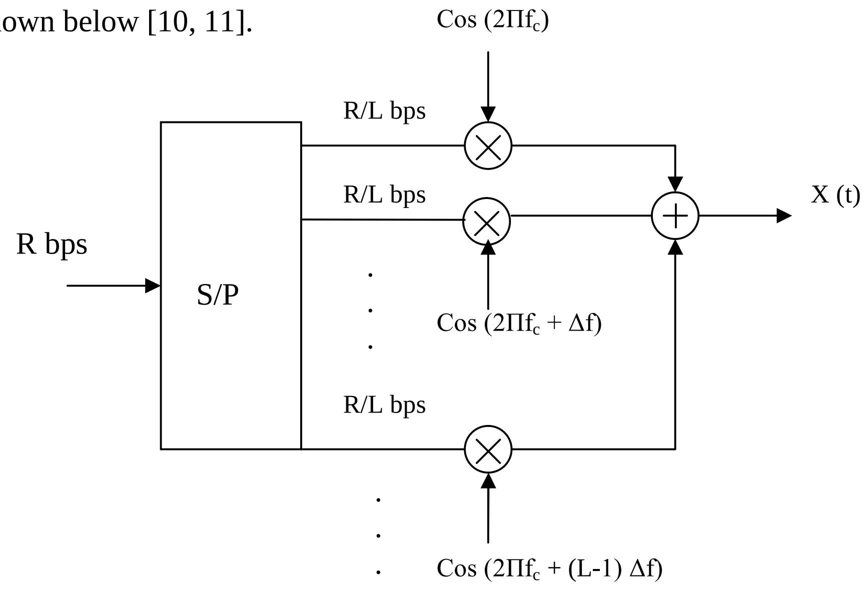

Figure 2.3 A Basic multicarrier transmitter

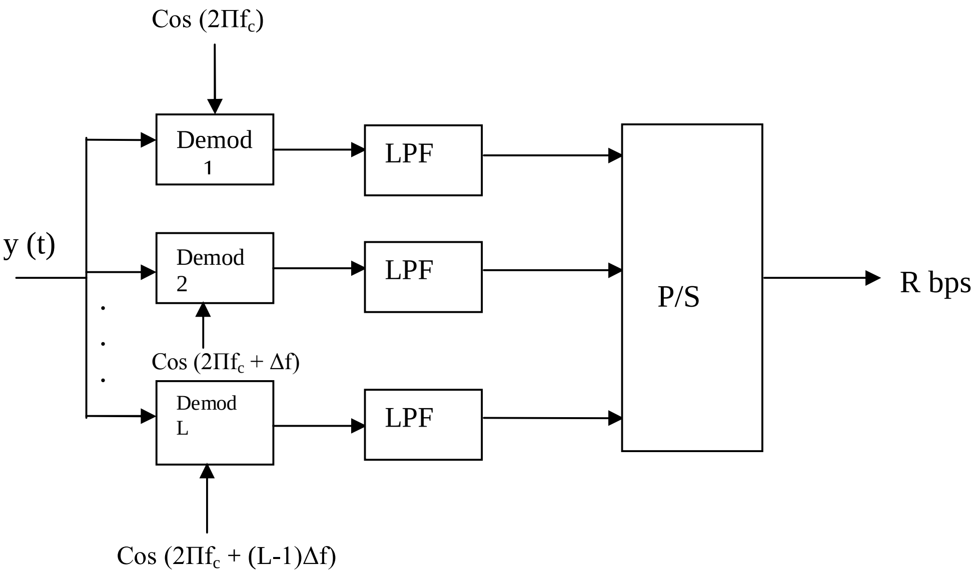

Figure 2.4 A basic multicarrier receiver

Essentially, a high data rate signal of rate R bps and with a passband bandwidth B is broken into L parallel substreams, each with rate R/L and passband Bandwidth B/L.
As long as the number of subcarriers is sufficiently large to allow the subcarrier bandwidth to be much less than the coherence bandwidth, that is, B/L<< Bc , it can be ensured that each subcarrier experiences approximately flat fading. The mutually orthogonal signals can then be individually detected, as shown in Figure shown above. Hence, the multicarrier technique has an interesting interpretation in both the time and frequency domains. In the time domain, the symbol duration on each subcarrier has increased to T= LTs, so letting L grow larger ensures that the symbol duration exceeds the channel-delay spread, $T >> \tau$, which is a requirement for ISI-free communication. In the frequency domain, the subcarriers have bandwidth B/L << Bc, which ensures flat fading, the frequency-domain equivalent to ISI-free communication.

2.2.3 Block Transmission with Guard Intervals

In OFDM the data symbols are grouped in a block and called OFDM block symbols. A block consists of T seconds can be formulated as

$$T = L\,T_s \qquad \text{Equation (2.1)}$$

Where, L is the number of sub stream and Ts is the time of one symbol to complete. In order to avoid interference among symbols while they pass through a wireless channel, the guard time is introduced between the OFDM symbols.

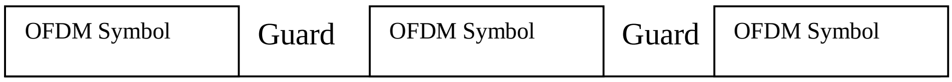

Figure 2.5 OFDM Guard Band Interval

This way, after receiving a series of OFDM symbols, as long as the guard time Tg is larger than the delay spread of the channel τ, each OFDM symbol will interfere only with itself.

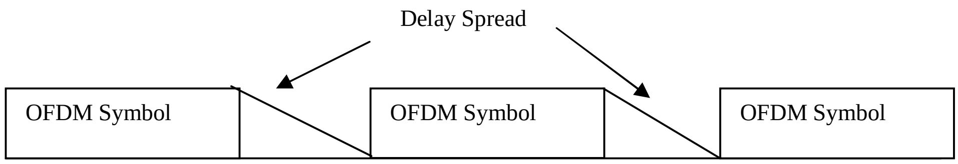

Figure 2.6 OFDM Guard Band and Delay Spread

Putting simply, OFDM transmissions allow ISI within an OFDM symbol. But by including a sufficiently large guard band, it is possible to guarantee that there is no interference between subsequent OFDM symbols [10].

2.2.4 Circular Convolution and DFT

As the OFDM symbols are orthogonal to each other with some guard interval between the two blocks. In order to remove the ISI within an each OFDM symbol, the concept of circular convolution is used. Since every discrete system has an input data x[n] that is sent over the channel having LTI impulse response h[n]. The output of this system is y[n] and that is the circular convolution of the input signal with the impulse response of the channel [10].

$y[n] = x[n] \circledast h[n] = h[n] \circledast x[n]$……………………………Equation (2.2)

For getting the frequency response of the system DFT is applied on both sides of the Equation 2.2 and hence get the transfer function H[z].

$$y[n] = x[n] \circledast h[n] = h[n] \circledast x[n] \overset{\Delta}{=} \sum_{K=0}^{L-1} h[k]\, x[n-k]_L \text{ ....Equation (2.3)}$$

2.2.5 OFDM System Implementation

The principle of OFDM was already around in the 50's and 60's as an efficient MCM technique. But, the system implementation was delayed due to technological difficulties like digital implementation of FFT/IFFT, which were not possible to solve on that time. In 1965, Cooley and Tukey presented the algorithm for FFT calculation and later its efficient implementation on chip makes the OFDM into application. The digital implementation of OFDM system is achieved through the mathematical operations called DFT and its counterpart IDFT. These two operations are extensively used for transforming data between the time domain and frequency domain. In case of OFDM, these transforms can be seen as mapping data onto orthogonal subcarriers. In order to perform frequency domain data into time domain data, IDFT correlates the frequency domain input data with its orthogonal basis functions, which are sinusoids at certain frequencies. In other ways, this correlation is equivalent to mapping the input data onto the sinusoidal basis functions. In practice, OFDM systems employ combination of FFT and IFFT blocks which are mathematical equivalent version of the DFT and IDFT. At the transmitter side, an OFDM system treats the source symbols as though they are in the frequency domain. These symbols are feed to an IFFT block which brings the signal into the time domain. If the N numbers of subcarriers are chosen for the system, the basis functions for the IFFT are N orthogonal sinusoids of distinct frequency and IFFT receive N symbols at a time. Each of N complex valued input symbols determines both the amplitude and phase of the sinusoid for that subcarrier. The output of the IFFT is the summation of all N sinusoids and makes up a single OFDM symbol. The length of the OFDM symbol is NT where T is the IFFT input symbol period. In this way, IFFT block provides a simple way to modulate data onto N orthogonal subcarriers [11].

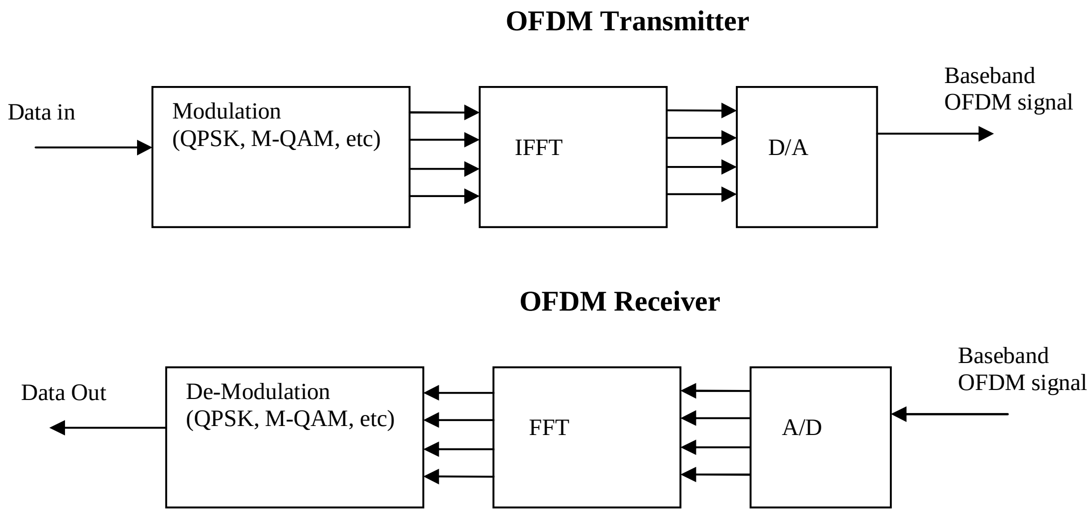

Figure 2.7 Basic OFDM transmitter and receiver

At the receiver side, The FFT block performs the reverse process on the received signal and bring it back to frequency domain. The block diagram in above Figure 2.7 depicts the switch between frequency domain and time domain in an OFDM system.

The block diagram of OFDM is defined in a way as follows [11, 1]:
Firstly a wideband signal having B bandwidth is breakdown into L narrow bands with each having bandwidth of B/L. By doing so, the system has maintained its aggregate symbol rate with no ISI. Cyclic prefix is used to increase the delay spread. Hence, each subcarrier experiences flat fading.

i. The information is sent through a channel by using L narrowband radios. Therefore, L narrow bands are modulated and after that IFFT technique is applied on those bands.
ii. IFFT is used to split the ISI channel in the form of orthogonal subcarriers. Cyclic prefix must be added after the IFFT operation and then the resulting symbol are sent serially through the wideband channel.
iii. At the receiver end, first cyclic prefix is removed then serial wideband spectrum is converted into L narrow band spectrums. After that these bands are demodulated using FFT operation which yields L data symbols.

iv. Every subcarrier can be equalized through Frequency Domain Equalization (FEQ). In FEQ, it is assumed that transmitter and receiver are perfectly synchronized with each other and the channel conditions are known by the receiver.

2.2.6 Cyclic Prefix

In an OFDM symbol the cyclic prefix is a repeat of the end of the symbol at the beginning. The purpose is to allow multipath to settle before the main data arrives at the receiver. The length of the cyclic prefix is often equal to the guard interval. Transmission of cyclic prefix reduces the data rate; hence the cyclic prefix duration should not be much more than the duration of the maximum expected multipath channel. The cyclic prefix (or guard interval) slightly reduces the effective data throughput as this duplicates data already present but the result is a robust signal that is immune to data errors caused by multipath reception.

The subcarrier orthogonality of an OFDM system can be jeopardized when passes through a multipath channel. CP is used to combat ISI and ICI introduced by the multipath channel. CP is a copy of the last part of OFDM symbol which is appended to the front of transmitted OFDM symbol. The length of the CP (T_g) must be chosen as longer than the maximum delay spread of the target multipath environment. Fig 6 depicts the benefits arise from CP addition, certain position within the cyclic prefix is chosen as the sampling starting point at the receiver, which satisfies the criteria $\tau_{\max} < T_x < T_g$ where $\tau_{\max}$ is the maximum multipath spread. Once the above condition is satisfied, there is no ISI since the previous symbol will only have effect over samples within $[0, \tau_{\max}]$. And it is also clear from the figure that sampling period starting from *Tx* will encompass the contribution from all the multipath components so that all the samples experience the same channel and there is no ICI [10, 1].

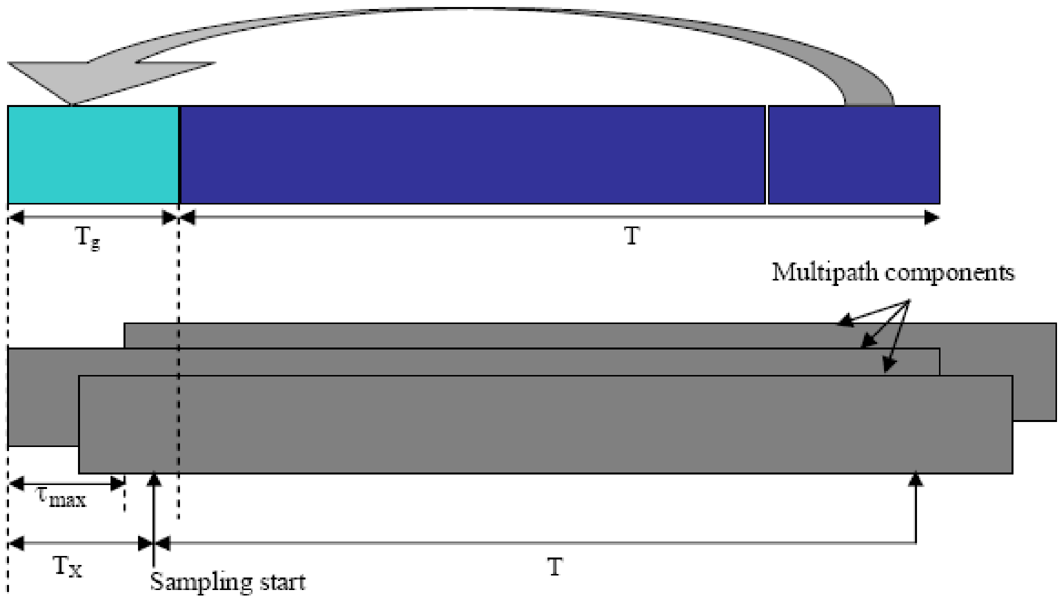

Figure 2.8 Cyclic Prefix in OFDM

Copying the end of a symbol and appending it to the start results

$T_{sym} = T_b + T_g$ ……………………………………… Equation (2.3)

where:

- T_{sym} is the OFDM symbol time,
- T_b is the useful symbol time, and
- T_g represents the CP time

The parameter G defines the ratio in a longer symbol time. Thus, the total length of the symbol is of the CP length to the useful symbol time. When eliminating ISI, it has to be taken into account that the CP must be longer than the dispersion of the channel. Moreover, it should be as small as possible since it costs energy to the transmitter.

2.2.7 Synchronization & PAR

There are two types of synchronization namely timing and frequency synchronization and these are required to demodulate the OFDM signal at the receiver end. In the timing synchronization, there is a need to determine the timing offset of the symbol and then the optimal timing instants. Whereas in the frequency synchronization, at the receiving end, the receiver must align the carrier frequency of the received signals as much as possible. In OFDM, the timing synchronization is achieved more easily because the OFDM symbol structure have a reasonable degree of synchronization error but frequency synchronization is more stringent to achieved because OFDM have narrow band signals which have their individual frequency domain and are orthogonal to each other .

The other important parameter in is OFDM high PAR which is also called as PAPR. It is defined as the ratio of peak instantaneous value to averaged time. The PAR is used to determine many parameters of the signal, such as current, voltage frequency, power and phase. The reason for high PAR is that in OFDM or multicarrier signal is the summation of many carrier signals. Due to this, its value is very high large and very small at different time intervals. These abrupt changes in PAR value introduce a challenge related to the implementation of OFDM. The PAR problem reduces the efficiency and to overcome this problem there is a need to increase the RF power which needs an amplifier and this increases the cost of the system because the power amplifier is the most expensive components in radio communication [1].

2.2.8 Sub Channelization

In WiMAX systems the subcarriers are distributed not on individual basis but on blocks of subcarriers that are allocated to users. This is done to reduce the complexity of the subcarrier allocation algorithm and to simplifying the mapping messages. This can be clearer by assuming that m number of users is allocated a block of B_m subcarriers. These subcarriers can be either spread out over the total bandwidth, i.e., distributed subcarrier permutation, or on the basis of frequency range, i.e., adjacent subcarrier permutation. The primary advantage of distributed permutation is robustness and improvement in frequency diversity while in the case of adjacent permutation; the major advantage is increase in multi-user diversity [10].

2.2.9 OFDM System Design Considerations

OFDM system design issues aim to decrease the data rate at the subcarriers, hence, the symbol duration increases and as a result, the multipath effects are reduced effectively. The insertion of higher valued CP will bring good results against combating multipath effects but at the same time it will increase loss of energy. Thus, a tradeoff between these two parameters must be done to obtain a reasonable system design.

2.2.9.1 System Design Requirements

OFDM system depends on the following four requirements:

- **Available bandwidth**: The bandwidth limit will play a significant role in the selection of number of subcarriers. Large amount of bandwidth will allow obtaining a large number of subcarriers with reasonable CP length.
- **Required bit rate**: The system should be able to provide the data rate required for the specific purpose.
- **Tolerable delay spread**: A user environment specific maximum tolerable delay spread should be known beforehand in determining the CP length.
- **Doppler values**: The effect of Doppler shift due to user movement should be taken into account.

2.2.9.2 System Design Parameters

The design parameters are derived according to the system requirements. The design Parameters for an OFDM system are as follows [11]:

- Number of subcarriers: We stated earlier that the selection of large number of subcarriers will help to combat multipath effects. But, at the same time, this will increase the synchronization complexity at the receiver side.
- Symbol duration and CP length: A perfect choice of ratio between the CP length and symbol duration should be selected, so that multipath effects are combated and not significant amount bandwidth is lost due to CP.

- Subcarrier spacing: Subcarrier spacing will depend on available bandwidth and number of subcarriers used. But, this must be chosen at a level so that synchronization is achievable.
- Modulation type per subcarrier: The performance requirement will decide the selection of modulation scheme. Adaptive modulation can be used to support the performance requirements in changing environment.
- FEC coding: A suitable selection of FEC coding will make sure the robustness of the channel to the random errors.

2.2.10 Benefits and Drawbacks of OFDM

In the earlier section, we have stated that how an OFDM system combats the ISI and reduces the ICI. Besides those benefits, there are some other benefits as follows:

- High spectral efficiency because of overlapping spectra
- Simple implementation by FFT
- Low receiver complexity as the transmitter combat the channel effect to some Extend
- Suitable for high data rate transmission
- High flexibility in terms of link adaptation
- Low complexity multiple access schemes such as OFDMA
- It is possible to use maximum likelihood detection with reasonable complexity.

On the other side, few drawbacks of OFDM are listed as follows:

- An OFDM system is highly sensitive to timing and frequency offsets. Demodulation of an OFDM signal with an offset in the frequency can lead to a high bit error rate.
- An OFDM system with large number of subcarriers will have a higher PAPR compared to single carrier system. High PAPR of a system makes the implementation of DAC and ADC extremely difficult.

2.2.11 Bit Error Probability

The chances of error arising from a digital modulation such as QPSK, for example, are also valid for OFDM, since the noise keeps its statistics even after applying the DFT in the receiver.

A white and steady process will remain white and stationary after applying a DFT. Therefore, a white noise, Gaussian and stationary characteristics keep the probability of error for QPSK. However, due to the difference between the transmitter and receiver filters, the curves of BER are somewhat modified.

The BER for BPSK, QPSK, 16-QAM and 64-QAM in AWGN noise conditions are:

$P_{b,\ BPSK} = (1/2)\ \mathrm{erfc}\ (\sqrt{(S/N)})$ ………………………………. . Equation (2.4)

$P_{b,\ QPSK} = (1/2)\ \mathrm{erfc}\ (\sqrt{(1/2*S/N)})$ ………………………….. Equation (2.5)

$P_{b,\ 16QAM} = (3/8)\ \mathrm{erfc}\ (\sqrt{(1/10*S/N)}$ for $S/N >> 1$ ……. Equation (2.6)

$P_{b,\ 64QAM} = (7/24)\ \mathrm{erfc}\ (\sqrt{(1/42*S/N)})$ for $S/N > 1$ …….... Equation (2.7)

We must bear in mind that real channels are not just consisting of a Gaussian white noise, but we will delay the channel and frequency selective fading. So when it is taken into account all characteristics channel, the probability of error per bit will be different from the above equations.

2.3 Modulation

After interleaving process described above, the bits are introduced into the corresponding constellations to map them properly. The adjustments that we choose are BPSK, QPSK, 16-QAM and 64-QAM (Considering a Gray encoding). However mapping support 64-QAM is optional in the license-exempt bands. The constellations should be standardized to get have the same average power.

BPSK

The BPSK is a binary level digital modulation scheme of phase variation which have two theoretical phase angle i.e. +90° and -90°. This gives high immunity beside the interference and noise and a robust modulation which gives improved BER performance. BPSK phase modulation uses the phase variation to encode the bits; each of the modulation symbols is equal to the one phase.

QPSK

QPSK is a phase modulation algorithm. Phase modulation is an adaptation of frequency modulation where the phase of the carrier wave is modulated to encode bits of digital information in each phase variation. The "PSK" in QPSK refers to the use of Phased Shift Keying. Phased Shift Keying is a form of phase modulation which is accomplished by the use of a discrete number of states. QPSK refers to PSK with 4 states. As QPSK is able to encode 2 bits per symbol, carriers are sent in the angle of 45°, 135°, 225° and 315°. Their states have been demonstrated in following figure.

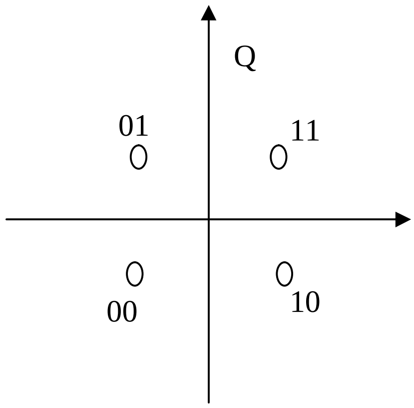

Figure 2.9 QPSK Constellation

QAM

QAM uses different kind of phases which are 16, 32 64 and 256. Each single state is defined as a specific phase and amplitude. This proves the detection of symbols and generation is much more complex than amplitude device or a simple phase. Total data and bandwidth increases each time the number of states per symbol is increased. The efficiency of a modulation scheme can be increased by increasing the number of levels.

In QAM two sinusoidal carriers are transmitted that change their amplitude depending on the digital sequence, these carriers are out of phase to each other by 90° from the digital communication theory it should be mentioned that the QPSK and QAM-4 are referred as the same modulation which is consider as the complex symbols of data. Both the 16-QAM and the 64 QAM in modulation are included in the WiMAX standard. The most efficient modulation of WIMAX is 64-QAM.

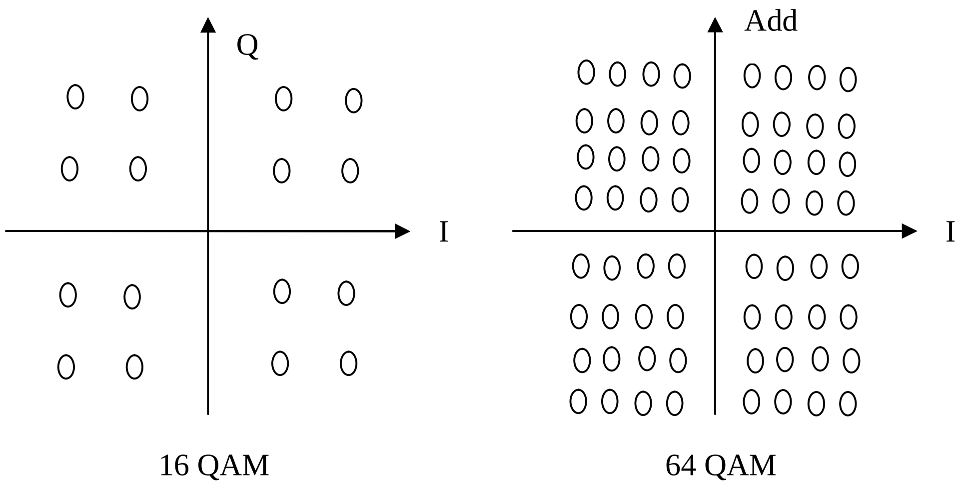

Figure 2.10 16 QAM and 64 QAM constellations

CHAPTER 3 RESEARCH METHODOLOGY

Simulation Model

This chapter discusses the simulation model employed by this research thesis. As stated before, the research goal is to evaluate performance of IEEE 802.16 OFDM physical layer. This task involves modeling of the physical layer as well as the propagation environment. Simulation would be chosen to be the primary tool for the study. I have employed Matlab 7.7 R2008b to develop the simulator. Before going for the physical layer setup, let us first define the OFDM symbol parameters used in the study.

3.1 OFDM Symbol Parameters

There are two types of OFDM parameters, primitive and derived, that characterize OFDM symbol completely. The later one can be derived from the former one because of fixed relation between them. The nominal channel BW, number of used subcarrier, sampling factor (n), and ratio of guard time to useful time (G) are taken as primitive OFDM symbol parameters. Sampling frequency, subcarrier spacing, useful symbol time, CP time, OFDM symbol time and sampling time are used as derived parameters. The value and the corresponding derivation of the parameters are mentioned in later section in simulation model.

3.2 Physical Layer Setup

This structure of the baseband part of the implemented transmitter and receiver is shown in figure 3.1 given below. This structure corresponds to the physical layer of the IEEE 802.162004 wirelessMAN-OFDM air interface. Channel coding part is composed of three steps randomization, Forward Error Correction (FEC) and interleaving. FEC is done in two phases through the outer Reed Solomon (RS) and inner Convolutional Code (CC). The complementary operations are applied in the reverse order at channel decoding in the receiver end. The complete channel coding setup is shown in Figure 3.1 while corresponding encoding and decoding setup is shown in Figure 3.2 and 3.3 respectively.

Through the rest of the sections, the individual block of the setup will be discussed with implementation technique.

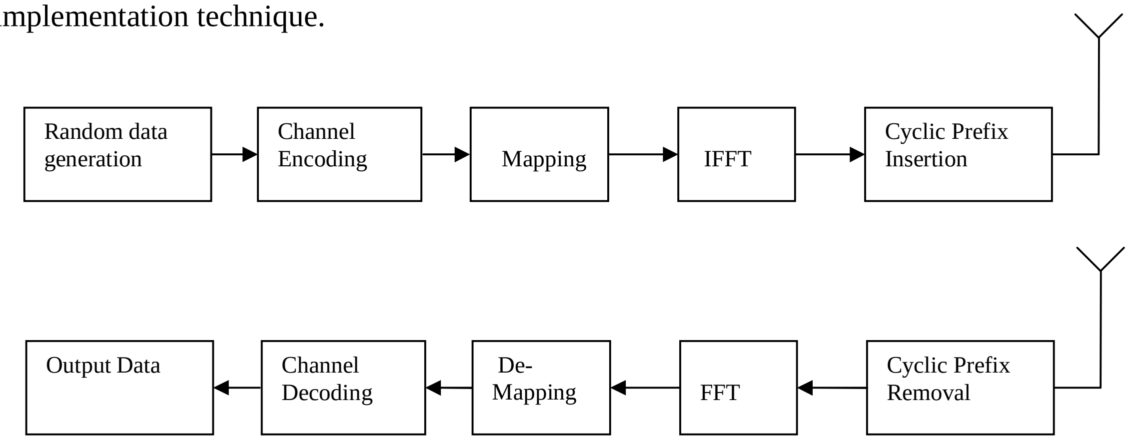

Figure 3.1 Simulation Setup

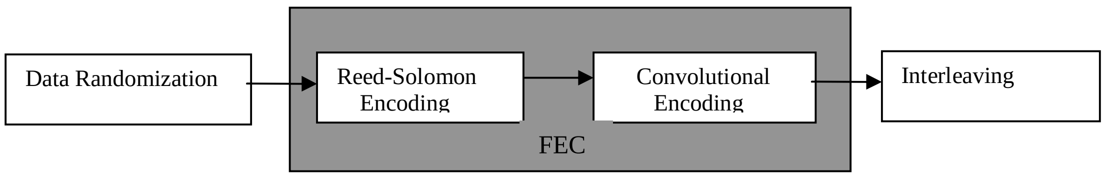

Figure 3.2 Channel Encoding Setup

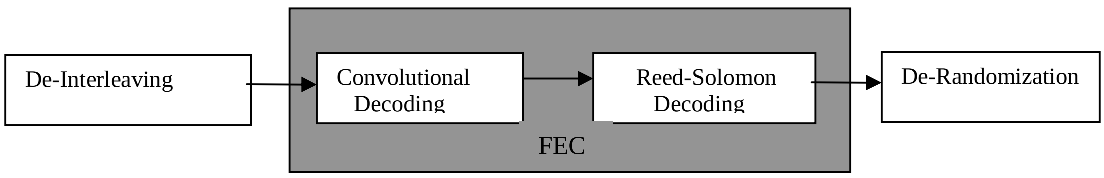

Figure 3.3 Channel Decoding Set Up

3.2.1 Scrambler (Data Randomization)

The scrambler performs randomization of input data on each burst on each allocation to avoid long sequence of continuous ones and zeros. Randomization is a function that randomizes the data to prevent the constant ones or zeros that can decrease the performance of coding and modulation. This is implemented with a Pseudo Random Binary Sequence (PRBS) generator which uses a 15 stage shift register with a generator polynomial of $1+x^{14}+x^{15}$ with XOR gates in feedback configuration as shown in figure 3.4 given below[13].

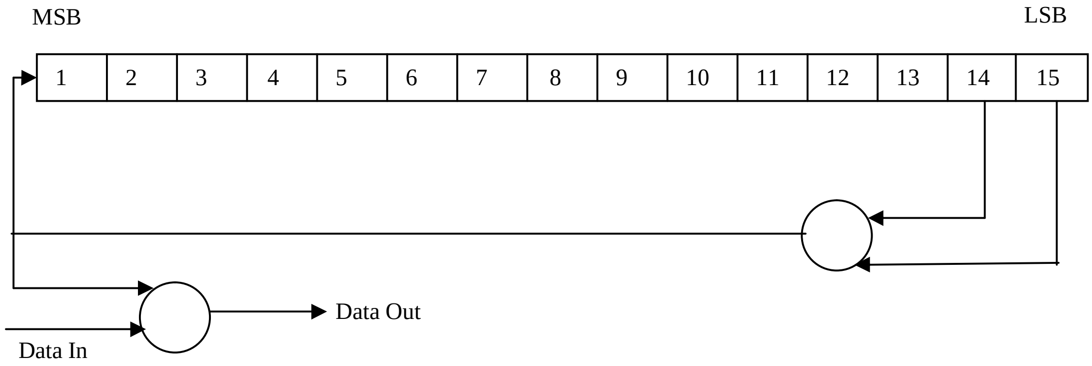

Figure 3.4 PRBS generator for randomization

3.2.2 Reed Solomon Encoder

Reed-Solomon codes are block-based error correcting codes with a wide range of applications in digital communications and storage such as storage devices (including tape, compact disk, DVD, barcodes etc), wireless or mobile communications(including cellular telephones, microwave links), satellite telecommunications, Digital Television, high speed modem . The Reed-Solomon encoder takes a block of digital data and adds extra "redundant" bits. Errors occur during transmission or storage for a number of reasons. The Reed Solomon decoder processes each block and attempts to correct errors and recover the original data. The number of types of errors that can be corrected depends on the characteristics of the Reed- Solomon code.

The properties of Reed-Solomon codes make them suitable to applications where errors occur in bursts. Reed-Solomon error correction is a coding scheme which works by first constructing a polynomial from the data symbols to be transmitted, and then sending an oversampled version of the polynomial instead of the original symbols themselves. A Reed-Solomon code is specified as RS (n, k, t) with l-bit symbols. This means that the encoder takes k data symbols of l bits each and adds 2t parity symbols to construct an n-symbol codeword. Thus, n, k and t can be defined as:

- n: number of bytes after encoding,
- k: number of data bytes before encoding,
- t: number of data bytes that can be corrected.

The error correction ability of any RS code is determined by (n-k), the measure of redundancy in the block. If the location of the erroneous symbols is not known in advance, then a Reed-Solomon code can correct up to t symbols, where t can be expressed as t = (n-k)/2. The FEC consists of a RS outer code and a rate compatible CC inner code. A block Reed Solomon (255, 239, 8) code based on the Galois field GF (2^8) with a symbol size of 8 bits is chosen that processes a block of 239 symbols and can correct up to 8 symbol errors calculating 16 redundant correction symbols [14]. The primitive and generator polynomials used for the systematic code are expressed as follows [12]:

Primitive Polynomial:

$p(x) = x^8 + x^4 + x^3 + x^2 + 1$ ……………………… Equation (3.1)

Generator Polynomial:

$g(x) = (x + \lambda^0)(x + \lambda^1)(x + \lambda^2)...(x + \lambda)^{2t-1}$ ….. Equation (3.2)

The primitive polynomial is the one used to construct the symbol field and it can also be named as field generator polynomial. The code generator polynomial is used to calculate parity symbols and has the form specified before, where λ is the primitive element of the Galois field over which the input message is defined.

To make the RS code flexible, i.e. to allow for variable block sizes and variable correction capabilities, it is shortened and punctured. When a block shortened to k bytes, 239-k zero bytes are added as a prefix, and, after the encoding process, the 239-k encoded zero bytes are discarded. Once the process of shortening has been done, the number of symbols going in and out of the RS encoder change, and also the number of symbols that can be corrected, t. With the puncturing, only the first 2t of the total 16 parity bytes [1] shall be employed.

[1] The parity bytes are calculated from the systematic RS (255, 239, 8) code, as 2t = n-k.

The randomized data are arranged in block format before passing through the encoder and a single 0X00 tail byte is appended to the end of each burst. The implemented RS encoder is derived from a systematic RS (N=255, K=239, T=8) code using GF (2^8).

3.2.3 Convolutional Encoder

The outer RS encoded block is fed to inner binary convolutional encoder. The implemented encoder has native rate of 1/2, a constraint length (K) of 7 and the generator polynomial in Equation (3.3) and (3.4) to produce to derive its two code bits [13, 15]. The generator is depicted in Figure 3.5.

$G1 = 171_{OCT}$ For X ………… Equation (3.3)

$G2 = 133_{OCT}$ For Y …………Equation (3.4)

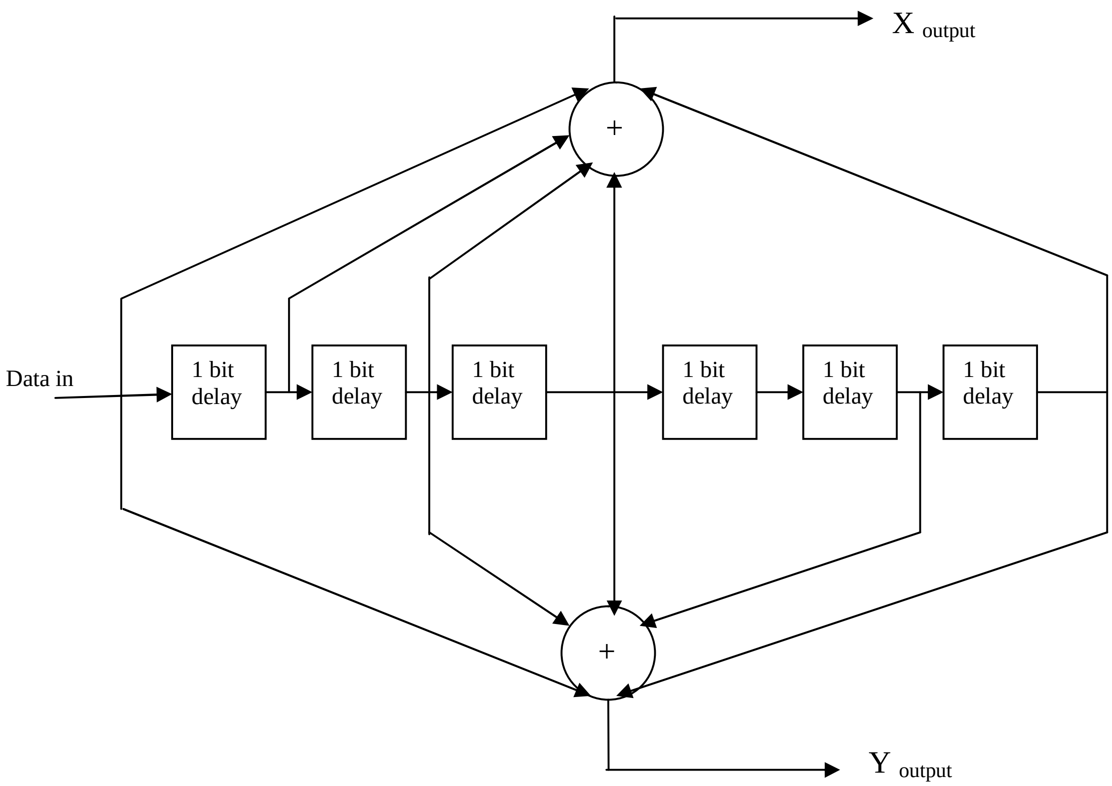

Figure 3.5 Convolutional encoder of rate ½

In order to achieve variable code rate a puncturing operation is performed on the output of the Convolutional Encoder in accordance to Table 3.1 given below. In this

Table "1" denotes that the corresponding Convolutional Encoder output is used i.e. transmitted bit, while "0" denotes that the corresponding output is not used i.e. removed bit. At the receiver Viterbi decoder is used to decode the convolutional codes.

Table 3.1 Puncturing configuration of the Convolutional code

Rate	**d_{FREE}**	**X $_{output}$**	**Y $_{output}$**	**XY (punctured output)**
1/2	10	1	1	X_1Y_1
2/3	6	10	11	$X_1Y_1Y_2$
3/4	5	101	110	$X_1Y_1Y_2X_3$
5/6	4	10101	11010	$X_1Y_1Y_2X_3Y_4X_5$

3.2.4 Interleaver

RS-CC encoded data are interleaved by a block interleaver. The size of the block is depended on the numbers of bit encoded per subchannel in one OFDM symbol, N_{cbps}. In IEEE 802.16, the interleaver is defined by two step permutation. The first ensures that adjacent coded bits are mapped onto nonadjacent subcarriers. The second permutation ensures that adjacent coded bits are mapped alternately onto less or more significant bits of the constellation, thus avoiding long runs of unreliable bits.

The Matlab implementation of the interleaver was performed calculating the index value of the bits after first and second permutation using Equation (3.5) and (3.6) respectively.

$f_k = (N_{cbps}/12).\ k_{mod12} + \text{floor}\ (k/2)\quad k = 0,1,2,\dots\ \dots\ ..N_{cbps}\text{-}1$ ……. Equation (3.5)

$S_k = S.\ \text{floor}\ (f_k/S) + (m_k + N_{cbps} - \text{floor}\ (12.m_k/N_{cbps}))_{mod(s)}$ ……… Equation (3.6)
$k = 0,1,2,\dots\ ….\ N_{cbps}\text{-}1$

where $S = \text{ceil}\ (N_{cpc}/2)$, while N_{cpc} stands for the number of coded bits per subcarrier, i.e. 1, 2, 4 or 6 for BPSK, QPSK, 16QAM, or 64QAM, respectively. K is the index of the bit encoded before first permutation. f_k is the index of the bit before the second permutation and after the first one, and Sk is the index after the second permutation, just before the mapping of the sign.

The default number of subchannels i.e. 16 is used for this implementation. The receiver i.e. de-interleaver also performs the reverse operation following the two step permutation using equations (3.7) and (3.8) respectively. Within the received block of N_{cbps} bits, let j be the index of a received bit before the first permutation, m_j be the index of that bit after the first and before the second permutation, and K_j be the index after the second permutation, just prior to delivering the block to the decoder.

First step permutation is defined as:

m_j = s. floor(j/s)+ (j+ floor(12.j/N_{cbps})) mod(s) ………………Equation (3.7)

j = 0,1,… … ..N_{cbps} -1

Second step permutation is defined as:

K_j = 12.f_j – (N_{cbps} 1). floor (12.fj/N_{cbps}) ……………………….Equation (3.8)

j = 0,1,2… … .. N_{cbps} -1

3.2.5 Data Mapping

After modulation, the constellation-mapped data are subsequently allocated onto slots and then to the burst area (OFDMA data region). The subcarrier allocation within a slot uses the algorithms described below:

- Modulated data shall span continuous 24 data subcarriers and two consecutive OFDMA symbols. Map the data such that the lowest numbered QAM symbol maps to the lowest numbered subcarrier and the lowest numbered OFDM symbol.
- Continue the mapping such that the subcarrier index is increased. When the edge of the slot is reached, continue the mapping from the lowest numbered subcarrier in the next available OFDMA symbol

3.2.6 IFFT

The grey mapped data are then sent to IFFT for time domain mapping. Mapping to time domain needs the application of IFFT. It is incorporated the MATLAB ´ifft´ function to do so. This block delivers a vector of 256 elements, where each complex number element represents one sample of the OFDM symbol.

3.2.7 Cyclic Prefix Insertion

A cyclic prefix is added to the time domain samples to combat the effect of multipath. Four different duration of cyclic prefix are available in the standard. Being G the ratio of CP time to OFDM symbol time, this ratio can be equal to 1/32, 1/16, 1/8 and 1/4.

3.3 Channel Model

In order to evaluate the performance of the developed communication system, an accurate description of the wireless channel is required to address its propagation environment. The radio architecture of a communication system plays very significant role in the modeling of a channel. The wireless channel is characterized by:

- Path loss (including shadowing)
- Multipath delay spread
- Fading characteristics
- Doppler spread
- Co-channel and adjacent channel interference

All the model parameters are random in nature and only a statistical characterization of them is possible, i.e. in terms of the mean and variance value. They are dependent upon terrain, tree density, antenna height and beam width, wind speed and time of the year. The different parameters of the channel model are described briefly hereunder.

3.3.1 Path loss

Path loss is affected by several factors such as terrain contours, different environments (urban or rural, vegetation and foliage), propagation medium (dry or moist air), the distance between the transmitter and the receiver, the height and location of their antennas, etc. It has only impact on the link budget that is why it will not be considered it in the channel modeling.

3.3.2 Multipath Delay Spread

Due to the NLOS propagation nature of the WirelessMAN OFDM, it is necessary to address multipath delay spread in our channel model. It results due to the scattering nature of the environment. Delay spread is a parameter used to signify the effect of multipath propagation. It depends on the terrain, distance, antenna directivity and other factors. The rms delay spread value can span from tens of nano seconds to microseconds.

3.3.3 Fading

In a multipath propagation environment, the received signal experiences fluctuation in its amplitude, phase and angle of arrival. The effect is described by the term multipath fading. The fading phenomenon is primarily a result of the time variations in the phases $\{\theta_{n(t)}\}$.That is the randomly time variant phases$\{\theta_{n(t)}\}$ associated with the vectors$\{\alpha_{ne}\text{-}j\theta_n\}$ at times result in the vectors adding destructively. The multipath propagation model for the channel embodied in the received signal rl (t) results in the signal fading. Due to fixed deployment of transmit and receive antenna, we just have to address the small scale fading in our channel model. Small scale fading refers to the dramatic changes in signal amplitude and phase that can be experienced as a result of small changes (as small as a half wavelength) in the spatial positioning between a receiver and a transmitter. Small scale fading is called Rayleigh fading if there are multiple reflective paths that are large in number and there is no line of sight signal component; the envelope of such a received signal is statistically described by a Rayleigh pdf. When a dominant non fading signal component is present, such as a line of sight propagation path, the small scale fading envelope is described by a Rician pdf. In other words, the small scale fading statistics are said to be Rayleigh whenever the line of sight path is blocked and Rician otherwise. In this project for the channel model Rician fading distribution would be considered. The key parameter of this distribution is the K factor, defined as the ratio of the direct component power and the scatter component power.

3.3.4 Doppler Spread

Since transmitter and receiver may move (e.g. when operating in a vehicle), Doppler shift may occur because the distance between the transmitter and the receiver changes over time. The Doppler shift causes a change in frequency of the signal. Reducing a distance between the transmitter and receiver increase the frequency, where as increasing the distance reduces the frequency. Within in OFDM system, a Doppler shift causes a change in carrier location, which means that the carriers move to lower frequencies when the distance between the transmitter and receiver is increased and vice versa.

The frequency shift Δf for a vehicle moving with a velocity v and operating at the nominal radio frequency f_0 can be calculated using the following formula:

$$\Delta f \approx (v/c)^* f_0$$ where c is the speed of light (300,000 Km/s)

The formula assumes that $v << c$ which is true for any transmitter-receiver environment. In cellular system, scattering causes the received signal to be a composite of many rays arriving at different angles incident on the received antenna. The received signal has components at continuum of frequency offset from the original by frequencies $-f_d$ Hz to $+f_d$ Hz. These signal components are characterized by the Doppler spectrum's of the radio channel. This represents the power spectral density as a function of frequency. Classical Doppler's spectrum is given by:

$$S(f) = \begin{cases} A/(1 - (f/fd)^2) & |f| < fd \\ 0, \text{ otherwise} \end{cases} \quad \text{.....................Equation (3.9)}$$

Doppler's effect is more complex when the mobile terminal is moving. In fixed wireless access, a Doppler frequency shift is induced on the signal due to movement of the objects in the environment. Doppler spectrum of fixed wireless channel differs from that of mobile channel. It is found that the Doppler is in the 0.12 Hz frequency range for fixed wireless channel. The shape of the spectrum is also different than the classical Jake's spectrum for mobile channel. Along with the above channel parameters, coherence distance, co-channel interference, antenna gain reduction factor should be addressed for channel modeling. Having the primary requirements for the channel model, there are two options to go with. Either we can use mathematical model for each of them or we can choose an empirical model that care of the above requirements. Here I opted for the later one and chose the SUI channel model for the simulation.

3.3.5 SUI Channel Models

SUI channel models are an extension of the earlier work by AT&T Wireless and Erceg etal. In this model a set of six channels was selected to address three different terrain types [16]. This model can be used for simulations, design, and development and testing of technologies suitable for fixed broadband wireless applications. The parameters for the model were selected based upon some statistical models. The Table 3.2 and Table 3.3 given below depict the parametric view of the six SUI channels [11]. The different SUI channel parameters are shown in Table 3.4, Table 3.5, Table 3.6, Table 3.7 and Table 3.8 given below [17].

Table 3.2 Terrain type for SUI channel

Terrain Type	SUI Channels
C (Mostly flat terrain with light tree densities)	SUI-1, SUI-2
B (Hilly terrain with light tree density or flat terrain with moderate to heavy tree density)	SUI-3, SUI-4
A (Hilly terrain with moderate-to-heavy tree density)	SUI-5, SUI-6

Table 3.3 General Characteristics of SUI channel

Doppler	Low Delay Spread	Moderate delay spread	High Delay spread
Low	SUI-1,2 (High K Factor) SUI-3		SUI-5
High		SUI-4	SUI-6

Table 3.4 Delay Spread of SUI Channels

Channel Model	Tap 1	Tap 2	Tap 3	RMS Delay Spread
	(µs)			
SUI-1	0	0.4	0.9	0.111
SUI-2	0	0.4	1.1	0.202
SUI-3	0	0.4	0.9	0.264
SUI-4	0	1.5	4.0	1.257
SUI-5	0	4.0	10.0	2.842
SUI-6	0	14.0	20.0	5.240

Table 3.5 Tap power (Omni directional antenna) of SUI channels

Channel Model	Tap 1	Tap 2	Tap3
	dB		
SUI-1	0	-15	-20
SUI-2	0	-12	-15
SUI-3	0	-5	-10
SUI-4	0	-4	-8
SUI-5	0	-5	-10
SUI-6	0	-10	-14

Table 3.6 90% K factor (omni directional antenna) of SUI channels

Channel Model	Tap 1	Tap 2	Tap3
SUI-1	4	0	0
SUI-2	2	0	0
SUI-3	1	0	0
SUI-4	0	0	0
SUI-5	0	0	0
SUI-6	0	0	0

Table 3.7 Maximum Doppler frequency of SUI Channels

Channel Model	Tap 1	Tap 2	Tap3
	Hz		
SUI-1	0.4	0.3	0.5
SUI-2	0.2	0.15	0.25
SUI-3	0.4	0.3	0.5
SUI-4	0.2	0.15	0.25
SUI-5	2.0	1.5	2.5
SUI-6	0.4	0.3	0.5

Table 3.7 Coeff. of Antenna Correlation and Normalizing Factor Gain of SUI Channels

Channel Model	Coefficient of Antenna Correlation	Normalizing Factor Gain (dB)
SUI-1	0.7	-0.1771
SUI-2	0.5	-0.3930
SUI-3	0.4	-1.5113
SUI-4	0.3	-1.9218
SUI-5	0.3	-1.51103
SUI-6	0.3	- 0.5683

3.4 Simulation Parameters

The different other key parameters that would be used during the simulation for IEEE 802.16 standards are as follows:

Nominal Channel Bandwidth [Hz]

The minimum channel bandwidth which can be used for the provision of service for a standard is Nominal Channel Bandwidth. $BW = F_s/n$

Used Bandwidth BW [Hz]

The bandwidth is the area which is physically occupied by the WiMAX signal in frequency domain. BW= $N_{used(max)}$. Δf. The used bandwidth must be smaller than the nominal BW.

Sampling Frequency F_s [Hz]

The sampling frequency is the "core" frequency of the transmission system, i.e. the frequency at which e.g. the D/A converter generates new samples. Fs is always greater than BW.

Sampling Factor n

The sampling factor is equal to the ratio of sampling frequency to the channel Bandwidth. n= F_s/BW. The different values of the factor of correction (n) that were used depending upon the channel Bandwidth (BW) in the simulation test are mentioned below:

Channel Bandwidth (BW), MHz	Factor of Correction (n)
1.75	8/7
1.5	86/75
1.25	144/125
2.75	316/275
2	57/50
For Other values	8/7

FFT size N_{FFT}

In OFDM, signals are very often processed using Fast Fourier Transformation. N_{FFT} specifies the number of samples for this processing step and is always a power of 2. Typical values are 256, 512, 1024, and 2048. In IEEE 802.16 2004 standard the FFT size of 256 is used.

(Sub-) carrier spacing Δf [Hz]

The distance between two adjacent physical OFDM carriers is the carrier spacing and the value is calculated by $\Delta f = F_s/N_{FFT}$

Useful Symbol Time T_b [s]

The time a symbol is "valid" which means the correct and undisturbed carrier modulation state (also called the "Orthogonality interval") is present, $T_b = 1/\Delta f$. For FFT analysis, this is the analyzed interval length.

Guard Period ratio/interval G, Cyclic Prefix (CP) time T_g [s]

In order to collect multipath information, a particular ratio of the useful symbol is added to the OFDM. The ratio is called guard period (Typical values of G: 1/4, 1/8, 1/16/ or 1/32), The absolute time is called cyclic prefix ($T_g = G.\ T_b$) [18].

(Overall) OFDM symbol time Ts [s]

The duration of the complete OFDM symbol with useful symbol time and cyclic prefix time ($T_s = T_b + T_g$)

Number of used Subcarriers N_{used}

Due to e.g. the shape of the transmission filter, the outer carriers of an OFDM signal may be attenuated and thus be disturbed. Also the DC carrier cannot be used. Consequently, the outer carriers do not carry any modulation data. N_{used} may vary e.g. depending on special transfer modes. For OFDM, N_{FFT} =256 and N_{used} = 200

DC subcarrier

The DC subcarrier is the carrier at the transmission frequency and is not used for data transmission (set to 0)

Pilot Carriers

Pilot carriers are used to synchronize the receiver to the transmitter by means of phase, frequency and timing.

Guard Subcarriers $N_{Guard, left}$ / $N_{Guard, right}$

The guard subcarriers are the outer carriers, which are not used for transmission

$N_{FFT} = N_{used (max)} + N_{Guard, left} + N_{Guard, right} + 1$ (DC $_{subcarrier}$)

The key simulation parameters can be summarized as bellows:

Channel Bandwidth BW:	1.25-28 MHz
Sampling Frequency F_s:	floor (n* BW/8000)*8000 i.e. 1.72-32 MHz
Sampling Factor n:	8/7, 86/75,144/125, 57/50, 316/275
FFT size, N_{FFT} :	256
Subcarrier Spacing Δf:	Fs/N_{FFT}
Useful Symbol Time T_b:	1/Δf
Cyclic Prefix Time T_g:	G. T_b
Cyclic Prefix i.e. Guard Period ratio G:	¼, 1/8, 1/16, 1/32
OFDM Symbol Time T_s:	T_b+T_g (i.e data + cyclic prefix)
Duration of each Carrier in μs:	1/Fs
Number of Used Subcarriers N_{used}:	200
Pilot carriers:	8 (fixed locations)[2]
Guard Subcarriers $N_{Guard, left}$/ $N_{Guard, right}$:	28 left 27 right

[2] ±13 ±38 ±63 ±88

CHAPTER 4 DISCUSSION AND RESULTS

4.1 Discussion

The Simulator was developed using modular approach in Matlab 7.7 (R2008b). The main procedure call each of the block in the manner a communication system works. The main procedure also contains initialization parameters, input data and delivers results. The parameters that can be set at the time of initialization are the number of simulated OFDM symbols, CP length, modulation and coding rate, range of SNR values and SUI channel model for simulation. The input data stream is randomly generated. Output variables are available in Matlab workspace while BER values for different SNR would be stored in text files which facilitate to draw plots. In the simulation, different functions were used in order to carry out different steps used in the system such as SUI channels, transmitter, channel impulse response, create symbol (with pilot carriers, data carriers, guard carriers), cyclic prefix, decoder, encoder, interleaving, mapping, transmitter, receiver . Each simulation depends on the signal to noise ratio of the system, type of modulation, size of the cyclic prefix, the channel models, channel Bandwidth, channel encoding, and the number of symbols taking into consideration.

There are two types of OFDM parameters - primitive and derived, that characterize OFDM symbol completely. The later one can be derived from the former one because of fixed relation between them. The simulation was carried out with the variation of different modulation techniques (BPSK, QPSK, 16 QAM and 64 QAM) in a specific cyclic prefix specification. Four different duration of cyclic prefix are available in the standard. Being G the ration of CP time to OFDM symbol time, this ratio can be equal to 1/4, 1/8, 1/16 and 1/32. Six different channel models (channel 1 to 6) were used for the simulation. Each of the channels has specific parameters defined by the SUI. The different parameters taken into consideration are power of each path (dB), Factor of K of the Ricean distribution, delay of each path (μs), Maximum Doppler frequency (Hz), coefficient of antenna correlation, and normalizing the factor of gain (dB). The frequency of 2.3 GHz was used as carrier frequency in the simulation. The different values of the parameters were used based on the document 802163c-01-29r4 was taken in consideration in the simulation. The different nominal channel Bandwidth starting from 1.25 MHz to 28 MHz can be used for the simulation.

Identifiers called BSID, DIUC, and no. of Frame are used along with the sequence of bits for the randomization with Pseudo Random Sequence Generator. The Three values of BSID, DIUC, and Frame that were used in the simulation to calculate the seed were 1, 7 and 1 respectively for the algorithm of randomization of the data. The values of number of bits that must be generated were taken from the standard depending upon the modulation techniques. The Data interleaving is carried out with numbers of bit encoded per sub channel in one OFDM symbol, N_{cbps} for a given bits per sub carrier i.e. 1, 2, 4 or 6 for BPSK, QPSK, 16QAM, or 64 QAM respectively using two step permutation. The number of bits encoded per sub channel in one OFDM symbol that were used in the simulation in BPSK, QPSK, 16 QAM and 64 QAM were 192, 384, 768, and 1152 respectively. The different cases of testing and simulation with the different results that were obtained in the simulation are described briefly hereunder.

4.2 Results

A key performance measure of a wireless Communication system is the BER, so the BER as well as SNR were used to compare the performance of different modulation techniques for given values of channel model, cyclic prefix size and coding scheme in consideration of given number of input symbols taken into consideration. From the simulation, various BER vs. SNR plots for all mandatory modulation i.e. BPSK, QPSK, 16 QAM, and 64 QAM were obtained. Some of the typical BER vs. SNR plots in which the system performance was evaluated and analyzed under different modulation techniques for the given channel Bandwidth, reference channel models, and cyclic prefix insertion are shown below.

The simulations were also carried out with the variation of the cyclic prefix size keeping the other parameters (modulation technique, channel model, channel Bandwidth) fixed. The results were also tested and simulated parameters were observed and analyzed for probability of the received symbols with respect to the SNR in case of received symbols with the variation of different channel models. The simulation and testing were also carried out with and without channel encoding and the corresponding results were taken into consideration for the comparison to have the impact of channel encoding in the system performance.

Testing and simulation result

The testing and simulations were carried out in different four cases as mentioned below. In each of the cases only one parameter varies and other simulation parameters are held constant. The simulations were carried out with a variation of modulation technique, cyclic prefix size, channel bandwidth, channel models separately keeping other given input parameters fixed as reference parameters. During the execution of the simulation, a typical sample that can be seen in the desktop asking for the choice among the different possible cases and the values of different simulation parameters as input parameters is shown in figure 5.1 given below.

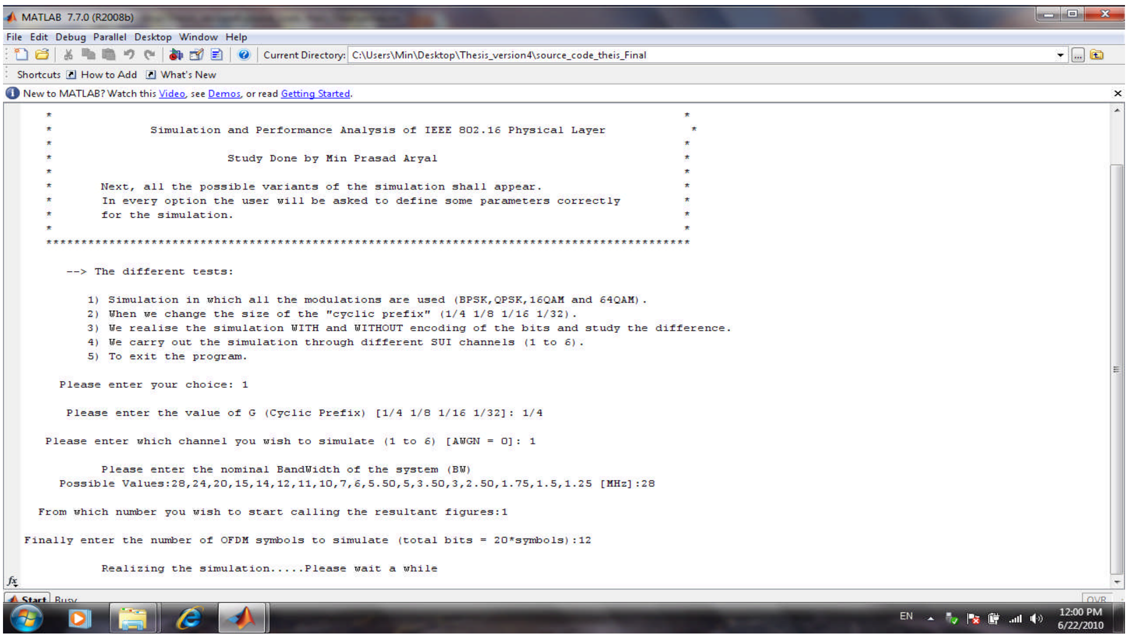

Figure 5.1 Typical Sample Output that can be seen in the desktop during the execution of the simulation

Below are the different cases and the corresponding results obtained in the testing and simulation with the variation of a parameter in different reference input parameters to be taken into account:

- **Modulations**

This test was performed with the same basic parameters, as the same simulation through the variations of modulation techniques that allows the standard. The results were four graphs, one for each type of modulation (BPSK, QPSK, 16QAM and 64QAM). It could be seen a plot of results for the received symbols through the simulation. The typical Eb/No vs. plots that were obtained for the received symbols with the variation of modulation techniques are shown in Figure 5.2 and Figure 5.3 hereunder. It can be observed that the lower modulation and coding scheme provides better performance with less SNR.

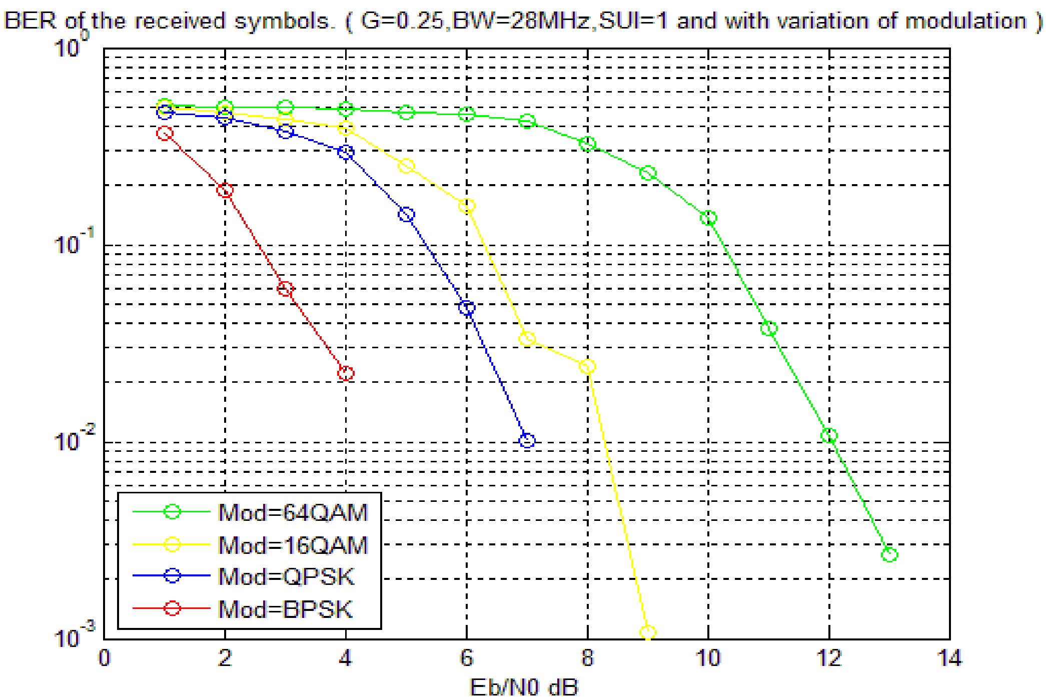

Figure 5.2 Sample output graph for the different modulation techniques for given other input parameters

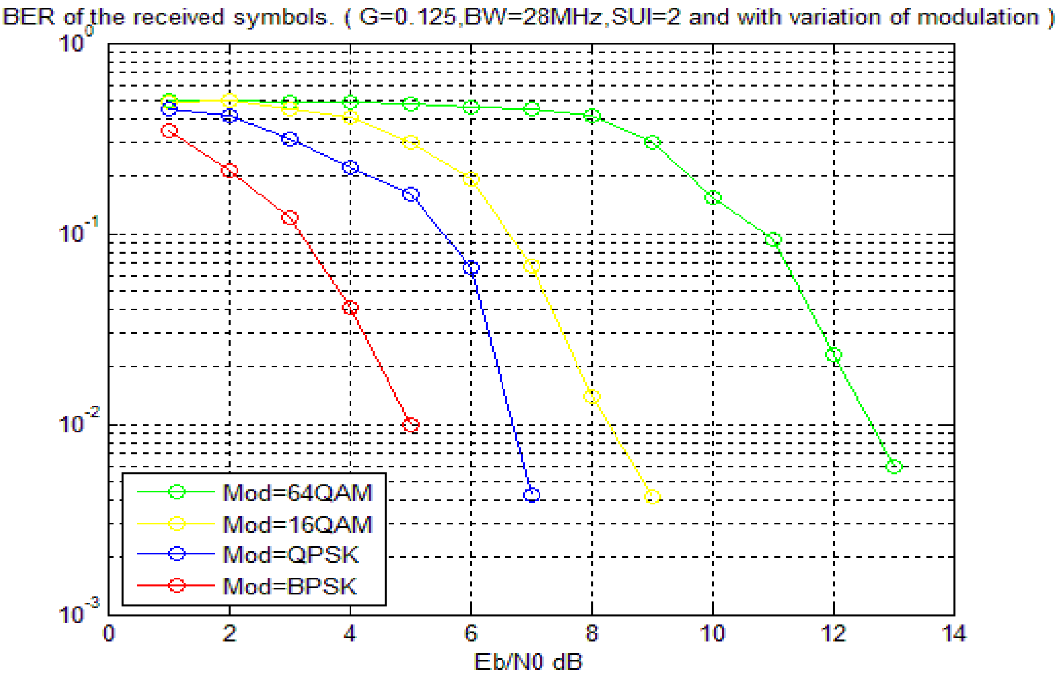

Figure 5.3 Sample output graph with the variation of modulation techniques for given input parameters

- **Channels**

In this case, all other parameters other than the transmission channel are kept constant. Thus simulations of the system in different SUI channels were carried out for the reference input variables of modulation technique, cyclic prefix, channel Bandwidth for particular number of symbols taken into consideration. The results were drawn in the same graph, the response of the system when working with different available channels (SUI-1 to 6). Some typical simulation results with the variation of SUI channels are shown in Figure 5.4 and Figure 5.5 given below:

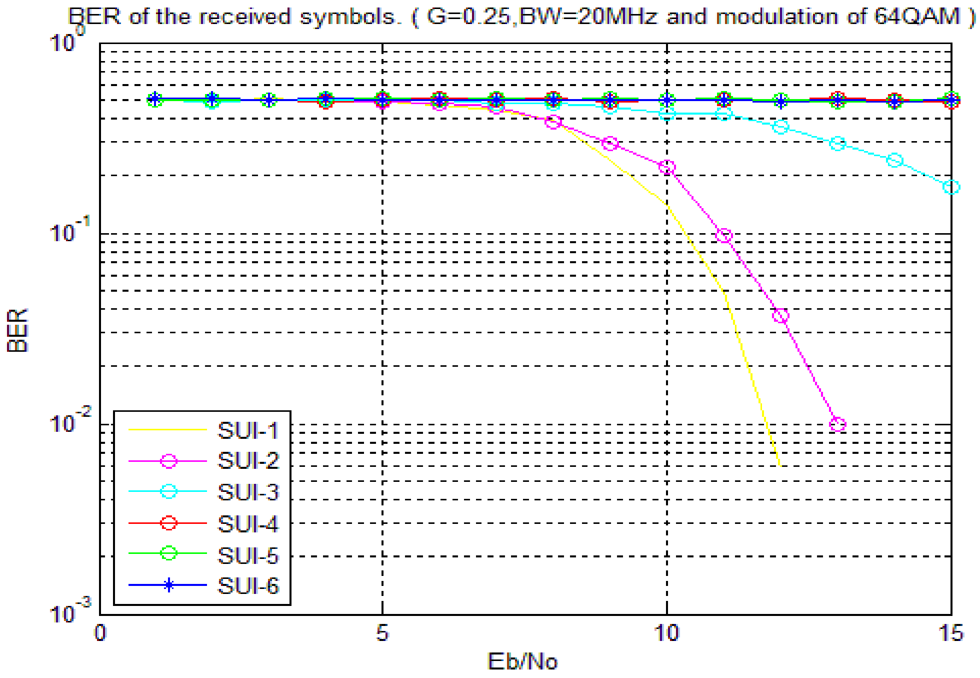

Figure 5.4 Sample output graph for different channel models with given input parameters

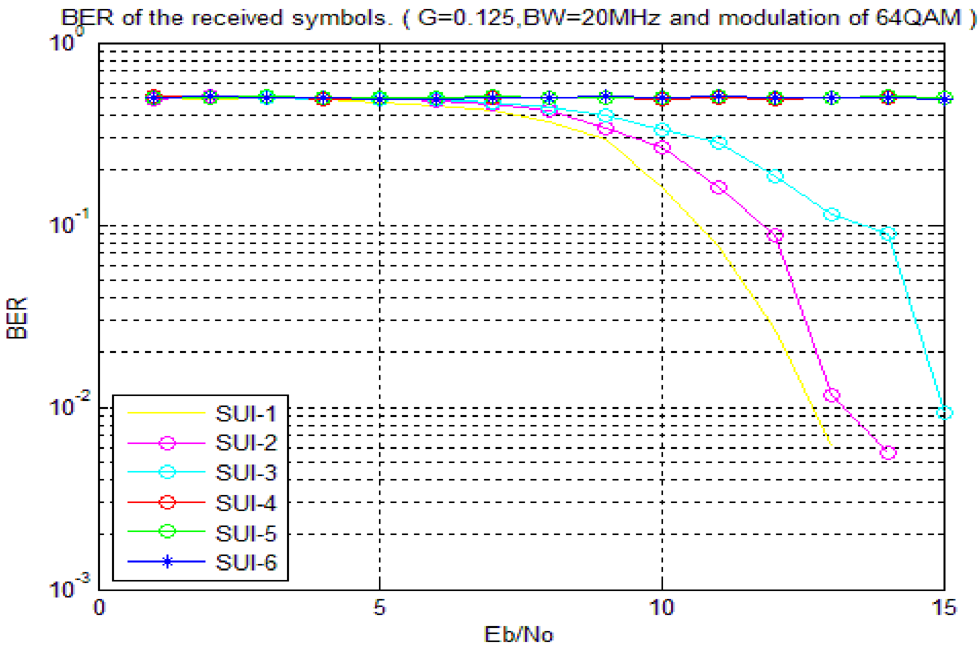

Figure 5.5 Sample output graph for different channel models with given input parameters

- **Cyclic Prefix Size**

In this case the BER and SNR were plotted for different sizes of the cyclic prefix i.e. 1/4, 1/8, 1/16, and 1/32 keeping all other input parameters fixed. The use of the size of cyclic prefix is to avoid the effect produced by the fading channel. The typical simulation results that were obtained for the different cyclic prefix sizes with the given reference channel, channel Bandwidth, modulation techniques with the particular number of symbols taken into consideration are shown in Figure 5.5 and Figure 5.6 given below. It was observed that in general, the addition of more cyclic prefix size reduces the probability of error.

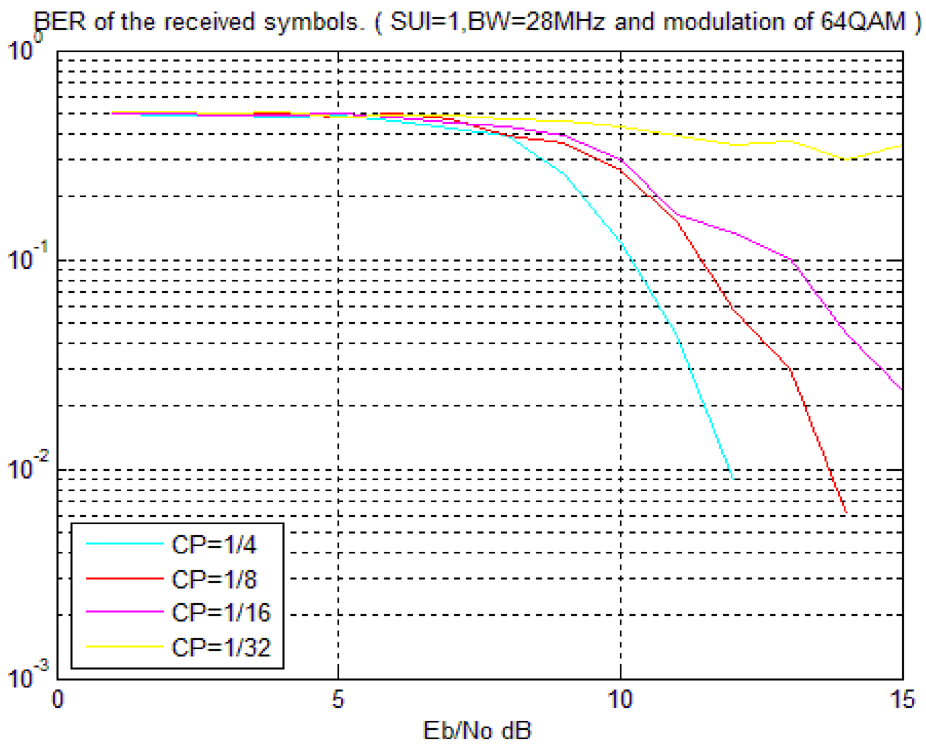

Figure 5.6 Sample output graph for different Cyclic Prefix sizes with given input parameters

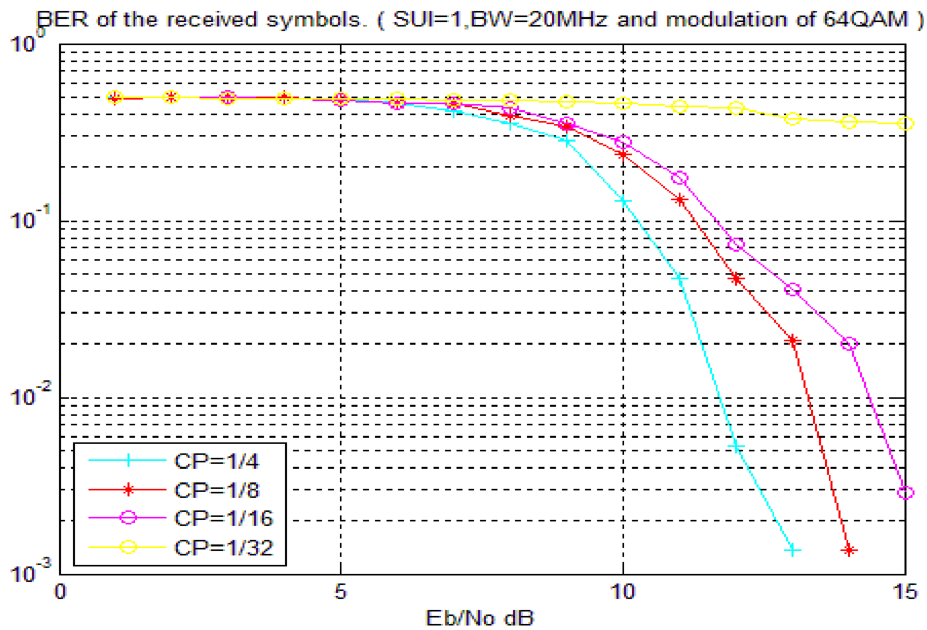

Figure 5.7 Sample output graph for different channel models with given input parameters

- **Encode**

One of the characteristics of the simulation was improving the performance of the system when performing all stages of coding that I have already mentioned. The simulation results obtained during the execution of testing that were observed with and without coding for given reference modulation technique, channel bandwidth, channel model, cyclic prefix with the particular number of symbols taken into consideration showing the BER and SNR plot are shown in the Figure 5.8, Figure 5.9 and Figure 5.10 given below .

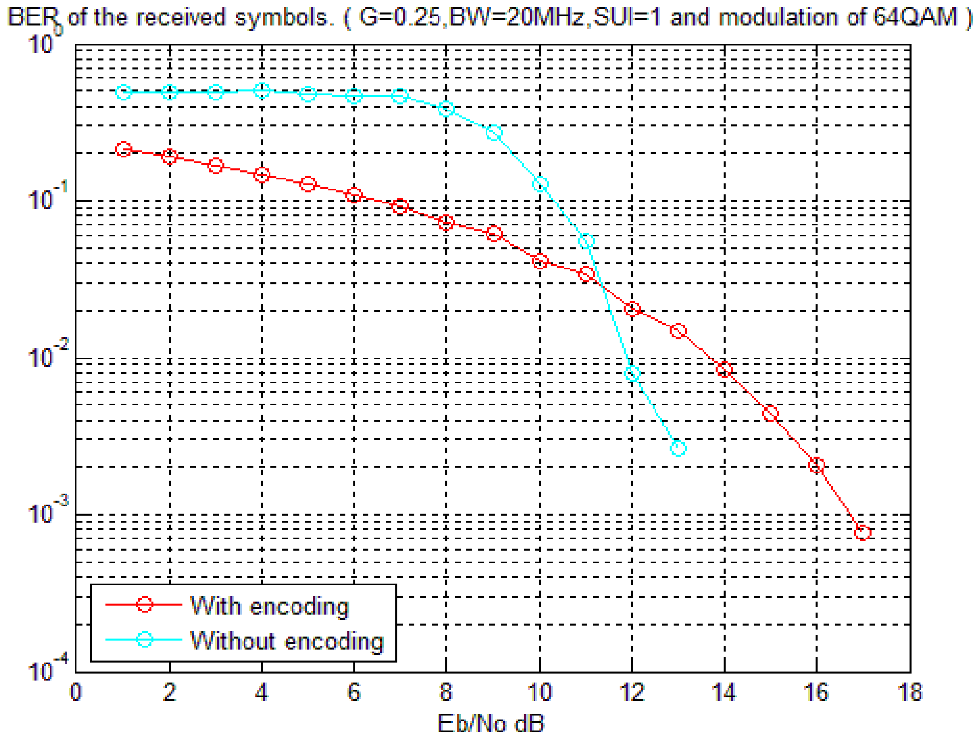

Figure 5.8 Sample output graph with and without encoding with given input parameters

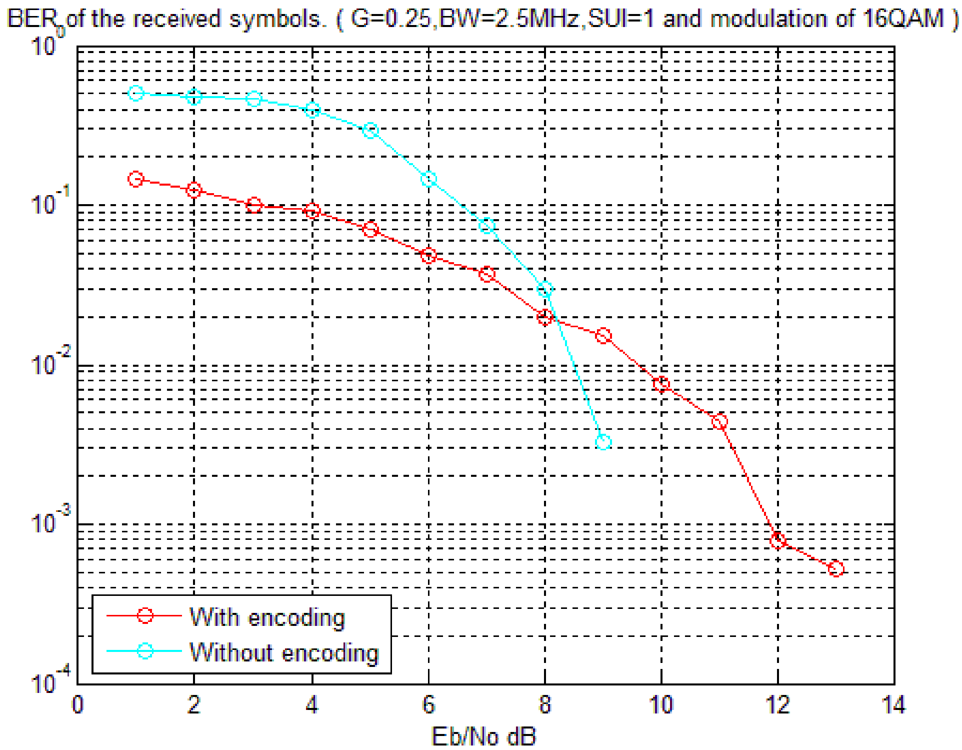

Figure 5.9 Sample output graph with and without encoding with given input parameters

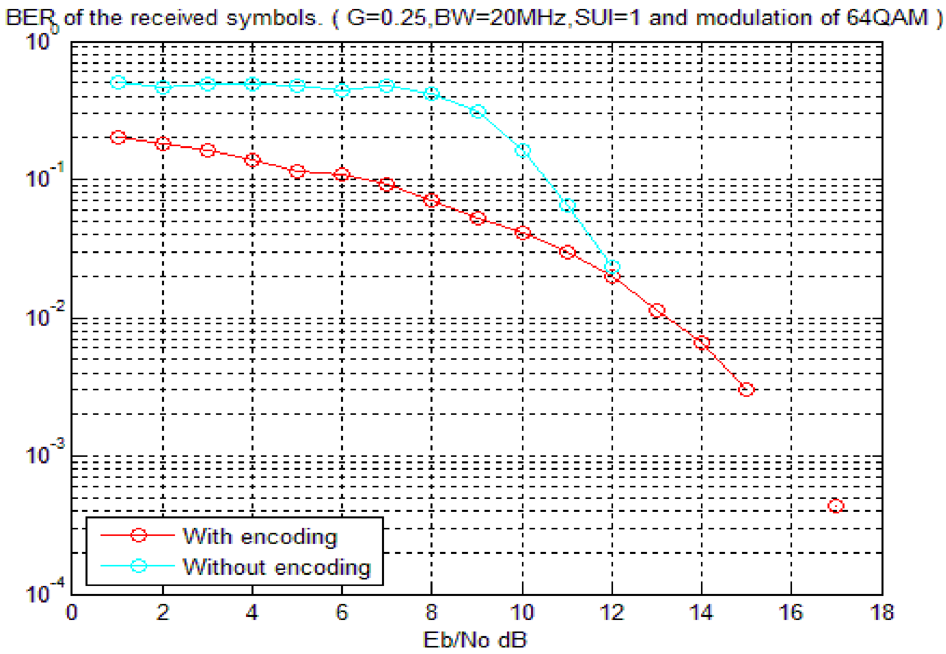

Figure 5.10 Sample output graph with and without encoding with given input simulation parameters

CHAPTER 5

CONCLUSIONS, LIMITATIONS & FUTURE WORKS

5.1 Conclusion

The key contribution of this project is to study the literature on new emerging/innovative technology, WiMAX, as well as the implementation of the IEEE 802.16 OFDM PHY layer using MATLAB in order to evaluate the PHY layer performance. The implemented PHY layer supports all the modulation and coding schemes as well as CP lengths defined in the specification. Simulation would be the methodology used to investigate the PHY layer performance. The system performance was evaluated in different cases with the variation a parameter and keeping other parameters constant. The simulation parameters were tested and results were taken in consideration with the variation of modulation techniques, channel Bandwidth, Cyclic Prefix, and channels separately and in each case the other parameters were kept constant. The A key performance measure of a wireless Communication system is the BER, so the probability of error as well as SNR were used to compare the performance of different modulation techniques, channel models and cyclic prefix size. It can be seen that the lower modulation and coding scheme provides better performance with less SNR. Similarly the addition of more cyclic prefix size reduces the probability of error. From the simulation, it was observed that the probability of error varies with respect to the Eb/No differently in different SUI channels. The simulation was carried out with and without coding to know the impact with the reference modulation technique, Cyclic Prefix, and channel model and channel Bandwidth. It was observed that the system performance was improved while using encoding compared to that of the value obtained without encoding. The study of different other competent BWA technologies was carried out in brief to have the comparative idea of other BWA technologies with respect to WiMAX in the key dimensions.

5.2 Limitations

The simulation result may be poor if the number of symbols bits taken in consideration is low resulting in less accuracy. The simulation time is relatively high due to the calculation of large number of communication phenomena involved in the system using Matlab R2008b. Since this thesis is focused on performance evaluation of IEEE-2004, the performance evaluation on the mobile standard IEEE 802.16e is not carried out.

5.3 Future Works

The future work is listed as bellows:

- The implemented PHY layer model still needs some improvement. The channel estimator can be implemented to obtain a depiction of the channel state to combat the effects of the channel using an equalizer.
- The IEEE 802.16 standard comes with many optional PHY layer features, which can be implemented to further improve the performance. The optional Block Turbo Coding (BTC) can be implemented to enhance the performance of FEC.
- Performance evaluation on mobile standard IEEE 802.16e

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