Chapter One

1.1 Background

WiMAX stands for **Worldwide Interoperability for Microwave Access** and it based on IEEE 802.16 standards [1]. WiMAX is a packet-based wireless technology that provides broadband access over long distances. It is used over wireless MANs (Metropolitan Area Networks), it provides access to fixed as well as mobile stations. It covers a range of about 30 miles for fixed stations and 3 to 10 miles for mobile stations. WiMAX provides both Line Of Sight (LOS) and Non Line of Sight (NLOS) modes of communication, and can handle data rates up to 70 Mbps [2].

One of the previous studies of WiMAX was done by Raza Akbar, Syed Aqeel Raza, and Usman Shafique at Blekinge Institute of Technology in 2009, as part of degree of Master of Science in Electrical Engineering.

Their thesis was concluded by: BPSK has the lowest BER while the 64-QAM has highest BER than others.

In the previous study mentioned above, many of the IEEE 802.16 standard techniques were not considered like Randomization, Interleaving, and Reed Solomon coding.

1.2 Problem Definition

The wireless channel for broadband communication including WiMAX, introduces several major impairments which are Distance-dependent decay of signal power, Blockage due to large obstructions, large variations in received signal envelope, Intersymbol interference (ISI) due to time dispersion, Frequency dispersion due to motion, Noise and Interference with the other signals. These impairments increase the bit error rate (BER). The high data rate also leads to increase in the BER.

1.3 The Objectives

The goal of this thesis work is to analyze the Orthogonal Frequency Division Multiplexing (OFDM) Physical layer specification of WiMAX. Modulation and coding techniques are considered along with wireless channel characteristics.

The performance analysis of OFDM physical layer in WiMAX is based on the simulation results of Bit-Error-Rate (BER) for different scenarios of modulation and coding schemes on different channel conditions.

1.4 Motivation

There are some technologies that provide broadband access.DSL (Digital Subscriber Line) is a point-to-point, broadband Internet connection method that transmits digital signals over existing phone lines. It has become a popular way to connect small businesses and households to the Internet because it is affordable and provides a relatively high download speed [3]. For example, Asymmetric Digital Subscriber Line (ADSL) services in Sudan offer about 2Mbps of downstream throughput to the end user. However, distance and the quality of the lines affect the total bandwidth available to a customer.WiMAX is a broadband wireless access technology that offered a data rate up to 70 Mbps which is based on IEEE 802.16 standards. The features of this technology which are described in Chapter 2 are the motivation for this work.

1.5 Methodology

Modeling and simulation using MATLAB is the method used in this work to evaluate and analyze the performance of WiMAX physical layer. The OFDM, modulation, coding techniques and WiMAX channel characteristics are arranged into three modules; the transmitter, the receiver and the channel. Bit error rate (BER) versus Eb/No ratio is the measure of performance that our analysis depends on.

1.6 Thesis Outlines

This report is divided into five chapters. Chapter 1 is an introduction of the thesis work. The other chapters are organized as follows:

Chapter 2 gives an overview of WiMAX, especially its standards, network layers, network topologies, features, and applications. OFDM, OFDMA and digital modulation techniques are discussed briefly.

In Chapter 3, modeling of WiMAX physical layer is discussed, the MATLAB simulation program is also described.

In Chapter 4, the simulation results are shown and their analysis is done.

Chapter 5 concludes our work along with some recommendations. The MATLAB simulation program is appended at the end of thesis.

Chapter Tow
Overview of WiMAX
2.1 Wireless Networks and Broadband Wireless Access

After the deployment of fixed Internet networks throughout the world, the need is now becoming more important for wireless access.

Based on a network scale, wireless data networks can be categorized as follows:

Wireless Personal Area Network (WPAN): The scope of this network is a few meters, generally assumed to be less than 10m. Bluetooth technology is classified as WPAN.

Wireless Local Area Network (WLAN): is a data network used for connecting data devices: computers, telephones, printers and personal digital assistants (PDAs). This network covers a relatively small area, like a home, an office or a small campus. The scope of a WLAN is of the order of 100 meters. The most famous presently used WLAN is Wi-Fi.

Wireless Metropolitan Area Network (WMAN): is a data network that may cover up to several kilometers, typically a large campus or a city. Fixed WiMAX can be considered as a WMAN.

Wireless Wide Area Network (WWAN): is a data network covering a wide geographical area, as big as the Planet. 3G and mobile WiMAX networks are classified as WWANs [4].

Figure 2.1 shows all these types of wireless data networks with most famous technologies for each type.

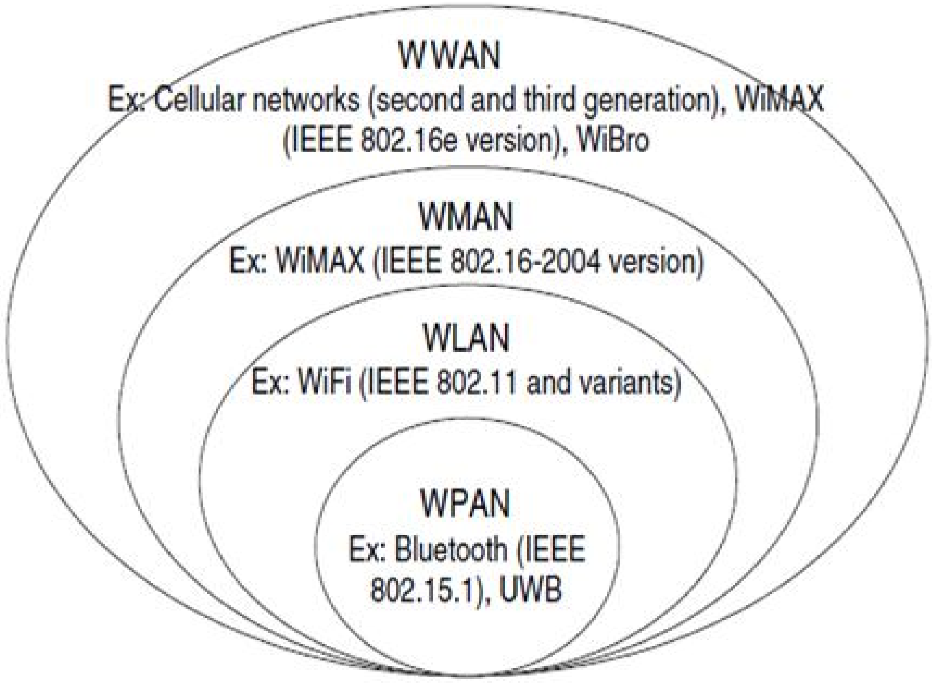

Figure 2.1 Types of wireless data networks [4]

The name ***WiMAX*** (Worldwide Interoperability for Microwave Access) was created by the WiMAX Forum to describe IEEE 802.16 based technology. The forum describes WiMAX as "a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL" [5].

2.2 IEEE 802.16 Family of Standards

The Institute of Electrical and Electronics Engineers (IEEE) has defined a family of broadband wireless MAN standards for WiMAX, referred to as IEEE 802.16. It consists of different versions of the standard. The purpose of developing 802.16 standards is to help the industry to provide compatible and interoperable solutions across multiple broadband segments and to facilitate the commercialization of WiMAX products.

Currently, WiMAX has two main variations: one is for fixed wireless applications (covered by IEEE 802.16-2004 standard) and another is for mobile wireless services (covered by IEEE 802.16e standard).

Both of them evolved from IEEE 802.16 and IEEE 802.16a, the earlier versions of WMAN standards.

The 802.16 standards only specify the physical layer and the media access control (MAC) layer of the air interface while the upper layers are not considered [6].

In the following subsections, some of the main IEEE 802.16 family standards are introduced.

2.2.1 IEEE 802.16 2001

This version was the first amendment of the standard. It uses LOS communication, and external antennas provide access to the network. This version, however, was not adequate for broadband wireless access (BWA).

2.2.2 IEEE 802.16a

This version is the most important amendment of 802.16, and was published to standardize the MMDS solutions in the licensed and unlicensed 2 to 11 GHz frequency range. As it works on a lower frequency range than 802.16-2001, 802.16a can provide NLOS communication. It additionally allows for the mesh mode of operation that facilitates communication between individual subscribers.

2.2.3 IEEE 802.16-2004

IEEE 802.16-2004 is a wireless access technology standard optimized for fixed and nomadic access, which was published in October 2004. It is a combined and improved version of IEEE 802.16, 802.16a. The goal of this standard is to enable global deployment of innovative, low-cost, and interoperable multivendor BWA products;

increase the capacity of competition of BWA systems against their wired counterparts; and facilitate global commercialization of BWA products [6].

2.2.4 IEEE 802.16e

This version is an amendment to the 802.16d specification to provide explicit support for mobility [3]. It is also referred to as 802.16-2005. It is considered the base version for mobile broadband wireless access using WiMAX. The main differences of 802.16e with regard to 802.16-2004 are the following:

- Mobile stations (MS) appear.
- MAC layer handover procedures.
- Power save modes (for mobility-supporting MSs): sleep and idle modes.
- SOFDMA (Scalable OFDMA)
- Security (privacy sublayer).
- Multiple-Input Multiple-Output (MIMO) and Adaptive Antenna System (AAS) techniques, both already introduced in 802.16-2004, have many enhancement and implementation details provided in 802.16e.
- Multicast and broadcast services (MBS) feature.
- Other: the Low-Density Parity Check (LDPC) code is an optional channel coding [2].Table 2.1 summarizes the main features of the above mentioned standards. In addition to the four main standards discussed before, there are some other IEEE 802.16 standards like IEEE 802.16f, IEEE 802.16g, IEEE 802.16h, IEEE 802.16i, IEEE 802.16j and IEEE 802.16k [6].

Table 2.1 Comparison among IEEE 802.16, 802.16a, 802.16-2004, and 802.16e [6]

	802.16	**802.16a**	**802.16-2004**	**802.16e**
Frequency range	10-66 GHz	2-11 GHz	2-11 GHz 10-66 GHz	2-6 GHz
Channel conditions	Line-of-sight only	Nonline-of-sight	Nonline-of-sight	Nonline-of-sight
Channel bandwidth	20,25,and 28MHz	1.25-28MHz	1.25-28MHz	1.25-20MHz
Modulation scheme	QPSK, 16QAM,and 64QAM	OFDM,QPSK 16QAM,and 64QAM	OFDM,QPSK 16QAM,and 64QAM	OFDM,QPSK 16QAM,and 64QAM
Network Architecture supported	PTP,PMP	PTP,PMP, mesh	PTP,PMP, mesh	PTP,PMP, mesh
Bit rate	32-134 Mbps	Up to 75Mbps	Up to 75Mbps	Up to 75Mbps
Mobility	Fixed	Fixed	Fixed	Pedestrian mobility-regional roaming, maximum mobility support: 125 Km/h
Typical cell radius	1-3 miles	Maximum range is 30 miles on the	Maximum range is 30 miles on the	1-3 miles

		basis of antenna height, antenna gain, and transmit power	basis of antenna height, antenna gain, and transmit power	
Application	Replacement of E1/T1 services for enterprises, backhaul for hot spots, residential broadband access, SOHO (small office/home office)	Alternative to E1/T1, DSL, cable backhaul for cellular and Wi-Fi, VoIP, Internet connections.	802.16 plus 802.16a applications	802.16-2004 applications plus fixed VoIP, QoS-based applications, and enterprise networking.

2.3 WiMAX Forum

The WiMAX forum is an organization that certifies conformance and compatibility to the IEEE 802.16 standard and ensures that products are interoperable. The forum includes equipment manufacturers, network operators, and academicians. It develops system profiles for WiMAX based on the IEEE 802.16 standard. It takes into account emerging trends in the industry, market demands, and international regulations for the development of WiMAX. It also provides guidelines for the end-to-end WiMAX architecture [7].

2.4 WiMAX Features

WiMAX has a distinct set of features that make it a flexible and viable wireless broadband solution. The main features are:

- OFDM-based physical layer: The use of OFDM allows WiMAX to operate in NLOS conditions.
- Very high peak data rates: WiMAX supports very high peak data rates of up to 70 Mbps. If the signal conditions are good, with the use of multiple antennas and spatial multiplexing even higher rates can be achieved.
- Scalable bandwidth and data rate support: The WiMAX protocol stack allows for the data rate to scale to the available channel's bandwidth. As this scaling can be dynamic, it can support a user roaming in different networks, each with different channel bandwidths allocated.
- Adaptive modulation and coding (AMC): WiMAX provides support for a number of modulation and coding schemes that can be modified based on channel conditions and user requirements. AMC is used to maximize the throughput in a variable channel.
- Link-layer retransmissions: WiMAX supports methods such as Automatic Repeat Requests (ARQ) that enhance the reliability of the connection. It requires that the receiver acknowledge the receipt of a data packet. If an acknowledgement is not received, the packet is retransmitted to ensure delivery.
- Support for TDD and FDD: IEEE 802.16-2004 and IEEE 802.16e-2005 supports both time division duplexing (TDD) and frequency division duplexing (FDD), as well as a half-duplex FDD, which allows for a low-cost system implementation.
- Orthogonal Frequency Division Multiple Accesses (OFDMA): Mobile WiMAX uses OFDMA as a multiple-access technique, whereby different users can be

allocated different subsets of the OFDM tones. As discussed in detail in this Chapter later, OFDMA facilitates the exploitation of frequency diversity and multiuser diversity to significantly improve the system capacity.

- Flexible and dynamic per user resource allocation: As the base station controls the allocation of resources, the capacity of a channel is allocated dynamically, and shared among multiple users.
- Support for advanced antenna techniques: The design of the WiMAX protocol stack allows for the use of multiple-antenna techniques, such as beam forming, space-time coding, and spatial multiplexing.
- Quality-of-service support: The WiMAX protocol stack is designed to support multiple users with different QoS requirements. It provides support for constant and variable bit rates, real-time and non-real-time traffic flows, and best-effort data traffic. This allows real-time multimedia services to be provided to users.
- Robust security: WiMAX uses the *Privacy Key Management (PKM)* protocol along with strong encryption using the Advanced Encryption Standard (AES). Authentication is done using the Extensible Authentication Protocol (EAP), which allows for a variety of user credentials, including the username and password, digital certificates, and smart cards.
- Support for mobility: WiMAX provides support for mobility to ensure secure, seamless handovers for applications that require full mobility. It also has built-in mechanisms for saving power on subscriber devices.
- IP-based architecture: The WiMAX reference network architecture defined by the WiMAX forum is based on an all-IP platform. This reduces operation costs and allows for convergence with other networks [7].

2.5 Applications of WiMAX

- WMANs: WiMAX can be used to provide connectivity to the Internet and broadband multimedia applications. The frequency availability, bandwidth requirement, and receiver sensitivity determine the range of the WMAN. The users in a WMAN are connected to a BS, and the BSs are in turn connected to the core network.
- Rural area broadband Services**:** WiMAX is a good alternative for wireless broadband service providers to deliver services in rural areas due to lower operations and deployment costs. This is because the subscriber base in rural areas is small, but the costs involved in setting up of the wired infrastructure are quite high. It is also easier to scale up when compared to a wired network.
- Last-mile broadband access: Last-mile broadband access to buildings is challenging due to higher costs involved in laying the cable and labor. WiMAX offers solutions at a much lower cost but comparable speeds.
- Network backhaul**:** WiMAX can act as a backhaul for cellular networks and can cover multiple cells and expand to provide better services. It can also serve as a cost-effective, high-capacity backhaul for Wi-Fi hotspots.
- Connectivity for enterprise or private networks: WiMAX can be used to connect enterprise or private networks. It can connect remote offices to the central office. It thus provides high-speed, reliable, secure wireless connections for enterprise connectivity.
- Wireless video surveillance**:** WiMAX can be used as a cost-effective, flexible tool for video surveillance. It requires the combination of both WiMAX and IP. It uses IP connections and infrastructure to transfer video images securely.

2.6 The Protocol Layers of WiMAX

In this section, the protocol layer architecture of WiMAX/802.16 is introduced. The protocol layering of IEEE 802.16 standards is shown is Figure2.2.

The IEEE 802.16 protocol layering consists of a MAC layer and a physical layer. The MAC comprises three sublayers, namely, the service-specific convergence sublayer (CS), the common part sublayer (CPS), and the security sublayer (or privacy sublayer). We briefly discuss the functions of the three sublayers and the physical layer in the following subsections [8].

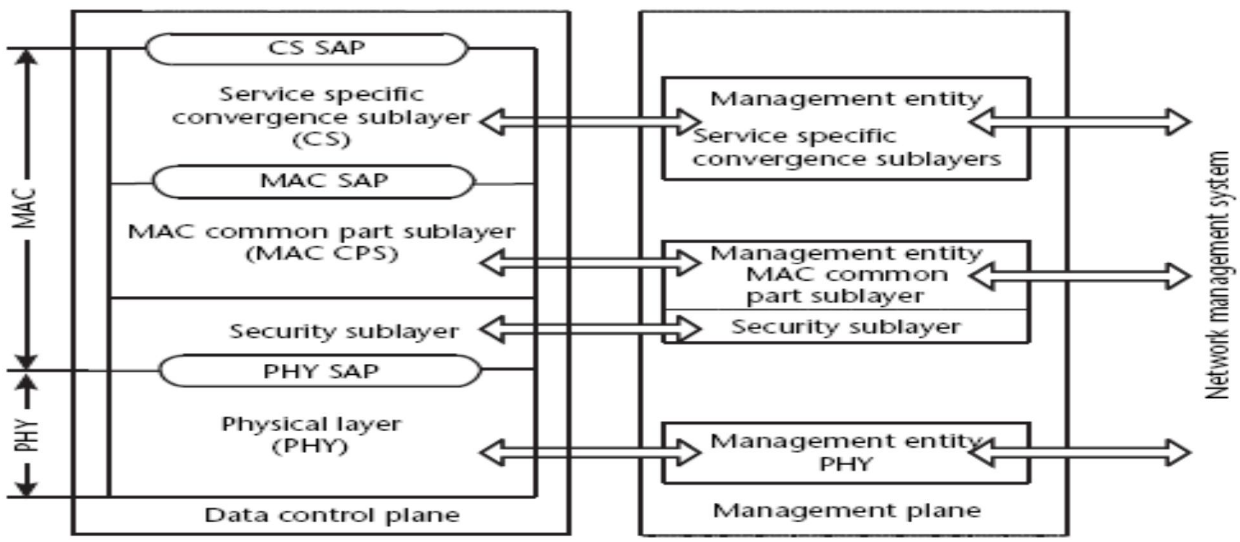

Figure 2.2 IEEE 802.16 protocol layering [8].

2.6.1 Convergence Sublayer (CS)

The Convergence sublayer (CS) is present between the Common Part sublayer and higher layers. It works with different protocols and technologies such as Ethernet, IP, and ATM. The CS receives MSDUs, maps the addresses of higher layers such as IP addresses to the PHY and MAC layers, and compresses the header before transmission. It also performs bandwidth allocation and QoS functions.

2.6.2 Medium Access Control Common Part Sublayer

The MAC Common Part sublayer is used for concatenating multiple MSDUs into an MPDU for transmission. First, each MSDU is divided into one or more fragments. The position of each fragment is tagged with a sequence number so that the receiver can reassemble all fragments in the correct sequence. This tagging helps in the efficient utilization of resources on the PHY layer. The sublayer also performs additional functions such as allocation of bandwidth, modulation, QoS control, scheduling, and ARQ.

2.6.3 Security Sublayer

The Security sublayer provides a secure connection for subscribers using the network by encrypting the connection between a BS and an SS. It protects BSs from unauthorized access and encrypts the service flow on the network. The Security sublayer also protects service providers against service theft by employing security techniques such as authorization and PKM.

In WiMAX, two types of MAC Protocol Data Units (MPDU)s are used: generic and bandwidth request. The generic MPDU is used for carrying both data and signaling messages on the MAC layer. It contains a generic header along with a payload and a Cyclic Redundancy Check (CRC) field. The bandwidth request MPDU is used by an SS to inform the BS that more bandwidth is needed to transmit data. It contains only a bandwidth request header without a payload or CRC.

2.6.4 Physical Layer

In the 802.16 protocol stack, the PHY layer is used for transferring data using radio waves. This layer is not responsible for other tasks such as ensuring QoS for the type of application used and its requirements.

These tasks are taken care of by the MAC layer. The PHY layer, which is based on OFDM, uses other techniques such as TDD, FDD, AAS, and adaptive modulation.

There are four variants of the PHY layer. Each of the variants can be used along with the MAC layer to develop a broadband wireless system.

- Wireless MAN SC: This variant is used for LOS transmissions using a single carrier PHY layer with frequencies beyond 11 GHz.
- Wireless MAN SCa: This variant is used for point-to-multipoint operations in NLOS conditions using a single-carrier PHY layer with frequencies between 2 and 11 GHz.
- Wireless MAN OFDM: This variant is used for point-to-multipoint operations in NLOS conditions using OFDM with frequencies between 2 and 11 GHz. This is the PHY layer that is used for fixed WiMAX applications.
- Wireless MAN OFDMA: This variant is used for point-to-multipoint operations in NLOS conditions using Scalable OFDMA (SOFDMA) with frequencies between 2 and 11 GHz. This is the PHY layer that is used for mobile WiMAX applications.

In chapter 3, WiMAX OFDM physical layer is modeled and simulated. In chapter 4, the simulation results are used to analyze the performance of WiMAX PHY layer.

2.7 WiMAX Topologies

The IEEE 802.16 standard defines two possible network topologies:

- PMP (Point-to-Multipoint) topology as shown in Figure 2.3.
- Mesh topology or Mesh mode as shown in Figure 2.4.

The main difference between the two modes is the following: in the PMP mode, traffic may take place only between a base station (BS) and its subscriber stations (SSs), while in the Mesh mode the traffic can be routed through other SSs until the BS and can even take place only between SSs.PMP is a centralized topology where the BS is the centre of the system while in Mesh topology it is not. The elements of a Mesh network are called nodes.

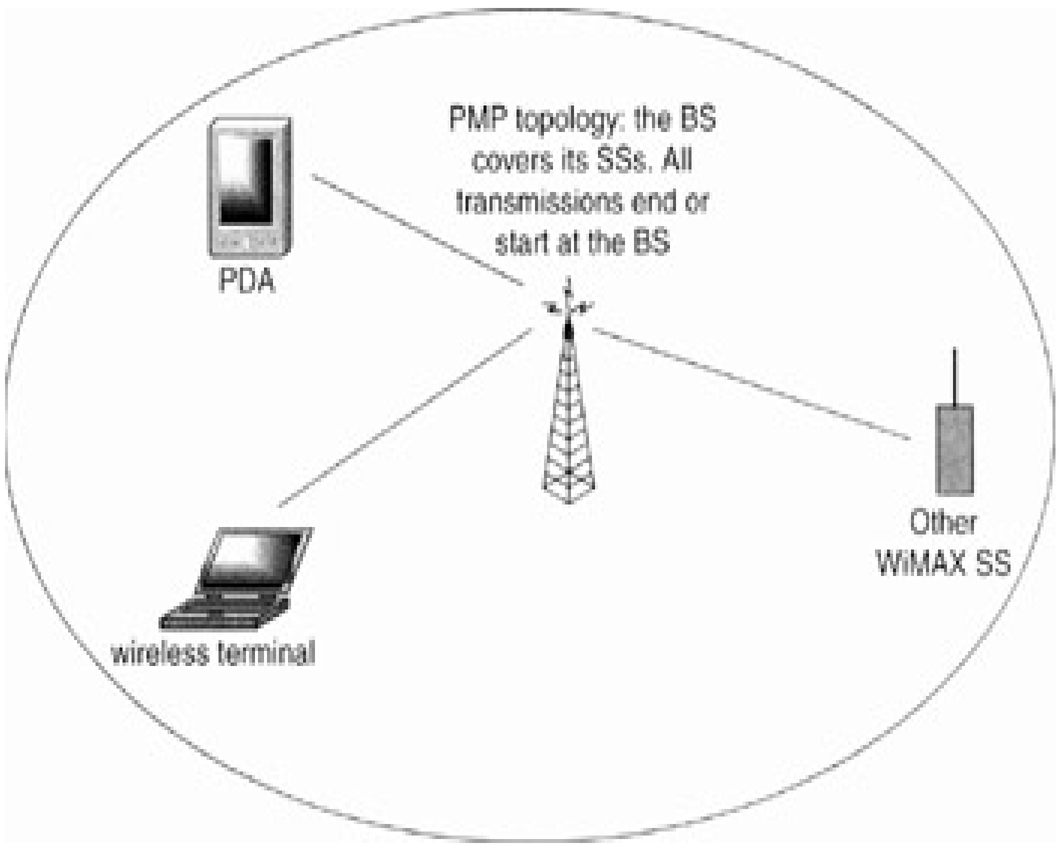

Figure 2.3 PMP topology [9]

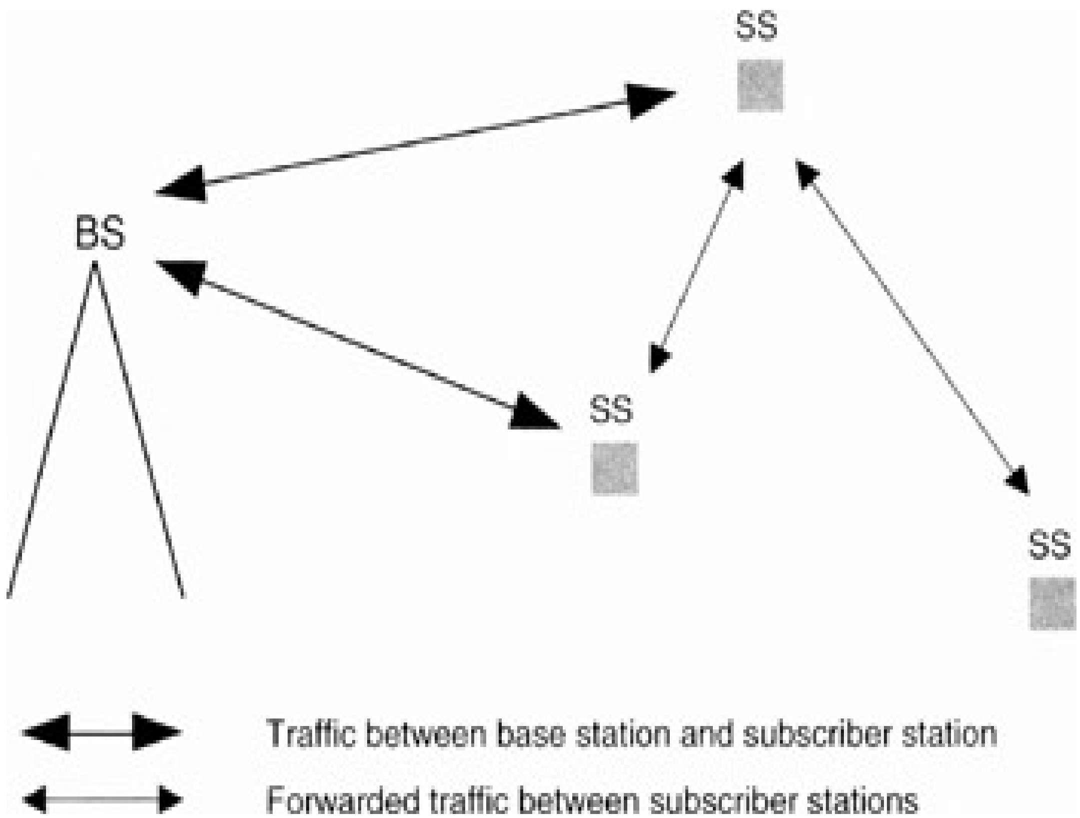

Figure 2.4 Mesh topology [9]

2.8 WiMAX System Profiles

System certification profiles are defined by the Technical Working Group (TWG) in the WiMAX Forum. The 802.16 standard indicates that a system (certification) profile consists of five components: MAC profile, PHY profile, RF profile, duplexing selection (TDD or FDD) and power class. The frequency bands and channel bandwidths are chosen such that they cover as much as possible of the worldwide spectra allocations expected for WiMAX [9].

WiMAX Forum introduced two system profiles: fixed system profile based on IEEE 802.16-2004 OFDM physical layer, and mobile system profile based on IEEE 802.16e-2005 scalable OFDMA physical layer. Besides system profile, certification profiles are defined to specify the operating frequency, channel bandwidth, and duplexing mode as shown in Tables 2.2 and 2.3 [9].

Table 2.2 Fixed WiMAX certification profiles, all using the OFDM PHY and PMP modes [10]

Frequency band (GHz)	Duplexing mode	Channel bandwidth (MHz)	Profile name
3.5	TDD	7	3.5T1
3.5	TDD	3.5	3.5T2
3.5	FDD	3.5	3.5F1
3.5	FDD	7	3.5F2
3.5	TDD	10	5.8T

Table 2.3 Release 1 Mobile WiMAX certification profiles, all using the OFDMA PHY and PMP modes [10]

Frequency band (GHz)	Duplexing mode	Channel bandwidth and FFT size (number of OFDMA subcarriers)
2.3-2.4	TDD	5MHz, 512; 8.75MHz, 1024; 10MHz, 1024
2.305-2.320	TDD	3.5MHz, 512; 5MHz, 512; 10MHz, 1024
2.496-2.690	TDD	5MHz, 512; 10MHz, 1024
3.3-3.4	TDD	5MHz, 512; 7MHz, 1024; 10MHz, 1024
3.4-3.8	TDD	5MHz, 512; 7MHz, 1024; 10MHz, 1024

2.9 Wireless Digital Communication System

Any wireless digital communication system consists of transmitter, channel and receiver, as shown in Figure 2.5.

The transmitter translates the received packets of bits from above protocol layer to electromagnetic waves to be transmitted, the steps to do that are:

- The encoder generally adds redundancy that will allow error correction at the receiver.
- The modulator prepares the digital signal for the wireless channel.
- The modulated digital signal is converted into a representative analog waveform by a digital-to-analog convertor (DAC) and then upconverted to one of the desired WiMAX radio frequency (RF) bands.
- This RF signal is then radiated as electromagnetic waves by a suitable antenna.

The receiver performs essentially the reverse of these operations. After downconverting the received RF signal and filtering out signals at other frequencies, the resulting baseband signal is converted to a digital signal by an analog-to-digital convertor (ADC). This digital signal can then be demodulated and decoded to reproduce the original bit stream.

The IEEE 802.16 standard and WiMAX focus almost exclusively on the digital aspects of wireless communication, in particular at the transmitter side.

The receiver implementation is unspecified; each equipment manufacturer is welcome to develop efficient proprietary receiver algorithms. [11]

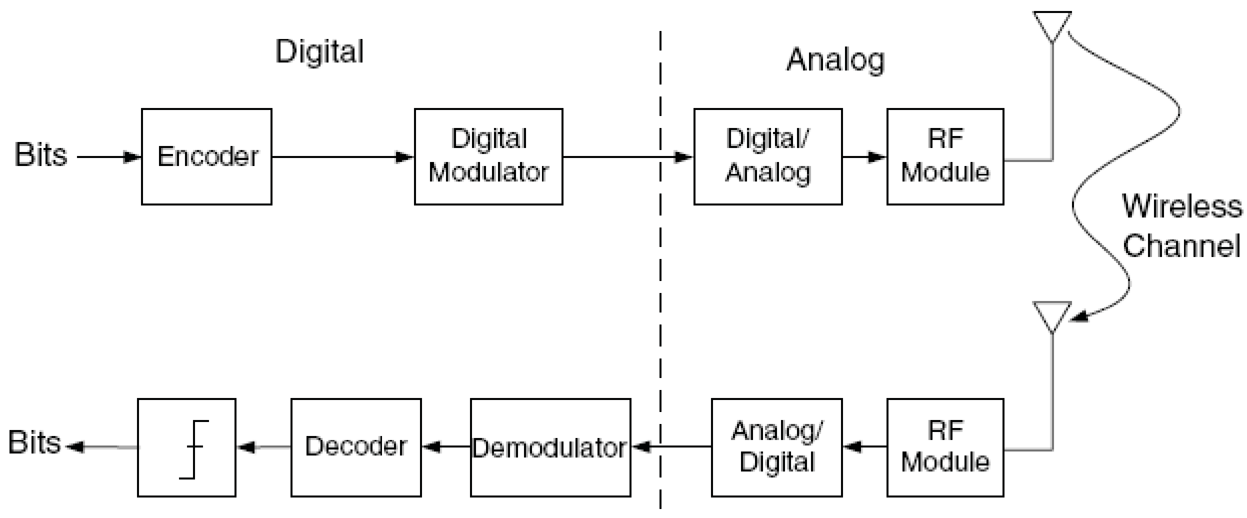

Figure 2.5 Wireless digital communication system [11].

The design of a communication system that will withstand the degradation effects of fading can be much more challenging than the design of its non-fading counterpart [12].

2.10 Modulation Techniques

Modulation can be defined as superimposition of the signal containing the information on a high-frequency carrier [13]. Digital modulation is the process by which digital symbols are transformed into waveforms that are compatible with the characteristics of the channel [14].

Like all recent communication systems, WiMAX uses digital modulation.

In this section the modulation techniques used in OFDM and OFDMA WiMAX physical layers are introduced.

2.10.1 Binary Phase Shift Keying (BPSK)

In BPSK, two phases are used to represent 1 and 0. The resulting transmitted signal for one bit time is [14]

$$\textbf{BPSK} \quad S(t) = \begin{cases} A\cos(2\pi f_c t) \\ A\cos(2\pi f_c t + \pi) \end{cases} = \begin{cases} A\cos(2\pi f_c t) & binary\ 1 \\ -A\cos(2\pi f_c t) & binary\ 0 \end{cases} \quad \ldots (2.1)$$

Where f_c is the carrier frequency.

The transmission bandwidth for BPSK is of the form

$$B_T = (1 + r)R \qquad \ldots\ldots\ldots (2.2)$$

Where R is the bit rate and r is related to the technique by which the signal is filtered to establish a bandwidth for transmission; typically $0 < r < 1$ Thus the bandwidth is directly related to the bit rate.

2.10.2 Quadrature Phase Shift Keying (QPSK)

QPSK considers two-bit modulation symbols. It uses phase shifts separated by multiples of π/2 (90°).The resulting transmitted signal for one bit time is

$$\text{QPSK} \quad S(t) = \begin{cases} A\cos\left(2\pi f_c t + \frac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \frac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \frac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \frac{\pi}{4}\right) & 10 \end{cases} \quad \ldots\ldots\ldots\ldots\ldots(2.3)$$

With QPSK, significant improvements in bandwidth can be achieved.

The transmission bandwidth for QPSK is of the form

$$B_T = \left(\frac{1+r}{2}\right) \quad R \quad \ldots\ldots\ldots\ldots (2.4)$$

Bandwidth efficiency (R/B_T) is the ratio of data rate, R, to transmission bandwidth B_T. This parameter measures the efficiency with which bandwidth can be used to transmit data. The advantage of multilevel modulation schemes (QPSK, QAM) over BPSK comes from their greater Bandwidth efficiency.

There is a tradeoff between bandwidth efficiency and error performance: An increase in bandwidth efficiency results in an increase in error probability [14].

2.10.3 Quadrature Amplitude Modulation (QAM)

The QAM changes the amplitudes of two sinusoidal carriers depending on the digital sequence that must be transmitted; the two carriers being out of phase of +π/2, this amplitude modulation is called Quadrature. Both 16-QAM (4 bits/modulation symbol) and 64-QAM (6 bits/modulation symbol) modulations are included in the IEEE 802.16 standard. The 64-QAM is the most efficient modulation of 802.16. Indeed, 6 bits are transmitted with each modulation symbol.

2.10.4 Adaptive Modulation Technique in WiMAX

Having more than one modulation has a great advantage: link adaptation can be used. When the radio link is good, a high-level modulation is used (64 QAM); when the radio link is bad, a low-level, but also robust, modulation is used like (QPSK).

Figure 2.6 illustrates the link adaptation. A good radio channel corresponds to a high-efficiency Modulation and Coding Scheme.

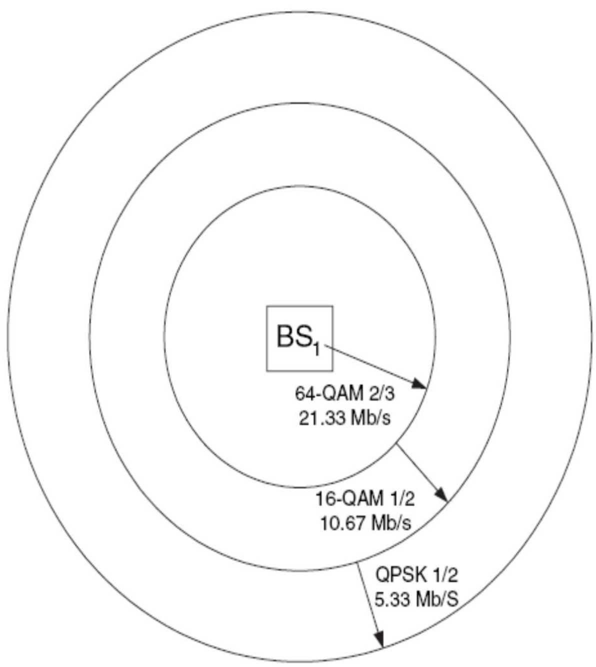

Figure 2.6 Illustration of link adaptation [15]

2.11 OFDM Overview

Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation technique that has recently been used in many of high-data-rate communication systems, including digital subscriber lines, wireless LANs (802.11a/g/n), digital video broadcasting, and WiMAX. The use of OFDM for high-data-rate applications came as a result of its efficient and flexible management of intersymbol interference (ISI) in highly fading channels [16].

In this section we will show how OFDM works in theory, OFDM system design, and implementation issues for WiMAX systems.

2.11.1 Multicarrier modulation

Multi-carrier modulation, in particular Orthogonal Frequency Division Multiplexing (OFDM), has been applied to many digital communications applications over the past few years [17].

The multicarrier modulation can be described as follows:

- The symbol time T_s has to be larger than channel delay spread, hence ISI is avoided.
- High-rate transmit bit stream is divided into *L* lower-rate substreams (ISI free).
  - Substreams are sent over *L* parallel subchannels.
  - Subchannels are orthogonal frequency carriers.
  - Subchannel bandwidth is less than coherence bandwidth of channel to experience flat fading.

In a basic multicarrier transmitter, a high-rate stream of *R* bps is broken into *L* parallel streams, each with rate *R/L* and then multiplied by a different carrier frequency as shown in Figure 2.7.

At the receiver side, each subcarrier is decoded separately, requiring L independent receivers as shown in Figure 2.8.

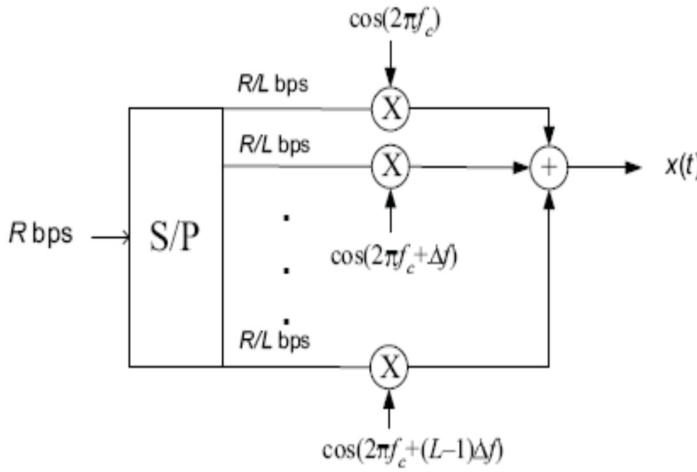

Figure 2.7 A basic multicarrier transmitter [18]

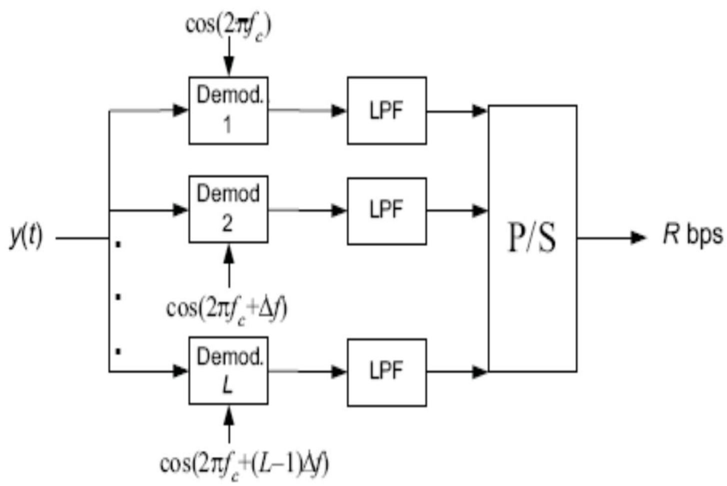

Figure 2.8 A basic multicarrier receiver [18]

In the time domain, the symbol duration on each subcarrier has increased to $T=LT_s$; the symbol duration exceeds the channel-delay spread, $T \gg \tau$, hence, no ISI. In the frequency domain, the subcarriers have bandwidth $B/L \ll B_c$, which ensures flat fading, the frequency-domain equivalent to ISI-free communication as depicted in Figure 2.9.

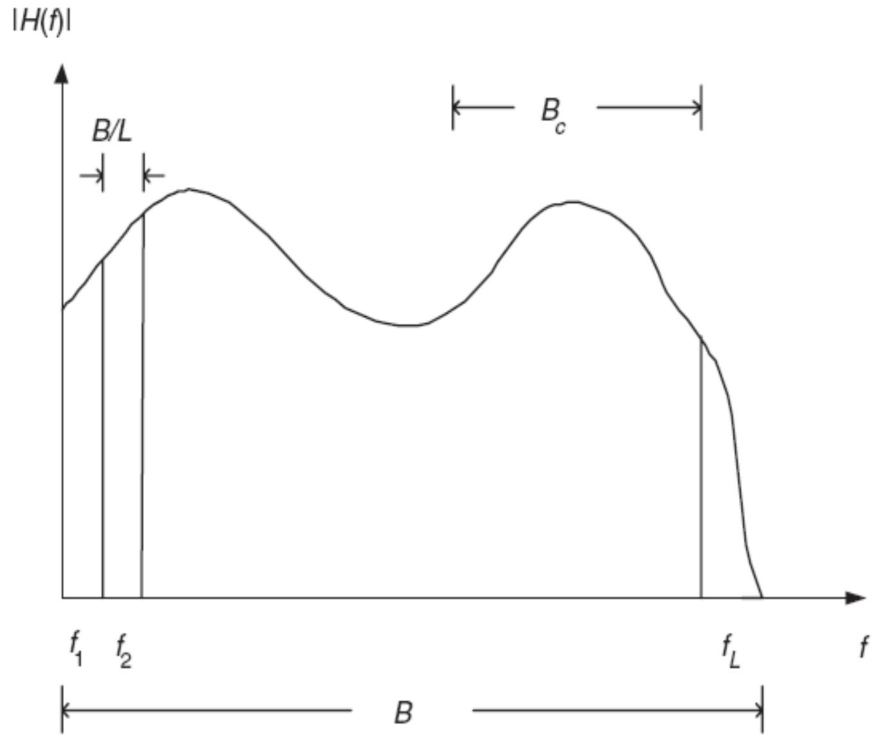

Figure 2.9 The transmitted multicarrier signal [18]

2.11.2 OFDM Basics

OFDM is a very powerful transmission technique. It is based on the principle of transmitting simultaneously many narrow-band orthogonal frequencies, often also called OFDM subcarriers or subcarriers. The number of subcarriers is often noted N. These frequencies are orthogonal to each other which (in theory) eliminates the interference between channels. Each frequency channel is modulated with a possibly different digital modulation (usually the same in the first simple versions). The frequency bandwidth associated with each of these channels is then much smaller than if the total bandwidth was occupied by a single modulation. This is known as the Single Carrier (SC). A data symbol time is N times longer, with OFDM providing a much better multipath resistance.

2.11.2.1 Basic Principle: Use the IFFT Operator

The FFT is the Fast Fourier Transform is a matrix computation that allows the discrete Fourier transform to be computed. The FFT works for any number of points. The operation is simpler when applied for a number N which is a power of 2.The IFFT is the Inverse Fast Fourier Transform operator, it realizes the reverse operation. OFDM theory shows that the IFFT of magnitude N, applied on N symbols, realizes an OFDM signal, where each symbol is transmitted on one of the N orthogonal frequencies [19]. The symbols are the data symbols of the type BPSK, QPSK, QAM-16 and QAM-64 discussed in the previous section.

2.11.2.2 Time Domain OFDM Considerations

After application of the IFFT, a Cyclic Prefix (CP) must be added at the beginning of the OFDM symbol as shown in Figure 2.10. The CP that occupies duration called the Guard Time (GT), often denoted by T_G. The ratio T_G/T is very often denoted *by* G in WiMAX/802.16 documents [19].

The choice of G is made according to the following considerations: if the multipath effect is important (a bad radio channel), a high value of G is needed; if the multipath effect is lighter (a good radio channel), a relatively smaller value of G can be used. For OFDM and OFDMA PHY layers, 802.16 defined the following values for G: 1/4, 1/8, 1/16 and 1/32. For the mobile (OFDMA) WiMAX profiles presently defined, only the value 1/8 is mandatory [19].

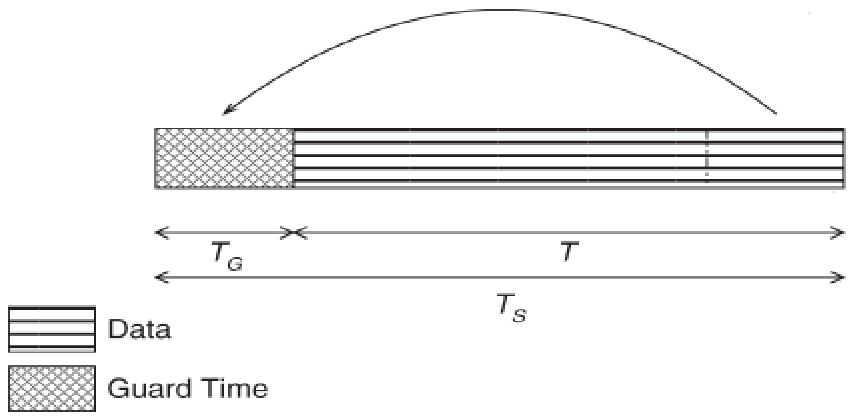

Figure 2.10 Cyclic Prefix insertion in an OFDM symbol [20]

2.11.2.3 Frequency Domain OFDM Considerations

Not all the subcarriers of an OFDM symbol carry useful data. As shown in Figure 2.11, there are four subcarrier types:

- Data subcarriers: useful data transmission.
- Pilot subcarriers: mainly for channel estimation and synchronization. For OFDM PHY, there are eight pilot subcarriers.
- Null subcarriers: no transmission. These are frequency guard bands.
- Another null subcarrier is the DC (Direct Current) subcarrier.

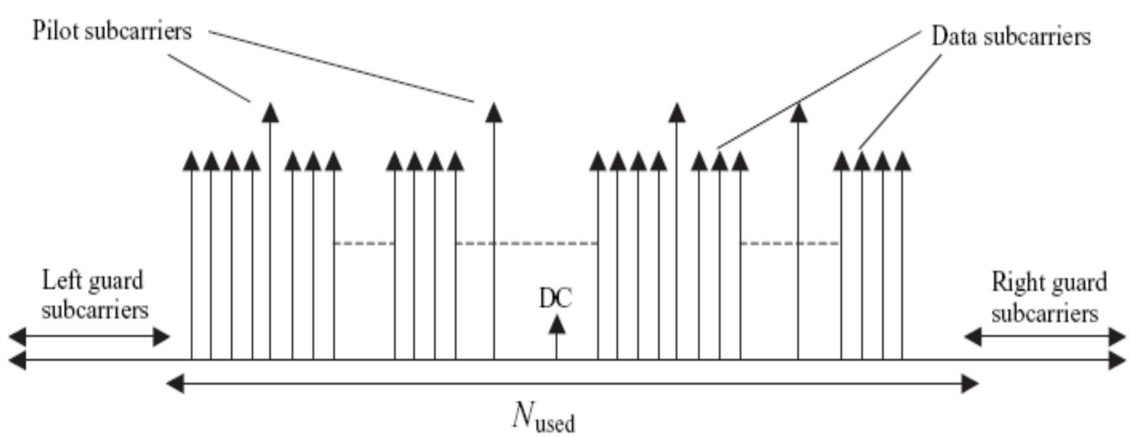

Figure 2.11 WiMAX OFDM subcarriers types.[20]

2.11.2.4 OFDM Symbol Parameters and Some Simple Computations

The main WiMAX OFDM symbol parameters are the following:

- The total number of subcarriers: for OFDM PHY, NFFT = 256, the number of lower-frequency guard subcarriers is 28 and the number of higher-frequency guard subcarriers is 27. Considering also the DC subcarrier, there remains N_{used}, the number of used subcarriers, excluding the null subcarriers. Hence; N_{used} = 200 for OFDM PHY, of which 192 are used for useful data transmission, after deducing the pilot subcarriers.
- BW, the nominal channel bandwidth
- *n*, the sampling factor, depends on the channel bandwidths. Possible values are 8/7, 86/75, 144/125, 316/275 and 57/50 for OFDM PHY and 8/7 and 28/25 for OFDMA PHY.

The sampling frequency, denoted f_s, is related to the occupied channel bandwidth by the following $f_s = n$ BW.

Duration of an OFDM Symbol

$$\begin{aligned}
\textit{OFDM symbol duration} &= \textit{useful symbol time} + \textit{guard time}\ (\textit{CP time}) \\
&= 1/(\textit{one subcarrier spacing}) + G \times \textit{useful symbol time} \\
&= (1/\Delta f)(1/G) \\
&= [1/(f_s/N_{FFT})](1/G) \\
&= [1/(nBW/N_{FFT})](1/G) \ldots\ldots (2.5)
\end{aligned}$$

Data Rate Values

The data rate is equal to:

Data rate = number of uncoded bits per OFDM symbol/OFDM symbol duration

Table 2.4 shows the data rates of Fixed WiMAX OFDM physical layers in Mb/s according to their parameters.

Table 2.4 OFDM PHY data rates in Mb/s.From IEEE Std 802.16-2004[20]

G ratio	BPSK 1/2	QPSK 1/2	QPSK 3/4	16-QAM 1/2	16-QAM 3/4	64-QAM 2/3	64-QAM 3/4
1/32	2.92	5.82	8.73	11.64	17.45	23.27	26.18
1/16	2.82	5.65	8.47	11.29	16.94	22.59	25.41
1/8	2.67	5.33	8.00	10.67	16.00	21.33	24.00
1/4	2.40	4.80	7.20	9.60	14.40	19.20	21.60

2.11.2.5 Physical Slot (PS)

The Physical Slot (PS) is a basic unit of time in the 802.16 standard. The PS corresponds to four (modulation) symbols used on the transmission channel. For OFDM and OFDMA PHY Layers, a PS (duration) is defined as PS = 4/*f*s, where *fs* is the sampling frequency.

Therefore the PS duration is related to the system symbol rate [21].

2.11.2.6 Peak-to-Average Power Ratio (PAPR)

A disadvantage of an OFDM transmission is that it can have a high Peak-to-Average Power Ratio (PAPR), relative to a single carrier transmission. The PAPR is the peak value of transmitted subcarriers to the average transmitted signal. A high PAPR represents a hard constraint for some devices (such as amplifiers). Several solutions are proposed for OFDM PAPR reduction, often including the use of some subcarriers for that purpose. These subcarriers are then no longer used for data transmission. The 802.16 MAC provides the means to reduce the PAPR [21].

2.12 OFDMA

2.12 Using the OFDM Principle for Multiple Access

The OFDM transmission mode was originally designed for a single signal transmission. Thus, in order to have multiple user transmissions, a multiple access scheme such as TDMA or FDMA has to be associated with OFDM. In fact, an OFDM signal can be made from many user signals, giving the OFDMA (Orthogonal Frequency Division Multiple Access) multiple accesses.

In OFDMA, the OFDMA subcarriers are divided into subsets of subcarriers, each subset representing a subchannel. In the downlink, a subchannel may be intended for different receivers or groups of receivers; in the uplink, a transmitter may be assigned one or more subchannels. The subcarriers forming one subchannel may be adjacent or not. The standard indicates that the OFDM symbol is divided into logical subchannels to support scalability, multiple access and advanced antenna array processing capabilities. The multiple accesses have a new dimension with OFDMA. A downlink or an uplink user will have a time and a subchannel allocation for each of its communications. Different subchannel distributions and logical renumbering are defined in the 802.16 standard.

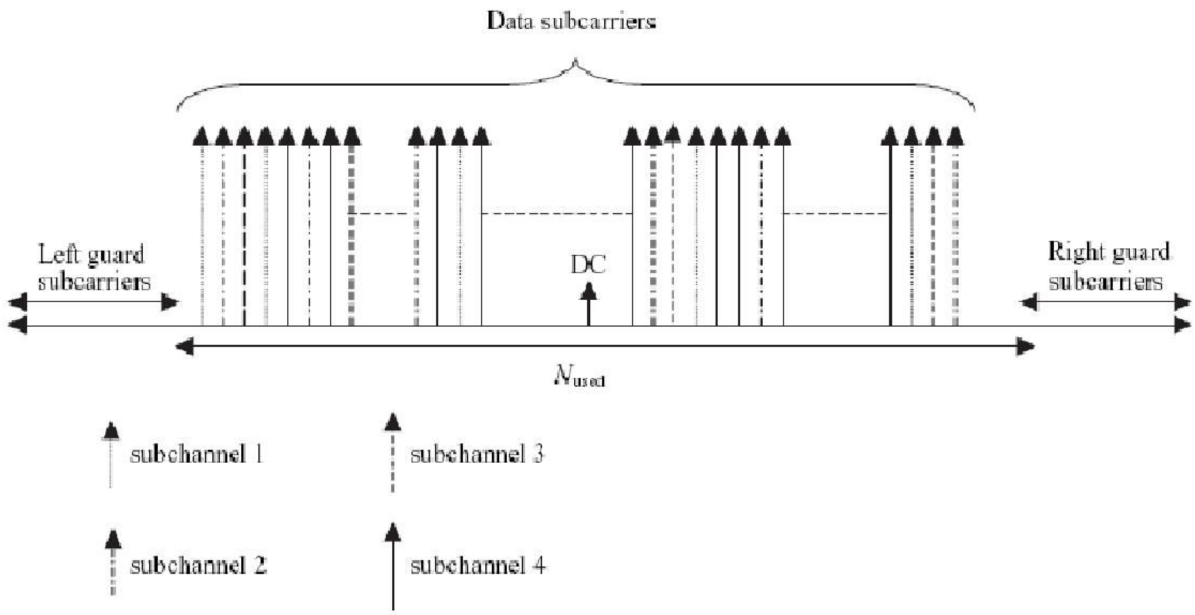

Figure 2.12 Illustration of the OFDMA principles. [22]

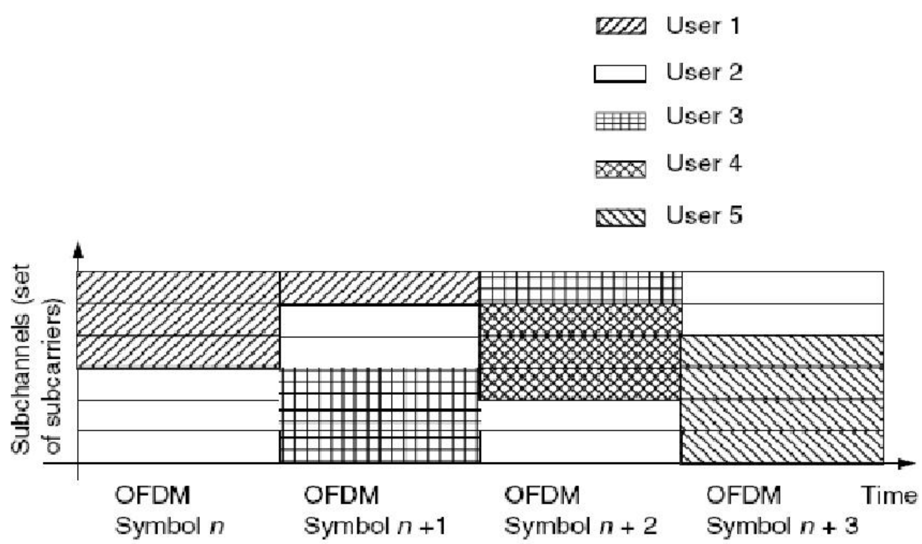

Figure 2.13 Illustration of the OFDMA Multiple Accesses [22]

Chapter Three

WiMAX Physical Layer: Modeling and Simulation

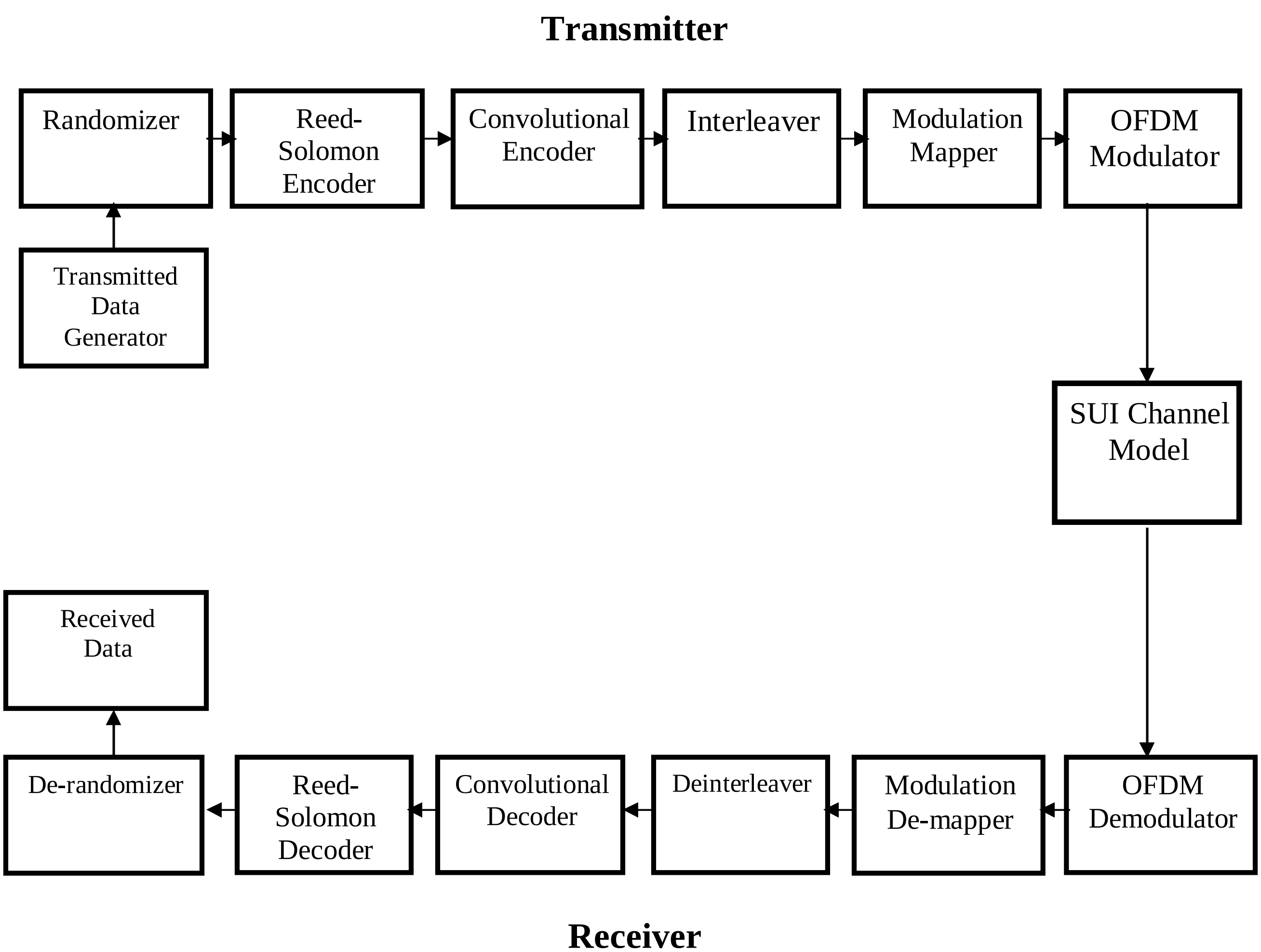

Figure 3.1 WiMAX physical layer simulation model [23]

3.1 Transmitter Module

In this section, the transmitter used in the simulation is described in some detail.

3.1.1 Data Generator

The transmitted data is generated randomly. In the simulation program which is written in MATLAB, randint is included in the transceiver function. Randint generates random integer matrices whose entries are in a range specified. In our simulation the length of the generated random binary data is specified according to the applied modulation scheme.

3.1.2 Randomizer

The randomizer performs randomization of input data in each burst in each allocation in order to avoid a long sequence of 1's and 0's. This is implemented by using a Pseudo Random Binary Sequence (PRBS) generator, which is made of a 15 bits long shift register and two XOR gates as shown in Figure 3.2 [24].

Each transmitted data byte enters sequentially into the randomizer, with the Most Significant Byte (MSB) first. The randomizer sequence is applied only to information bits.

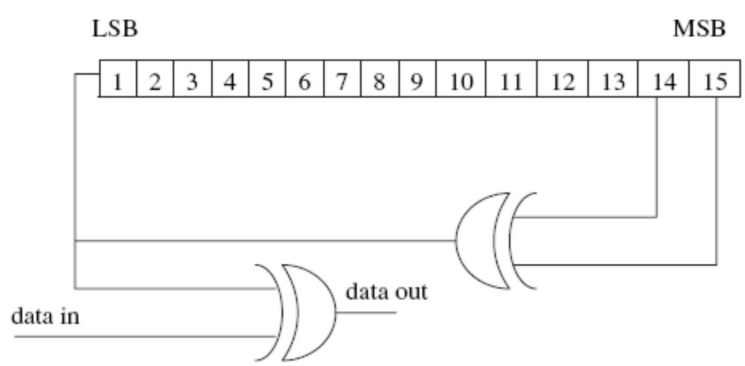

Figure 3.2 PRBS generator [24]

The shift-register of the randomizer is initialized for each new burst allocation. For OFDM PHY, on the downlink, the randomizer is reinitialized at the start of each frame with the sequence: 1 0 0 1 0 1 0 1 0 0 0 0 0 0 0. The randomizer is not reset at the start of burst 1. At the start of subsequent bursts (starting from burst 2), the randomizer is initialized with the vector shown in Figure 3.3. This PRBS generates a Pseudo-Noise (PN) sequence of length $2^{15} - 1$. The frame number used for initialization refers to the frame in which the downlink burst is transmitted. BSID is the BS identity and DIUC the burst profile indicator. For other cases (uplink, OFDMA), the details can be found in the standard. The bits issued from the randomizer are then applied to the FEC encoder.

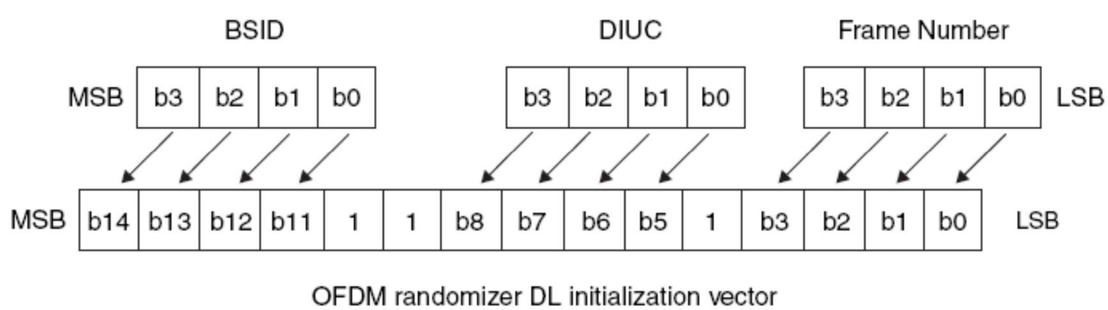

Figure 3.3 OFDM randomizer downlink initialization vector for burst 2,…,*N* [24]

3.1.3 Channel Encoding

The channel encoder consists of an FEC scheme (a concatenation of an outer RS code and an inner CC), puncturing and interleaving as shown in Figure 3.1. The randomized data passes to the RS encoder and then passes to CC encoder. After this, the encoded data is punctured and interleaved.

In the simulation program the puncturing includes the convolutional encoder function.

3.1.3.1 Reed Solomon Encoder

The RS code (Reed Solomon Code) is special kind of linear block codes, which is suitable for correcting burst errors. The RS encoder adds redundancy to the data sequence in order to correct the errors, which occur during transmission. This RS code is derived from a systematic RS (N = 255,K= 239,T = 8) code using a Galois field specified as GF (2^8), where N is the number of bytes after encoding, K is the number of data bytes before encoding and T is the number of data bytes that can be corrected.

In WiMAX RS code is shortened and punctured to enable variable block sizes and variable error-correction capability. We can obtain a shortened block of K' bytes by adding 239 − K' zero bytes before the data block, these 239 − K' zero bytes are discarded after encoding. RS code can correct up to T symbols, where T can be expressed as T = (N − K)/2. When a codeword is punctured to permit T′ bytes to be corrected, only the first 2T′ of the total 16 parity bytes shall be employed as shown in Figure 3.4. For instance, QPSK with (5⁄6) CC code rate, the RS code is ((N'= 40), (K' = 36), (T' = 2)) as shown in Table 5.1. The bit/byte conversion has to be MSB first. [24]

Table 3.1: Mandatory channel coding per modulation [24]

Rate ID	M-QAM	Data block *k* (bytes)	Coded block *n* (bytes)	Coding rate *k/n*	RS Code	CC coding rate
0	2	12	24	1/2	(12,12,0)	1/2
1	4	24	48	1/2	(32,24,4)	2/3
2	4	36	48	3/4	(40,36,2)	5/6
3	16	48	96	1/2	(64,48,8)	2/3
4	16	72	96	3/4	(80,72,4)	5/6
5	64	96	144	2/3	(108,96,6)	3/4
6	64	108	144	3/4	(120,108,6)	5/6

3.1.3.2 Convolutional Encoder

The random errors which occur during the transmission over a channel can be corrected by using the convolutional encoder. Unlike a block coder, convolutional coder is not a memoryless device. The RS encoded bits are encoded by the binary convolutional encoder, which has native rate of 1/2, a constraint length equal to 7 and a polynomial description [171 133] as G1=171_{OCT} and G2=133_{OCT} to produce its two code bits. The generator is shown in Figure 3.4. [24]

In WiMAX, after the randomized data is encoded by RS encoder, the encoded bits are forwarded to convolutional encoder. The block sizes and the code rates, which are used for the different types of modulation and code rates, are given in Table 3.1.

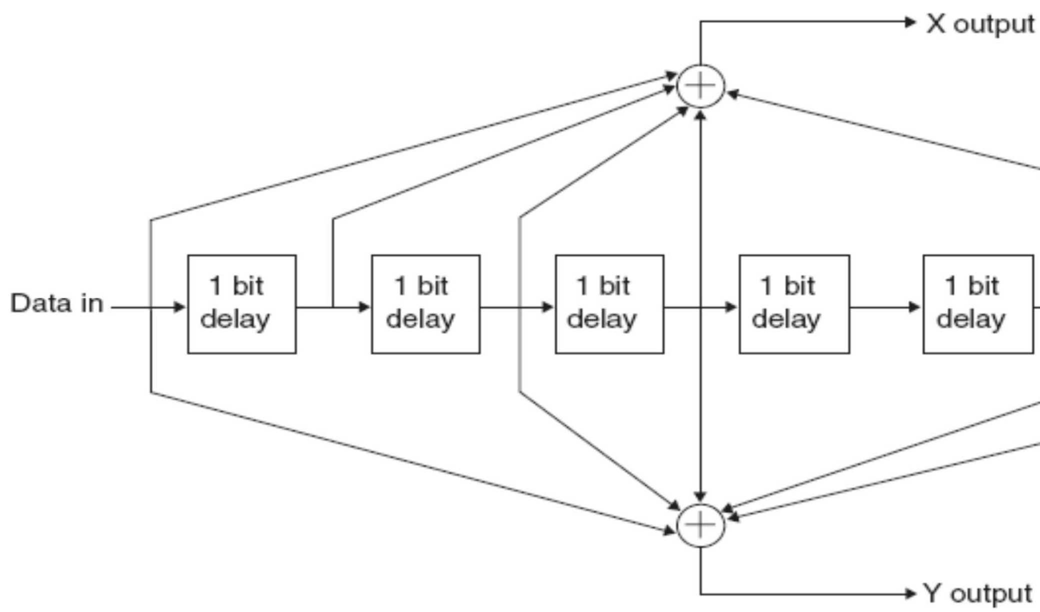

Figure 3.4 Convolutional encoder of rate 1/2. [24]

Puncturing is a technique that is utilized on the output of the convolutional encoder. It allows the encoding and decoding of higher code rates using standard rate 1/2 encoders and decoders. The purpose of using puncturing is to achieve variable code rate. This is done by deleting bits from the output stream of a low rate encoder. The bits are deleted according to the Table 3.2.

In this Table, “1” means a transmitted bit and “0” denotes a removed bit, whereas and are in reference to Figure 3.4[24].

Table 3.2: The inner convolutional code with puncturing configuration [24].

	Code rates			
Rate	1/2	2/3	3/4	5/6
D_{free}	10	6	5	4
X	1	10	101	10101
Y	1	11	110	11010
XY	X_1Y_1	$X_1Y_1Y_2$	$X_1Y_1Y_2X_3$	$X_1Y_1Y_2X_3Y_4X_5$

3.1.4 Interleaver

All encoded data bits are interleaved by a block interleaver. First, interleaver maps the adjacent coded bits to nonadjacent subcarriers. Second, interleaver insures that adjacent coded bits are mapped alternately onto less or more significant bits of the constellation [25].

3.1.5 Modulation Mapper

In the modulation mapper, the interleaved bits are converted to a sequaence of complex valued symbols. WiMAX supports different modulation schemes shown in Figure 3.5. The modulation constellation used in WiMAX is two types of phase shift keying (PSK) modulation (binary (BPSK) and quadrature (QPSK)) and two types of quadrature amplitude (QAM) modulation (16QAM and 64QAM). The complex constellation value is scaled by factor c (Normalization constant), such that the average transmitted power is unity, values of c are shown in Figure 3.5.

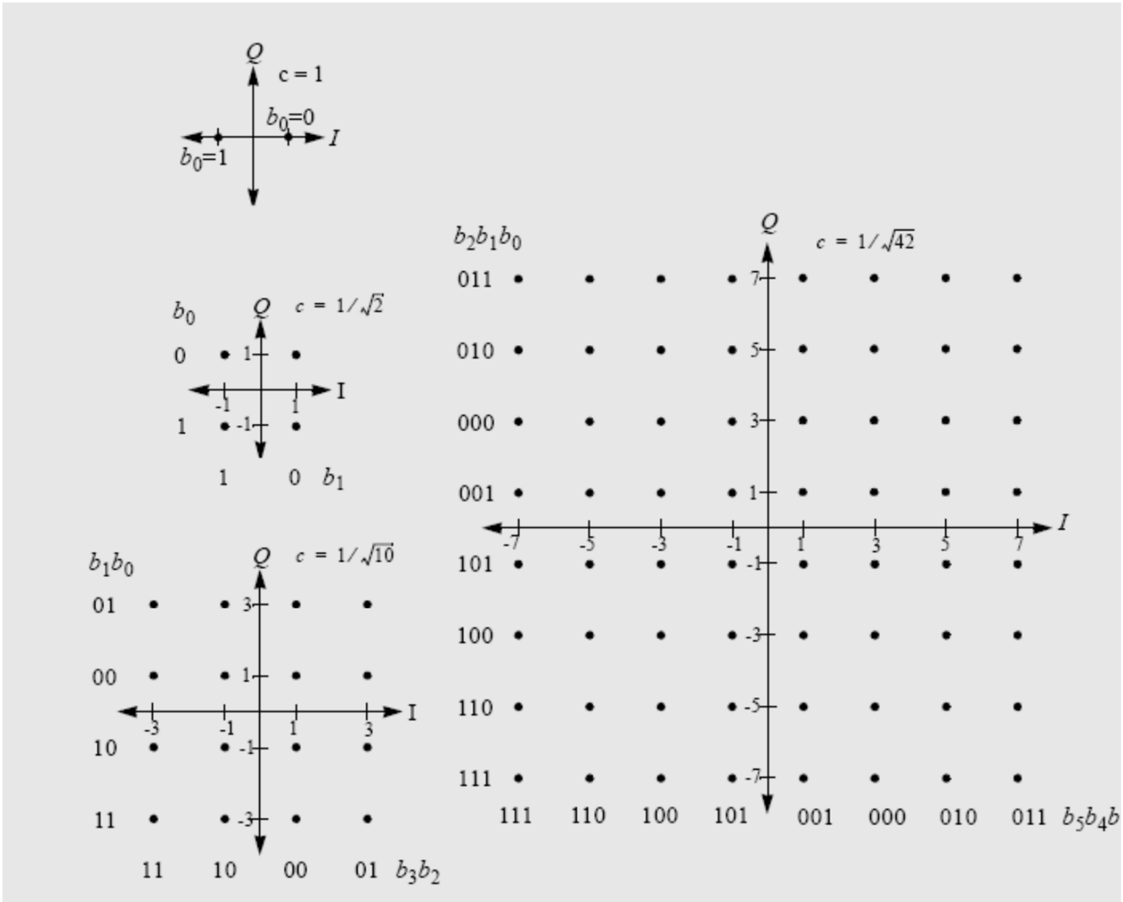

Figure 3.5 BPSK, QPSK, 16-QAM and 64-QAM constellations. [26]

3.1.6 OFDM Modulator

In WiMAX, each OFDM symbol consists of 256 subcarriers as shown in Figure 3.6. They can be divided into.

- 192 data subcarriers that are used for conveying data.
- 8 pilot subcarriers that are used for conveying pilot symbols.
- 56 null subcarriers that have no power allocated to them, including the DC subcarrier and the guard subcarriers toward the edge.

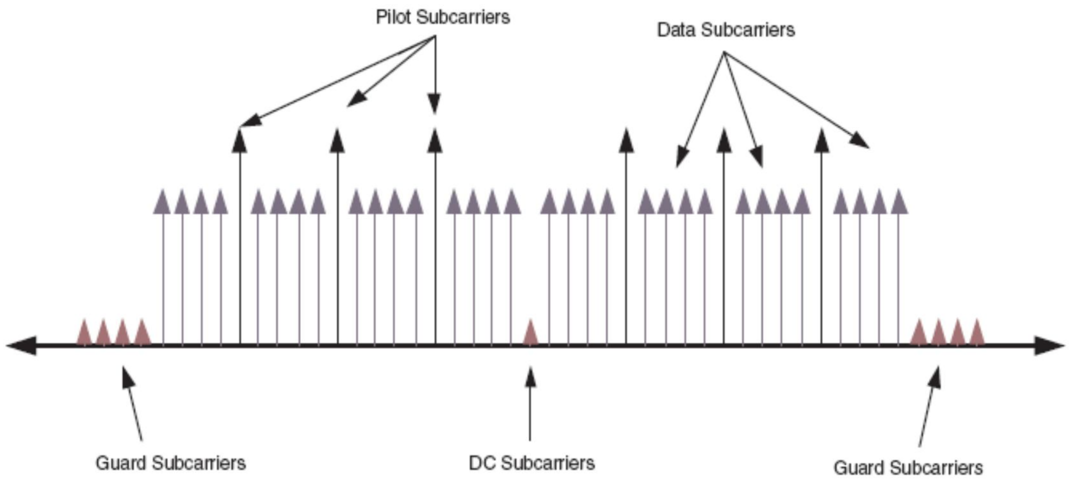

Figure 3.6 Frequency-domain representation of OFDM symbol [26]

3.1.6.1 Pilot Modulation

Before inserting a pilot to its specified position, as shown in Figure 3.6, it has to be modulated. Pilots can be generated by Pseudo Random Binary Sequence (PRBS) generator as shown in Figure 3.7.

The polynomial of PRBS generator is:

$$g(x) = x^{11} + x^{9} + 1 \quad (3.1)$$

Pilot subcarriers are used for various estimation purposes.

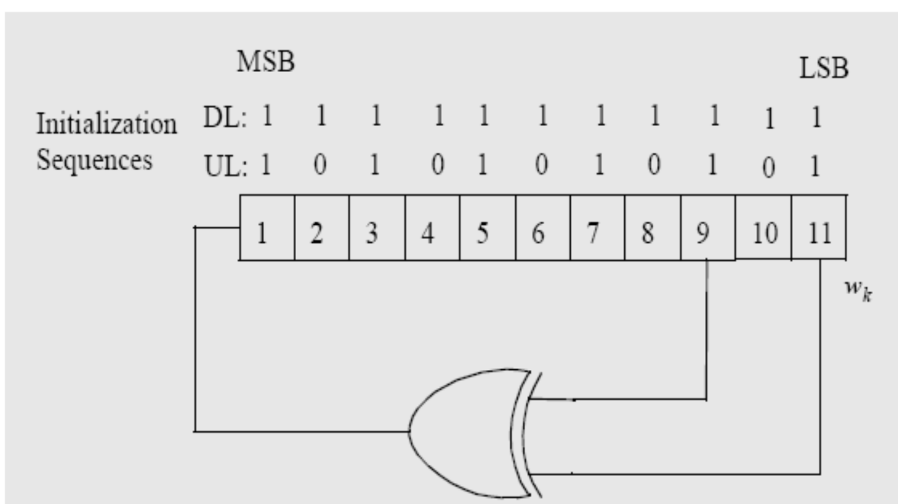

Figure 3.7 PRBS for pilot modulation. [26]

3.1.6.2 Inverse Fast Fourier Transform (IFFT)

To convert mapped data, which is assigned to all allocated data subcarriers of the OFDM symbol, from frequency domain into time domain, the IFFT is used. We can compute time duration of the IFFT time signal by multiplying the number of FFT bins by the sample period.

Zeros are added at the end and beginning of OFDM symbol. These zero carriers are used as guard band to prevent inter channel interference (ICI).

3.1.6.3 Cyclic Prefixes Insertion

To avoid inter symbol interference (ISI) a cyclic prefix is inserted before each transmitted symbol. That is achieved by copying the last part of an OFDM symbol to the beginning as shown in Figure 3.8. WiMAX supports four different durations of cyclic prefix (i.e. assuming G is the ratio of guard time to OFDM symbol time, this ratio is equal to 1/32, 1/6, 1/8 and 1/4).

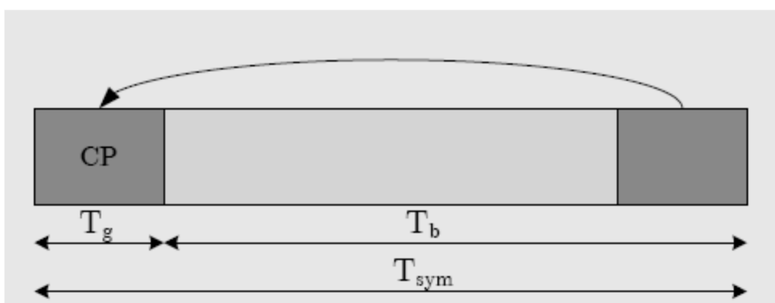

Figure 3.8 OFDM symbol with the cyclic prefix [27].

3.2 Channel Module

The SUI (Stanford University Interim) channel model deals with the same environment as in the IEEE 802.16 channel model. Using the different combinations of the channel parameters, it identifies six different channel models that can describe the typical three terrain types in North America A, B and C [28].

This is a set of 6 channel models representing three terrain types and a variety of Doppler spreads, delay spread and line-of-sight/non-line-of-site conditions that are shown in Table 3.3[29].

Category A is hilly terrain with moderate-to-heavy tree density and has a high path loss. Category C is mostly flat terrain with light tree density and has a low path loss. Category B is hilly terrain with light tree density or flat terrain with moderate-to-heavy tree density.

Table 3.3 Terrain Type and Doppler Spread for SUI Channel Models [30]

Channel	**Terrain type**	**Doppler Spread**	**Spread**	**LOS**
SUI-1	C	Low	Low	High
SUI-2	C	Low	Low	High
SUI-3	B	Low	Low	Low
SUI-4	B	High	Moderate	Low
SUI-5	A	Low	High	Low
SUI-6	A	High	High	Low

In our modeling and simulation only the first three channel models are used (SUI-1, 2, 3).

Table 3.4 shows the values of channel parameters of the SUI-1 channel model which are used in our simulation.

Table 3.4 SUI-1 Channel Parameters [31]

Parameter	Tap1	Tap2	Tap3
Power of each path (dB)	0	-15	-20
Factor K of the Rician distribution (Linear)	4	0	0
Delay of each path (microseconds)	0.0	0.4	0.9
Maximum Doppler frequency (Hertz)	0.4	0.3	0.5
Coefficient of antenna correlation	0.7		
Normalizing factor of gain (dB)	-0.1771		

Table 3.5 shows the values of channel parameters of the SUI-2 channel model which are used in our simulation.

Table 3.6 shows the values of channel parameters of the SUI-3 channel model which are used in our simulation.

Table 3.5 SUI-2 Channel Parameters [31]

Parameter	Tap1	Tap2	Tap3
Power of each path (dB)	0	-12	-15
Factor K of the Rician distribution (Linear)	2	0	0
Delay of each path (microseconds)	0.0	0.4	1.1
Maximum Doppler frequency (Hertz)	0.2	0.15	0.25
Coefficient of antenna correlation	0.5		
Normalizing factor of gain (dB)	-0.3930		

Table 3.6 SUI-3 Channel Parameters [31]

Parameter	Tap1	Tap2	Tap3
Power of each path (dB)	0	-5	-10
Factor K of the Rician distribution (Linear)	1	0	0
Delay of each path (microseconds)	0.0	0.4	0.9
Maximum Doppler frequency (Hertz)	0.4	0.3	0.5
Coefficient of antenna correlation	0.4		
Normalizing factor of gain (dB)	-1.5113		

3.3 Receiver Module

The functional blocks which compose the WiMAX receiver as shown in Figure 3.1 are the reverse functional blocks of WiMAX transmitter. The received data coming from AWGN channel is fed into the OFDM demodulation, which consist of removal of CP, Fast Fourier Transform (256 FFT) and disassemble OFDM frame. Then, the data is performed by de-mapper and afterwards the

demapped data enter the channel decoder. Channel decoder consists of de-interleaver, depuncture, convolutional decoder and finally RS decoder. The final block in receiver is the derandomizer.

The individual blocks of the WiMAX receiver will be explained, next.

3.3.1 OFDM Demodulator

The OFDM demodulation is the reverse operation of OFDM modulation. Here, the signal is converted back from time domain to frequency domain. The first step in OFDM demodulation is to remove the CP. Then FFT is performed. Afterwards the OFDM frame is disassembled.

3.3.1.1 Removal of CP

The first step after the arrival of data is to remove CP .CP is useful when the multipath channel is used. If CP larger than the delay spread multipath the ISI is completely removed.

3.3.1.2 Fast Fourier Transform (FFT)

To convert received data from time domain to frequency domain, the FFT is used. Afterward, the zeros, which were added at the end and beginning of OFDM symbol (guard bands) at the transmitter are removed from the assigned places.

3.3.1.3 Disassemble OFDM Frame

After doing FFT and removing guard bands, the data and pilots, which are described in section 3.1.6, should be separated. This is achieved by using the disassembler.

3.3.2 Demodulation De-mapper

To convert the waveforms created at the modulator to the original transformed bits, the de-modulator is used. The demodulator is used for decision rules with the goal of making a decision about which bit "zero" or "one", was sent. The decision metric can be hard decision or soft decision.

3.3.3 Channel Decoding

The channel decoder consists of deinterleaving, depuncturing, Viterbi decoder and RS decoder. The sequence of bits coming from the modulator passes to channel decoder. The channel decoder tries to recover the original bits.

3.3.3.1 De-interleaver

Deinterleaver is used to remove the effect of interleaving process achieved at the transmitter.

3.3.3.2 De-puncturing

Depuncturing is the reverse process of puncturing. Puncturing is done by deleting bits from certain places which was explained in Table 2.2 in the previous chapter. At receiver, the values of deleted bits are unknown, so the receiver adds zeros in those places.

These inserted zeros can be seen as erasures from the channel. They have no effect on the metric measurement of the Viterbi algorithm.

3.3.3.3 Convolutional decoder

To decode the bit stream coming after depuncturing, the convolutional decoder is used. The Viterbi algorithm is one of the methods, which is commonly used for decoding the convolutional codes. The Viterbi algorithm performs the maximum likelihood decoding.

3.3.3.4 Reed Solomon Decoder

The RS decoder is the last part in channel decoder. The operation of RS decoder is the reverse operation of RS encoder.

3.3.4 De-randomizer

The stream of bits coming from RS decoder is forwarded to the de-randomizer. The structure and the operation of the de-randomizer is the same as the randomizer.

3.4 Simulation Program

In this section the MATLAB simulation program is described in some detail.

3.4.1 The simulation_starter.m function

The simulation execution begins by running the file which accept the input values of the simulation parameters, which are:

- The length of cyclic prefix G (1/4, 1/8, 1/16 or 1/32).
- The modulation scheme (BPSK, QPSK, 16 QAM or 64 QAM).
- Enter the number of OFDM symbols
- Channel Bandwidth (20, 15,10,5,1.5,1.25) MHz

The simulation_starter.m function calls the transceiver.m, and the simulation is done for each of the channels (SUI-1, SUI-2, and SUI-3) using "for loop".

3.4.2 The main.m function

This function is called from the simulation_starter.m function and returns the BER values. It receives its parameters values which are: SNR, number of bits per modulated symbol L (L=log2M, M is the modulation level), number of OFDM symbols, channel BW, and the channel model (SUI-1, SUI-2, and SUI-3).

Before calling the transmitter.m function some values are assigned to the transmission parameters which are:

- The code rate (1/2, 3/4, 2/3) according to the 802.16 standard specifications.
- Number of points in FFT, Nfft=256.
- The parameters of convolution and RS coding is also given values according to the IEEE 802.16 standard specifications as shown in Table 3.1.
- The data generation is done randomly using the randint() Matlab function.
- The pilot and guard subcarriers are placed according to the standard.
- The transmitter.m, SUIchannel.m, and receiver.m functions are called respectively.
- The bit error rate is calculated and returned back to the simulation_starter.m function.

3.4.3 The transmitter.m function

In this function the implementations of randomization, RS encoding, convolutional encoding, interleaving, modulation, and OFDM modulation are done.

The reverse operations are done in the receiver.m function.

There are two functions called by the transmitter.m and the receiver.m which are tx_mapper.m and rx_mapper.m respectively.

3.4.4 The SUI channel.m function

It generates the Channel Impulse Response of the channel variant by using Jakes Model. The Channel used depends on the parameters that are indicated to it. We can simulate SUI channels 1, 2 and 3, with different bandwidths.

The function Parameters are: N_SUI (Channel to simulate), G (Size of the cyclic) prefix, v (Speed of the system) and BW (Bandwidth of the channel).

3.4.5 The receiver.m function

In this function the different stages of the WiMAX receiver are called to undo all the stages realized in the transmitter.(encoding, interleaving, randomization).

All the parameters that have comprised the transmitter: used modulation, Reed Solomon code, template of puncturing, the SNR, size of the cyclic Prefix and the received symbol. It gives back the chain of bits corresponding to the sent data.

3.4.6 BER plotters

There are other files designed especially for plotting the results which concatenated from the simulation results to satisfy our analysis needs.

These Files are:

- Channel1.m which plots the BER vs EbNo for different modulation and coding schemes on SUI-1 channel model.
- Channel2.m which plots the BER vs EbNo for different modulation and coding schemes on SUI-2 channel model.
- Channel3.m which plots the BER vs EbNo for different modulation and coding schemes on SUI-3 channel model.
- QAM64.m which plots BER vs EbNo for 64 QAM 3/4 on different channels.
- QAM16.m which plots BER vs EbNo for 16 QAM 1/2 on different channels.

- Rs_effect.m which plots BER versus EbNo for both cases with RS encoding and without it to show the effect of RS encoding in the performance of WiMAX physical layer.
- Interleav_effect.m which plots BER versus EbNo for both cases with interleaving and without it to show the effect of interleaving in the performance of WiMAX physical layer.

Chapter Four

Simulation Results and Analysis

In this chapter the simulation results are presented and analyzed. The structure of the implemented simulator is discussed and the simulation results are presented for validation of implementation. The values for various parameters that characterize the performance of the physical layer are also given.

The objective of simulating the WiMAX physical layer in MATLAB is to study the BER performance under different channel conditions and varying parameters that characterize the performance.

4.1 BER Plotting

In this chapter we have presented various BER vs. E_b/N_0 plots for all the mandatory modulation and coding profiles as specified in the 802.16 standard on same channel models.

E_b/N_0 is the ratio of signal energy per bit to noise power density per Hertz. $E_b/N_0$is related to S/N (Signal to the noise ratio, SNR) by

$$\frac{E_b}{N_0} = \frac{S}{N}\frac{B_T}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

Where E_b is the energy per bit in a signal, N_0 is the noise power density in Watts/Hertz, S is the signal power, N is the noise in a signal, B_T is the transmission bandwidth and R is the data rate.

The advantage of E_b/N_0over SNR is that the latter quantity depends on the bandwidth.[32]

Figure 4.1, shows the performance of different modulation schemes on SUI1 channel model. It can be seen from this Figure that the lower modulation and coding scheme provides better performance with lessE_b/N_0.

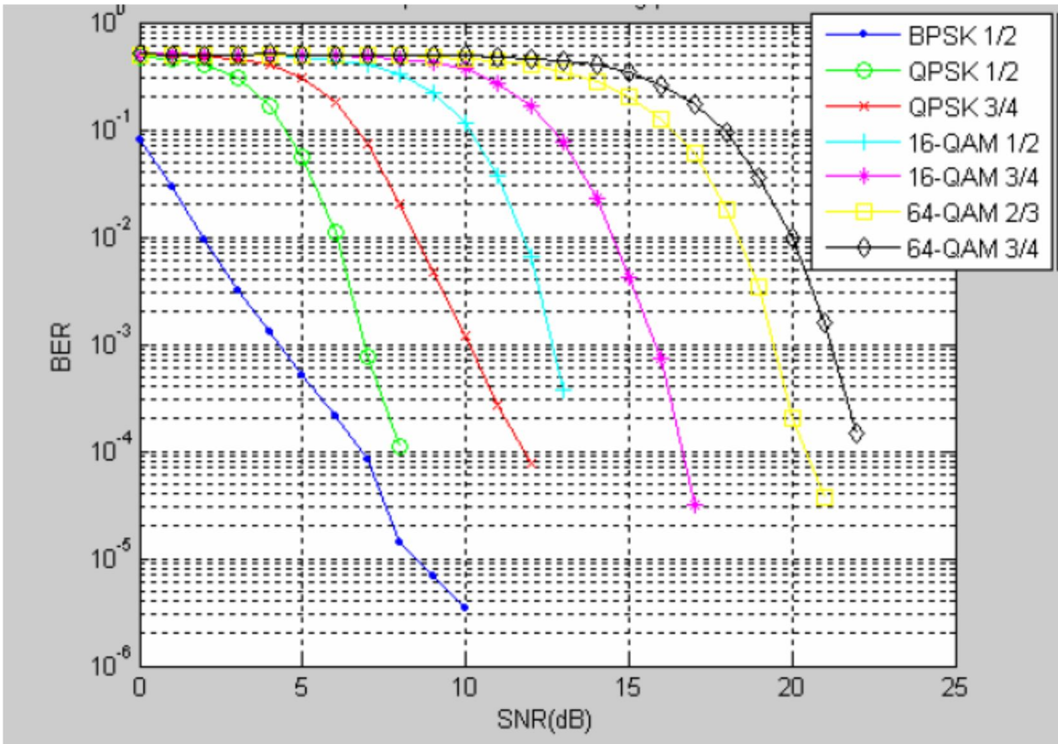

Figure 4.1 BER vs. SNR plot for different coding profiles on SUI1 channel

Figure 4.2, shows the performance of different modulation schemes on SUI2 channel model.

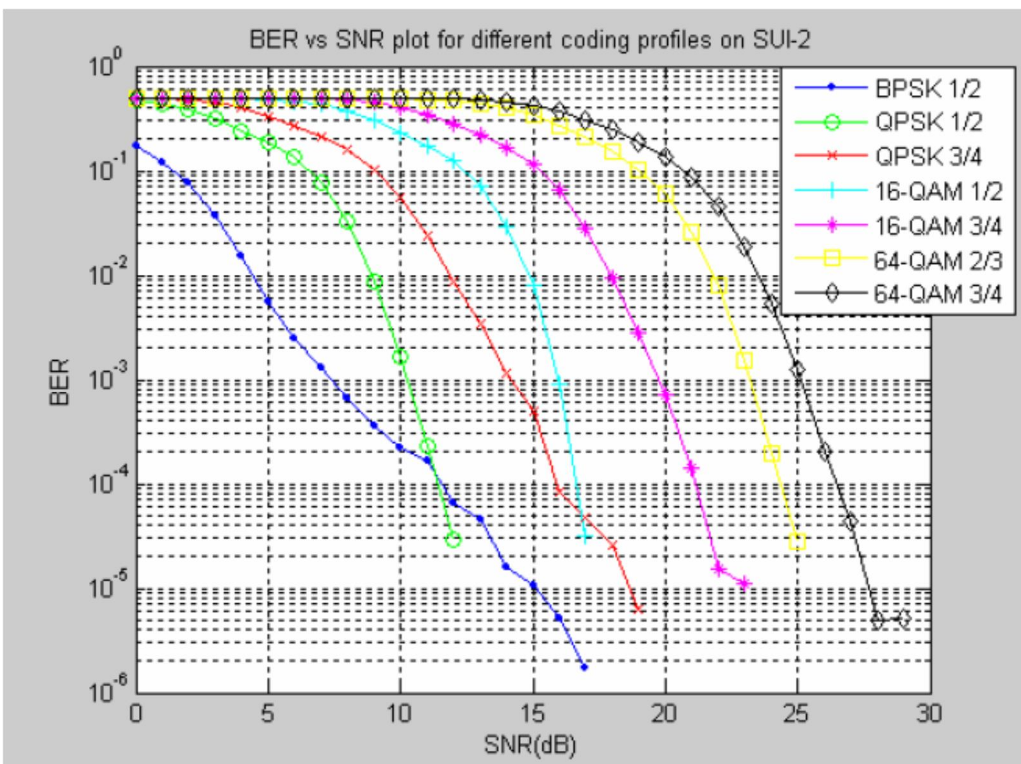

Figure 4.2 BER vs. SNR plot for different coding profiles on SUI-2 channel

Figure 4.3, shows the performance of different modulation schemes on SUI-3 channel model.

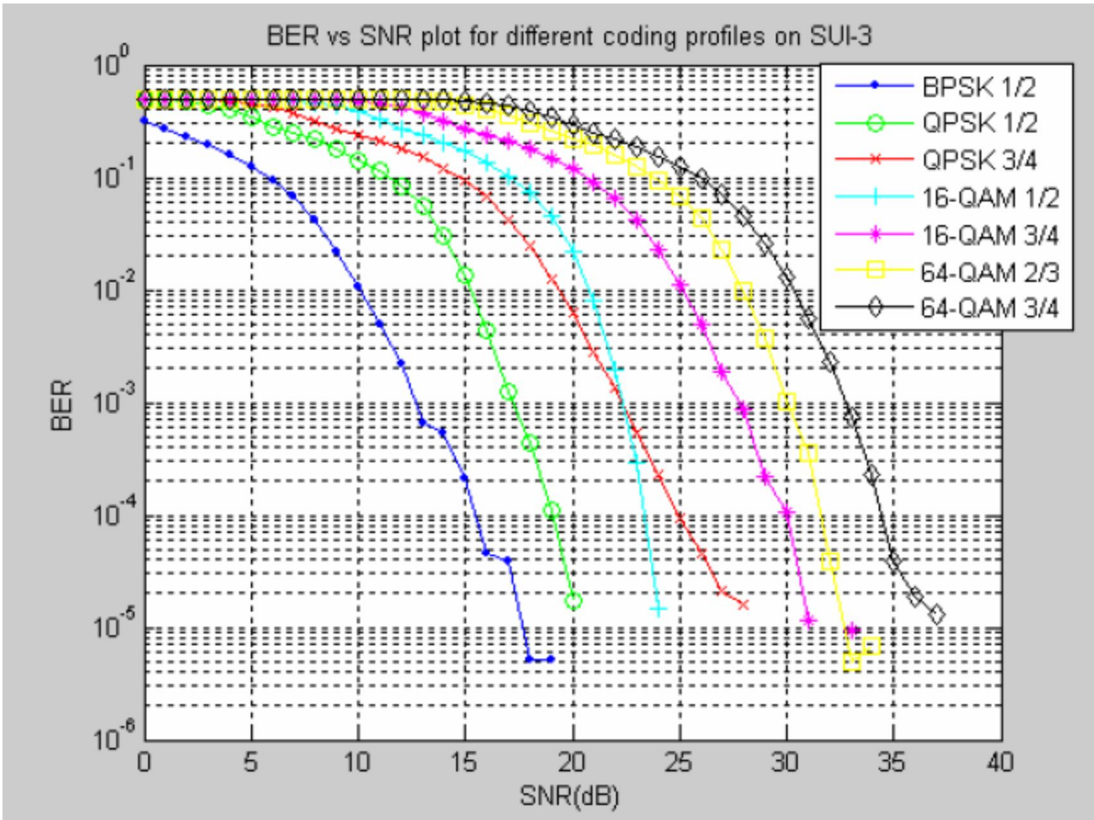

Figure 4.3 BER vs. SNR plot for different coding profiles on SUI3 channel

As shown in Figure 4.1, Figure 4.2 and Figure 4.3, comparing the values of BER we can see that the lowest values appeared in Figure 4.1(SUI-1 channel) , the highest values appeared in Figure 4.3(SUI-3 channel) and the values of Figure 4.2 (SUI-2 channel) are approximately greater than the first(SUI-1channel) and less than the second(SUI-3 channel) .

The result above is supported by findings shown in the next three Figures; Figure 4.4 shows the BER versus E_b/N_0 for 64 QAM 3/4 on the three channels (SUI-1, 2, 3) and the same result is obtained.

The same result can be repeated for other modulation /coding scenarios as shown in Figure 4.5 for 16 QAM 1/2 profile.

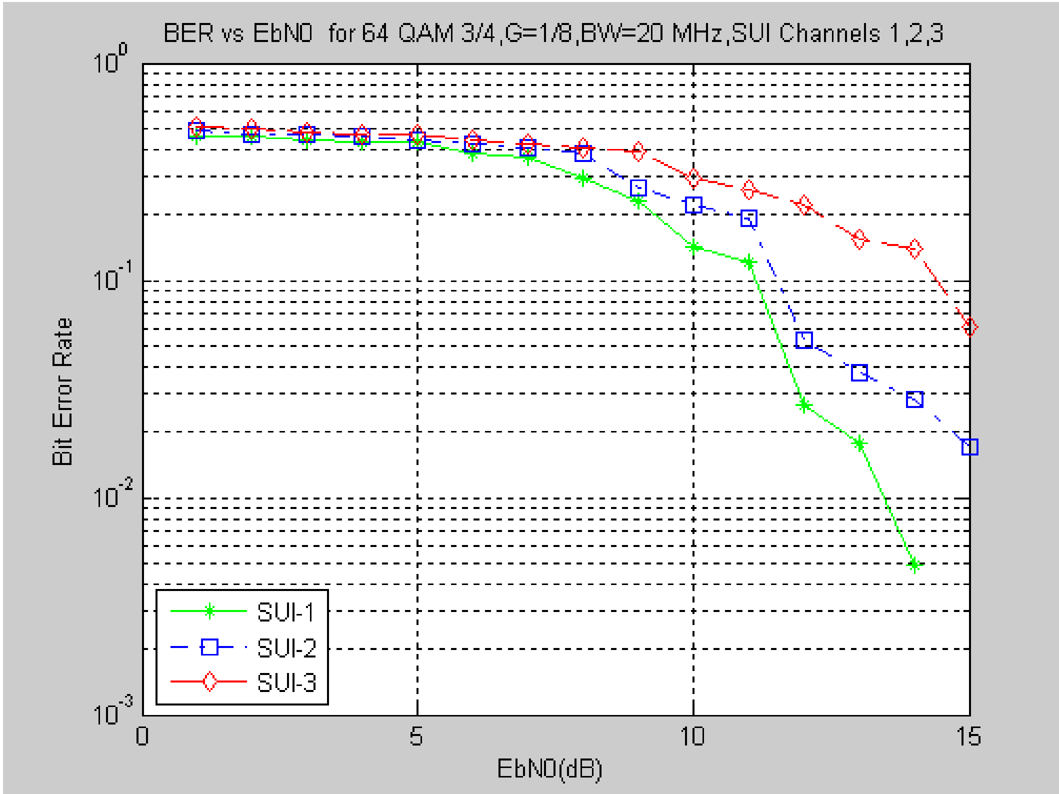

Figure 4.4 BER vs. SNR for 64 QAM 3/4 on different channels

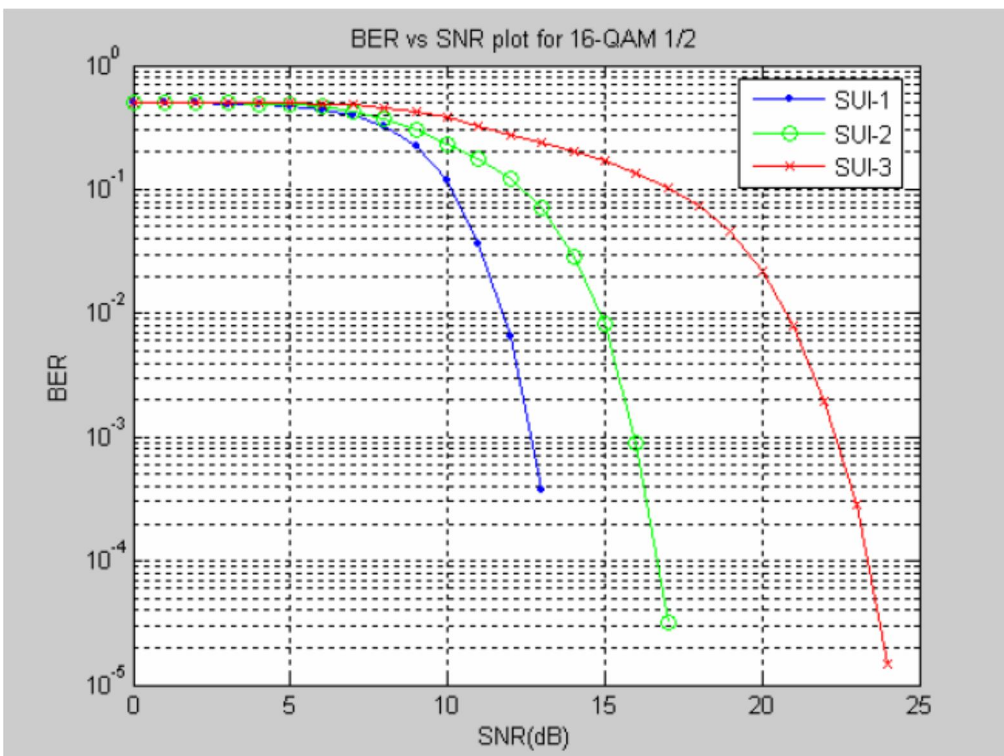

Figure 4.5 BER versus SNR for 16 QAM 1/2 on different channels

4.2 The Effect of Reed Solomon Encoding

Another interesting simulation of FEC is that without the Reed-Solomon encoder, how much performance will appear in this design. The performance improvement due to RS codec on different modulation and coding profiles has been observed on SUI-3 channel model. The performance can be observed from figures 4.6 to 4.8, when the Reed Solomon encoding is used the BER is decreased; hence the performance is increased.

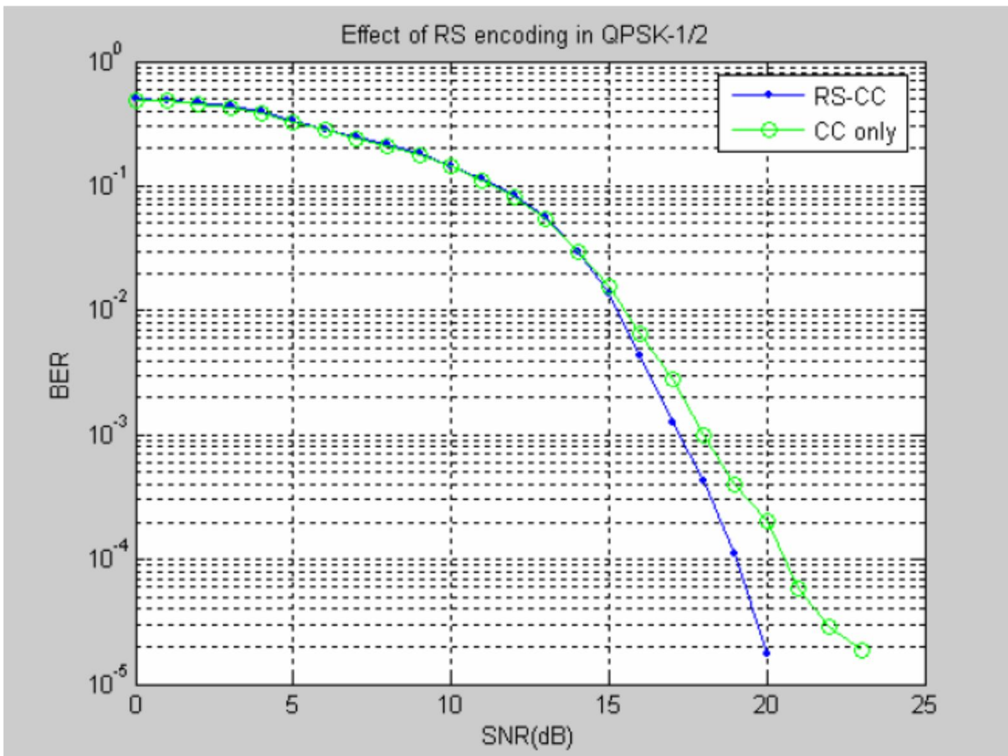

Figure 4.6 Effect of Reed Solomon encoding in QPSK 1/2 on SUI-3 channel model

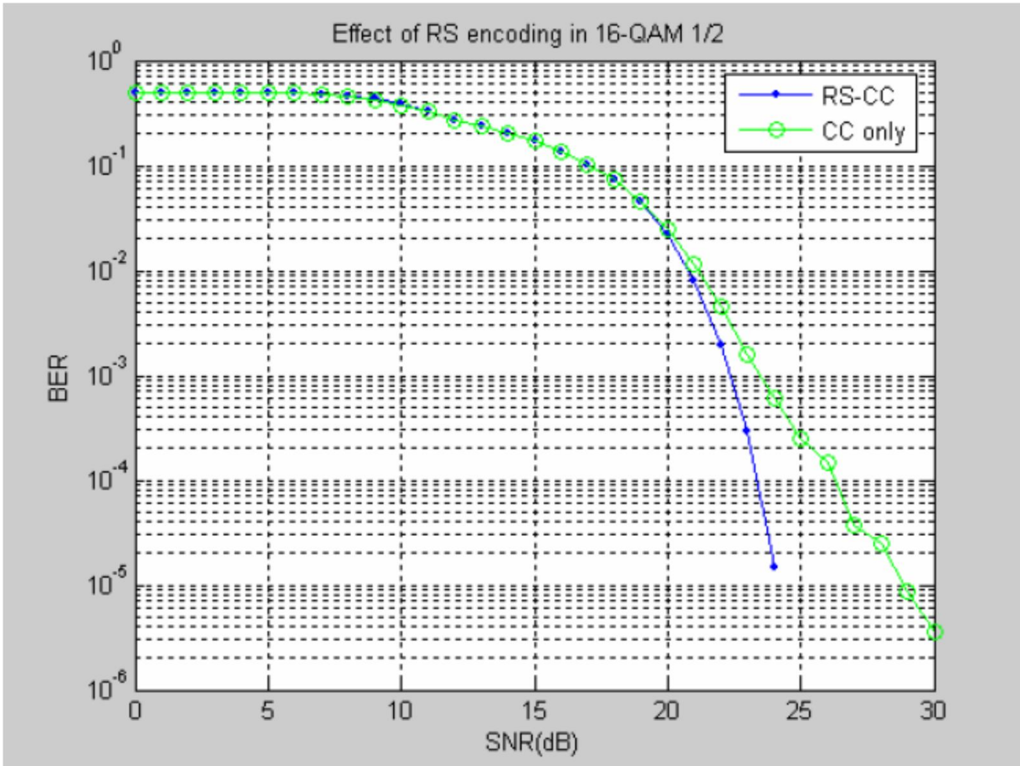

Figure 4.7 Effect of Reed Solomon encoding in 16-QAM 1/2 on SUI-3 channel model

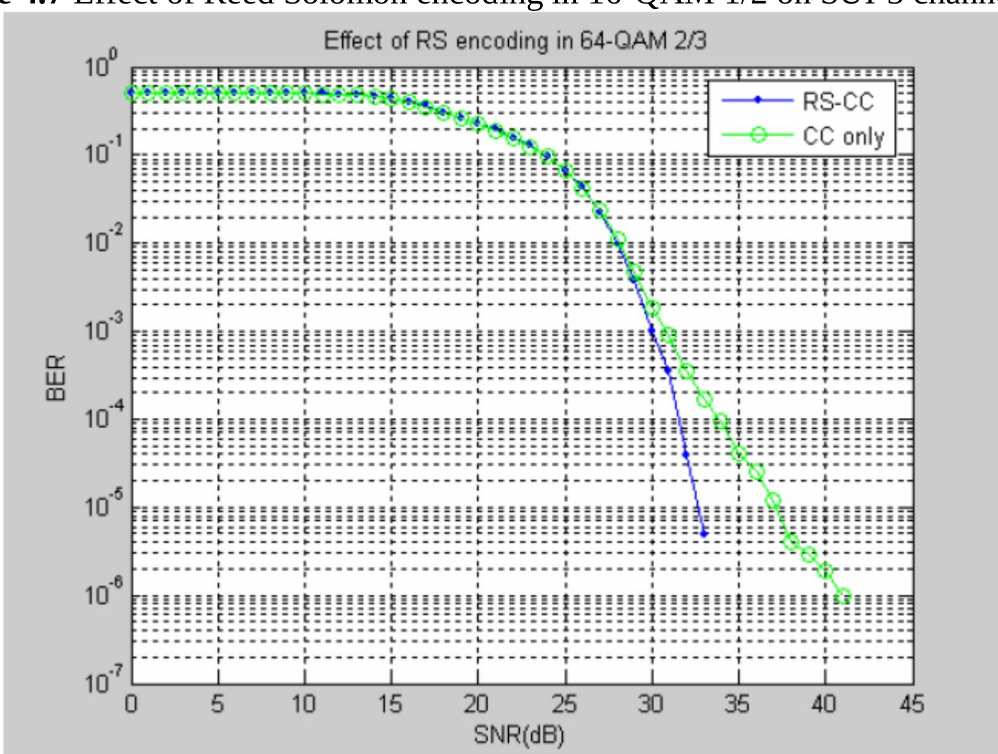

Figure 4.8 Effect of Reed Solomon encoding in 64-QAM 2/3 on SUI-3 channel model

4.3 Effect of Bit interleaving

The effect of Bit interleaving on the performance of different modulation and coding schemes has been observed here. It can be seen from the figure 4.9 that bit interleaving gains improvement in BER level for BPSK.Figures 4.10 to Figure 4.12 Shows the performance improvement due to bit interleaving for QPSK 1/2, 16-QAM 1/2 and 64-QAM 2/3.When the interleaving is used the BER is decreased; hence the performance is increased. In this case we did the simulation on SUI-2 channel model.

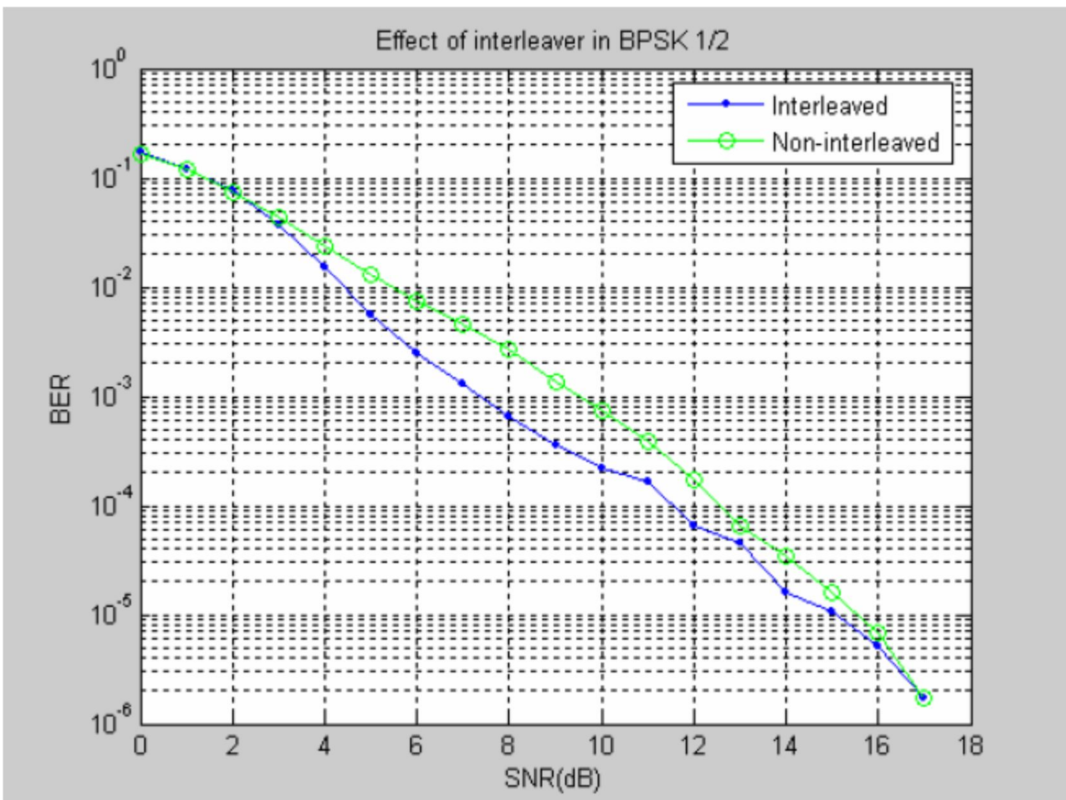

Figure 4.9 Effect of Block interleaver in BPSK 1/2 on SUI-2 channel model

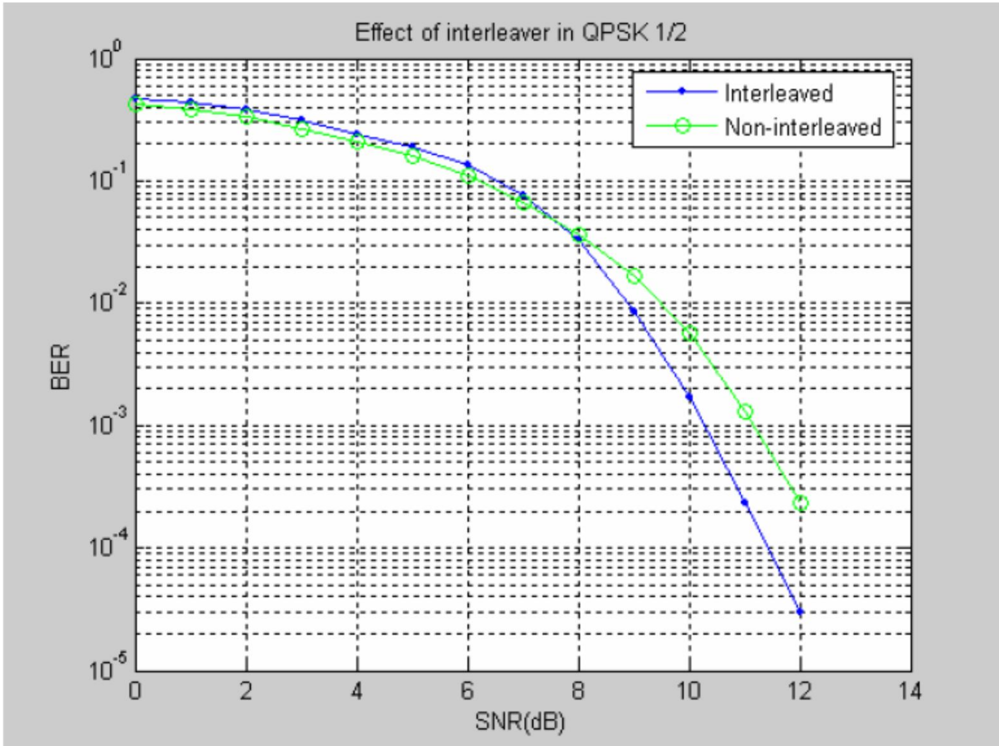

Figure 4.10 Effect of Block interleaver in QPSK 1/2 on SUI-2 channel model

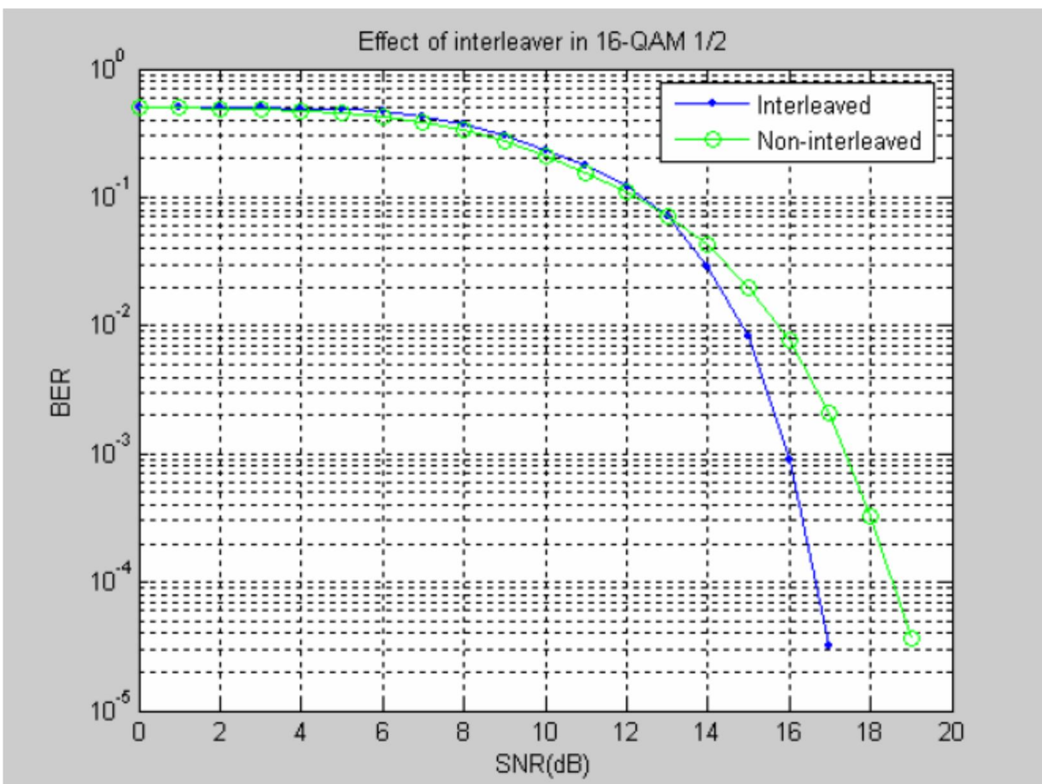

Figure 4.11 Effect of Block interleaver in 16-QAM 1/2 on SUI-2 channel model

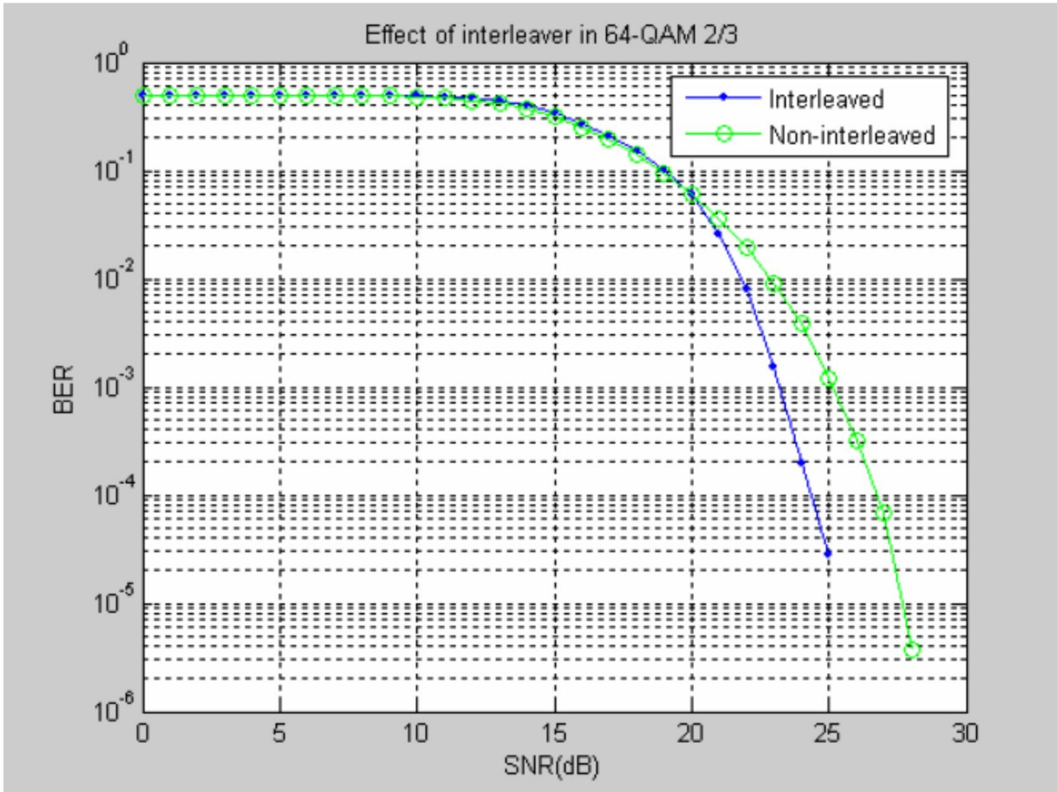

Figure 4.12 Effect of Block interleaver in 64-QAM 2/3 on SUI-2 channel model

Chapter Five

Conclusion and Recommendations

5.1 Conclusion

The target of this thesis is the performance analysis WiMAX physical layer based on IEEE 802.16 OFDM PHY layer which is implemented using MATLAB.

The performance analysis of the physical layer is evaluated based on modeling and simulation that involves modulation and coding schemes as well as cyclic prefix lengths defined in the specification of the 802.16 standard. The receiver and the transmitter are assumed to be synchronized. The channel characteristics are also taken into account using the SUI channel models (SUI-1, SUI-2 and SUI-3) and the comparison among them is established based on BER.

A key performance measure of a wireless communication system is the BER. The BER curves are used to compare the performance of different modulation and coding schemes that are employed.

The effects of the reed Solomon coding and interleaving are also analyzed using BER. These provided us with a deep analysis of the performance of the OFDM physical layer based on different conditions of the wireless fading channel (SUI-1, 2, 3).

For example it can be seen from figure 4.6 that the Reed Solomon encoder gains 1dB SNR improvement at BER level of 10^{-3} for QPSK 1/2 on SUI-3, the improvement is about 6.5%.Also from figure 4.9 the Bit interleaver gains 2.2dB SNR improvement at BER level of 10^{-3} for BPSK, the improvement is about 22%.

5.2 Recommendations

The modeling and simulation of the WiMAX physical layer can be optimized to increase the performance by including more optional features of the IEEE 802.16 standard.

Here are some of the optional features that can be added to optimize our model in the future work of modeling and simulation of the physical layer:

- The optional Block Turbo Coding can be implemented to enhance the performance of FEC.
- Space Time Block Code can be employed in down link to provide transmit diversity.
- Multiple Input Multiple Output (MIMO) can be used as a multiple antenna technique to :

  - Increase the system reliability (decrease the bit or packet error rate)

  - Increase the achievable data rate and hence system capacity

  -Increase the coverage area

  -Decrease the required transmit power

The future work can be done using any higher level program.

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Appendix

Simulation Program in MATLAB

```
close all;
clear all;
SUI = [];
G = [];
mdt = [];
figur =1;
run = 'y';
while run=='y'
   clc;
   disp('   *************************************************************************************');
   disp('   *                          Performance Analysis of  IEEE 802.16-2004 WiMAX Physical Layer                          *');
   disp('   *                    A thesis Submitted in Partial Fulfillment for The Requirements of The M.Sc in                    *');
   disp('   *                                        Electronic Engineering                                        *');
   disp('   *                                                  by                                                  *');
   disp('   *                                        Mohamed Elhassan Elamin                                        *');
   disp('   *                                          Supervised by                                          *');
   disp('   *                                        Dr.Ibrahim Khider Eltaher                                        *');
   disp('   *                              Collage of Graduate Studies                              *');
   disp('   *                                  Sudan University of Science and Technology
*');
   disp('   *                                                                                     *');
   disp('   *************************************************************************************');
   disp('  ');

   disp('  ');
   G = input('     Please enter the Lenght of CP [1/4 1/8 1/16 1/32]: ');
   disp('  ');
   mdt = input('     Enter the modulation Scheme (1 for BPSK, 2 for QPSK, 3 for 16QAM, 4 for 64QAM): ');
   if mdt == 3
     mdt = 4;
   elseif mdt == 4
     mdt =6;
   end
   disp('  ');
   BW = input('     Enter the Channel BandWidth (28,24,20,15,14,12,11,10,7,6,5.50,5,3.50,3,2.50,1.75,1.5,1.25 [MHz]);');
   disp('  ');
   samples = input('    Enter the number of OFDM symbols :');

   disp('  ');
   disp('     Simulation is starting....... wait........');

   figure(figur);

% Different SUI channels to simulate.
v_SUI = [1 2 3 ];

v_EbN0_dB=[1:15];
encode = 1;          % transmission

% The simulations for each of the channels.
for SUI = v_SUI
   channel = SUIchannel(SUI,G,BW);
   s_ber=[];
   for SNR = v_EbN0_dB
```

```
        n_ber = main(SNR,mdt,G,SUI,encode,samples,BW,channel);
        s_ber = [s_ber n_ber];
    end
    figureplotter('Channels',SUI,v_EbN0_dB,s_ber,1);
    %storing results for combining

    switch SUI
        case 1
            ber1=s_ber;
        case 2
            ber2=s_ber;
        case 3
            ber3=s_ber;
             end
end


switch mdt
    case 1
        modulation = 'BPSK';
    case 2
        modulation = 'QPSK';
    case 4
        modulation = '16QAM';
    case 6
        modulation = '64QAM';
end

title(['BER of the received symbols. ( G=',num2str(G),',BW=',num2str(BW),'MHz and modulation of ',modulation,' )']);

label = legend('SUI-1','SUI-2','SUI-3',3);

    disp('  ');
    run = input ('     --> Do you wish to run other simulations (y/n): ','s');
end



function n_ber = main (SNR,mdt,G,N_SUI,encode,samples,BW,channel);
if mdt == 1
  rate = 1/2;
else
rate =3/4;
end

Nfft = 256;

data_total_rx = [];
data_total = [];
data_out = [];
data_in = [];

n_symbols = samples;          % Total transmitted symbols

switch mdt
    case 1
        amount = 11;
        amount_coded = 192;
        template = [1];
        codeRS=[12 12];
```

```
    case 2
       if rate == (1/2)
          amount = 23;
          template = [1 0 1 1];          %  Templates used for Convolutional encoding and  the Virerbi algorithm.
          codeRS=[32 24];
       elseif rate == (3/4)
          amount = 35;
          template = [1 0 1 0 1];
          codeRS=[40 36];
       end
       amount_coded = 384;
    case 4
       if rate == (1/2)
          amount = 47;
          template = [1 0 1 1];
          codeRS=[64 48];               % Reed-Solomon encoding indicator
       elseif rate == (3/4)
          amount = 71;
          template = [1 0 1 0 1];
          codeRS=[80 72];
       end
       amount_coded = 768;
    case 6
       if rate == (2/3)
          amount = 95;
         template = [1 1 0];
          codeRS=[108 96];
       elseif rate == (3/4)
          amount = 107;
          template = [1 0 1 0 1];
          codeRS=[120 108];
       end
       amount_coded = 1152;
end

% data are generated for each case
 data_total = randint (1,amount*8*n_symbols);
 n_symbols = n_symbols;

 rate = amount_coded/(amount*8);

if encode==0

    % If encoding is not employed, the necessary bits are generated.
    n_symbols = floor(length(data_total)/amount_coded);
    amount = amount_coded/8;

    % Again, once the bytes needed to generate are found, they are generated.
    data_total = randint (1,amount*8*n_symbols);

end

bits_ofdm = amount * 8;

 for i=1:n_symbols
    % combination to form an OFDM symbol.
     data_in = data_total( 1+(i-1)*bits_ofdm : i*bits_ofdm );

    % transmitter call
```

```
    [pilot_mapping,data_mapping] = transmitter(data_in,codeRS,template,mdt,encode);

pilots=pilot_mapping;
data=data_mapping;
guard1 = complex (0,0) * ones (1,28);
DC = complex (0,0);
guard2 = complex (0,0) * ones (1,27);

% The pilot and guard subcarriers  according to the standard.

symbol= [guard1 data(1:12) pilots(1) data(13:36)...
   pilots(2) data(37:60) pilots(3) data(61:84) pilots(4)...
   data(85:96) DC data(97:108) pilots(5) data(109:132) pilots(6)...
   data(133:156) pilots(7) data(157:180) pilots(8) data(181:192) guard2];
symbol_ofdm = sqrt(Nfft) .* ifft(symbol,Nfft);
margin = length(symbol_ofdm)*G;
symbolTx = [symbol_ofdm((end-margin+1):end) symbol_ofdm];

   % The channel simulation
    if N_SUI == 0                    % AWGN channel
       symbol_channel = symbolTx;
    elseif N_SUI~=0                  %  fading channel

       NextSymbol = 8 .* sqrt(Nfft) .* ifft(randint(1,Nfft));
       symbolTx = [NextSymbol NextSymbol symbolTx];
       symbol_channel = filter(channel,1,symbolTx);
       symbol_channel = symbol_channel(end-(256*(1+G))+1:end);
    end

   % The receiver


margin = length(symbol_channel)*G;
margin = margin/(1+G);
symbol_ofdm_rx = symbol_channel(margin+1:end);
symbol_channel_rx = fft(symbol_ofdm_rx,Nfft) ./ sqrt(Nfft);



if encode == 1
   Eb = 1;
elseif encode == 0
   Eb = rate;
end

% Calculation of the noise varriance.
sigma = (Eb*10^(-SNR/10)) / mdt / 2;


% addition of noise
noise_channel = sqrt(sigma)*(randn(1,length(symbol_channel_rx)) + j*randn(1,length(symbol_channel_rx)));


    symbol_channel_rx = symbol_channel_rx + noise_channel;
```

```
   % Decoding
    data_out = receiver
(pilot_mapping,data_mapping,symbol_channel_rx,mdt,codeRS,template,SNR,encode,bits_ofdm,channel,N_SUI);

   % The accumulation of results to   verify the error.
    data_total_rx = [data_total_rx data_out];

 end

%  the rate of error of verification

  n_ber = mean( data_total_rx(:) ~= data_total(:));




function [pilot_mapping,data_mapping] = transmitter (data_in,RScode,template,mdt,encode)

%  values for the randomization .
 BSID = 1;
 DIUC = 7;
 Frame = 1;
 n_symbol = 1;

 Tx = 1;
if encode
   seed = zeros (1,15);
   seed=[de2bi(BSID,4,'left-msb') 1 1 de2bi(DIUC,4,'left-msb') 1 de2bi(Frame,4,'left-msb')];
   random_data =zeros(1,length(data_in));
   for i=1:length(data_in)
       next = xor(seed(14),seed(15));
       random_data(i) = xor( data_in(i),next);
       seed = [next seed(1,1:14)];
   end



 % Reed-Solomon encoding:
 m = 8;                       %  symbollength
 n = RScode(1);               %  the codeword length
 k = RScode(2);               % Number of information symbols

 % To realize the Reed-Solomon code, the information is needed in decimal.

  random_data = reshape(random_data,8,length(random_data)/8)';
  random_data = bi2de(random_data,'left-msb');

%  stuffing zero at the end of the vector
yk=[random_data' 0];

msg = gf([yk],m);
if n==k
   RScode = msg;
elseif n~=k
   RScode = rsenc(msg,n,k);
end
data_RS= RScode.x;
```

```
data_RS= double (data_RS);
data_RS= de2bi (data_RS,8,'left-msb');
% Serial the data for the next step.
data_RS = reshape (data_RS', 1, length(data_RS)*8);


%  to th convolutional encoder.
t=poly2trellis(7, [171 133]);
block = length (template);              % Length of the template
code_final=[];
% Transmitting --> encode.
code = convenc(data_RS,t);
code_punctured = code;
repeat = length(code)/block;        % When the template needs to be applied.

for i=0:repeat-1
   sample = code_punctured (i*block+1:(i+1)*block);
   for j=1:block
      if template(j)==1
         code_final = [code_final sample(j)];
       end
    end
end
data_convolutional = code_final;


switch mdt
   case 1                    % for BPSK
      Ncbps=192;
   case 2                    % for QPSK
      Ncbps=384;
   case 4                    % for 16-QAM
      Ncbps=768;
   case 6                    % for 64-QAM
      Ncbps=1152;
end

s=ceil(mdt/2);

   k = 0:Ncbps-1;
   mk = ((Ncbps/12)*mod(k,12))+floor(k/12);                  % First permutation
   jk = s*floor(mk/s)+mod(mk+Ncbps-floor(12*mk/Ncbps),s);      % Second permutation


   [a c] = sort(jk);

 i = 1:Ncbps-1;
data_interleaved = zeros(1,Ncbps);
data_interleaved(i) = data_convolutional(c(i));

    else

   data_interleaved = data_in;

end


 data_mapping = tx_mapper (data_interleaved, mdt);
```

```
seed = [1 1 1 1 1 1 1 1 1 1 1];

for i=1:n_symbol+2
   wk(i) = seed (11);
   next = xor(seed(9),seed(11));
   seed = [next seed(1,1:10)];
end


wk = wk(n_symbol+2);

A = 1 - wk;                          % Values defined in the standard.
B = 1 - (~wk);
value_carrier = [A B A B B B A A];

% For uplink, the values should be [A B A B A A A A]

pilot_mapping = 2*tx_mapper(value_carrier,1);




return;

function [symbolRx,hHat] = receiver (pilots_tx,data_tx,symbol_channel_rx,mdt,RScode,template,snr,encode,bits_ofdm,channel,SUI);

 BSID = 1;           % These three values comprise the algorithm of the
 DIUC = 7;            % randomization of data. The are used to calculate
 Frame = 1;          % the seed.

 Tx = 0;            % Indicate that we are not transmitting.


 v_pilots = [41 66 91 116 142 167 192 217];


if SUI == 0
   estimate_rx = symbol_channel_rx;
elseif SUI ~= 0

     v_estimate = fft(channel,256);
     v_estimate = conj(v_estimate');
     % We undo what the channel has done to each of the samples in the symbol.
     estimate_rx = symbol_channel_rx ./ v_estimate;
end


 v_data = setxor(1:length(estimate_rx),v_pilots);


 data_total = estimate_rx(v_data);


 data_mapped_rx = [data_total(29:124) data_total(126:221)];


  data_interleaved_rx = rx_mapper(data_mapped_rx,mdt);
```

```
 if encode
    switch mdt
         case 1                    % for BPSK
             Ncbps=192;
         case 2                    % for QPSK
             Ncbps=384;
         case 4                    % for 16-QAM
             Ncbps=768;
         case 6                    % for 64-QAM
             Ncbps=1152;
   end
   s=ceil(mdt/2);
   j = 0:Ncbps-1;
   mj = s*floor(j/s) + mod((j + floor(12*j/Ncbps)),s);         % First permutation
   kj = 12*mj-(Ncbps-1)*floor(12*mj/Ncbps);                     % Second permutation
   % The indices are ordered to know what must be taken.
   [a c]= sort(kj);
   i = 1:Ncbps-1;
   data_convolutional_rx = zeros(1,Ncbps);
   data_convolutional_rx(i) = data_interleaved_rx(c(i));


% to convolutional decoder.
t=poly2trellis(7, [171 133]);
block = length (template);              % Length of the template
code_final=[];
repeat= length(data_convolutional_rx)/sum(template);  % Times the process needs to be repeated.
lengtht = sum(template);

code = -2*data_convolutional_rx +1;

for i=0:repeat-1
   sample = code (i*lengtht+1:(i+1)*lengtht);
   k=1;
   for j=1:block
      if template(j)==1
         code_final = [code_final sample(k)];
         k = k+1;
       elseif template(j)==0
             code_final = [code_final 0];
      end
   end
end
tb = 105;
if length(code_final) == 192        % for BPSK
  data_RS_rx = vitdec (code_final,t,96,'trunc','unquant');
elseif length(code_final) ~= 192
      data_RS_rx = vitdec (code_final,t,tb,'trunc','unquant');
end

%  ReedSolomon decoder.
m = 8;                       % Number of bits per symbol
n = RScode(1);               % Length of the codeword
k = RScode(2);               % Number of information symbols
% To realize the Reed-Solomon code, the information is needed in decimal.
data_RS_rx = reshape(data_RS_rx,8,length(data_RS_rx)/8)';
data_RS_rx = bi2de(data_RS_rx,'left-msb');
yk = data_RS_rx;          % In the receiver, nothing needs to be completed.
msg = gf([yk],m);         % In this case, the encoding is undone.
if n==k
  RScode = yk;
```

```
elseif n~=k
   RScode = rsdec(msg',n,k);
   RScode = RScode.x;
end
random_data_rx = RScode(1:end-1);
% The binary data to continue working:
random_data_rx = double (random_data_rx);
random_data_rx = de2bi (random_data_rx,8,'left-msb');
% Serial the data for the next step.
random_data_rx = reshape (random_data_rx', 1, length(random_data_rx)*8);
seed = zeros (1,15);
seed=[de2bi(BSID,4,'left-msb') 1 1 de2bi(DIUC,4,'left-msb') 1 de2bi(Frame,4,'left-msb')];
 symbolRx=zeros(1,length(random_data_rx));

for i=1:length(random_data_rx)
    next = xor(seed(14),seed(15));
    symbolRx(i) = xor( random_data_rx(i),next);
    seed = [next seed(1,1:14)];
end

  else

     symbolRx = data_interleaved_rx;

 end

 return;

function channel = SUIchannel(N_SUI,G,BW)

% Speed of the receiver in  m/s
v = 0.001;

 FrameLength = 1;

 Nfft = 256;
BW = BW*1e6;

% Factor of correction
if mod(BW,1.75)==0
    n = 8/7;
elseif mod(BW,1.5)==0
    n = 86/75;
elseif mod(BW,1.25)==0
    n = 144/125;
elseif mod(BW,2.75)==0
    n = 316/275;
elseif mod(BW,2)==0
    n = 57/50;
else
    n = 8/7;
end

if N_SUI~=0
    Fs = floor(n*BW/8000)*8000;        % Sampling frequency
    deltaF = Fs / Nfft;                % Subcarrier spacing.
    Tb = 1/deltaF;                     % Useful symbol time (data only)
    Ts = Tb * (1+G);                   % OFDM symbol time (data + cyclic prefix)
    T = 1/(Fs*1e-6);                   % Duration in microseconds of each carrier
```

```
switch N_SUI
  case 1
      powers = [ 0 -15 -20 ];
      K = [ 4 0 0 ];
      delays = [ 0.0 0.4 0.9 ];
      Dop = [ 0.4 0.3 0.5 ];
      ant_corr = 0.7;
      Fnorm = -0.1771;
  case 2
      powers = [ 0 -12 -15 ];
      K = [ 2 0 0 ];
      delays = [ 0.0 0.4 1.1 ];
      Dop = [ 0.2 0.15 0.25 ];
      ant_corr = 0.5;
      Fnorm = -0.3930;
  case 3
      powers = [ 0 -5 -10 ];
      K = [ 1 0 0 ];
      delays = [ 0.0 0.4 0.9 ];
      Dop = [ 0.4 0.3 0.5 ];
      ant_corr = 0.4;
      Fnorm = -1.5113;

end
 Dop = max (Dop);

 %% The delays are normalized
 sz=size(delays);
 if (and(sz(1) ~= 1,sz(2) == 1)) delays=delays.';
 elseif (and(sz(1) ~= 1,sz(2) ~= 1)) 'Error: The delay must be a vector';
 end

 % Now the delays express themselves in number of samples.
 delays=delays/T;

 nbtaps=length(powers);
 len_cir=1+round(max(delays));
 variances=zeros(1,len_cir);

 %% Calculate the amplitude of each path.
 sz=size(powers);
 if (and(sz(1) ~= 1,sz(2) == 1)) powers=powers.';
 elseif (and(sz(1) ~= 1,sz(2) ~= 1)) 'Error: The powers must be a vector';
 end



 variances2=10.^(powers/10);

 %% Normalize the powers
 variances2=variances2/sum(variances2);


 for i=1:nbtaps
  variances(1+round(delays(i)))=variances(1+round(delays(i)))+ variances2(i);
 end

 Lc=length(variances)-1;
```

```
 hfr=[];
  fc = 2.3e9;          % Carrier Frequency in Hertz (2.5GHz 3.2GHz)
  fdmax = Dop;

  N = 100;                   % Number of incident waves
  t = Ts:Ts:Ts*FrameLength;             % The variable "time"

  len = length(t);
  theta = rand(1,N)*2*pi;            % Generating the uniform phases
  fd = cos(2*pi*((1:N)/N))*fdmax;      % Generate eqaul-spaced frequencies from  "-fdmax" to "+fdmax"


  E = exp(j.*(2*pi*fd(:)*t(:)'+repmat(theta(:),1,len)));
  E = E/sqrt(N);
  fadingcoeff = sum(E);



    for ih=1:Lc+1
      hfr=[hfr;fadingcoeff];
    end
    hfr=diag(variances.^0.5)*hfr;
    %% hfr has a size of (Lc+1)x(FrameLength)

    % Finally, the values of the channel are normalized.
    channel = hfr ./ norm(hfr);

elseif N_SUI == 0
    channel = 1;
end

function data_mapping = rx_mapper( data_interleaving, mdt)

 switch mdt
    case 1                       % for BPSK
        type_map = 'MPSK';
        M = 2;
        M1 = 0;
        M2 = 0;
        c = 1;
    case 2                       % for QPSK(or 4-QAM)
        type_map = 'QAM';
        c = 1/sqrt(2);
    case 4                       % for 16-QAM
        type_map = 'QAM';
        c = 1/sqrt(10);
    case 6                       % for 64-QAM
        type_map = 'QAM';
        c = 1/sqrt(42);
end

if mdt~=1
    M = 0;
    M1 = sqrt(2^mdt);
    M2 = sqrt(2^mdt);
end
type_mapping=type_map;
```

```
if strcmp(type_mapping,'QAM')
   k1 = ceil(log2(M1));
   k2 = ceil(log2(M2));
   M1 = 2^k1;
   M2 = 2^k2;
   M = M1*M2;

   Aicd = zeros(1,k1);
   Aisd = zeros(1,k2);
   table1 = zeros(M1,2);
   table2 = zeros(M2,2);
   alphabet = zeros(M,3);


   d1 = 0:1:M1-1;
   d1 = d1';
   d2 = 0:1:M2-1;
   d2 = d2';
   ind1 = bi2de(fliplr(gray2bin(fliplr(de2bi(d1)),'QAM',4)));
   table1 = [d1,ind1+1];
   ind2 = bi2de(fliplr(gray2bin(fliplr(de2bi(d2)),'QAM',4)));
   table2 = [d2,ind2+1];

else

   k = ceil(log2(M));
   M = 2^k;

   % We initialize
   Aicd = zeros(1,k);          % The values different from the coefficients in phase
   Aisd = zeros(1,k);          % The values different from the coefficients in quadrature
   table = zeros(M,2);         % A table with indices
   alphabet = zeros(M,3);      % Alphabet


   d = 0:1:M-1;
   d = d';
   ind=bi2de(fliplr(gray2bin(fliplr(de2bi(d)),'QAM',4)));
   table = [d,ind+1];

end

% Block of computation
%
if strcmp(type_mapping,'PAM')
   Aicd = -(M-1):2:M-1;
   Aisd = [];

   % We create alphabet
   for i=1:M
      index = find_index(i-1,table);
      alphabet(i,:) = [i-1,Aicd(index),0];
   end

elseif strcmp(type_mapping,'MPSK')
   angle = 0:2*pi/M:2*pi*(M-1)/M;
   Aicd = cos(angle);
   Aisd = sin(angle);
```

```
    % We create alphabet
    for i=1:M
        index = find_index(i-1,table);
        alphabet(i,:) = [i-1,Aicd(index),Aisd(index)];
    end


elseif strcmp(type_mapping,'QAM')
    Aicd = -(M1-1):2:M1-1;
    Aisd = (M2-1):-2:-(M2-1);

    % We create alphabet
    for i=1:M1
        for j=1:M2
            index1 = find_index(i-1,table1);
            index2 = find_index(j-1,table2);
            l = i+M1*(j-1);
            alphabet(l,:) = [l-1,Aicd(index1),Aisd(index2)];
        end
    end

end



if mdt~=1
    constellation_gray = alphabet(:,3) + j*alphabet(:,2);
else
    constellation_gray = [0 1]';
end

l = length(data_interleaving);

data_normalized = data_interleaving ./ c;
% Now the inverse of the mapping must be realized.
for i=1:l
    v_data_mapping = data_normalized (i);
    v_decode = genqamdemod(v_data_mapping,constellation_gray);
    data_decimal(:,i) = v_decode;
    data_mapping = de2bi(data_decimal,mdt,'left-msb')';
    data_mapping = data_mapping(:)';
end

function data_mapping =tx_mapper( data_interleaving, mdt)
 switch mdt
    case 1                  % for BPSK
        type_map = 'MPSK';
        M = 2;
        M1 = 0;
        M2 = 0;
        c = 1;
    case 2                  % for QPSK(or 4-QAM)
        type_map = 'QAM';
        c = 1/sqrt(2);
    case 4                  % for 16-QAM
        type_map = 'QAM';
        c = 1/sqrt(10);
    case 6                  % for 64-QAM
        type_map = 'QAM';
        c = 1/sqrt(42);
end
```

```
if mdt~=1
   M = 0;
   M1 = sqrt(2^mdt);
   M2 = sqrt(2^mdt);
end
type_mapping=type_map;

if strcmp(type_mapping,'QAM')
   k1 = ceil(log2(M1));
   k2 = ceil(log2(M2));
   M1 = 2^k1;
   M2 = 2^k2;
   M = M1*M2;



   Aicd = zeros(1,k1);
   Aisd = zeros(1,k2);
   table1 = zeros(M1,2);
   table2 = zeros(M2,2);
   alphabet = zeros(M,3);

   d1 = 0:1:M1-1;
   d1 = d1';
   d2 = 0:1:M2-1;
   d2 = d2';
   ind1 = bi2de(fliplr(gray2bin(fliplr(de2bi(d1)),'QAM',4)));
   table1 = [d1,ind1+1];
   ind2 = bi2de(fliplr(gray2bin(fliplr(de2bi(d2)),'QAM',4)));
   table2 = [d2,ind2+1];

else

   k = ceil(log2(M));
   M = 2^k;

   % We initialize
   Aicd = zeros(1,k);          % The values different from the coefficients in phase
   Aisd = zeros(1,k);          % The values different from the coefficients in quadrature
   table = zeros(M,2);         % A table with indices
   alphabet = zeros(M,3);      % Alphabet
   d = 0:1:M-1;
   d = d';
   ind=bi2de(fliplr(gray2bin(fliplr(de2bi(d)),'QAM',4)));
   table = [d,ind+1];

end

% Block of computation
%
if strcmp(type_mapping,'PAM')
   Aicd = -(M-1):2:M-1;
   Aisd = [];

   % We create alphabet
   for i=1:M
      index = find_index(i-1,table);
      alphabet(i,:) = [i-1,Aicd(index),0];
   end
```

```
elseif strcmp(type_mapping,'MPSK')
    angle = 0:2*pi/M:2*pi*(M-1)/M;
    Aicd = cos(angle);
    Aisd = sin(angle);

    % We create alphabet
    for i=1:M
        index = find_index(i-1,table);
        alphabet(i,:) = [i-1,Aicd(index),Aisd(index)];
    end

elseif strcmp(type_mapping,'QAM')
    Aicd = -(M1-1):2:M1-1;
    Aisd = (M2-1):-2:-(M2-1);

    % We create alphabet
    for i=1:M1
        for j=1:M2
            index1 = find_index(i-1,table1);
            index2 = find_index(j-1,table2);
            l = i+M1*(j-1);
            alphabet(l,:) = [l-1,Aicd(index1),Aisd(index2)];
        end
    end

end


if mdt~=1
    constellation_gray = alphabet(:,3) + j*alphabet(:,2);
else
    constellation_gray = [0 1]';
end

l = length(data_interleaving);
matrix_data = reshape (data_interleaving,mdt,l/mdt);
m_data_decimal = bi2de (matrix_data','left-msb');

for i=1:(l/mdt)
    v_data_decimal = m_data_decimal (i);

    v_encode = genqammod(v_data_decimal,constellation_gray);

    output(:,i) = v_encode;
end

data_mapping = c.*output;

function index = find_index(num,table)
dim = size(table);
num_col = dim(1);

for i=1:num_col
    if num==table(i,1);
        index = table(i,2);
        return
    end
end
```