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Performance Analysis for WiMAX Wireless Systems with Multiple Receive Antennas

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PERFORMANCE ANALYSIS FOR WIMAX WIRELESS SYSTEMS WITH MULTIPLE RECEIVE ANTENNAS

by

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ABSTRACT

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Broadband wireless access has become the best way to meet the growing demand for fast Internet connections. WiMAX is one of the most promising broadband access technologies that allows fast deployment as well as low maintenance costs. WiMAX allows efficient use of available bandwidth by using orthogonal frequency division multiplexing (OFDM) which is an efficient multi-carrier modulation technique. Diversity is a method for improving the reliability of a signal in fading environments by using two or more communication channels and is usually achieved by multiple antenna techniques.

In this thesis, receiver side diversity combining methods are studied and the performance of WiMAX Systems with multiple receive antennas is analyzed using numerical results obtained from simulations. This study discusses diversity techniques and explains the basic parameters with mathematical calculations. Simulations include the Bit Error Rate (BER) of a WiMAX system with maximal ratio combining (MRC) and Selection Combining (SC) diversity techniques which are used to increase the communication system performance especially in fading environments. The simulation tool used in this thesis is MATLAB. Various scenarios are simulated and analyzed in terms of BER performance.

This thesis is dedicated to my beloved wife, Olga.

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CHAPTER 1

INTRODUCTION

The development of wireless phone service in the late 1980's and early 1990's has prompted a new demand for wireless data services in the late 1990's. High-speed access to the Internet provided by land-based connectivity such as DSL or cable services provide data rates to the order of megabits per second to the end user. In order to provide comparable high-speed wireless data services also referred to as wireless broadband such as Internet access and data network access, there are two types of approaches. The first type, called *fixed wireless broadband,* provides services similar to DSL or cable but utilizes wireless as the medium of transmission and assumes that there is no mobility in the network. The second type of broadband wireless, called *mobile broadband,* brings the additional functionality of mobility.

1.1 Evolution of Broadband Wireless Systems

The second generation (2G) mobile systems use digital multiple access technologies like Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). The major achievement of this generation is the Global System for Mobile Communications (GSM) which uses TDMA for supporting multiple users. 2G systems use a mobile-assisted hands off mechanism that allows mobile units to switch from one base station to another in a seamless way.

The 2.5 Generation (2.5G) provides adequate data connectivity without making major changes in the existing 2G technologies. Extensions have been made to the GSM standard to improve throughput. One of these is the GPRS (General Packet Radio System) service, which allows higher data rates. Another extension is the Enhanced Data rate for GSM Evolution (EDGE). With the help of EDGE, GSM operators provide multimedia services and applications based on Internet Protocol (IP).

Third generation (3G) technologies have enabled faster data transmission speeds, greater network capacity and more advanced network services. Compared to 2G and 2.5G services, 3G allows simultaneous use of speech and data services, and higher data rates.

A Local Area Network (LAN) is a data network that connects computers and devices in a limited small area. Ethernet over twisted pair cabling and Wi-Fi are the most widely used technologies. Wi-Fi is the industry name for Wireless Local Area Network (WLAN) communication technology related to the IEEE 802.11 standards. A Wi-Fi hotspot typically covers a few hundred feet radius [8].

A Metropolitan Area Network (MAN) is a large network which extends to a large university campus or a city. Like in universities, a MAN incorporates multiple LANs. MANs can also be interconnected with other MANs to form a Wide Area Network (WAN).

WANs often connect multiple LANs and MANs to each other through dedicated lines. The most popular WAN is the Internet. Other examples include 3G systems and WiMAX networks (Wireless WANs). Wireless network categories with the most famous technologies for each type of network are illustrated in Figure 1.1.

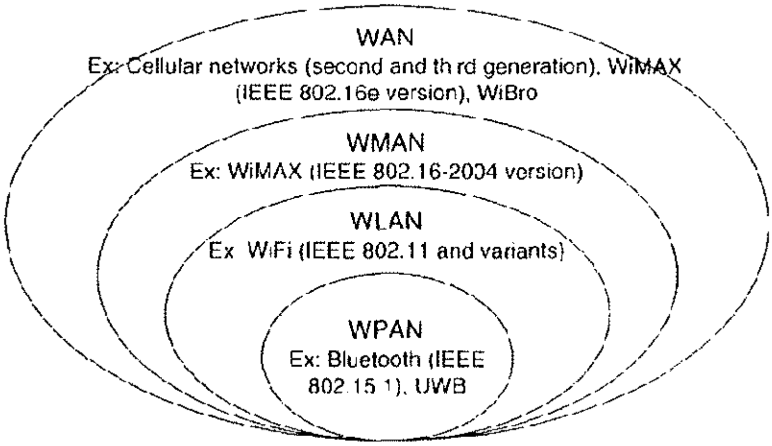

Figure 1.1 Wireless networks with corresponding technologies.

1.2 WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) technology, also known as the IEEE 802.16 standard, has been designed to accommodate both fixed and mobile Internet access. It has been regarded as the next milestone of Broadband Wireless Access (BWA) technology. It enables the convergence of mobile and fixed broadband networks through a common wide area radio access technology.

WiMAX is expected to provide fixed wireless broadband access with the same quality service as DSL and Cable technologies. It is easy to deploy, offers high data rates, and supports interoperability that is the ability to function usefully with other wireless standards. Compared to DSL and Cable, WiMAX will become an excellent solution for remote areas where accessibility is an issue and where costs of deployment and maintenance of such technologies would not be profitable.

Mobile WiMAX offers additional functionality of portability and mobility. It provides mobile access just like 3G. It has also been considered as a competitive alternative or even the replacement of 3G applications. WiMAX provides broadband wireless access up to 30 miles (50 km) for fixed stations, and 3-10 miles (5-15 km) for mobile stations [1].

WiMAX defines a Wireless Metropolitan Area Network (WMAN) and is similar to a huge hot-spot that provides interoperable broadband wireless connectivity to fixed, portable, and nomadic users. By means of interoperability, products using WiMAX technology can be integrated with other broadband access technologies in many of the possible scenarios of utilization. WiMAX connects rural areas as well as metropolitan areas and provides a cost effective, rapidly deployable solution that will dominate enterprises, campuses, and Wi-Fi hot-spots.

Fixed WiMAX utilizes Orthogonal Frequency Division Multiplexing (OFDM), a multicarrier modulation scheme, which divides a given high-bit-rate data stream into several parallel lower bit-rate streams and modulates each stream on subcarriers. Equalizing on a subset of subcarriers instead of a single carrier improves the efficiency and overcomes the interference and fading caused by multipath.

Mobile WiMAX utilizes Orthogonal Frequency Division Multiple Access (OFDMA) as the preferred multiple-access method in the downlink and uplink to accommodate many users in the same channel at the same time and to improve multipath performance. WiMAX technology is becoming more popular as many service providers are deploying WiMAX to provide wireless broadband connectivity.

1.3 The IEEE 802.16 Standards for Broadband Wireless Data Systems

The IEEE 802.16 standard, commonly referred to as WiMAX, is also known as the air interface for Fixed Broadband Wireless Access Systems. WiMAX technology enables mobility and reduces dependence on wired connections.

The early version of the 802.16 standard, approved by IEEE in April 2002, defines the use of bandwidth between the licensed 10GHz and 66GHz frequency ranges and requires line-of-sight (LOS) transmission.

The 802.16a extension, ratified in March 2003, specifies the transfer of non-visual connections (NLOS) and allows the use of both licensed and unlicensed lower frequencies (2 to 11 GHz). It supports a 31 mile range and 70 Mbps data rates that can support thousands of users [2].

IEEE.802.16d is the amendment to IEEE 802.16a. It was designed to provide fixed BWA for fixed and portable users. It supports both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) transmission modes. The key aspects of this standard can be noted as the support for advanced antenna systems and adaptive modulation and coding techniques.

The current WiMAX revision is based upon 802.16e standard and was approved in December 2005. It is the amendment to 802.16d-2004. 802.16e supports mobility through soft and hard handover, which is one of the most important aspects of mobile WiMAX. The most notable technical differences between 802.16d and 802.16e are the support for scalable OFDMA, handover between base stations, and antenna diversity techniques. These enhancements over 802.16d are primarily required to support mobility between cells and increase signal penetration. The standard is being utilized primarily in a licensed spectrum for mobile applications [3].

The basic difference between fixed and mobile variants of WiMAX is their mobility. Mobile WiMAX supports users moving at speeds up to 120 km/h with no performance degradation. When a user moves from one Base Station to another, both real-time and non-real time applications are supported through handover [4]. A comparison between Fixed and Mobile WiMAX parameters is shown in Table 1.1.

Table 1.1 802.16d and 802.16e comparison.

	802.16d-2004 (Fixed WiMAX)	**802.16e-2005 (Mobile WiMAX)**
Release	June 2004	December 2005
PHY Layer	256-OFDM 2048-OFDM	Scalable OFDMA with 128, 512, 1024 and 2048 subcarriers
Diversity Technique	SISO	MiMO
Hand Off	None	Soft and Hard Handoff
Target Applications	Fixed and some Nomadic Operations	Mobile operations requiring soft handoff
Typical Cell Radius	5-15 Km typical; up to 50 Km	<5 Km

Antenna diversity using multiple antenna systems such as MIMO yields higher data rates and increases coverage. It is crucial for improved link reliability. Spatial multiplexing and multi-user diversity improve overall system capacity. The integration of OFDM, OFDMA, and MIMO boosts the throughput performance.

1.4 Thesis Outline

In this thesis, receiver side diversity combining methods are studied and the performance of WiMAX Systems with multiple receive antennas is analyzed using numerical results obtained from simulations. The study discusses diversity techniques and explains the basic parameters with mathematical calculations.

An overview of the WiMAX system has already been exposed in the present chapter, where the main features of the standard are summarized. The motivation of the study is presented and current developments in the technical literature are reviewed. A general discussion about Broadband Access and WiMAX is also provided in this chapter. Chapter 2 summarizes the OFDM fundamentals and OFDM structure in WiMAX. Chapter 3 presents channel diversity and explains two prevalent receive antenna schemes. Chapter 4 describes WiMAX simulator, flow-chart for the code and BER calculations. In Chapter 5, simulations for various antennas, paths, and bandwitdhs are presented. Observations for each simulation are discussed. A comparison with LTE, which is a leading technology similar to WiMAX in many aspects, is also provided in this chapter. Chapter 6 includes conclusions and future work.

CHAPTER 2

OVERVIEW OF OFDM

OFDM is based on frequency division multiplexing (FDM) where multiple signals are transmitted in parallel. Each signal uses a unique frequency range called subcarrier. Between subcarriers, guard bands are introduced which lower the efficiency of spectrum but prevent overlapping in frequency. These subcarriers are demodulated at the receiver by using filters to separate the bands.

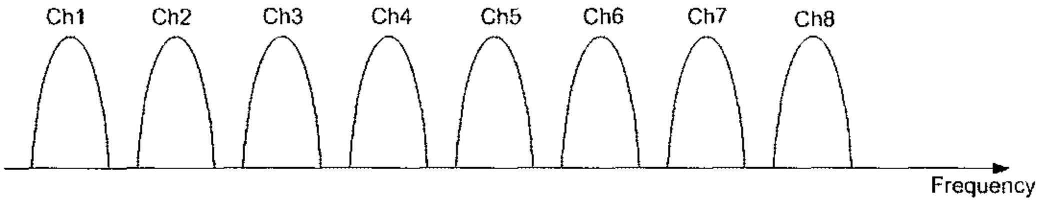

Figure 2.1 Frequency division multiplexing.

OFDM achieves better spectral efficiency by allowing adjacent subcarriers to overlap. This is done by using orthogonal signals with different frequencies. Removing the guard bands and overlapping the subcarriers reduces the required bandwidth [5].

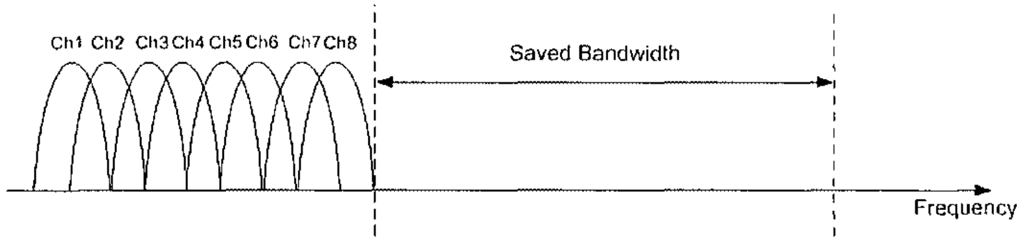

Figure 2.2 Overlapped subcarriers in OFDM.

Each subcarrier is provided with a lower data rate which is useful to reduce the inter symbol interference (ISI). Overlapping and saved bandwidth are shown, respectively, in Figure 2.2.

2.1. OFDM Implementation

A cyclic prefix (CP) is added at the beginning of the OFDM symbol to mitigate the delay spread caused by multipath propagation. The time occupied by CP is called Guard Time (T_G). Guard Time eliminates ISI from the previous symbol. The duration of one transmitted data symbol is called T_d. T_G/T_d provides the guard interval, also known as CP ratio. CP ratio changes with respect to the FFT size.

Figure 2.3 Guard intervals.

Adding an adequately large guard band eliminates the interference between subsequent OFDM symbols. Guard time is shown in Figure 2.3.

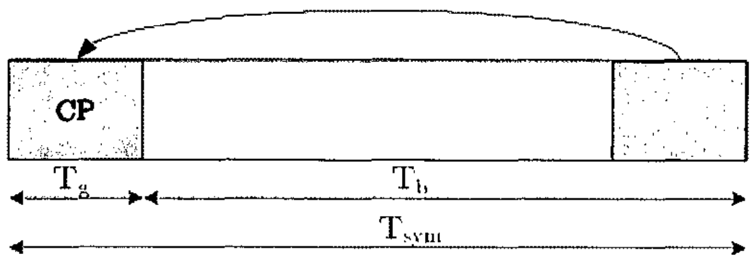

Figure 2.4 OFDM symbol with cyclic prefix added.

Not every subcarrier conveys useful data. An OFDM symbol is composed of three types of subcarriers:

1. *Data Subcarriers* convey useful data.

2. *Pilot Subcarriers* are used to synchronize the receiver to the transmitter by means of frequency, phase, and timing. The number of pilot subcarriers depends on the total number of subcarriers available.

3. *Null Subcarriers* include the frequency guard bands and the DC subcarrier. Guard subcarriers are the outer subcarriers that do not convey any data. A DC subcarrier is at the center of transmission frequency and also not used for data

transmission [4], [9]. Subcarriers used in WiMAX OFDM are shown in Figure 2.5.

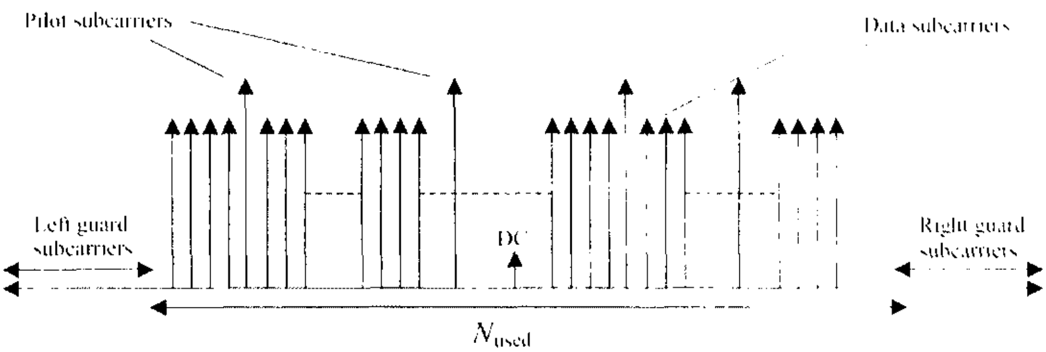

Figure 2.5 Structure composed with data, pilot, guard and zero DC subcarriers.

The block diagram of an OFDM-based communication system is shown in Figure 2.6. Each of the blocks will be described in the following discussion.

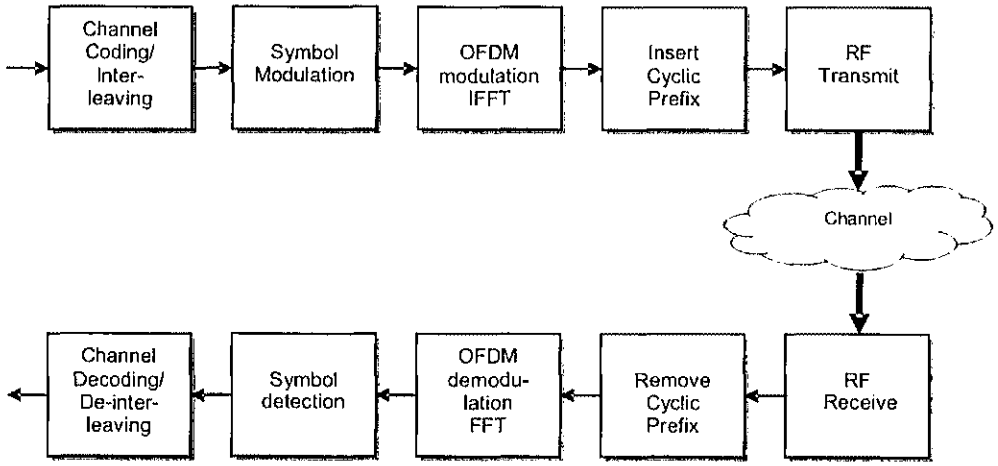

Figure 2.6 OFDM block diagram.

Channel coding is a practical way to decrease the information rate through the channel and to increase reliability. It is done by adding redundancy to the information symbol vector which causes a longer coded symbol vector that is distinct at the output of the channel [13].

In order to enhance the OFDM system performance, channel coding is applied to the sequential binary input data. Channel coding refers to the forward error correction code and bit interleaving in digital communication.

The basic principle of OFDM is to divide a high-rate data stream into N lower rate streams, which are then individually modulated by using M-ary Phase Shift Keying (PSK) or M-ary Quadrature Amplitude Modulation (QAM). According to the modulation technique used, symbol mapping is performed. In this thesis, Quadrature Phase Shift Keying (QPSK) is implemented as the modulation technique and gray coding is used for the symbol mapping. After the symbol mapping, a complex envelope of the digitally modulated data is created.

Each of the discrete samples before applying the IFFT algorithm corresponds to an individual subcarrier. In other words, the symbols attained after modulation are the amplitudes of sinusoids. IFFT represents a fast way for modulating these subcarriers in parallel. Using the IFFT algorithm prevents spending extra time to perform the same operation by using multiple modulators and demodulators. The IFFT, which ensures the orthogonality of the symbols, is used to generate a time domain signal.

After symbol mapping, a N-point IFFT is applied to the complex data symbols where N is the number of orthogonal sub-carrier frequencies used. In this thesis' simulations, 128, 512, and 1024-point Fast Fourier Transforms (FFT) were used. The length of the IFFT output is called the OFDM symbol duration.

The guard interval for each OFDM symbol is chosen to be larger than the expected channel delay spread. The guard interval does not carry any specific data. By using guard interval, ISI is reduced to a large extent and Inter-Carrier Interference (ICI) becomes manageable with equalization. The only downside of this principle is the decrease in the efficiency of OFDM transmissions.

The last stage in the transmitter side is RF modulation of the signal. The OFDM symbols are altered to a specified radio frequency carrier and are amplified and transmitted through the antenna. At the receiver, the signal is altered back to baseband and dispatched to the FFT processor.

The Cyclic Prefix (CP) is removed from the received OFDM symbols and only the useful data parts of the OFDM signals are demodulated by the FFT into the separate sub-carriers. These frequency-domain samples are then used to get the estimate of the original transmitted symbol.

In order to estimate the original transmitted OFDM symbol, precise channel state information is needed. Transmitted data and pilot tones can be used to attain channel state information. There are various channel estimation techniques. Detailed information about channel estimation can be found in [14].

After channel estimation, demapping is made according to the constellation used at the transmitter side.

2.1.1 Multiple Access and OFDMA

OFDM assigns all subcarriers to a single user, so only one user can transmit at a time. To have multiple user transmissions, OFDM system has to employ a multiple access scheme, such as Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA). Multiple-access techniques allow users to share the available bandwidth by allocating each user some fraction of the total system resources [4], [9].

Mobile WiMAX (802.16e-2005) uses OFDMA, whereby users share subcarriers and time slots. OFDMA is a multi-user OFDM that allows multiple access on the same channel. In OFDMA, subcarriers are divided into subsets of subcarriers and distributed among users so all users can send and receive at the same time. Each subset represents a subchannel. Figure 2.6 represents the OFDMA structure.

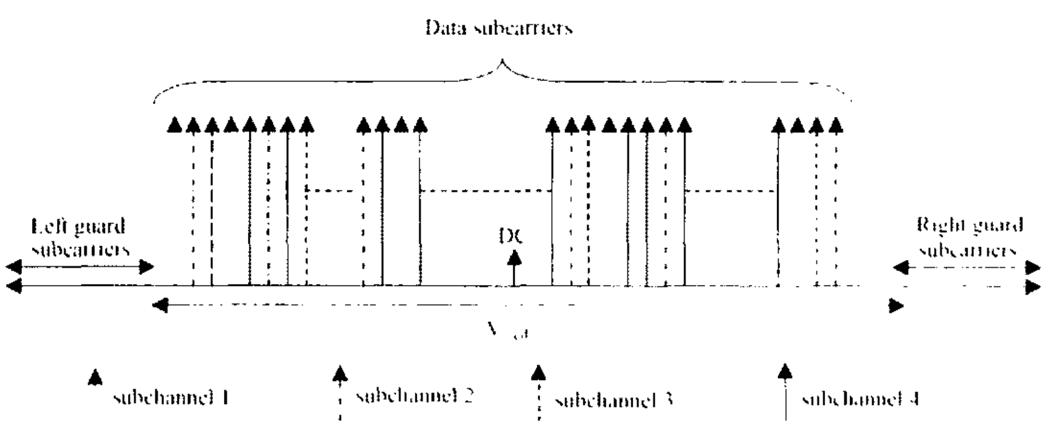

Figure 2.7 OFDMA Frequency Spectrum.

2.1.2 Peak to Average Power Ratio (PAPR)

OFDM signals tend to have higher Peak-to-Average-Power-Ratio (PAPR) than single carriers. PAPR is the ratio of peak signal power to the average signal power. An OFDM signal is composed of many independent narrowband sub-carrier frequencies. In some cases, the sum of the narrowband frequencies is large and other times small which causes the peak value of the signal to be noticeably larger than the average value.

In multicarrier signal systems, subcarriers invariably come in phases (by forming peaks and valleys) and out of phase (by forming values close to zero). Figure 2.7 shows an OFDM signal example with peaks and valleys.

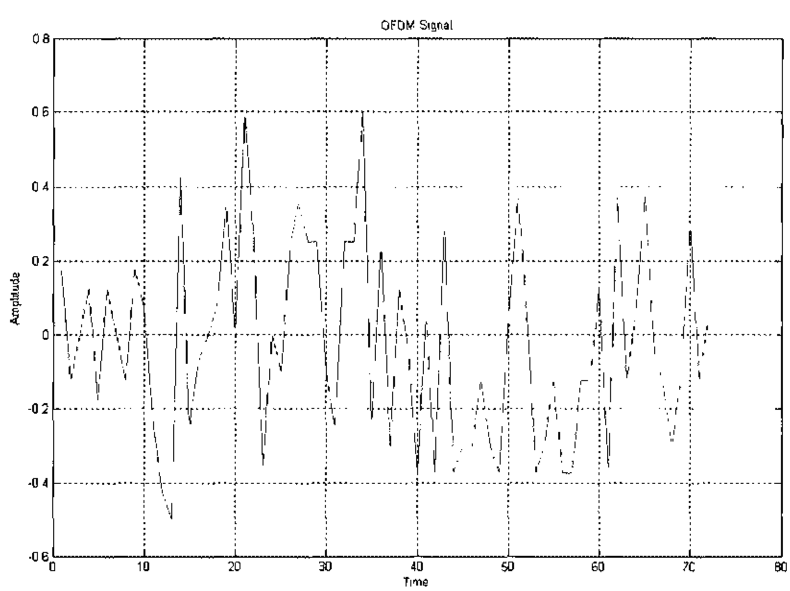

Figure 2.8 OFDM Signal with high peaks.

A high PAPR is a common issue for OFDM systems because it can drive RF amplifiers into their unlinear operating ranges. Minimizing the PAPR allows higher average powers to be transmitted and improves the SNR at the receiver.

Techniques exist to cope with the PAPR problem in OFDM. Some well known PAPR reduction techniques are clipping, block coding, phase shifting, tone injection, and reservation. An overview of the PAPR-reduction techniques for OFDM can be found in [7].

2.1.3 Advantages of OFDM

The main advantage of OFDM is its robustness against multi path propagation. OFDM divides the high data rate stream into several narrowband flat fading channels. Hence, it is less vulnerable to frequency selective fading than single carrier systems are.

IFFT and the CP are crucial features of OFDM that reduce ISI. The use of a Cyclic Prefix simplifies the channel equalization in the receiver. Thus, it can easily adapt to severe channel conditions without complex equalization. FFT techniques used in OFDM simplify the implementation of the modulation and demodulation functions. Overlapping and orthogonality of subcarriers give OFDM high spectral efficiency. OFDMA is more suitable for broadband mobile systems since it can dynamically allocate resources both in frequency and in time.

2.1.4 Disadvantages of OFDM

A high PAPR can drive RF amplifiers into their unlinear operating ranges. Since subcarriers are spaced closely in frequency, OFDM signals suffer from both time variations in the channel and the presence of a carrier frequency offset. Inadequate frequency synchronization causes a loss in subcarrier orthogonality that degrades performance. Insertion of a guard band reduces the spectral efficiency and, thus, total channel capacity decreases.

2.2 The WiMAX Wireless Standard

The WiMAX Wireless Standard [7] denotes the primitive parameters to be specified by users or system requirements. Once the primitive parameters are set, derived parameters can be defined in terms of the primitive ones [4]. WiMAX OFDM symbol has five distinctive parameters:

- Nominal channel bandwidth (BW)
- Number of data subcarriers (N_{data})
- Number of pilot subcarriers (N_{pilot})
- Sampling factor (n_f) to determine the subcarrier spacing and the useful symbol time
- Cyclic Prefix ratio (T_G / T_d)

Based on the above-defined parameters, the following parameters can be computed:

- Number of used subcarriers (N_{used})

$$N_{used} = N_{data} + N_{pilot} \tag{2.1}$$

- FFT size (N_{FFT})

$$N_{FFT} = 2^{[\log_2(N_{data})]} \quad (2.2)$$

- Sampling frequency (F_S)

$$F_S = BW\ x\ n_f \quad (2.3)$$

- Subcarrier spacing (Δ_f)

$$\Delta_f = \frac{F_S}{N_{FFT}} \quad (2.4)$$

- Duration of transmitted useful data (T_d)

$$T_d = \frac{1}{\Delta_f} \quad (2.5)$$

- OFDM symbol duration (T_S)

$$T_s = T_d + T_G \quad (2.6)$$

The number of subcarriers and the FFT size are the scalability factors. FFT sizes used in scalable OFDMA are 128, 512, 1024 and 2048. Since fixed WiMAX accommodates a 256 FFT size, it is not included in scalable OFDMA. As the bandwidth increases, the FFT size and subcarrier spacing increase as well. Hence, subcarrier spacing (Δ_f) remains constant (10.94 kHz). The spacing of 10.94 kHz helps to mitigate the delay spread and the Doppler spread that causes orthogonality deterioration. Scalability also reduces cost due to support of various bandwidths (1.25 MHz to 20 MHz) without any extra instruments. Parameters used in mobile and fixed WiMAX are given in Table 2.1.

By using these primitive parameters given above, useful symbol time, guard duration, OFDM symbol duration and number of OFDM symbols in a given period can be derived. There are also mobile WiMAX profiles such as WiBro that uses different bandwidth. A WiBro profile accommodates 8.75MHz channel bandwidth and 1,024 FFT size. Thus, it requires different subcarrier spacing and different parameters.

Table 2.1 OFDM parameters used in fixed and mobile WiMAX.

Parameter	Fixed WiMAX (OFDM)	Mobile WiMAX (sOFDMA)			
FFT Size	256	128	512	1024	2048
# of used data subcarriers (N_{used})	192	72	360	720	1440
# of pilot subcarriers (N_{pilot})	8	12	60	120	240
# of guardband subcarriers	56	44	92	184	368
CP ratio	1/8	1/32	1/16	1/8	1/4
Oversampling rate	8/7	28/25			
Channel BandWidth(MHz)	3.5	1.25	5	10	20
Subcarrier Spacing (Δ_f) (kHz)	15.625	10.94			

CHAPTER 3

MULTIPLE ANTENNA TECHNIQUES AND DIVERSITY

Diversity is a method for improving the reliability of a signal by using two or more uncorrelated and independent communication channels. It enhances wireless system performance in a fading environment. Symbols passing through multiple signal paths, each of which fades independently, can be combined to ensure a reliable communication provided that one of the paths is strong. Diversity plays an important role in mitigating fading and co-channel interference. There are several diversity schemes. In time diversity, multiple versions of the same signal are transmitted at different intervals. In frequency diversity, the signal is transmitted using several frequency channels. Both of these schemes bring redundancy. The utilization of time diversity requires extra time while frequency diversity requires bandwidth expansion. Spatial diversity is an alternative solution that does not require extra time or bandwidth expansion. Spatial diversity uses multiple transmit and receive antennas to create additional paths between transmit and receive antennas and utilizes these paths to achieve higher performance [10].

3.1 Spatial Diversity

Using multiple antennas at the receiver and transmitter is the key technique that improves the data rate without consuming additional bandwidth or power. Spatial diversity utilizes multiple antennas at the transmitter and receiver with various configurations. There are three types of spatial diversity techniques. The first scheme is called a Single Input Multiple Output (SIMO) system. SIMO architecture collects more energy at the receiver to improve the SNR.

The second scheme is called Multiple Input Single Output (MISO) system. It can be implemented by using two or more transmit antennas and one receive antenna. MISO achieves the same diversity gain as SIMO.

The third scheme is called Multiple Input Multiple Output (MIMO) communication. MIMO exploits multiple antennas at transmitter and receiver. Since MIMO already contains the advantages of the SIMO and MISO systems, it achieves greater performance in comparison. These three schemes are shown in Figure 3.1.

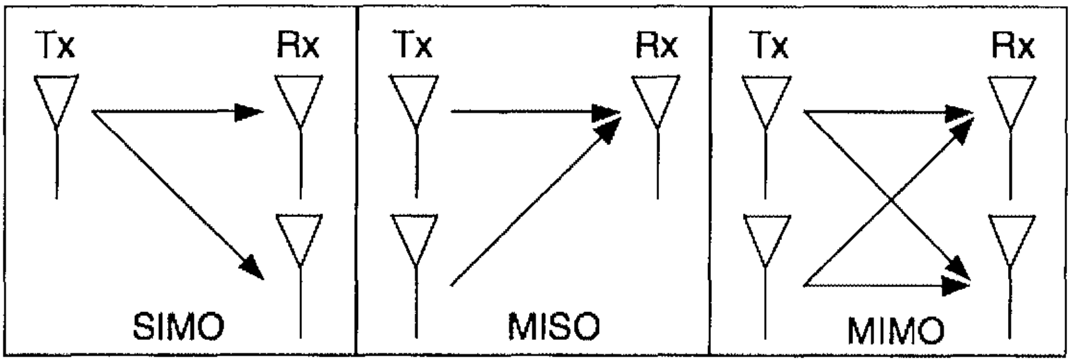

Figure 3.1 Spatial diversity schemes.

Spatial diversity is achieved by implementing either transmit diversity or receive diversity. Transmit diversity utilizes multiple antennas at the transmitter and one antenna at the receiver. Transmit diversity is usually applied to the downlink for two reasons. First, the base station has more transmit power available. It serves many different users at the same time. Therefore, the downlink has to be the strongest of the two links. Second, since the size and the processing power of the mobile device are limited, placing more than one antenna on it is difficult. Transmit diversity reduces the need for multiple receive antennas, decreases receiver complexity, and moves the complexity to the base station [12].

Mobile WiMAX supports various multiple-antenna system technologies. The multiple-antenna system technologies are divided into two types: open loop and closed loop. Open loop MIMO includes space-time block coding and spatial multiplexing. Transmitters using open loop MIMO do not require explicit knowledge of the fading channels. For closed loop MIMO, a transmitter forms antenna beams adaptively based on channel side information. There are two types of closed loop MIMO schemes. The first scheme, maximum ratio transmission, is where an antenna beam is formed on each OFDM subcarrier. The second scheme, beamforming, is where only one antenna beam is formed across multiple allocated subcarriers. Space Time Block Coding known as the Alamouti Scheme is applied after constellation mapping and implemented on encoded modulated symbols. Each symbol is transmitted twice, once per antenna, so that the overall space-time coding rate is one. Subcarrier mapping is performed independently for each transmit antenna signal.

In cyclic shift transmit diversity, each antenna sends a circularly shifted version of the same OFDM symbol. For instance, the first antenna transmits an unshifted version of the OFDM symbol and N^{th} antenna transmits the (N-1) times circularly shifted version of the same OFDM symbol. Each antenna adds a Cyclic Prefix after circularly shifting the OFDM symbol and thus the interblock interference is prevented.

With spatial multiplexing, multiple data streams are transmitted at the same time. They are transmitted on the same channel, but by different antennas. They are recombined at the receiver using MIMO signal processing. Spatial multiplexing doubles, triples, or quadruples the data rate depending on the number of transmit antennas [11]. Spatial multiplexing increases the system performance when the system is bandwidth restricted. A similar spatial multiplexing scheme is implemented in mobile WiMAX on an uplink.

When multiple antennas are present at the receiver, two types of spatial gain are available. These are array gain and diversity gain.

Array gain is attained when the receiver coherently combines the signals with a combining technique and increases the received signal-to-noise-ratio (SNR). It can easily be noticed as a shift of the BER curve due to the gain in SNR. Array gain depends on the amount of signal power collected by multiple antennas. Even if the channels are correlated, the array gain is still present and SNR increases linearly.

Diversity gain is the increase in signal-to-interference ratio. In other words, how much transmission power can be reduced without performance loss. The diversity gain is the improvement in link reliability obtained by receiving replicas of the information signal through (ideally independent) fading links. With an increasing number of independent copies, the probability that at least one of the signals is not experiencing a deep fade increases, thereby improving the quality and reliability of reception [13].

3.2 Combining Methods

Receive diversity is the most common form of spatial diversity. Receive diversity does not require any particular process on the transmitter side. Instead, several independent copies of the signal are processed and combined on the receiver side. Receiver antennas get K independent copies of the same signal. If the receive antennas are located appropriately apart, the K paths between the transmitter and the receiver will be uncorrelated. These uncorrelated paths are vital because when one path experiences a deep fade, another path would likely not experience a fade. If at least one copy has reasonable power, then the signal can be processed [10], [14].

In order to get uncorrelated paths, the minimum distance between omnidirectional antennas is nearly one-half wavelength. ($\lambda/2$). For the directional antennas, wavelength (λ) can be calculated by dividing the speed of light into the carrier frequency (f_c).

Once the receive antennas get the copies of the same signal owing to uncorrelated paths, a suitable combining scheme is used. For systems that use receive diversity, there are two prevalent combining schemes: selection combining and maximal ratio combining.

3.2.1 Selection Combining

Figure 3.2 illustrates the SC scheme. SC picks the particular receiver output with the largest SNR as the received signal. The SC technique has a straightforward implementation and is comparatively the easiest form of receive diversity techniques.

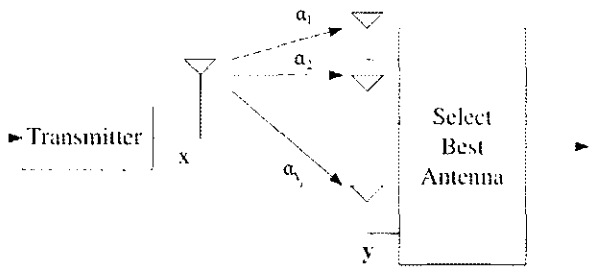

Figure 3.2 Selection combining.

To understand the advantage of selection combining it is assumed the channel is a frequency flat, slowly fading Raleigh channel. In a frequency-flat fading channel, the coherence bandwidth of the channel is greater than the bandwidth of the signal. Therefore, all frequency components of the signal will experience the same magnitude of fading. In a slow fading channel, the channel coherence time is larger than the symbol period and, hence, the channel remains approximately static over a symbol or multiple symbols [14].

Let $\tilde{s}(t)$ represent the complex envelope of the transmitted signal. With the given channel, the complex envelope of the received signal of the *k*th antenna is

$$\tilde{x}_k(t) = \alpha_k e^{j\theta_k}\tilde{s}(t) + \widetilde{w}_k(t) \tag{3.1}$$

Fading is denoted by the term $\alpha_k e^{j\theta_k}$ and the additive channel noise is represented by $\widetilde{w}_k(t)$. In a slow fading channel, phase shift θ_k can be accurately estimated and removed. This simplifies Eq. (3.1) to

$$\tilde{x}_k(t) = \alpha_k \tilde{s}(t) + \tilde{w}_k(t) \tag{3.2}$$

where, $\alpha_k \tilde{s}(t)$ is the signal component and $\tilde{w}_k(t)$ is the noise component. Consequently, the average SNR at the output of the kth antenna is

$$(SNR)_k = \left(\frac{\mathbf{E}[|\alpha_k \tilde{s}(t)|^2]}{\mathbf{E}[|\tilde{w}(t)|^2]}\right) = \frac{\mathbf{E}|\tilde{s}(t)|^2}{\mathbf{E}|\tilde{w}(t)|^2}\,\mathbf{E}[\alpha_k^2] \tag{3.3}$$

The mean square of the noise component is same for every diversity branch. This gives us

$$(SNR)_k = \frac{E}{N_0}\,\mathbf{E}[\alpha_k^2] \tag{3.4}$$

where E stands for symbol energy and N_0 stands for the white noise power spectral density. Further, replacing the $\mathbf{E}[\alpha_k^2]$ with the instantaneous value $|\alpha_k|^2$ gives us the instantaneous SNR $= \gamma_k$, that is

$$(SNR)_k = \gamma_k = \frac{E}{N_0}\,|\alpha_k|^2 \tag{3.5}$$

If it is assumed that each branch has the same average SNR (γ_{av}) then for all the diversity branches we can write the probability density function for each branch as

$$f_{\Gamma_k}(\gamma_k) = \frac{1}{\gamma_{av}} \exp\left(-\frac{\gamma_k}{\gamma_{av}}\right) \tag{3.6}$$

The probability of an instantaneous SNR of a branch less than some threshold γ is

$$\Pr[\gamma_i \leq \gamma] = \int_{-\infty}^{\gamma} f_{\Gamma_k}(\gamma_k) d\gamma_k = 1 - \exp\left(-\frac{\gamma_k}{\gamma_{av}}\right) \tag{3.7}$$

The probability of all M independent branches receive signals which are less than some specific SNR threshold γ is

$$\Pr[\gamma_1, \gamma_2 .., \gamma_k \leq \gamma] = \prod_{k=1}^{k} \left[1 - \exp\left(-\frac{\gamma}{\gamma_{av}}\right)\right] = \left[1 - \exp\left(-\frac{\gamma}{\gamma_{av}}\right)\right]^k \tag{3.8}$$

The probability decreases exponentially with the number of elements.

Since it disregards the energy on the other signals, selection combining is noticeably mediocre. However its plainness makes it attractive in many cases. The average bit error probability calculations for different selection combining scenarios will be shown in detail in Chapter 5.

3.2.2 Maximal Ratio Combining

Although Selection Combining is straightforward to implement, it is clearly not the optimal solution as it ignores the information from all the diversity branches except for the one that has the largest instantaneous SNR.

Maximal ratio combining (MRC) combines the information from all the diversity branches in order to maximize the SNR. MRC is illustrated in Figure 3.3.

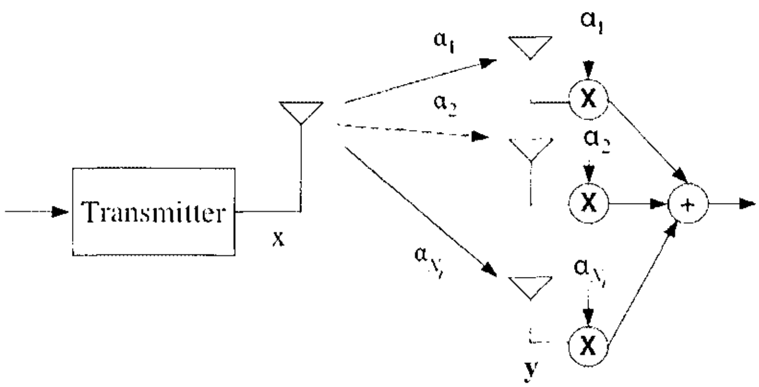

Figure 3.3 Maximal ratio combining.

Using the complex envelope in Eq. (3.1), the resulting signal envelope can be defined as

$$\tilde{y}(t) = \sum_{k=1}^{Nr} a_k \, \tilde{x}_k(t) \tag{3.9}$$

$$\tilde{y}(t) = \sum_{k=1}^{Nr} a_k \left[\alpha_k e^{j\theta_k} \tilde{s}(t) + \widetilde{w}_k(t)\right] \tag{3.10}$$

$$\tilde{y}(t) = \tilde{s}(t) \sum_{k=1}^{Nr} a_k \, \alpha_k e^{j\theta_k} + \sum_{k=1}^{Nr} a_k \widetilde{w}_k(t) \tag{3.11}$$

where the first part of the Eq. (3.11) is the complex envelope of the output signal and the second part is the complex envelope of the output noise. Assuming the $\widetilde{w}_k(t)$ are mutually independent for all branches, the output SNR is defined as

$$(SNR)_c = \frac{\boldsymbol{E}\left[\left|\tilde{s}(t)\sum_{k=1}^{Nr} a_k\, \alpha_k e^{j\theta_k}\right|^2\right]}{\boldsymbol{E}\left[\left|\sum_{k=1}^{Nr} a_k \widetilde{w}_k(t)\right|^2\right]} \tag{3.12}$$

$$(SNR)_c = \left(\frac{E}{N_0}\right)\frac{\boldsymbol{E}\left[\left|\sum_{k=1}^{Nr} a_k\, \alpha_k e^{j\theta_k}\right|^2\right]}{\boldsymbol{E}\left[\sum_{k=1}^{Nr}\left|a_k\right|^2\right]} \tag{3.13}$$

To calculate the instantaneous SNR of the output (γ_c), we use the instantaneous values instead of the expected values in Eq (3.13). That is

$$\gamma_c = \left(\frac{E}{N_0}\right)\frac{\left|\sum_{k=1}^{Nr} a_k \alpha_k e^{j\theta_k}\right|^2}{\sum_{k=1}^{Nr}\left|a_k\right|^2}. \tag{3.14}$$

Maximizing this expression by taking the derivative with respect to weighting parameters (a_k) maximizes the combining values. Another way to do maximization is to apply a Cauchy Schwarz inequality since the weighting parameters are complex numbers. Thus, applying an Cauchy Schwarz inequality to instantaneous output SNR of Eq. (3.14), we obtain

$$\gamma_{mrc} = \left(\frac{E}{N_0}\right)\sum_{k=1}^{Nr} \alpha_k^2 \tag{3.15}$$

According to Eq. (3.5), (E/N_0) a_k^2 is the instantaneous output SNR of the kth diversity branch. Thus, the SNR out of the diversity combiner is simply the sum of the instantaneous SNR values of each individual branches; that is

$$\gamma_{mrc} = \sum_{k=1}^{Nr} \gamma_k \tag{3.16}$$

From probability theory, the probability density function of γ_{mrc} is called chi-square with 2N_r degrees of freedom [15]. That is

$$f_{\Gamma_{mrc}}(\gamma_{mrc}) = \frac{1}{(N_r - 1)!} \frac{\gamma_{mrc}^{N_r - 1}}{\gamma_{av}^{N_r}} \exp\left(-\frac{\gamma_{mrc}}{\gamma_{av}}\right) \tag{3.17}$$

The cumulative distribution function for the maximal ratio combiner is defined by

$$\Pr(\gamma_{mrc} \leq \gamma) = \int_0^{\gamma} f_{\Gamma_{mrc}}(\gamma_{mrc})\, d\gamma_{mrc} \tag{3.18}$$

MRC can be applied to any system but it brings greater cost and complexity comparing to other diversity techniques. The average bit error probability calculations for different maximal combining scenarios will be shown in detail in Chapter 5.

CHAPTER 4

WiMAX SIMULATOR

The main objective of this thesis is to study the performance of WiMAX systems with multiple receive antennas and diversity combining methods. To achieve this objective a software simulator was developed that implements the WiMAX transmitter and receiver, simulates propagation over multipath channels and reception thorugh multiple antennas, and combines the multiple received signals using SC and MRC diversity methods.

MATLAB is ideal for simulating digital communication systems. It has an easy scripting language and exceptional data visualization capabilities. Bit Error Rate (BER) testing is one of the most common simulation tasks in the field of communications.

MATLAB simulation is implemented based on the 802.16 IEEE standards. BER is computed both for SISO and SIMO scenarios. Simulations and performance analysis for different scenarios are given in Chapter 5. In the simulations a QPSK modulation scheme was used. Different modulation schemes can also be adopted to observe how modulation schemes affect the BER. The implementation of OFDM was done in Chapter 2.

In order to have a general idea of the WiMAX simulator used in this thesis, a complete flow-chart of the MATLAB code is given in Figure 4.1. To compare the system in terms of diversity schemes receive antenna diversity techniques were implemented on the system. The parameters used in the simuations are given in the Chapter 5.

WiMAX promises to transmit real time data at high speed. To fulfill this, it requires a reliable link and maximum data throughput. As with any other communication scheme, WiMAX suffers from errors when the channel is in a deep fade. Diversity aims to increase the reliability of the link and eliminate fading and interference. There are many ways to obtain diversity. Diversity can be obtained over time, frequency and space. Time and frequency diversities require extra time and bandwidth. Spatial diversity does not require additional bandwith or time. Moreover, adding an extra antenna considerably changes broadcast reliability. The main objective of this thesis is to calculate the bit error rate (BER) of a WiMAX system which implements single input multiple outputs (SIMO) antenna diversity technique.

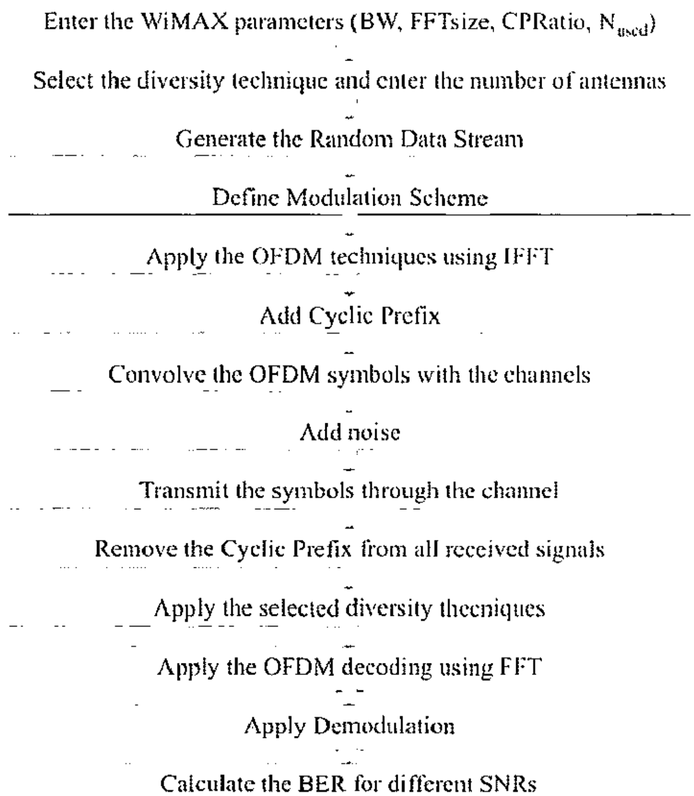

Figure 4.1 Wimax Simulation Flow-Chart.

Receive antenna diversity was studied for 2, 4 and 8 antennas. In terms of receive antenna diversity Selection Combining and Maximal Ratio Combining techniques were implemented on the receiver side. To understand the best way to exploit receive diversity various number of antennas, paths and bandwidths were used in different scenarios. While changing the variables (number of paths, antennas and bandwidth) the BER was observed.

4.1 Calculating the Bit Error Rate

In digital transmission, Bit Error Rate can be calculated as the number of bit errors divided by the total number of bits in the transmitted signal. Received bits of a stream over a communication channel experience noise, interference, and distortion. BER is a unitless measure, often expressed as a percentage. BER is an important calculation that indicates the performance of a system. After the transmitting and receiving process, received bits are compared with the original bits. Then, the number of bits in error is divided by the number of received bits. The result is the Bit Error Rate.

In the simulations QPSK was used as the modulation scheme. For QPSK modulation in an AWGN channel, the probability of error is computed by integrating the tail of the Gaussian probability density function for a given value of bit energy to noise ratio E_b/N_0. That is

$$P_e = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{4.1}$$

However, for a Rayleigh channel, in the presence of α, the effective SNR is

$$\gamma = \frac{E}{N_0} |\alpha|^2 \tag{4.2}$$

So the bit error probability for a given value of γ is

$$P(error|\gamma) = \frac{1}{2} erfc(\sqrt{\gamma}) \tag{4.3}$$

To find the error probability over all random values of $|\alpha|^2$, we need to calculate the conditional probability density function $f(error|\gamma)$ over the probability density function of γ [14]. The probability density function of γ is

$$f_{(\gamma)} = \frac{1}{E/N_0} \exp\left(-\frac{\gamma}{E/N_0}\right) \qquad \gamma \geq 0 \tag{4.4}$$

By definition, the probability of error is calculated by multiplying the conditional probability $P(error|\alpha)$ by the probability density function of γ and then integrating the product with respect to γ. That is

$$P_e = \int_0^\infty P\,(error|\gamma) f_{(\gamma)} d\,\gamma \tag{4.5}$$

Substituting Eqs. (4.4) and (4.3) with Eq. (4.5), we get

$$P_e = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma_0}{1+\gamma_0}}\right) \tag{4.6}$$

which is the BER formula for the QPSK in a slow fading Rayleigh channel.

CHAPTER 5

NUMERICAL RESULTS AND PERFORMANCE ANALYSIS

This chapter describes the simulation results of a WiMAX system that implements multiple antenna techniques. The system was simulated by using Receive Diversity (MRC and SC) techniques. In the first part, diversity was investigated with various antennas and simulations of SC and MRC were performed in comparison with a theorethical fading curve. Fixed bandwidth was used for both combining schemes. In addition, an Additive White Gaussian Noise (AWGN) channel was also used. In the second part, different bandwidths were used along with SC and MRC schemes and their performance was analyzed in terms of Bit Error Rate. In the third part, the system was simulated using multiple paths. A multipath effect on Bit Error Rates was observed for both receive antenna diversity schemes. In the last part, WiMAX is compared to LTE that is a similar technology for broadband access. The parameters used in simulations are given in Table 5.1.

Implementing a BER simulation can be a lengthy process. With the parameters given in Table 5.1, simulations are performed at each SNR and channel bandwidth. Once statistically meaningful results are received, the data can be discussed. High BER indicates that many bits will be in error. Results can be observed easily by plotting a curve of the Bit Error Rate as a function of the SNR. A BER of 10^{-5} means that one bit out of every 10^{5} bits will be in error. If the simulation contains only 10^{3} bits, there will hardly be an error. On the contrary, it is hard to simulate at high SNRs since the BER becomes very low and many more bits are required in the simulation to notice transmission errors. Measuring the bit error ratio helps to choose the appropriate forward error correction.

Table 5.1 Parameters used in simulations.

Parameter	Value		
Channel BandWidth(MHz)	1.25	5	10
FFT Size	128	512	1024
CP ratio	1/32	1/16	1/8
Number of Bits	1E6		
Oversampling rate	28/25		
Modulation Scheme	QPSK		
Antennas	2,4 and 8 Antennas For Each Configuration		
Multiple SNR values	0-16, 0-20 (In steps of 4)		

5.1 Performance Evaluation of the Simulated Systems

In this simulation, a stream of random numbers are generated and sent to a modulator. Applying Inverse Fast Fourier Transform (IFFT) to modulated signals generates orthogonal carriers. CP is added afterwards. Channel fading vectors are generated as many paths. After adding the noise, the encoded signals are then transmitted through the Rayleigh channel.

At the receiver side, the received signals are combined with the chosen combining technique. In this thesis, SC and MRC techniques are used. BER is observed after applying the chosen technique. 2, 4, and 8 antennas are used and BER is calculated respectively.

5.2.1 BER Performance for Fixed Bandwidth

Figure 5.1 shows the BER for different values of the SNR using 2,4 and 8 receive antennas. The channel bandwidth is set to 1.25 MHz and 10^6 bits are transmitted. Since the bandwidth is 1.25 MHz, the FFT size is set to 128 according to the standard specifications. For this simulation, SC, MRC and AWGN channels have been compared.

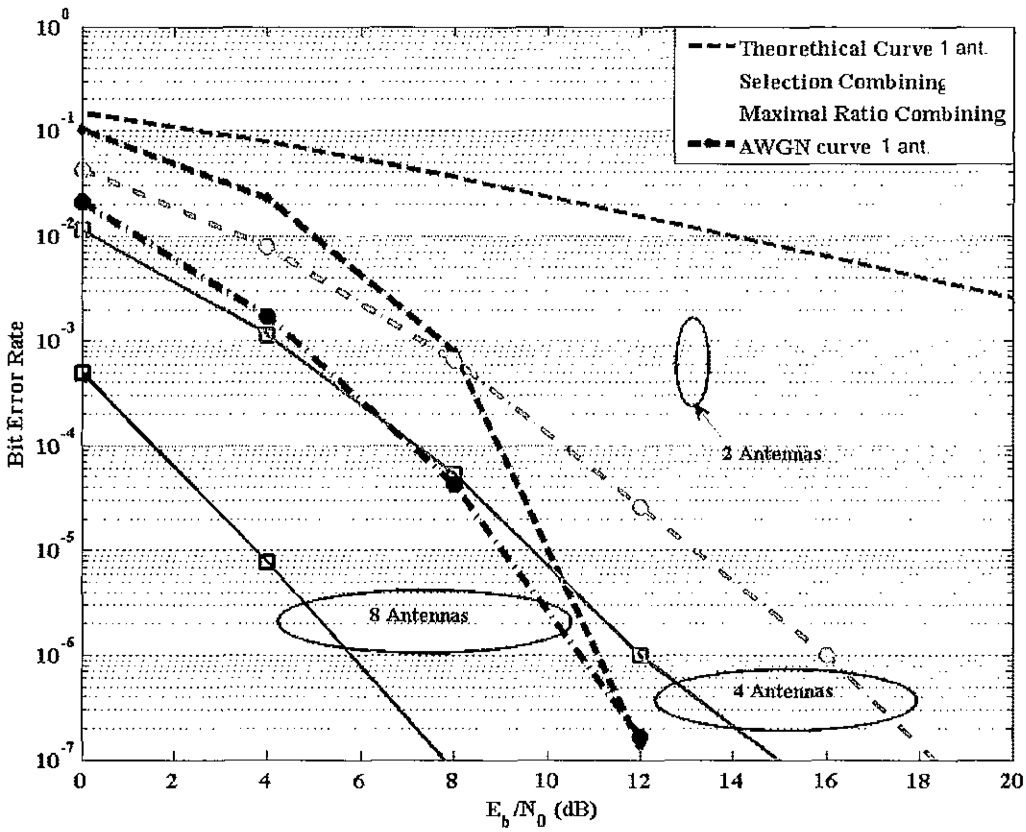

Figure 5.1 Combining schemes with 2,4 and 8 antennas (1.25 MHz bandwidth).

The simulation shows that for 2 antennas, comparing to Selection Combining the Maximal Ratio Combining technique, gives slightly better performance in terms of BER. For SNR values upto 4 dB, MRC gives less bit errors than the AWGN channel. To get the same error rate, SC requires 1 dB more than Maximal Ratio Combining.

For 4 and 8 antennas, performance improves drastically for both diversity schemes. In 4 receive antenna scenario, the MRC scheme requires about 2 dB less power to give the same error ratio as SC. Respectively in the 8 antenna scenario, the MRC requires 4 dB less for the same error rate as SC.

MRC utilizes the whole antenna gain by simply adding up the signals, whereas SC chooses the signal with the best SNR. An MRC with 8 antennas gives the best results. An MRC with 4 anntenas requires 15 dB to provide a bit error rate of 10^{-7}, whereas an MRC with 8 anntenas requires 8 dB for the same rate. Likewise, a SC with 4 anntenas requires 18 dB to provide a bit error rate of 10^{-7}, whereas a SC with 4 anntenas requires 12 dB for the same rate. It can also be observed that a MRC performance with 4 antennas is better than the AWGN channel performance. However, SC performance barely outruns AWGN channel performance with 8 antennas. The simulation also shows that diversity techniques significantly enhance the performance compared to the case of no diversity.

5.2.2 BER Performance For Different Bandwidths

To observe how bandwidth variation affects the BER, the system was simulated with different channel bandwidths. Figure 5.2 shows receive antenna diversity with 1.25MHz and 5 MHz channel bandwidth. FFT size is set to 128 and 512 respectively.

Simulations were also performed with a 10 MHz channel bandwidth to compare the results.

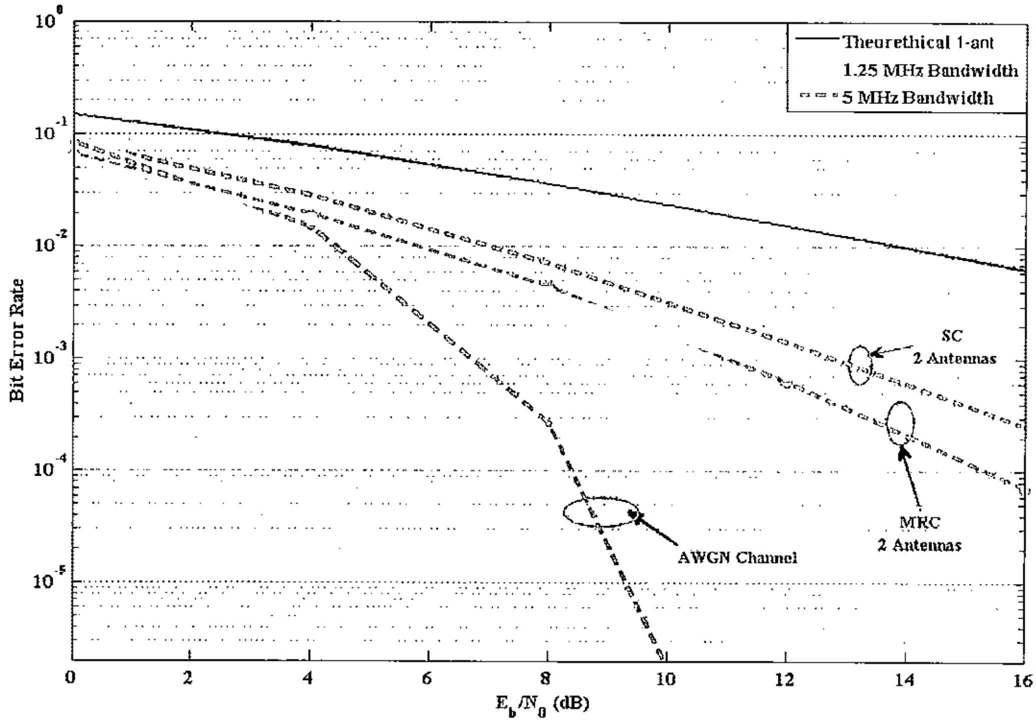

Figure 5.2 Combining Schemes with Various Bandwidths (2 Antennas).

The system was simulated with 1.25, 5, and 10 MHz channel bandwidths. While changing the channel bandwidth, changes in diversity scheme performance was observed. One thing to be noted from Figure 5.2 is the BER performance improved slightly. For SC there is almost no difference between a 1.25 MHz bandwidth and a 5 MHz channel bandwidth. MRC produces less error by a small margin as the bandwidth increases. Only after $E_b/N_0 > 12$dB does MRC show a better performance with a reduced BER. It can be also concluded that there is a not so significant improvement for the AWGN channel.

After observing the slight difference between 1.25 MHz and 5 MHz channel bandwidth, the system was simulated with a 10 MHz channel bandwidth. In light of the results for 5 MHZ, better results for 10 MHz were expected. While the system exhibits a slow improvement in BER with 5 MHz, it does not improve further with a 10 MHz channel bandwidth. A small degradation was even observed in terms of BER performance. The conclusion is that the size of the bandwidth does not have a direct effect on the BER performance. While it shifts the scale slightly upward or downward, the behavior of the system remains the same.

5.2.3 BER Performance For Varying Number of Fading Paths

To understand the effect of having several paths over the bit error rate, a 1 path-channel and 5 path-channel were compared for both diversity schemes. A 1.25 MHz fixed bandwidth was used for both schemes. It was found that multipath affects OFDM signal transmission. The multipath size is varied between L=1, L=3, and L=5 path models.

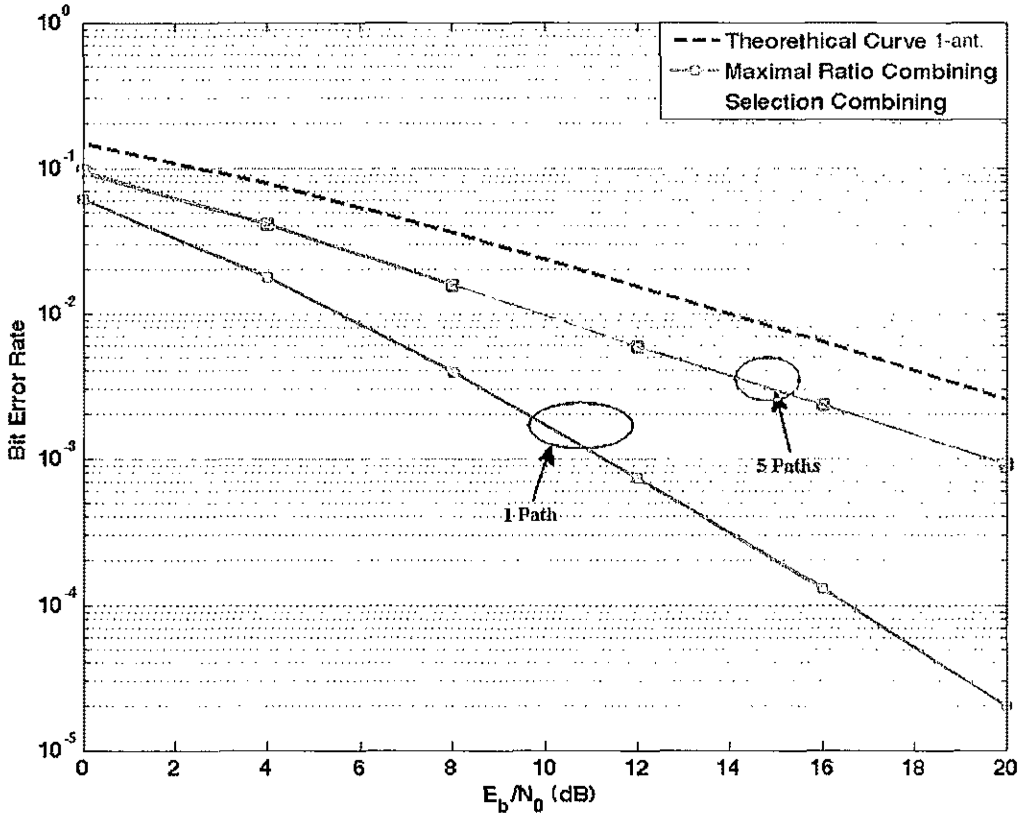

Figure 5.3 Combining Schemes with Various Paths (2 antennas).

Varying the path number, L, changes the frequency response to a longer or shorter term. The more the paths, the longer the transfer function becomes. As the number of paths increases, in terms of BER probability, it was noticed that there is not much difference. The BER probability is almost the same for L=3 and L=5. It was also observed that MRC and SC probabilities are very close to each other in a multipath environment. As the number of paths increases, the performance of the OFDM system worsens.

5.2.4 Comparison between WiMAX and LTE

LTE was developed in the Third-Generation Partnership Project (3GPP) as a natural progression of High-Speed Packet Access (HSPA). Both WiMAX and LTE are technically similar standards. WiMAX and LTE share common characteristics. They both have the same physical layer based on OFDM. They use multiple antenna system techniques to achieve high data rates. Nevertheless, the implementation of these features is different in both technologies. There are some differences present in the uplink access method used by both technologies. LTE uses SC-FDMA, whereas WiMAX uses OFDMA as an access method.

The simulations were run using LTE parameters and were compared to the WiMAX results. SC and MRC schemes were used to observe these two rival systems in terms of antenna diversity performance. Because LTE uses Frequency Division Duplexing (FDD) and WiMAX uses Time Division Duplexing (TDD), a fair comparison would be between 2.5 MHz LTE and 5 MHz WiMAX [6].

Figure 5.4 shows a comparison between WiMAX and LTE with 2 antennas. The bandwidth is set to 2.5 MHz for LTE and 5 MHz for WiMAX.

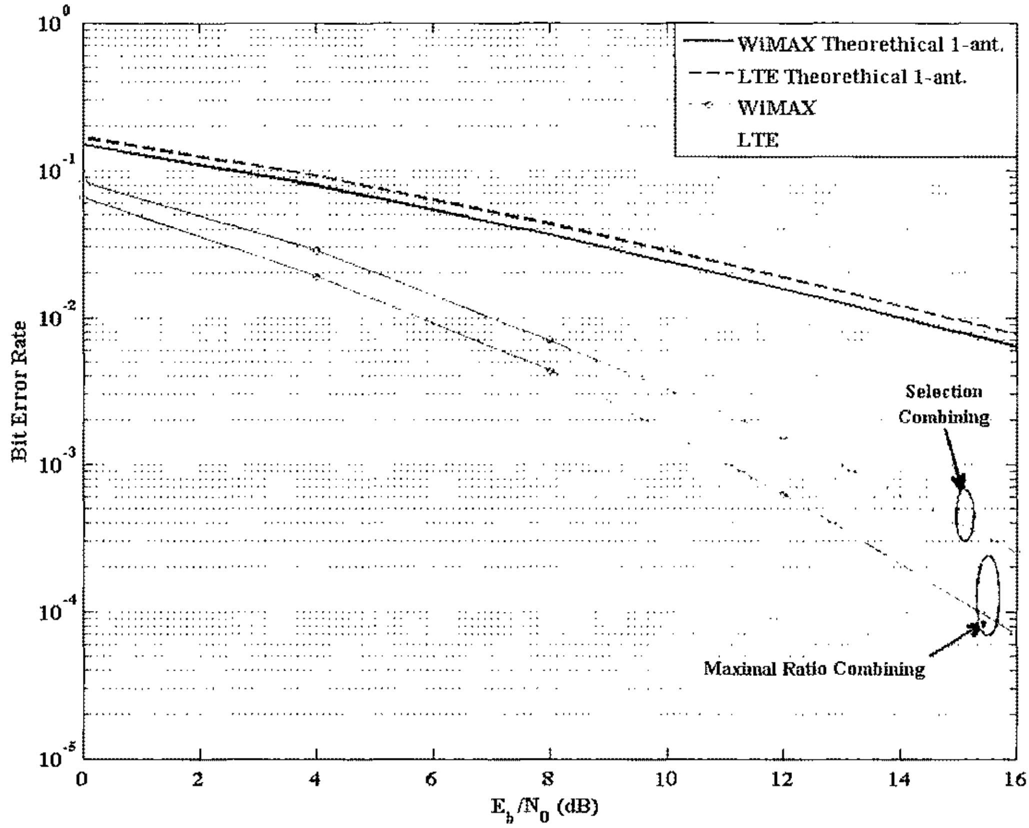

Figure 5.4 Comparison between LTE and WiMAX.

In the simulations, a fixed number of bits is used to calculate the BER. MRC has better results for both LTE and WiMAX in terms of BER. For SC, WiMAX produced less errors than OFDM by a small margin. WiMAX showed a slightly noticeable performance with reduced BER for MRC after $E_b/N_0 > 8$ dB.

As they have similar standards and have similar physical layer, results show that there are not radical differences between LTE and WiMAX in terms of BER performance.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

In this thesis, the calculation of the Bit Error Rate (BER) was studied for OFDM-based IEEE802.16 WiMAX systems. This thesis has presented a detailed study of the comparison of receive antenna diversity schemes when applied to WiMAX. BER results were presented for various scenarios. In the simulations, AWGN and multipath channels were used with diversity schemes to compute the BER performance curves.

For better performance, the antenna number should be increased. However, antennas should be mounted properly apart to provide uncorrelated paths. If the paths are uncorrelated, it is unlikely for them to experience deep fading simultaneously. Increasing the number of antennas also increases the overall cost. A high peak-to-average ratio (PAPR) is an inherent problem of OFDM. It reduces the efficiency and increases the implementation cost. PAPR can be reduced by various techniques. PAPR reduction increases the cost of the RF power amplifier, which is one of the most expensive components in the radio. Hence, while increasing the number of antennas to improve the performance, the most cost effective way should be decideed by taking these problems into account. After vigilantly comparing the plots of these scenarios, it can be concluded that a MRC scheme provides the best BER performance in Diversity techniques regardless of the number of antennas. A MRC with 4 antennas gives better results than SC with 8 atennas. However, implementation of SC is easier than MRC. For 2 antenna system, at lower values of

SNR, either MRC or SC scheme can be implemented, as there is not a significant BER difference between them. However, both for 4 antenna and 8 antenna systems, MRC gives significantly better results. It can be also concluded that the number of paths directly affects the BER performance of the system. In contrast, bandwidth size does not affect the BER performance directly as it shifts the scale upward or downward while the behavior of the system remains the same.

In the light of results in this thesis, it can be concluded that increasing the number of antennas on the receiver side improves the BER. Maximal Ratio Combining gives better performances compared to Selection Combining for any scenario.

6.2 Future Work

In all simulations, it was assumed that there was perfect synchronization between the transmitter and the receiver. As a consequence, frequency or timing offset errors were not taken into consideration. In order to reduce the effects of lack of synchronization, frequency offset estimation should be performed. In a further study, this feature may be combined with the diversity algorithms developed in this thesis.

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