Spring 2011

A Study of Diversity Techniques for LTE Wireless Systems

Ferhat Kaplan
Old Dominion University

A STUDY OF DIVERSITY TECHNIQUES FOR LTE WIRELESS SYSTEMS

by

Ferhat Kaplan
B.S. August 2003, Turkish Air Force Academy

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirement for the Degree of

MASTER OF SCIENCE

ELECTRICAL AND COMPUTER ENGINEERING

OLD DOMINION UNIVERSITY
May 2011

Approved by:

Dimitrie C. Popescu (Director)

Jiang Li (Member)

Danda B. Rawat (Member)

ABSTRACT

A STUDY OF DIVERSITY TECHNIQUES FOR LTE WIRELESS SYSTEMS

Ferhat Kaplan
Old Dominion University, 2011
Director: Dr. Dimitrie C. Popescu

The demand of attaining information and the wish to communicating anytime and anywhere has caused numerous innovations in the digital communication world. Today, approximately half of the people on earth somehow use wireless technology which is in every part of our lives. LTE (Long Term Evolution) and WIMAX (Worldwide Interoperability for Microwave Access) standards are the two leading wireless technologies, which support high data rates, multimedia applications, and voice video communications at very high speeds, also called 4G cellular systems in the global market.

These high expectations from wireless technology have revealed multiple antenna techniques which improve the performance and robustness of wireless channels using an array of antennas for both receiving and transmitting. Antenna arrays improve the channel quality by mitigating the effects due to multipath propagation.

In this thesis, better performance of LTE systems with multi antenna techniques is studied. After introducing multi antenna techniques, a wireless channel environment with fading paths is implemented using MATLAB software. The receive diversity techniques considered are maximal ratio combining (MRC) and selection combining (SC) and they are investigated for different number of antenna

configurations. Also varying numbers of fading paths are simulated in the thesis. Finally, a comparison between LTE and WIMAX is performed for several fading paths and their performances are evaluated.

Dedicated to my beloved wife Seda,to my dear son Tuna,

and to my baby girl Melek.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my advisor, Dr. Dimitrie C. Popescu for his guidance during my research and study at Old Dominion University. Without his support, expertise and positive outlook this thesis would not have been completed. I am grateful to Dr. Oktay Baysal who helped me at every stage of my journey at ODU. I also thank to my friends, First Lieutenants Aydin Meric and Gokhan Caliskan, for their moral support. I would like to thank to my mother, my father, my sisters and my brother for inspiring and encouraging me throughout my life. I also thank to my colleague, Selcuk Taskin, for his support in thesis and courses. And I would like to express my thanks to my other colleagues and friends at ODU whose names are not written here.

I am immensely grateful to Turkish Air Forces for this exceptional opportunity to further my education.

Finally, my sincere thanks go to my wife for her patience and emotional support.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Thirty years ago, wireless communication with a handheld device was like a dream. Today we are searching for the ways of having a video conference using smartphones while travelling at high speed in a fast train. It is not a part of our imagination anymore. The Long Term Evolution (LTE), a new standard developed by the Third Generation Partnership Project (3GPP), created demonstrations at high vehicular speeds with download speeds of 50 Mbps in a moving vehicle at 68 mph in April 2008 [1]. The growth of wireless technology in cellular systems made huge progress in the last 25 years. Today there are approximately 5 billion wireless subscribers in the world and approximately 2 billion internet users, according to an estimate by Ericsson [2]. Wireless mobile technology is the fastest growing part of communications industry and LTE is one of the most important ones.

The objective of this thesis is to study the use of receiver diversity techniques for LTE systems and to provide a comparison between LTE and the alternative broadband wireless technology Wimax (Worldwide Interoperability for Microwave Access) technologies.

In this chapter, a brief overview of mobile wireless technology is provided as it relates to LTE and discuss about LTE. Why is it needed? What are its aims and key requirements?

1.1Evolution of Broadband Wireless Standards

The first generation (1G) of wireless communication systems was developed in the United States, Japan and Europe, and their main focus was on providing wireless phone service. These systems were characterized by analog modulation schemes with FDMA (Frequency Division Multiple Access) being used for modulation [3]. The objective of 1G cellular systems was just to make voice transfer while moving.

The second generation (2G) systems emerged in the mid 1990s and their purpose was similar to 1G cellular systems. But the difference was that 2G systems used digital modulation instead of analog modulation. Digital modulation brought improvements to communications technology: it enabled the use of TDMA (Time Division Multiple Access) and FDMA (Frequency Division Multiple Access) together, and it improved performance and quality of service. The European companies, which were unsuccessful at 1G cellular systems, gathered for 2G systems and developed Groupe Special Mobile (GSM).

During the late 1990s the International Telecommunications Union (ITU) has created a standard for the third generation (3G) cellular systems which covers both wireless phone and data services. The standard, referred to as International Mobile Telecommunications 2000 (IMT-2000), assumes a data rate 2 Mbps in a fixed- or office-type environment, 384 kbps in a pedestrian urban environment and 144 kbps in wide area vehicular enviroments [4]. GSM provides these standards with W-CDMA (Wideband-Code Division Multiple Access) by 3GPP. W-CDMA is a direct spread sequence spectrum (DSSS) CDMA where synchronization, channelization, and scrambling are improved by multiplexing user data with pseudo-random codes, and operates on a bandwidth of 5 MHz. High speed packet access (HSPA) have been introduced by 3GPP using two important features: High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA) [3]. HSPA increases peak data rates up to 14.4 Mbps in the downlink (DL) and 5.8 Mbps in the uplink (UL). It also has capacity improvements both in the DL and UL [5]. An upgraded version of HSPA (HSPA+) is still used in the most of the world. For achieving higher data rates the 3GPP has developed an evolution of GSM/HSPA technology which is referred to as Long Term Evolution and also called 3GPP Release 8. Selected LTE parameters are shown in Table 1.1, and additional details can be found in [4].

Table 1.1 LTE Parameters.

Standard	3GPP Release 8	**Duplexing**	FDD and TDD
Peak DL Data Rate in 20 MHz	173 Mbps (2x2 MIMO) 326 Mbps (4x4 MIMO)	**Peak UL Data Rate in 20 MHz**	86 Mbps (1x2 Antenna Configuration)
Mobility	217.5 Mph	**Modulation**	QPSK, 16QAM, 64QAM
Multiple Access DL	OFDMA	**Multiple Access UL**	SC-FDMA
Frame Size	1 ms sub-frames	**User-Plane Latency**	5-15 ms
Channel Bandwidth	1.25, 2.5, 5, 10, 15, 20	**Channel Coding**	Convolutional and Turbo

1.2Why Long Term Evolution?

An important characteristic of LTE systems is their flexible bandwidth, which varies from 1.25 MHz to 20 MHz, instead of being fixed like in HSPA systems which makes LTE applicable to different scenarios where the size of the available spectrum varies. LTE uses three main technologies in the physical layer: OFDMA (Orthogonal Frequency-Division Multiple Access), SC-FDMA Single Carrier-FDMA, and MIMO (Multiple-Input Multiple-Output). OFDMA's main drawback is the high peak-to-average power ratio (PAPR) of the transmitted signals. A high PAPR forces the transmit power amplifier to have a large backoff, which is reducing input power to power amplifier and results in a lower average SNR at the receiver and a reduced transmit range, in order to ensure a linear amplification of the signal. It reduces efficiency of the transmit power amplifier and requires an expensive RF power amplifier [6]. These amplifirers can be used by LTE base stations (BS) but are not acceptable for mobile users. LTE overcomes this problem by using a type of OFDMA which is called Single Carrier-FDMA (SC-FDMA) that offers a better power efficiency in the UL and decreases the PAPR. MIMO antenna technology is one of the main advantages of LTE. By using multiple antennas, capacity, robustness and spectral efficiency are improved. Another advantage of LTE systems is the higher data rates provided: in the best scenario (20 MHz, 4x4 Antennas) LTE provides data rates up to 326 Mbps in the DL and 86 Mbps in the UL, which is faster than other wireless technologies. LTE has shorter frames that support faster feedback for retransmission. Thus, latencies are low and LTE provides better performance at high speeds. It also offers best support for Voice over Internet Protocol (VoIP) by using permanent scheduling. It reduces the overhead bit rate and this makes a difference when the timing is important [3].

Recently, handheld devices are not used only for talking or sending short messages anymore. The demand for live video streams, VoIP or using interactive applications is rapidly increasing. LTE intends to fulfill all these requests. LTE supports IP based network architecture and is expected to function more efficiently when Internet Protocol version 6 (IPv6) is deployed.

None of the wireless technologies have completed 4G cellular system standard, IMT-Advanced, which was defined by ITU. LTE also is not a 4G cellular system. But it is the most leading one in order to fulfill these requirements of IMT-Advanced standard. For this reason, 3GPP has established a new research group called LTE-Advanced and the target is to implement 4G cellular system standard.

1.3 Thesis Organization

In this thesis, the receive diversity is studied for LTE downlink with multi-antenna configurations and performed simulations using SC and MRC techniques.

In Chapter 2 the structure of OFDM, which is a multicarrier modulation method, usage of OFDM in LTE, and frame structure of LTE are discussed. Chapter 3 describes the multi acces techniques from past to the present and how LTE implemets OFDMA and SC-FDMA.

In Chapter 4, multiple antenna techniques, MIMO antenna configurations, transmit and receiver diversities are discussed. Problem definition is also done at the last section of this Chapter.

In Chapter 5, the simulations and numerical results are presented for LTE. The effects of different bandwidths, using various antenna configurations and receiver diversity techniques are analyzed. Also two alternative 4G systems, LTE and WIMAX, are compared owing to the performance of receive diversity.

In Chapter 6, the future works and the conclusions about using multiple antenna cofigurations are discussed.

CHAPTER 2

MULTICARRIER MODULATION AND OFDM

2.1 Introduction

Multicarrier modulation transmits a high data rate bit stream by dividing it into lower rate parallel streams and sending these streams over separate carrier frequencies referred as subcarriers. At the receiver, streams received over distinct subcarriers are reassembled and delivered to the user. The use of multicarrier modulation is widespread, e.g., Asymmetric Digital Subscriber Line (ADSL), wireless LAN (Local Area Network), and other high data rate communications. OFDM is the most common type of multicarrier modulation.

The main reason to use multicarriers is to have higher data rates without ISI (Inter Symbol Interference). OFDM implements this using N narrow band subcarriers over a wide channel bandwidth. In order to eliminate ISI, subcarrier bandwidth must be less than B_{COH} (Coherence Bandwith). If the all channel bandwidth is B, then B_{SUB} (subcarrier bandwidth) is B / N which is smaller than B_{COH} ($B_{SUB} << B_{COH}$) while B is larger than B_{COH} ($B >> B_{COH}$). If N is large enough all subcarriers experience flat fading and therefore ISI is small on each of them. Orthogonality between subcarriers does not deteriorate and the signals are detected correctly at receiver.

In time domain, if the symbol duration (T_s) is efficiently larger than the delay spread then the channel will be ISI-free. Normally, T_s is less than the delay spread. But using multicarriers, symbol duration is N x T_s and the result of N x T_s is larger than the delay spread. But the real implementations are still time limited and in order to get a rectangular pulse shape at the receiver low pass filters are needed. The main problem is the N RF unit requirement. OFDM overcomes this by using IFFT (Inverse Fast Fourier Transform) which is equivalent to modulating data symbols and combining them. At the receiver, FFT, which is reverse of IFFT, is used for retrieving the data stream.

2.2 OFDM

OFDM, by using orthogonal subcarriers, not only decreases ISI but also saves the bandwidth used for transmitting OFDM signal. As it seen in Figure 2.1, the classical FDM use more bandwidth than OFDM.

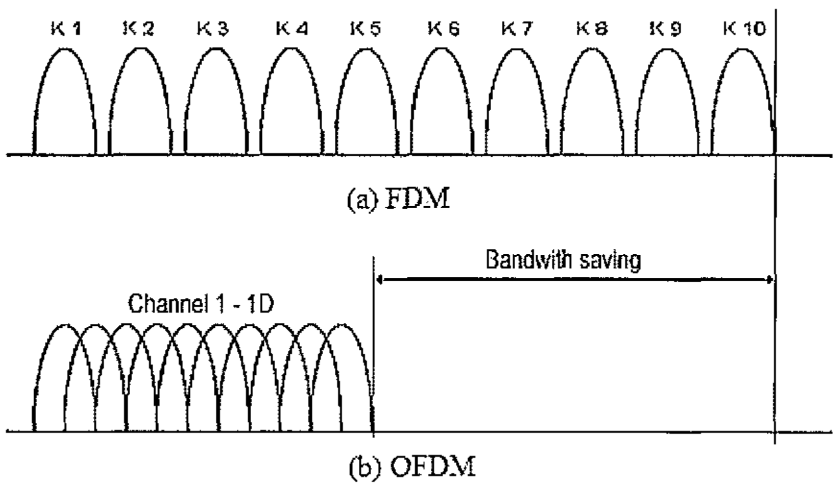

Figure 2.1 Comparison between Conventional FDM and OFDM [7].

2.2.1 Guard Intervals and Cyclic Prefix

We have seen how OFDM managed to defeat ISI above, but there is also Intercarrier Interference (ICI) which is the undesired effect or interference on a subcarrier generated by adjacent subcarriers. ICI can be decreased by leaving an efficient interval between two OFDM symbols. An efficient interval means that the guard time (T_g) must be larger than the channel delay spread, because there are many delayed versions of transmitted signals in a multipath fading channel.

The cyclic prefix is the addition which is taken from the last part of an OFDM symbol and added to the beginning of that symbol at the transmitter and then is removed at the receiver. The cyclic prefix also makes the OFDM symbol periodic which is required for circular convolution. Normally the OFDM symbol is a linear convolution of a frequency selective channel. But, adding a cyclic prefix to the OFDM symbol causes the signal to be modeled as a circular convolution. And if a channel provides circular convolution, FFT and IFFT algorithms, which lessen mathematical operations, can be used for computing DFT and IDFT. Usage of a cyclic prefix can be seen as a waste of bandwidth and power. But if N (Number of carriers) is chosen to be large enough, the length of the cyclic prefix is shortened and this tradeoff can be in favor of the system. Another important reason for using cyclic prefix is to reduce ISI. If the length of cyclic prefix is larger than maximum channel delay spread, the ISI is mostly defeated.

2.2.2 Frequency Equalization

Whenever a transmitted signal passes through a channel it is exposed to a distortion (phase or amplitude) by the channel and weakened by noise. Equalizers are used to eliminate this distortion. In OFDM, received symbols (*Y[n]*) are divided by channel gains (*H[n]*) after the FFT. This is called frequency equalization.

$$X[n] = \frac{Y[n]}{H[n]} \tag{2.1}$$

On the other hand, frequency equalization also increases noise by scaling nth subcarrier $1 / H[n]$.

2.3 Timing and Frequency Synchronization

There are two main synchronization methods for demodulating OFDM symbols, timing and frequency synchronizations. Timing and frequency offsets are used in these methods. OFDM symbols are very sensitive to the frequency offset. If the transmitter and receiver work in the same frequency, subcarriers will be orthogonal. But it is not actually possible because of the discrepancy of the oscillators between the transmitter and the receiver. This is why the ICI is always mentioned for OFDM rather than single carrier systems. OFDM is less insensitive to the timing errors. The cyclic prefix already reduces the timing offsets substantially.

Timing offsets can alter in an interval equal to or less than guard time without resulting in ISI and ICI as long as this interval is protected with the phase shift which is introduced by timing offset can be fixed by equalizer. It is then assumed that phase variation remains constant. If the timing offset is not in this interval, the ISI appears and SNR (Signal-to-Noise Ratio) loss is inevitable.

The ICI is unavoidable after FFT if the frequency offset is not zero. Subcarriers, which are near the middle of the frequency band, have more interference than the ones at the band edge. Two main reasons for frequency offsets are inharmonious oscillators at the transmitter and the receiver and the Doppler Effect. SNR loss increases very fast with the frequency offset and the number of subcarriers. Decreasing the cyclic prefix which is one of the methods of more bandwidth usage is a tradeoff between choosing frequency offset and more bandwidth.

2.4 Peak to Average Power Ratio

OFDM's main drawback is the high peak-to-average power ratio (PAPR). A large PAPR has disadvantages like severe non linear distortion, unefficient power amplifier, high cost of the system, and high resolution complexity for A/D converter at the receiver. In OFDM, the goal is minimizing the PAPR or holding it at a certain level. There are also some methods for decreasing the PAPR which are explained in [8].

There are N numbers of subcarriers, which are modulated independently, in an OFDM signal. When all are summed up adherently, a high PAPR results, which is proportional to N. As it seen, as the number of subcarriers goes up the PAPR also increases. However, increasing N is desired as much as possible for a lesser ratio of the cylic prefix. There is again a tradeoff between PAPR and the number of subcarriers. A larger PAPR requires expensive high power amplifier (HPA) of which power consumption mostly relates to peak power values rather than average power values. Obviously, if the peak power and average power is close enough HPA operates more efficiently. In the DL, the PAPR problem is handled by using expensive equipment at BSs; this is possible for BSs because their numbers are few. But mobile users are many and the cost is not acceptable. That is why LTE uses SC-FDMA at the UL which defeats the PAPR problem. SC-FDMA is explained in the following part.

2.5 Multiple Access Systems

If a channel is shared with multiple users it is called a 'Multiuser Channel'. When these multiple users try to achieve this channel or resource it is called 'Multiple Access'. The goal of multiple access is for multiple users to share the resource without having any interference. An uplink channel is also a multiple access channel. In a multiple access channel, some certain channels are assigned to users for specific opeations, e.g. VoIP, video calls. Because the bandwidth is inadequate and expensive, assigning it to users must be done very efficiently. Asssigning these channels from the signal space to the users is done with different methods such as frequency division, time division, code division, space division or some combination of these methods. Most popular ones of these are TDMA, FDMA and CDMA.

For the most part, all of these methods use orthogonality except in some forms of CDMA. Although orthogonality mostly defeats the interference there are many methods that do the same because they all use one of the frequencies, time slots or codes. In theory, there must not be so much difference between them. However, the truth of the matter is different. Namely, orthogonality can not be obtained in some wireless areas. In multi cell wireless systems, the same frequency or time slot sometimes can be used simultaneously. Frequency selective and flat fading is also a very important issue in different wireless areas. All of these methods behave differently from each other in various wireless areas due to their characteristics. That is why all these multi access methods are in use.

2.5.1 Random Access vs. Multiple Access

When the bandwidth is shared among multiple users with random allocation it is called 'Random Access'. The choice of the usage of either multi access or random access mostly depends on the characteristics of the channel and the performance and user requirements.

The most popular random access method is Carrier Sense Multi Access (CSMA) which uses packet-based communication system. In CSMA, the users, in contrast to the methods which channels are dedicated to, compete for the channel. They listen to the channel. The ALOHA method, in which if there is no acknowledgment for those packets they are transmitted again after sending the packets, is also used for random access. It is an unefficient method because of the collisions and delays. An improvement to ALOHA is Slotted ALOHA (or SALOHA) which works the same way but uses time slots.

2.5.2 FDMA

In FDMA, the frequency axis is partitioned into the nonoverlapping bands and the channel is used concurrently by all users. The easiest method for allocation of the bandwidth is done by assigning sets of subcarriers to the users. A multiplexer is used for allocation before the IFFT process. There are also guard bands between channels in order to decrease the adjacent channel interference. FDMA also can provide bandwidth efficiency by estimating which channels are weak for which users. Each user is assigned to a different set of frequencies illustrated in Figure 2.2. There are guard bands between adjacent channels which decrease the adjacent channel interference. Co-channel interference, which originates from the users who have the same frequency in different cells, must also be considered and distances between the cells must be arranged due to this factor.

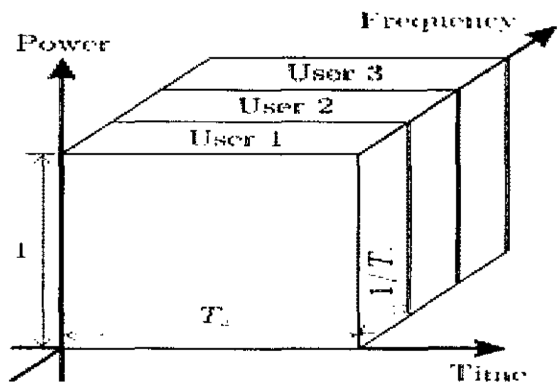

Figure 2.2 Frequency Division Multiple Access.

2.5.3 TDMA

In TDMA, a certain time slot is periodically dedicated to a specific user. The users have the whole bandwidth in this time interval that is shown in Figure 2.3.

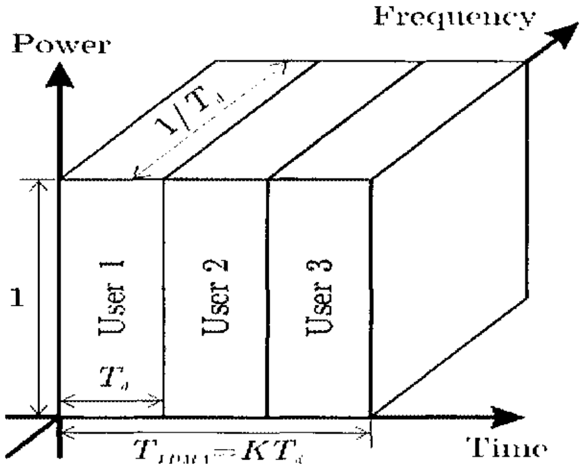

Figure 2.3 Time Division Multiple Access.

Periodic repetition of the time slots shows that the transmission is not continuous. For this reason, users do not permanently know the channel characteristic and also have to estimate channel impulse response every time.

Being affected from fading and synchronization errors is the major disadvantage of the TDMA. Because TDMA uses time slots and the synchronization becomes more important between users especially in the UL where every user transmits data with different channels.

2.5.4 CDMA

CDMA assigns whole frequency and time plane to all users simultaneously, which makes it different from TDMA and FDMA, which share time and frequency. CDMA is shown in Figure 2.4. Both orthogonal and nonorthogonal codes are used for modulation. In order to differentiate users at the receiver and to spread the signal to the dedicated bandwidth, a pseudo-random code is used [9]. The most popular of these codes are direct sequence spread spectrum and the frequency hopping spread spectrum. CDMA is also the most favorite multiple access method in 3G cellular systems.

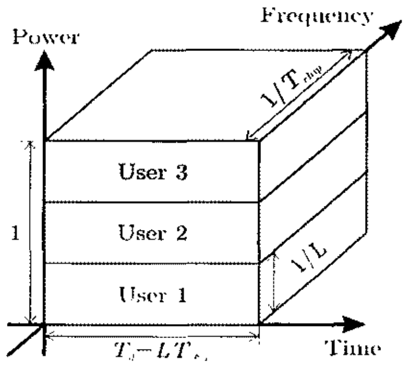

Figure 2.4 Code Division Multiple Access.

CDMA ensures the user privacy with unique spreading codes. Multiple access interference is one of the disadvantages of CDMA. Wideband channels can weaken the orthogonality of the codes. Usage of the orthogonal codes also causes a hard limit on the number of ortohogonal channel. For nonorthogonal channels, there is no such hard limit. The distance of the mobile users to the BS is also a problem in CDMA. The received powers of the signals change due to the distance of the mobile users. The power of near users makes interference on the far ones and this is called 'near-far effect'. Thus, an efficient power control system is needed.

CHAPTER 3

OFDM IN LTE SYSTEMS

3.1 OFDM in LTE

OFDM technology is very popular for multicarrier modulation in wireless technologies. Before describing OFDM usage in LTE, the elements of OFDM are illustrated in Figure 3.1. The main block diagram of OFDM and basic elements are also illustrated.

Firstly, using QPSK a serial data stream is modulated and then transmitter splits these data to parallel streams which are carried over a number of subcarriers. If all the bandwidth is B and there is N number of subcarriers then all subcarriers have a narrow bandwidth B/N. Thus, all subcarriers have flat fading.

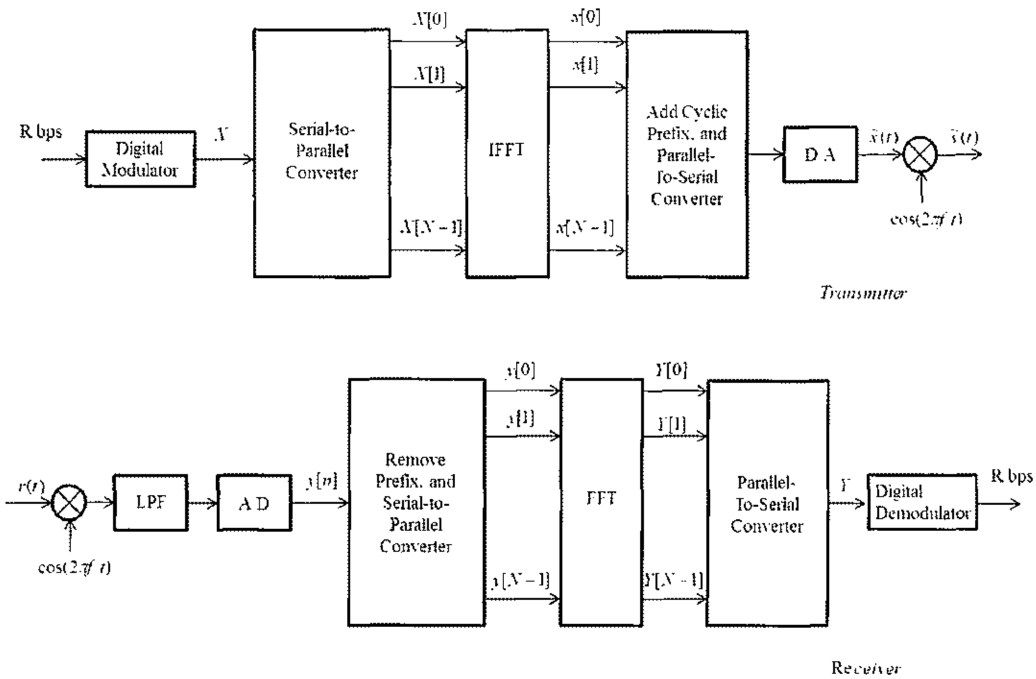

Figure 3.1 OFDM Main Block Diagram [10].

IFFT operation takes place for transmitting data in a single RF antenna instead of using *N* RF antennas.

Next, the cyclic prefix, which is longer than delay spread, is added in order to reduce the ICI. Then the bit stream is sent in serial through the channel.

Channel will have effects on symbols like multipath, noise and interference. Receiver makes the reverse of the transmitter. Firstly, the receiver splits the serial stream into parallel sets and then the cyclic prefix is discarded.

FFT converts time domain samples to frequency domain. Finally, frequency equalizer divides each subcarrier with channel gain and the parallel sets are serialized in order to be used.

3.2 LTE Frame Structure

LTE physical layer is designed for the needs of a flexible channel bandwidth (1.25 MHz-20 MHz) and high data rates (100 Mbps in DL, 50 Mbps in UL). There are two frame types in LTE; Frequency-Division Duplexing (FDD), which is more common recently, and Time-Division Duplexing (TDD). In the DL, adaptive modulation and coding is provided with 16QAM, 64QAM, and QPSK. The UL is optional. The LTE frame structure in frequency domain is illustrated in Figure 3.2.

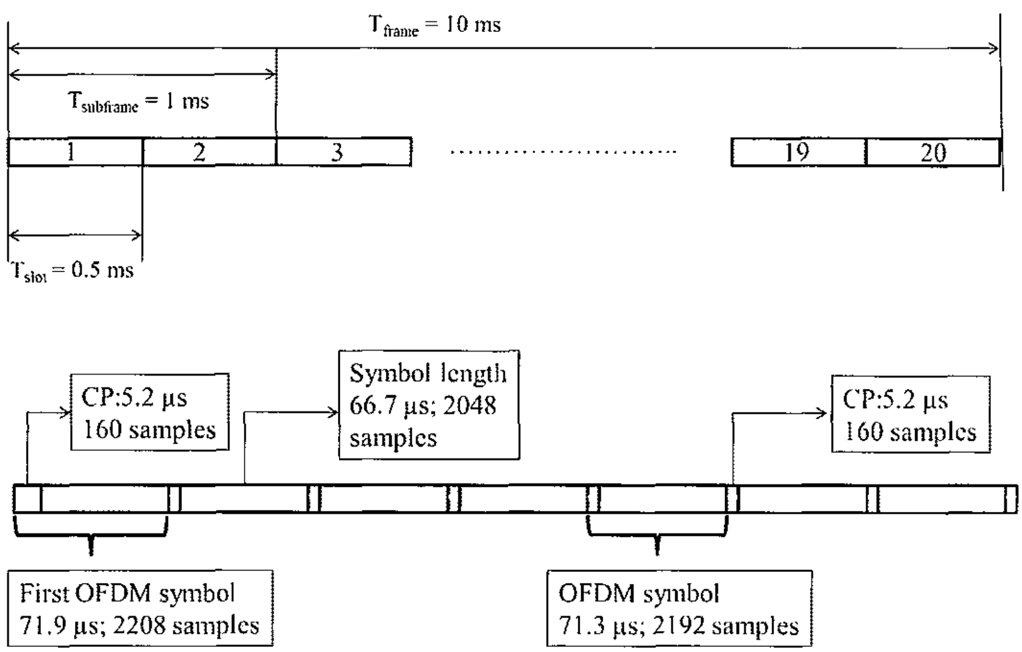

Figure 3.2 LTE Frame Structure.

In time domain, LTE uses a main sample time T_s with FFT size, $N_{FFT} = 2048$ and the subcarrier spacing is $\Delta f = 15$ kHz. FFT size changes due to the transmission bandwidth.

$$T_s = \frac{1}{15000 \cdot 2048} = \frac{1}{30720000} s \quad . \tag{3.1}$$

The length of a radio frame is

$$T_{frame} = 307200 \cdot T_s = 307200 \cdot \frac{1}{30720000} = 10ms \ . \tag{3.2}$$

One frame is split into 10 equally sized subframes,

$$T_{subframe} = 30720 \cdot T_s = 30720 \cdot \frac{1}{30720000} = 1ms \quad . \tag{3.3}$$

Each subframe has two slots,

$$T_{slot} = 15360 \cdot T_s = 15360 \cdot \frac{1}{30720000} = 0.5ms \quad . \tag{3.4}$$

In each slot there are 6 or 7 OFDM symbols which change due to the usage of the cyclic prefix that has two forms being extended and normal. The useful symbol length is 66.7 μs.

$$T_u = 2048 \cdot T_s = 66.7\mu s \tag{3.5}$$

The first and the other six OFDM symbols' cyclic prefixes and the extended cyclic prefix are, respectively,

$$T_{CPFirst} = 160 \cdot T_s = 5.2\mu s \tag{3.6}$$

$$T_{CPSix} = 144 \cdot T_s = 4.7\mu s \tag{3.7}$$

$$T_{CPExtended} = 512 \cdot T_s = 16.7\mu s \tag{3.8}$$

The sampling rate, f_s is equal to Δf x N_{FFT}. This result for all FFT sizes is multiple or sub-multiple of the chip rate of WCDMA, 3.84MHz. Hence, WCDMA/LTE terminals can work with a single clock circuitry [3].

There are 2,048 subcarriers, and each of them carries data in a bandwidth, *B/N*, have to accept approximately 7% of the overhead for the cyclic prefix in order to degrade the ICI.

3.3 OFDMA

In Orthogonal Frequency Division Multiple Access (OFDMA), each user has a portion of the available subcarriers over contiguous OFDM symbols. The available subcarriers can be expanded to the entire spectrum or be a group of adjacent subcarriers. Expanded subcarriers are a good choice when there are few weak subcarriers that can be corrected due to the accuracy ratio of overall band. So the effect of weak subcarriers is minimized and the integrity is protected by coding and interleaving. A group of adjacent subcarriers also may be a good choice when the SNRs of some certain subcarriers are known. In this way, users can choose which group of subcarriers has more SNR, and transmit over to that group of subcarriers. But when a fast moving user is the point in question it is difficult to have the knowledge of which subcarriers to move to.

The BS can also distribute subcarriers to the users owing to the channel state information (CSI) which shows the quality of the channel for a specific frequency. When it is done, each user will have a strong signal.

3.3.1 How OFDMA Works

In OFDMA, N subcarriers are shared by L users and a certain number of subcarriers, M_l, are assigned to each user. The total number of M_l is equal to N. OFDMA transmitter block diagram is illustrated in Figure 3.3.

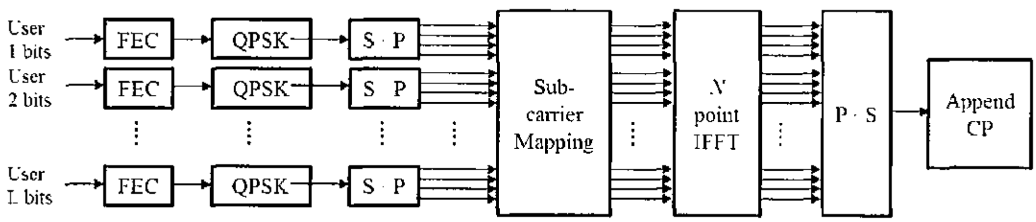

Figure 3.3 OFDMA Transmitter.

At the receiver each user only looks for its own subcarriers. Firstly N-point FFT is done and the whole band is demodulated. Although the user only needs a portion of the waveform, the FFT and demodulation process is done for entire band which causes additive power consumption. Figure 3.4 shows a OFDMA receiver block diagram.

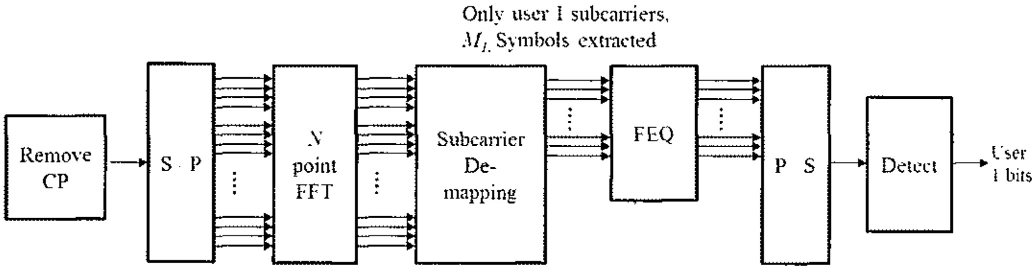

Figure 3.4 OFDMA Receiver (for User 1).

OFDMA is used in the DL in LTE. If OFDMA is assumed for the UL, there is a large frequency offset and subcarriers loose their orthogonality substantially. There are also time offsets which require being less than delay spread. But in the UL, because every user transmits its data independently, larger time offsets become inevitable.

3.3.2 Advantages and Disadvantages

OFDMA is a very scalable multi access technique. It has a wide range of bandwidth that changes from 1.25 MHz to 20 MHz and these bandwidths answer the needs of a variety of users. Even if the FFT size changes, subcarrier spacing and the symbol duration are stable.

OFDMA subcarriers protect their orthogonality against the multi paths as long as the cyclic prefix is longer than the delay spread. When the CSI information is used OFDMA has a better performance than TDMA and FDMA. The deployment of the MIMO technologies is also easier for OFDMA.

In OFDMA, bandwidth is divided to narrow bands. Thus, the frequency offsets affect the OFDMA system performance widely. Another downside of the

OFDMA is the high PAPR which arises from Gaussian distribution of the waveform and incurs the need of expensive power amplifiers [11].

3.4 SC-FDMA

UL transmissions are problematic because of the limited power, which mostly depends on the distance from a mobile user to the BS, on users' handheld devices. In order to discard this power amplifier issue, LTE uses single carrier frequency division multiple access (SC-FDMA) which has a low PAPR in the UL. Single carrier frequency domain equalization (SC-FDE) can be accepted as the source of the SC-FDMA. But SC-FDMA takes the low PAPR feature of this source and, the use of a portion of a frequency band is also acquired with OFDMA technology.

3.4.1 How SC-FDMA Works

As can be seen in Figure 3.5, after the Forward Error Correction (FEC) and the modulation, the data are transformed to the frequency domain by M-point FFT and subcarrier mapping. Subcarrier mapping generally can be done in two ways: distributioning and localizing. Distributioning maps the FFT outputs to the subcarriers with equal intervals by spreading them all over the bandwidth. It is good for frequency diversity but bad for multiple address interference. The other method is localizing which maps the FFT outputs to the contiguous subcarriers. In this way frequency diversity decreases but multiple address interference is minimized. After the subcarrier mapping the data are converted into the time domain by M-point IFFT. After M-point FFT if N-point IFFT is implemented with $N>M$ unused inputs except from M are set to the zero. And output of the IFFT becomes a signal with single carrier properties [12]. After that, a cyclic prefix is added and the signal is finally created by pulse shaping filters.

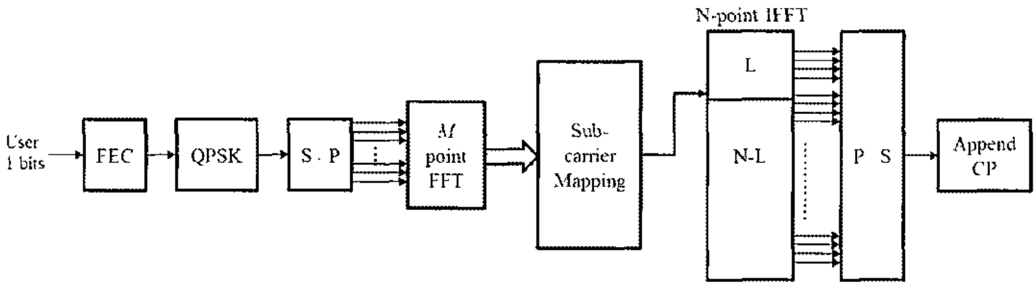

Figure 3.5 SC-FDMA Transmitter (for user 1).

In fact, the reverse of the transmitter side is done at the receiver side and is also shown in Figure 3.6. Additionally frequency equalization is done for each user and after that the original signal is obtained with M-point IFFT.

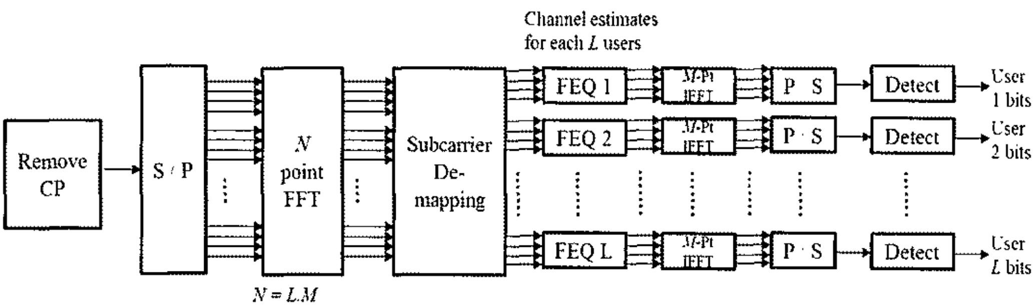

Figure 3.6 SC-FDMA Receiver.

3.4.2 Advantages and Disadvantages

The most noticeable advantage of SC-FDMA is PAPR which is notably less than in OFDMA. The PAPR requires high power amplifiers which are very expensive. Because of their costs they cannot be requested by users.

SC-FDMA also makes use of the OFDMA structure which only uses a portion of the frequency band. Thus, by using the channel state information, adaptive usage of the frequency band is provided. Since the whole bandwidth is not used the transmit power also becomes lower.

In SC-FDMA, an additional FFT process is done both at the transmitter and at the receiver for every user. The sensitivity to the frequency diversity and the Doppler Effect is not seen in SC-FDMA as much as OFDM because of its single carrier character.

3.4.3 OFDMA and SC-FDMA in LTE

LTE uses a basic time and frequency unit in order to provide exact timing elements and different time intervals. LTE also defines protocols in order to show the state and the resources of the system e.g., channel allocation information. Another issue is the distance of the users to the BS. There are a lot of factors like different transmit powers which also affect the other users' quality of service parameters and need to be taken into account.

Mobile units are grouped into the 'resource block' which consists of 12 subcarriers over 7 OFDM symbols in case of normal cyclic prefix. A resource block is considered as a time slot which is 0.5ms and there are also 84 'resource elements' in a resource block. Two contiguous time slots make a subframe. A resource block is defined over a time slot the main time domain unit in LTE, a subframe which is also called 'a pair of resource blocks'. As mentioned before, subcarriers are allocated in two ways; distributed allocation and adjacent subcarrier allocation. In distributed allocation, users' subcarriers are spread over the band with equal intervals which provides the frequency diversity in a good manner. This is also used in the DL (OFDMA). As an alternative, a group of subcarriers can be spread over the bandwidth which is used in the UL (SC-FDMA) in order to take advantage of the frequency diversity. In adjacent subcarrier allocation, each user uses the group of subcarriers where they have the strongest channel.

LTE provides a channel, which is called physical downlink control channel (PDCCH), in order to get the information of transmissions and receptions subcarriers. A BS sends this information over the first 2 or 3 OFDM symbols which correspond to approximately 17% of a subframe. In order to help the UL scheduling, users send the queue length and the channel quality information to the BSs. Those are called buffer status reporting (BSR) and channel quality information (CQI), respectively.

LTE uses the same frequency and time in the different cells which, in one hand, prevents the ISI and, on the other hand, causes inter cell interference. Inter cell interference is crucial for edge users who are at the same distance to the BSs and incur high interference. There is also range problem which originates from different received powers at the BS and the strong ones received powers deteriorate the weak ones. Clearly, these two problems indicate the need for efficient power control mechanisms. In the DL, a BS can define power offsets due to the distance of mobile users. But in the UL, a LTE can use a closed-loop power control. A BS determines the power densities for users and this information is sent to the users by PDCCH. Also users can arrange transmit power due to the received average power which also accommodates to the varying channel characteristics.

CHAPTER 4

RECEIVER DIVERSITY TECHNIQUES

In wireless channels, Rayleigh fading and log normal shadowing are one of the main reasons of performance degradation. The best way to defeat this deterioration is to use techniques for combining signals received over uncorrelated independent paths at the receiver which are referred to as diversity techniques as it is assumed that independent signal paths are not affected by large fading at the same time. Obtaining multiple independent paths can be accomplished with the use of multiple antennas either at the transmitter or at the receiver.

For omnidirectional transmitter or receiver antennas, the minimum distance for independent fading on each antenna in a uniform scattering environment is nearly one half-wavelength (λ). If the antennas are directional the multipath is limited to a small angle relative to the line of sight ray. The scenarios and antenna configurations for LTE are listed in Table 4.1 where λ is the wavelength defined as $\lambda = c / f_c$, c is the speed of light (3.10^8 m/s) and f_c is the carrier frequency [13].

Table 4.1 Scenarios for LTE Antenna Spacing.

Propagation Scenario	**BS Arrangement**	**Mobile User Arrangement**
Suburban Macro	3-sector, 0.5λ spacing	Handset, talk position
Urban Macro (low spread)	6-sector, 0.5λ spacing	Handset, data position
Urban Macro (High spread)	3-sector, 4λ spacing	Laptop
Urban Macro	6-sector, 4λ spacing	Laptop

Multi antenna techniques are also referred to as Multiple-Input-Multiple-Output (MIMO) as they create Transmitter-Receiver systems with multiple inputs and outputs. In this thesis, the focus is on receiver diversity where multiple antennas are used at the receiver to provide diversity.

4.1 Spatial Diversity

Spatial diversity is provided with indepenedent fading signal paths which are obtained with multiple antennas at the receiver and the transmitter. These multiple antennas are called antenna arrays in which enough distance between antennas is needed for achieving uncorrelated fading paths. The distance is related to the frequency of carrier and the environment. Antenna configurations can be various which are shown in Figure 4.1 and Figure 4.2.

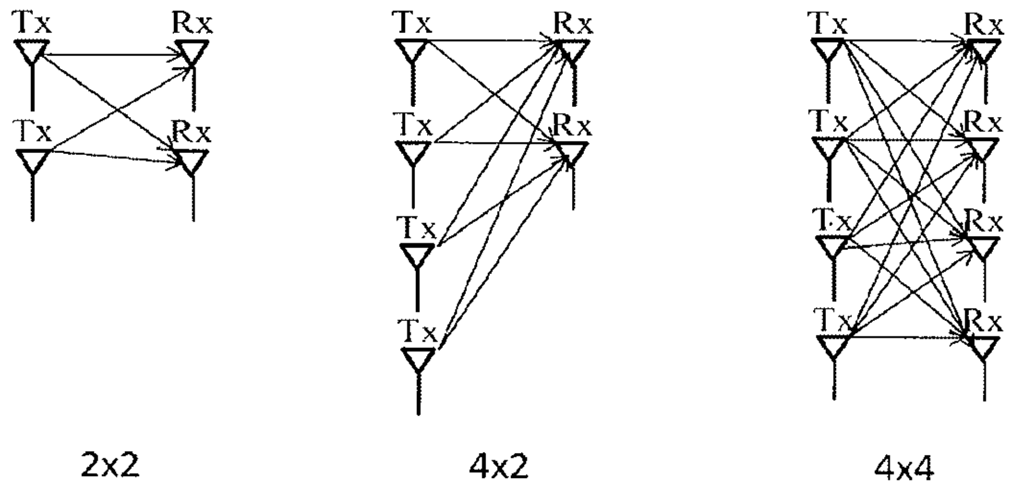

Figure 4.1 LTE DL Antenna Configurations.

LTE antenna configurations are 2x2, 4x2, and 4x4 at the DL, and 1x2, 1x4 at the UL.

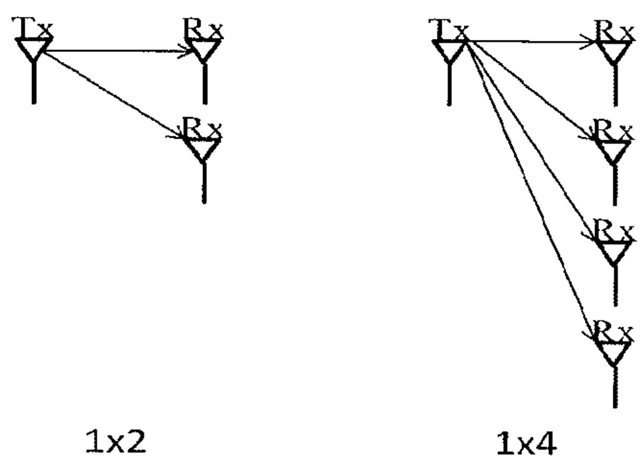

Figure 4.2 LTE UL Antenna Configurations.

The most important advantage of the spatial diversity is that it does not require any additional signal power or bandwidth. Only the additional RF antennas and signal processing cost is taken into account. When the received diversity signals are combined, the SNR is more than the SNR when one receiver antenna is used. The rise in the SNR is called 'array gain'. The array gain increases linearly with the number of received antennas (N_r) even if the received diversity signals are completely correlated. In array gain, the SNR values of each received signals are added contiguously without paying attention to the antenna distances. In diversity gain, which definitely needs diversity signals, antenna spacing is very important.

The uncorrelated signal paths, which occur in a fading channel, cause a decrease in the probability of error (P_e). This decline is called 'diversity gain' and in contrast to an array gain if diversity signals are not uncorrelated there becomes no diversity gain. But, if they are uncorrelated, P_e decrease is exponentially proportional with the multiplication of the transmitter and receiver antennas.

When the replicas of a signal are transmitted on different antennas it is called transmit diversity where the transmit power is shared between antennas. Transmit diversity is usually implemented in systems where transmitters have more power and space than receivers. That is why transmit diversity is more rational for BSs, where more antennas can be used, than for mobile users. Transmit diversity is considered due to the knowledge about the channel. If the channel is known at the transmitter it is called a 'Closed-Loop', otherwise it is called an 'Open-Loop'.

In closed-loop transmit diversity (CL), feedback from the receiver is needed and, using this gain, a signal is weighted and sent through the transmitter antennas. At the receiver the transmitted signals are combined coherently. This is shown in Figure 4.3.

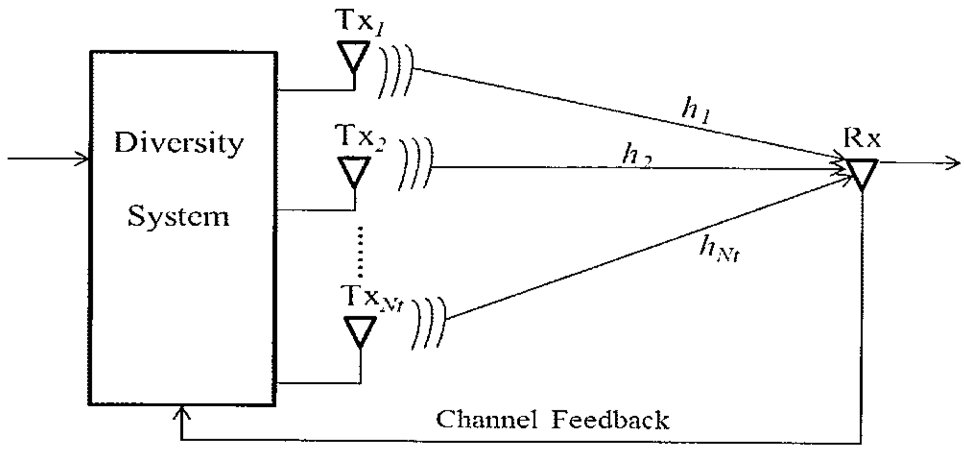

Figure 4.3 Closed-Loop Transmit Diversity.

When the channels' gains are known at the transmitter, transmit diversity is more like MRC. If all antennas have same channel gain, diversity gain is like an array gain [9]. It is more likely to use CL diversity in fixed systems instead of highly mobile ones. Because channel information is needed a lot in CL diversity and in highly mobile systems channel varies very fast. This feedback from the receiver can be done by putting channel information to the every acknowledgment frame.

In open-loop diversity (OL), transmitters do not have any information about the channel gains. One of the popular OL diversity techniques is Space Time Block Coding (STBC). In STBC, a code, which is also known by a receiver, is applied at transmitter. Alamouti developed an easy orthogonal space time block code which can be implemented at both transmitter and receiver. This scheme supports complete diversity gain using a maximum likelihood decoding algorithm. This scheme provides the same diversity gain as MRC (1x2 Antenna configuration) by using two antennas at the transmitter and one antenna at the receiver. It can also be generalized to more than two antennas at the transmitter [14]. When the channel information is unavailable and fast varying, like the Doppler Effect, OL is a good option. Mobile units can use this technique at their receivers because it does not reqire complex detectors.

The antenna elements can suppress the undesired interference in certain directions while increasing the power towards a desired user direction. Beamforming combines the signal paths exploiting array and diversity gain, but the channel information is mandatory. Beamforming is done using a weighting vector, which is acquired with instantaneous user information. According to this vector, channel gain in the direction of the target receiver is increased while the direction of undesired interference is suppressed. It can be implemented both at transmitter and receiver. This method minimizes the interference from other users, but the gain from these users is wasted.

In spatial multiplexing, a signal data stream is divided into several streams and these multiple streams are transmitted at the same time via different antennas on the same channel. Received signals are combined at the receiver which has the exact channel information. In order to combine the transmitted streams linear, successive and maximum likelihood decoding methods are used at the receiver. Spatial multiplexing increases data rates, which are proportional to the number of antennas at transmitter and receiver, using multiple paths for carrying additional data. One of the important advantages of spatial multiplexing is that no additional bandwidth or power is required.

4.2 Receiver Diversity

Multiple antennas at the receiver side are called receive diversity, which is useful on both frequency selective and flat fading. If it is used on flat fading it becomes array gain. In receiver diversity, the frequency-selective fading received signals are combined in various ways. There are two popular methods for combining these signals; Selection Combining (SC) and Maximal Ratio Combining (MRC). In SC the best received signal is chosen. In MRC the diversity signals are weighted with the channel factor and combined. The number of receive antennas (N_r) depends on the standard used and for LTE this can be either 2 or 4.

4.2.1 Selection Combining

The easiest version of diversity combining is Selection Combining (SC) which estimates the instantaneous signal power (or the SNR) for N_r receiver antennas and selects the highest one. It is mostly used for its ease and decreased system needs.

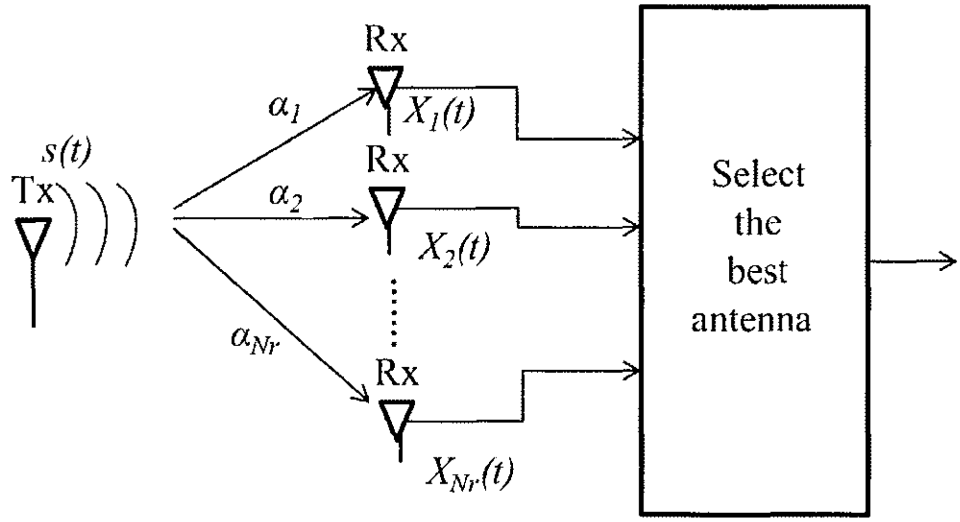

Figure 4.4 Selection Combining.

Figure 4.4 shows a SC receiver diversity structure. A common transmitted signal $s(t)$ is received by N_r antennas. SC selects the received signal with the highest instantaneous SNR. Furthermore, because only one branch is used co-phasing of multiple branches are not needed.

It is assumed that the wireless channel is a frequency-flat, slowly fading Rayleigh channel in order to show why SC is useful. Frequency-flat shows that the $s(t)$ has the same random attenuation and phase shift for all received signals. In slow fading, fading is constant during the transmission of each symbol and fading is described by Rayleigh distribution.

$s(t)$ is transmitted in and the complex envelope of the modulated signal is $\tilde{s}(t)$. And the complex envelope of the received signal at the kth receiver is

$$\tilde{X}_k(t) = \alpha_k e^{j\theta_k} \tilde{s}(t) + \tilde{w}_k(t), \qquad k = 1,2,...N_r \qquad (4.1)$$

The fading term is represented with $\alpha_k e^{j\theta_k}$ and the additive channel noise is $\tilde{w}_k(t)$. Assuming slow fading with respect to symbol duration T, the phase shift θ_k can be estimated and removed. In this case, Equation 4.1 is simplified to

$$\tilde{X}_k(t) = \underbrace{\alpha_k \tilde{s}(t)}_{Signal} + \underbrace{\tilde{w}_k(t)}_{Noise} \tag{4.2}$$

Then the average SNR can be written for k diversity branches at the output of the receiver as

$$(SNR)_k = \gamma_k = \frac{E\left[\left|\tilde{s}(t)\right|^2\right]}{E\left[\left|\tilde{w}_k(t)\right|^2\right]} \cdot E\left(\alpha_k^{\ 2}\right) \tag{4.3}$$

The mean square value of the noise is generally the same, N_0, for all of the k branches and the transmitted signal energy is E.

$$\gamma_k = \frac{E}{N_0} \cdot E\left(\alpha_k^{\ 2}\right) \tag{4.4}$$

Replacing the mean square value with instantaneous $\alpha_k^{\ 2}$ then theinstantaneous SNR is written as

$$\gamma_k = \frac{E}{N_0} \cdot \alpha_k^{\ 2} \tag{4.5}$$

and the highest instantaneous γ_k value is choosen in SC.

It is assumed that α_k is Rayleigh distributed. Rayleigh distribution is explained in the Appendix. Assuming that the average SNR for the short-term fading is the same for all of the receiver antennas, and the probability density functions of the random variables Γ_k related to every branch

$$f_{\Gamma_k}(\gamma_k) = \frac{1}{\gamma_k}\exp(-\frac{\gamma_k}{\gamma_{av}}) \qquad \gamma_k \geq 0, \qquad k = 1,2,...,N_r \qquad (4.6)$$

For some SNR value γ the distribution function of the individual branches

$$prob(\gamma_k \leq \gamma) = \int_{-\infty}^{\infty} f_\Gamma(\gamma_k)d\gamma_k = 1 - \exp\left(-\frac{\gamma}{\gamma_{av}}\right), \qquad \gamma \geq 0 \qquad (4.7)$$

All of the Nr banches are independent and the probability that all branches have a less SNR than γ is the multiplication of individual probabilities.

$$prob(\gamma_k \leq \gamma) = \prod_{k=1}^{Nr} prob(\gamma_k < \gamma) = (1 - \exp(\frac{-\gamma}{\gamma_{av}}))^{N_r}, \qquad \gamma > 0 \qquad (4.8)$$

The probability $\gamma_k < \gamma$ decreases while the number of antennas increases. By using SC a frequency-flat, slowly fading Rayleigh channel is modified into a Gaussian channel when N_r is very large.

4.2.2 Maximal Ratio Combining

Maximal ratio combining (MRC) weighs all branches of the received signals with a complex factor a_i, which is proportional to the signal amplitude, and combines N_r branches in order to maximize SNR. Branches with a strong signal are enhanced while weak ones are reduced. In contrast to SC which wastes the energy of N_r -1 branches, MRC uses all branches. Knowledge of the phase and signal amplitude is needed in MRC. The structure of the MRC is illustrated in Figure 4.5.

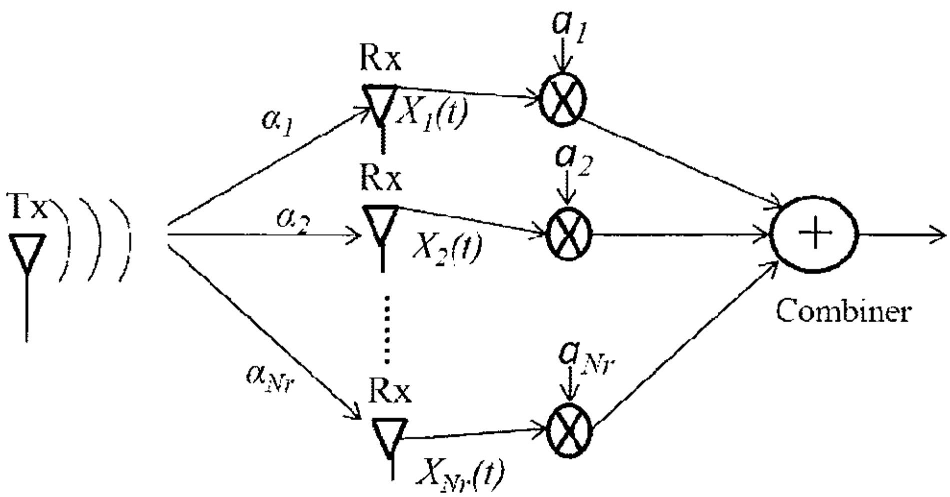

Figure 4.5 Maximal Ratio Combining.

The complex envelope of the i[th] diversity branch is given in Equation 4.1. The corresponding complex envelope of the combiner output is

$$\tilde{y}(t) = \sum_{i=1}^{N_r} a_i \tilde{X}_i(t) \tag{4.9}$$

$$= \sum_{i=1}^{N_r} a_i \left[\alpha_i e^{j\theta_i} \tilde{s}(t) + \tilde{w}_i(t)\right] \tag{4.10}$$

$$= \underbrace{\sum_{i=1}^{N_r} a_i \alpha_i e^{j\theta_i} \tilde{s}(t)}_{Signal} + \underbrace{\sum_{i=1}^{N_r} a_i \tilde{w}_i(t)}_{Noise} \tag{4.11}$$

Now the combiner needs to be designed in order to maximize the SNR at each instant of time. The average SNR at the output of the combiner can be written as

$$(SNR)_C = \frac{E\left[\left|\tilde{s}(t)\sum_{i=1}^{N_r} a_i \alpha_i e^{j\theta_i}\right|^2\right]}{E\left[\left|\sum_{i=1}^{N_r} a_i \tilde{w}_i(t)\right|^2\right]} \tag{4.12}$$

$$= \frac{E}{N_0} \frac{E\left[\left|\sum_{i=1}^{N_r} a_i \alpha_i e^{j\theta_i}\right|^2\right]}{E\left[\left|\sum_{i=1}^{N_r} a_i\right|^2\right]} \tag{4.13}$$

The instantaneous SNR, γ_C , which is required to maximize, is

$$= \frac{E}{N_0} \frac{\left|\sum_{i=1}^{N_r} a_i \alpha_i e^{j\theta_i}\right|^2}{\left|\sum_{i=1}^{N_r} a_i\right|^2} \tag{4.14}$$

Using a Cauchy-Schwarz inequality for Equation 4.14 , the equation can be rewritten as

$$\gamma_C \le \left(\frac{E}{N_0}\right) \frac{\left|\sum_{i=1}^{N_r} a_i\right|^2 \left|\sum_{i=1}^{N_r} \alpha_i e^{j\theta_i}\right|^2}{\left|\sum_{i=1}^{N_r} a_i\right|^2} \tag{4.15}$$

Cancelling the common terms, and removing the phase shift θ_k Equation 4.15 yields to

$$\gamma_C \le \left(\frac{E}{N_0}\right) \left|\sum_{i=1}^{N_r} \alpha_i\right|^2 \tag{4.16}$$

Equation 4.16 proves that γ_C can't be more than $\sum_i \gamma_i$, where γ_i is defined in Equation 4.5, and γ_C becomes maximum where it equals to $\left(\frac{E}{N_0}\right)\left|\sum_{i=1}^{N_r}\alpha_i\right|^2$. Then the instantaneous output SNR of the maximal ratio combiner can be written as

$$\gamma_{MRC} = \left(\frac{E}{N_0}\right)\left|\sum_{i=1}^{N_r}\alpha_i\right|^2 \tag{4.17}$$

MRC weighs all branches without looking how at weak some of them are and combines them and the results with the best gain among receive diversity methods. But the cost for estimating phase and amplitude on each branch is a tradeoff. MRC exploits frequency diversity completely instead of choosing a standard frequency interval and experiencing same deep fades every time.

4.3 Problem Statement

When a signal is transmitted over a time varying multi path channel, fading is inevitable and is due to random attenuation, phase shift, and delay in the received signals over multiple paths with random channel impulse responses.

As discussed in this chapter, performance in the presence of fading can be improved by using diversity techniques. These effects have been investigated for different numbers of antennas, bandwidths, and fading paths. MRC and SC are used as receive diversity techniques. All these simulations are done at DL using OFDMA.

One of the targets of this thesis is to see whether, when there is more than one fading path in the communication channel, the effects of deep fades, which weaken the signal at the receiver, are minimized. And, as described in receive diversity section it is expected that MRC will perform better than SC in different bandwidths. Performance is evaluated in being terms of BER (Bit Error Rate).

4.3.1 Bit Error Rate

Bit Error Rate (BER) is an important parameter to understand the performance of the communication systems. In order to calculate BER, the number of received error bits, which have been disrupted due to channel distortion, interference, phase jitter and noise, are divided by total number of bits that are sent in a certain time interval.

If the transferred bits over a channel are altered due to the effects written above, the integrity of the data are lost and the performance decreases. BER is used for determining the reasonable error ratio which does not reduce overall system performance. BER is usually stated as a function of normalized carrier-to-noise ratio denoted with Eb/N_0. In terms of Eb/N_0 and SNR, the BER can also be expressed as probability of error, P_e. If the SNR is high the BER will decrease, if the noise is high the BER will increase. As it seen, BER is affected from many parameters. By changing some of these parameters it is possible to have an optimal system which ensures the requirements for better performance. If the bandwidth is decreased, the intereference level can be low; but this will reduce the data rate. All of these parameters can be arranged for a satisfactory result or performance but, to make everything perfect is not possible surely. There will be always tradeoffs.

Finally, it is expected that better results will be found in the case of using multi antenna techniques instead of one-antenna case.

CHAPTER 5

SIMULATION AND NUMERICAL RESULTS

In this chapter, three scenarios are considered for LTE receive diversity performance and one scenario is considered for comparing LTE and WIMAX performances. In all these scenarios, MRC and SC receive diversity techniques are implemented with the MATLAB software environment.

5.1 Simulation Setup

The LTE parameters which are used in simulations are shown in Table 5.1.

Table 5.1 LTE Simulation Parameters.

Parameters	**Values**		
Channel Bandwidth (MHz)	2.5	10	20
FFT Size	256	1024	2048
CP Ratio (Long)	¼		
Number of Bits in Simulation	10^6		
Oversampling Rate	1.53125		
Modulation Scheme	QPSK		
Antennas	2,4, and 8 for each configuration		
Multiple SNR Values	0-8,12, and 16 dB for different antennas		

This chapter goes on to provide bit error rate plots, which show the performance of the receive diversity techniques. Each result is discussed and different system behaviors are explained. Each horizontal axis in each plot gives the SNR in the dB and each vertical axis gives the BER. In this chapter, numerical results are presented to demonstrate the performance of the proposed receive diversity techniques. The BER is evaluated theoretically and via simulation.

The probability of error for QPSK over an AWGN channel due to [15] can be written as

$$\Pr ob(error \mid \gamma_k) = \frac{1}{2} erfc\left(\sqrt{\gamma_k}\right) \tag{5.1}$$

where γ_k is substituted for the signal energy-to-noise spectral density ratio E/N_0. γ_k is the instantaneous SNR and is also a random variable. In order to determine the average probability of symbol error of Equation 5.1 with respect to γ_k

$$P_e = \mathrm{E}\left[\Pr ob(error \mid \gamma_k)\right] \tag{5.2}$$

by definition and using the density function in Equation 4.6 it can write Equation 5.2 as

$$P_e = \int_0^\infty \Pr ob(error \mid \gamma_k) \cdot f_\Gamma(\gamma_k) d\gamma_k \tag{5.3}$$

The result can then be written, where the communication channel is now a frequency-flat, slowly fading Rayleigh channel, is from [16] as

$$P_e = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma_k}{1+\gamma_k}}\right) \tag{5.4}$$

In this simulation, a frame consisting of 10^6 bits are transmitted through a Rayleigh flat fading channel. The noise is assumed to be a zero mean complex Gaussian process with variance $N_0/2$. The channel is also considered as multipath fading in order to estimate the performance of antennas. It is assumed that the fading channel coefficients are available at the respective receivers for decoding the received signal.

Ordinarily, the received signal is the sum of several kinds of a transmitted signal. These versions of the transmitted signals are called fading paths. In this thesis, the number of those fading paths is denoted with "L". The third simulation shows the varying fading paths for L=1 and L=3.

5.2 Numerical Results for Fixed LTE System Bandwidth

In this simulation, a LTE system with the bandwidth of 2.5 MHz was considered and the performance improvement obtained with SC and MRC methods was studied with 2, 4, and 8 receive antennas. The theoretical curve is the QPSK 1 receive path.

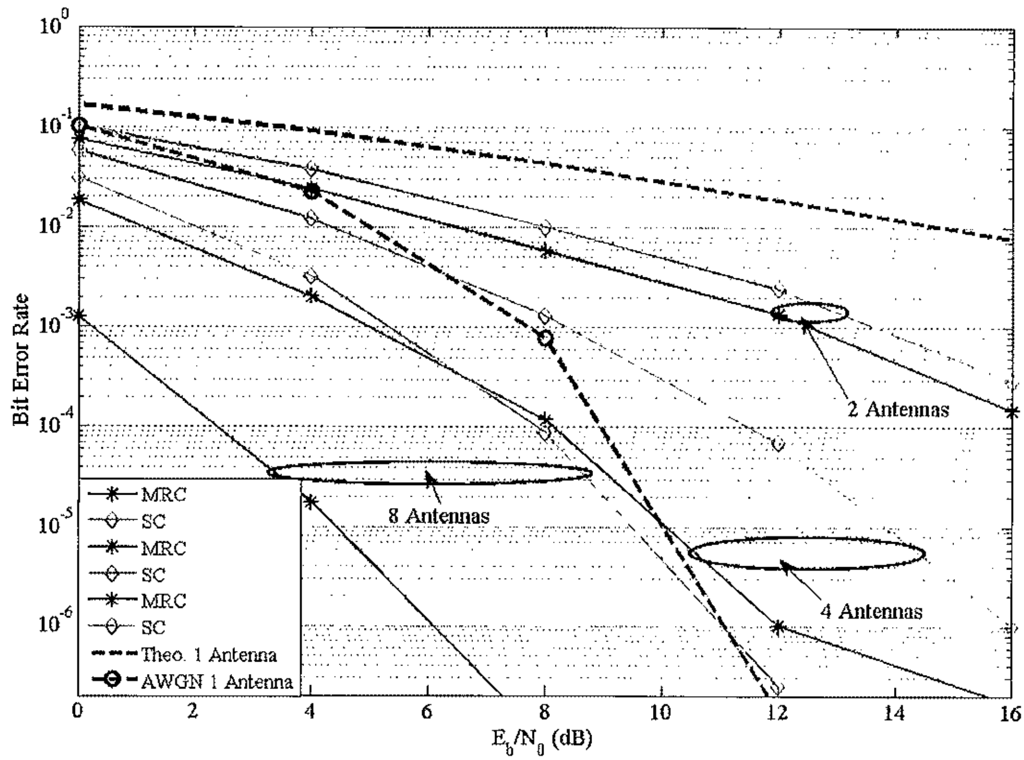

Figure 5.1 Recive Diversity Performance 2.5 MHz, L=1 Fading Path.

Results of this experiment are shown in Figure 5.1 where the BER is flat versus *Eb/No* for all cases considered. It is observed that the SC and MRC results are very close for two of the antennas. But the difference between MRC and SC grows with the number of antennas. There is approximately a 2 dB difference in the 2-antenna case in which these two receive diversity techniques are the closest.

BER reduces largely as the number of antennas grows. The best BER performance is shown in 8-antenna case. But, as the number of antennas increase in the simulation, the decrease in BER becomes less. As more antennas are used performance becomes even better than in the AWGN only case.

5.3 Numerical Results for Same Number of Receive Antennas and Different Bandwidth

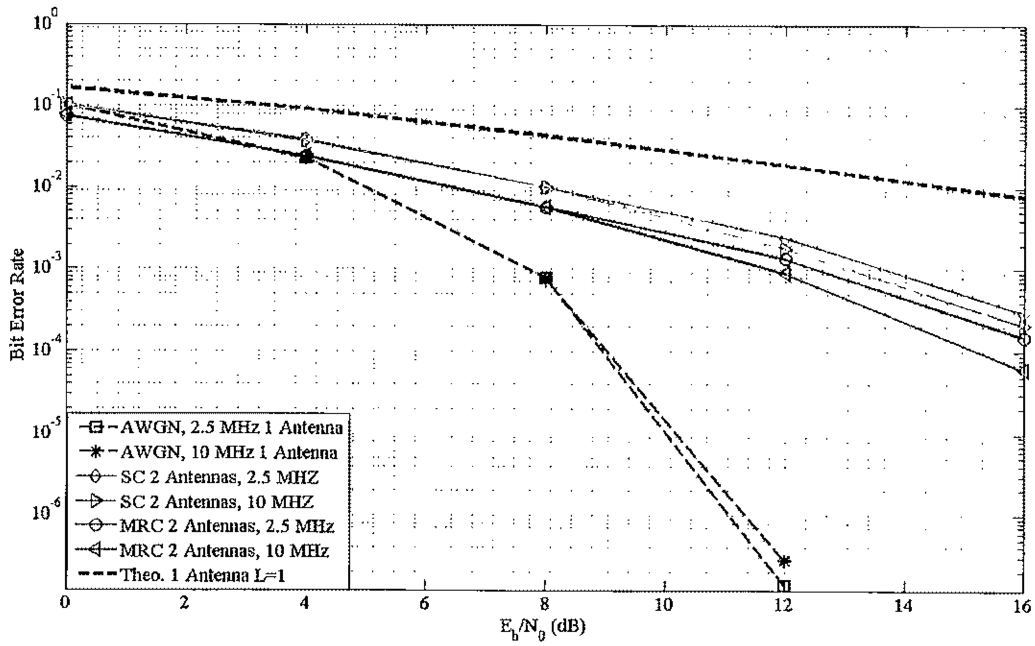

Figure 5.2 AWGN, SC, and MRC with 2.5 MHz and 10 MHz.

In Figure 5.2, the different bandwidths are used in order to measure if a change in the bandwidth affects the BER in AWGN and fading channel. In this scenario 2.5 MHz and 10 MHz bandwidths are used. The BER performance of the smaller bandwidth is worse, 2.5 MHz, for fading channels in the 2-antenna case. In contrast to a fading channel, BER performance is better for smaller bandwidth, 2.5 MHz, for the AWGN channel. The simulation result for 20 MHz bandwidth have also been found. But the results for different bandwidth values are not consistent in a certain SNR interval. For this reason the bandwidth is not an effective factor for BER performance in multi antenna configurations.

5.4 Numerical Results for Varying Numbers of Fading Paths

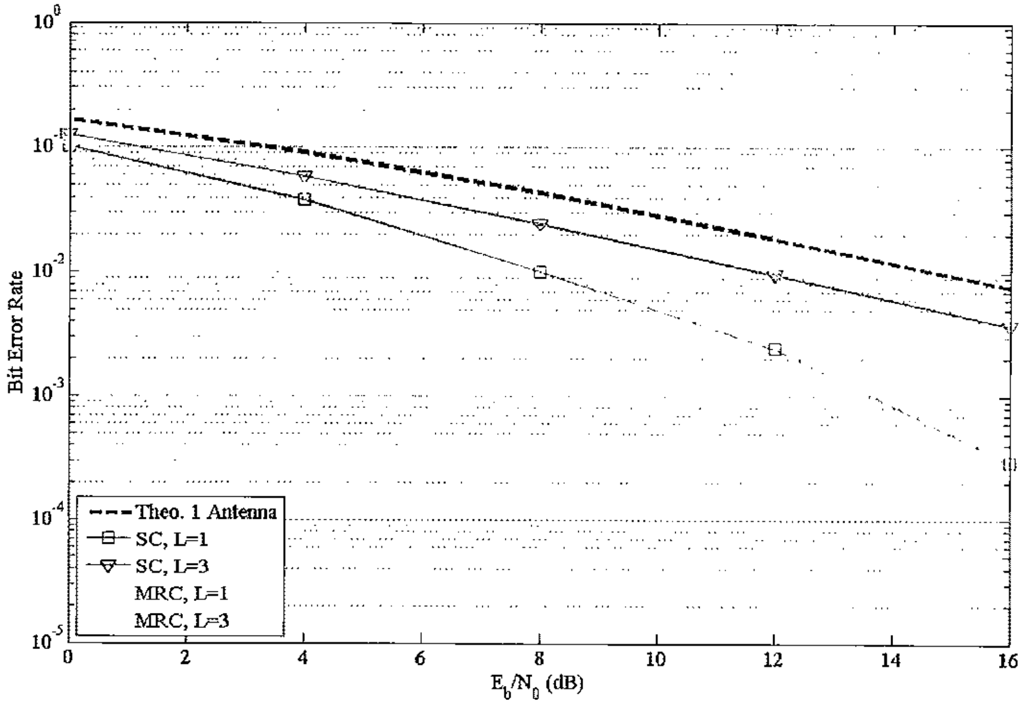

Figure 5.3 SC and MRC with L=1 and L=3 Paths.

In this section different numbers of fading paths, L, are used. In Figure 5.3, L=1 and L=3 are shown for MRC and SC receive diversity techniques in 2-antenna case and the bandwidth is constant for all results, 2.5 MHz. As it seen, BER performance gets worse as the number of paths increase. Simulation results for L=5 fading channels were also computed, but for the simplicity and comprehensibility they were not put into the plots. The biggest decrease in BER is between the first and the second paths. After the second path, BER slightly gets worser for any number of paths.

5.5 Comparison between LTE and WIMAX

WIMAX, which was developed by IEEE and also called IEEE 802.16, was approved as an IMT-2000 standard by ITU in 2007. It is an alternative system to the LTE in wireless mobile market. It has also very high peak data rates using a range of bandwidths like LTE from 1.25 MHz to 20 MHz. OFDMA is used as physical layer both in DL and UL. WIMAX supports both TDD and FDD. In contrast to LTE, TDD

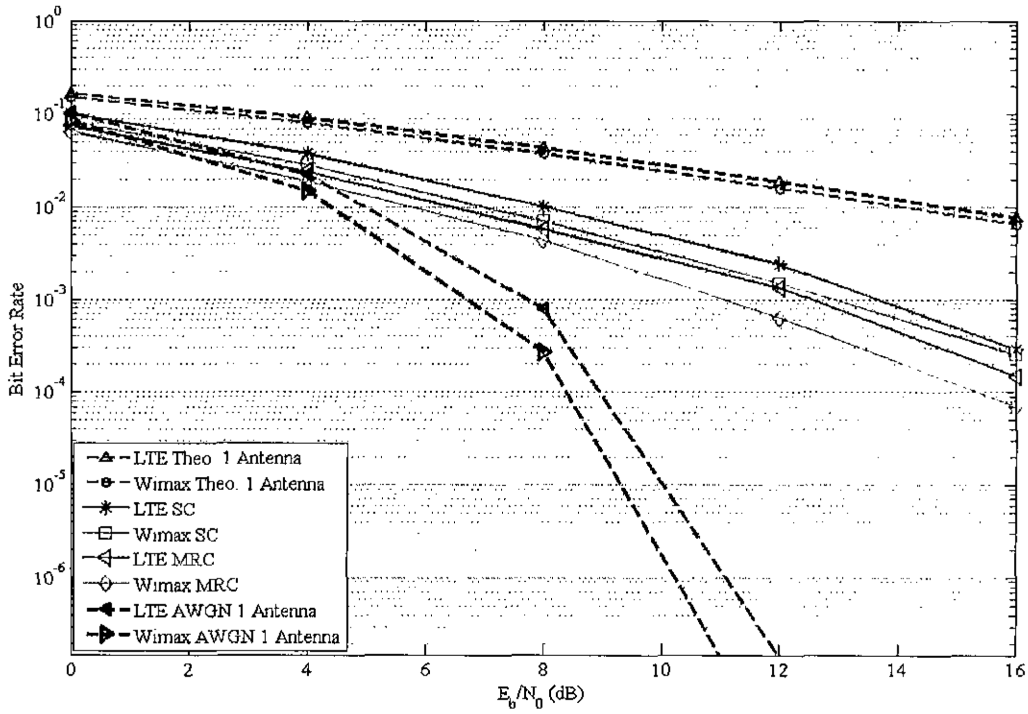

Figure 5.4 Comparison between LTE and WIMAX with 2 Antennas.

is more common. IEEE 802.16 has an IP-based architecture which shows that it is also preparing for IPv6 and it uses MIMO technologies as LTE.

The comparison among LTE and WIMAX is not in equal bandwidths. Because LTE uses FDD and WIMAX uses TDD, an honest bandwidth rate is 2.5 MHz for LTE and 5 MHz for WIMAX [16]. Wimax and LTE parameters are shown in Table 5.2.

Table 5.2 LTE and WIMAX Parameters.

Parameters	**LTE**	**WIMAX**
Channel Bandwidth (MHz)	2.5	5
FFT Size	256	512
CP Ratio	1/4	1/16
Number of Bits	10^6	
Oversampling Rate	1.53125	28/25
Modulation Scheme	QPSK	
Antennas	2 antennas configuration	
Frame Lengths (ms)	10	5

In Figure 5.4, the simulation is run using 5 MHz bandwidth for Wimax and 2.5 MHz bandwidth for LTE and in 2-antenna case. It was found that Wimax has slightly better performance than LTE for fading channels. The difference between them mostly arises from the cyclic prefixes and oversampling rates. In addition, this difference is a bit more for AWGN channel. Lastly, it can be said that these two leading technologies approximately have equal performance for diversity gain.

It is clear from the figures above that when the number of antennas increase the BER performance improves largely. And the SC and MRC techniques are better than theoretical result in each plot. It was also observed that the BER performance of MRC is always better than the BER performance of SC. The BER performance of multi antenna usage does not show so many differences due to the various bandwidth usages.

CHAPTER 6

CONCLUSIONS

In this thesis, the simulations of multi antenna techniques are presented to show the benefits of diversity. Maximal Ratio Combining and Selection Combining, which are receiver diversity techniques, are implemented in a software environment. These simulations are performed in order to prove that how multi antenna usage at the receiver side affects the BER performance.

Wireless technology is very useful in each stage of our daily lives and we use it frequently. Our environment is an important factor to consider while exploiting this technology. Wireless signals are attenuated from a time varying media and that is called fading. This study is to reverse the effects of these fading paths by using multi antennas at the receiver. In our simulations, different numbers of antennas are used at the receiver in order to degrade the effects of deep fades in the received signal. In real life, there are a lot of factors that cause a lot of fading paths. Those fading paths are also simulated in this study. Performance of the two 4G technologies, LTE and WIMAX are compared due to their BER performance in the 2-antenna case. These new standards present a flexible bandwidth to their users. Multi antenna performance for different bandwidths were also implemented.

In the light of results in this thesis, the importance of the multi antenna usage in wireless channels is underlined. Multi antennas at receiver cost more but the quality of received signals considerably improves when the number of antennas increase and that is an acceptable tradeoff. Thus, MRC and SC receiver diversity methods, which are very effective, are implemented in the simulations. Moreover, with the usage of multi antennas the capacity is improved.

For future work, transmit diversity techniques, which improve the link quality, can be considered using LTE parameters. While receiver diversity is mostly considered for mobile units, transmit diversity can be more suitable for base stations where antenna spacing is more convenient. In transmit diversity, open-loop techniques can be used with Alamouti Space-time Block Codes. Moreover, closed-loop methods can be implemented using channel feedback information.

REFERENCES

1. "4G Mobile Broadband Evolution: 3GPP Release 10 and Beyond HSPA+, LTE/SAE and LTE-Advanced", www.4gamericas.org, Accessed on Date, February 24, 2011.
2. "Mobile subscriptions hit 5 billion mark", www.dailywireless.org, Accessed on Date March 31, 2011.
3. Ghosh, A., Zhang J., Andrews, J.G., and Muhammed, R., *Fundamentals of LTE*, Westford, MA: Pearson Education, Inc., 2010, pp.5-22.
4. Khan, F., *LTE for 4G Mobile Broadband: Air Interface Technologies and Performance*, Cambridge: Cambridge UP, 2009, p.1.
5. Andrews, J.G., Ghosh, A., and Muhamed, R., *Fundamentals of WiMAX: Understanding Broadband Wireless Networking*, Westford, MA: Pearson Education, Inc., 2007, p.14.
6. Priyanto, B.E., Codina, H., Rene, S., Sorensen, T.B., Mogensen, P., "Initial Performance Evaluation of DFT-Spread OFDM Based SC-FDMA for UTRA LTE Uplink," *Vehicular Technology Conference, 2007.VTC2007-Spring. IEEE 65th*, pp. 3175-3179, 22-25 April 2007.
7. Nee, R.V., and Prasad, R., *OFDM for Wireless Multimedia Communications*, Boston: Artech House, 2000.
8. Bogucka, H., "Directions and Recent Advances in Papr Reduction Methods," *Signal Processing and Information Technology, 2006 IEEE International Symposium on*, pp.821-827, August 2006.
9. Hanzo, L., Yang, L.-L., Kuan, E.-L., and Yen, K., *Single- and Multi-Carrier CDMA: Multi-User Detection, Space-Time Spreading, Synchronization and Standards*, New York, NY: Wiley, 2003.

10. Goldsmith, A., *Wireless Communications*, New York, NY: Cambridge University Press, 2005, p.387.

11. Yin, H., Alamouti, S.M., "OFDMA: A Broadband Wireless Access Technology," *Sarnoff Symposium, 2006 IEEE*, pp.1-4, 27-28 March 2006.

12. Dahlman, E., Parkvall, S., Sköld, J., and Beming, P., *3G Evolution HSPA and LTE for Mobile Broadband,* Cornwall, Great Britain: MPG Books, 2008, p. 74.

13. Sesia, S., Toufik, I., Baker, M., *LTE – The UMTS Long Term Evolution from Theory to Practice*, Great Britain: John Wiley & Sons, Ltd., 2009, p.488.

14. Alamouti, S.M., "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol.16, no.8, pp.1451-1458, October 1998.

15. Haykin, S., Moher, M., *Modern Wireless Communications*, Upper Saddle River, NJ: Pearson Education, Inc, 2005, p. 159.

16. "WiMAX-LTE Technology Migration", www.tsiwireless.com, Accessed on Date, March 11, 2011.

APPENDIX

RAYLEIGH DISTRIBUTION

It is assumed that wireless communication is done in a Rayleigh channel. If X_l and X_2 are zero mean Gaussian random variables with the variance then the random variable $R = \sqrt{X^2 + Y^2}$ has a Rayleigh distribution.

$$\Pr ob(R < r) = 1 - e^{-\frac{r^2}{2\sigma^2}}, \qquad r \geq 0$$

The probability density function is

$$f_R(r) = \frac{r}{\sigma^2} \cdot e^{-\frac{r^2}{2\sigma^2}}, \qquad r \geq 0$$

The first and second moments of R are given by

$$E[R] = \sqrt{\frac{\pi}{2}}\sigma \qquad and \qquad E[R^2] = 2\sigma^2$$

And the variance is

$$\sigma_R{}^2 = \left(2 - \frac{\pi}{2}\right)\sigma^2.$$

VITA

DEGREES

- ***Bachelor of Science : Computer Engineering***

  Turkish Air Force Academy, Istanbul, August, 2003

PROFESSIONAL CHRONOLOGY

- Air Corps Schools and Technical Training Center Command, Izmir, Officer Branch Training, August 2003- August 2004

- 6^{th} Main Jet Base, Bandirma, Ground Based Air Defence (GBAD) Battery Commander, August 2004 - August 2009

- Turkish Air Force Academy, Istanbul- Computer Engineering Department, Old Dominion University, Norfolk, Virginia, M.S. Student, September 2009-May 2011