KUVEMPU UNIVERSITY

DEVELOPMENT OF OFDM BASED MIMO TEHNIQUES USING QPSK AND MQAM MODULATION FOR HIGH SPEED NETWORK APPLIATIONS

Thesis submitted to the Kuvempu University

For the award of the degree of

DOCTOR OF PHILOSOPHY
in

ELECTRONICS

by

Bhagya.R

Reg. No. 594

Under the Guidance of

Dr. A.G.Ananth
Professor, R. V.Center for Cognitive Technologies,
RV College of Engineering, Bangalore

Carried out at

R.V.Center for Cognitive Technologies,
R.V.College of Engineering, Mysore Road, Bangalore-560 059

AUGUST - 2015.

R.V.Center for Cognitive Technologies
(RVCCT)
R.V.College of Engineering Campus, Bangalore-560 059

CERTIFICATE

This is to certify that the work presented in the thesis entitled *"DEVELOPMENT OF OFDM BASED MIMO TECHNIQUES USING QPSK AND MQAM MODULATION FOR HGH SPEED NETWORK APPLICATIONS "* embodies the results of bonafide research work done by *Mrs. Bhagya.R,* Research Scholar, *R.V.Center for Cognitive Technologies (RVCCT), Bangalore* for the award of degree of *Doctor of Philosophy in Electronics, in the Faculty of Science and Technology, Kuvempu University,* Shankaraghatta, Shimoga under our guidance and supervision.

We further certify that the results of this thesis have not been previously formed the basis for the award of any degree or diploma.

Ananth

.G.Ananth
de,
essor, Department of Electronics
Center for Cognitive Technologies,
C.E Campus, Bangalore - 560059

PROFESSOR
R.V. CENTER FOR COGNITIVE TECHNOLOGIE
RVCE Campus 560 059
R. V. Post

Dr.Sridhar.S
Director,
R.V.Center for Cognitive Technologies
R.V.C.E Campus, Bangalore - 560059

DIRECTOR
R.V. CENTRE FOR COGNITIVE TECHNOLOGI
R.V. Teachers College Building,
II Block, Jayanagar, Bengaluru - 560

R.V.Center for Cognitive Technologies
(RVCCT)

R.V.College of Engineering Campus, Bangalore-560 059

DECLARATION

I hereby declare that the entire work embodied in this doctoral thesis entitled ***"DEVELOPMENT OF OFDM BASED MIMO TECHNIQUES USING QPSK AND MQAM MODULATION FOR HIGH SPEED NETWORK APPLICATIONS"*** has been carried out by *me in the Department of Electronics, at* ***R. V. Center for Cognitive Technologies (RVCCT), Bangalore*** affiliated to the ***Kuvempu University, Jnanasahyadri, Shankaraghatta, Shimoga ,*** under the supervision of research guide, ***Dr.A.G.Ananth, Professor, R.V.Center for Cognitive Technologies, Bangalore.***

I further declare that the results presented in the thesis or any part thereof has not been submitted elsewhere for any other degree or diploma of other Universities.

Bhagya.R

Bhagya.R
Research Student,
Department of Electronics,
R.V.Center for Cognitive Technologies,
R.V.C.E Campus,
Bangalore-560059.

I dedicate the thesis to my

beloved parents

ACKNOWLEDGEMENTS

My research work would not have been possible without the support and encouragement of many people. It is a great pleasure for me to thank them all for their contribution for the successful completion of the work.

I would like to express my profound sense of gratitude to the guide **Dr.A.G.Ananth,** Professor, Department of Telecommunication Engineering, RVCE, Bangalore, for his guidance, advice and constant support throughout my research work. His motivation, patience, enthusiasm and immense knowledge helped me in all the time of research and writing of this thesis.

I am greatly thankful to Rashtriya Sikshana Samithi Trust, my almamatar for providing me all the encouragement to carry out my research work.

I express my sincere thanks to **Dr. G. Sadashivappa,** Professor & Head of the Department, Telecommunication Engineering, RVCE, for his immense support and encouragement extended to carry out my research.

I would like to convey my sincere gratitude to **Dr. B.S.Satyanarayana,** Principal, **Prof. K.N.Rajarao,** Advisor and **Dr. K.N.Subramanya,** Vice Principal, RVCE, for all the support and facilities extended to me during my research work.

I would like to articulate my gratitude towards **Dr. Sridhara.S,** Director, RVCCT and **Dr. Basavaraj Jagadale,** Kuvempu University who encouraged me in all aspects for pursuing my research.

I express my deepest regards to my husband **Mr. Gopalakrishna.A,** my son **Chaitanya krishna.G** and my daughter **Danyatha Gopalakrishna** without their support I would not have been successful in my work.

Finally words cannot express my feeling of gratitude to all my friends and non teaching staff/technical staff of Dept. of TCE, RVCE, for their kind support.

Bhagya.R

ABSTRACT

The increasing demand for network services and the growth of internet related contents led to improving of the Bit rate efficiency of wireless communication systems. The requirement for wide bandwidth and flexibility imposes the use of efficient transmission methods that would fit to the characteristics of wideband channels especially in wireless environment where the channel is very challenging. In wireless environment the signal is propagating from the transmitter to the receiver along number of different paths, collectively referred as multipath. While propagating the signal power drops of due to three effects: path loss, macroscopic fading and microscopic fading. Fading of the signal can be mitigated by different diversity techniques. To obtain diversity, the signal is transmitted through multiple (ideally) independent fading paths e.g. in time, frequency or space and combined constructively at the receiver. Multiple Input-Multiple-Output (MIMO) exploits spatial diversity by having several transmit and receive antennas.

Wireless communication systems today, play a dominant role in the deployment of commercial networks. These networks require highly demanding features such as high data transmission rates, efficient storage and reliability of data transmission over lossy links. MIMO technology is one of the many technologies used to mitigate channel propagation effects such as Inter-Symbol Interference and frequency-selective fading in broadband communication systems. MIMO systems employ multiplexing gain and spatial diversity gain in order to increase channel capacity. The channel capacity can further be enhanced by integrating MIMO systems with Orthogonal Frequency Division Multiplexing (OFDM). Since OFDM performs well against frequency fading, along with the advantages of a high spectral efficiency, it forms an important physical layer technology for use with high speed wireless communication systems. Therefore, by incorporating MIMO-OFDM transmission systems in wireless networks, an increase in channel capacity leading to high data rates and the ability to mitigate multipath fading and channel impairments can be expected.

The present thesis investigation aims at designing of a composite MIMO transceiver configuration with specifications and modified algorithms to develop an efficient

MIMO transceiver system with different modulation schemes. BPSK, QPSK, 16-QAM multiplexing techniques, OSTBC, CDMA and OFDM and higher MIMO systems (3x3) MIMO and (4x4) MIMO at the transmitter end. At the receiver end the MIMO system is combined with various detectors such as ZF, MMSE and ML with SIC for the reduction of BER and increase of signal strength to improve link reliability, increase spectral efficiency and achieve higher data rate efficiency and lower computational complexity. The MIMO-OFDM system is implemented on wireless networks such as WLAN, WiMAX and LTE to achieve higher data rate efficiency. In every case the SNR (E_b/N_o) performance as a function of BER is determined and the lowest value of SNR (E_b/N_o) at a particular BER is used for determining the Bit rate to Bandwidth (BR/BW) efficiency of MIMO transceiver system.

The results of the present research investigations clearly indicate that for (2x2) MIMO-OSTBC system, the SNR values increases with BER for lower BPSK modulation to higher 16-QAM modulation as per the theoretical consideration. The MIMO-OSTBC system with BPSK modulation for ML detector systems shows the lowest SNR (E_b/N_o) ~14.46 dB at BER 10^{-3} and displays better performance of SNR ~10 dB (BR/BW efficiency ~10) compared to other detector systems. The MIMO-OFDM multiplexing indicates lowest SNR (E_b/N_o) ~12.6 dB at BER 10^{-3} and shows better performance of SNR ~1.86 dB (BR/BW efficiency ~ 1.53) compared to other multiplexing systems. The higher (4x4) MIMO-OFDM with ML detection system shows lowest SNR (E_b/N_o) ~10.5 dB at BER 10^{-3} and improved performance of SNR ~2.03 dB (BR/BW efficiency ~1.58) compared to lower (2x2) MIMO-OFDM system. The higher (4x4) MIMO-OFDM with Monte Carlo Detection system shows lowest SNR (E_b/N_o) ~6.9 dB at BER 10^{-3} and better performance of SNR ~3.6 dB (BR/BW efficiency ~2.29) compared to ML detection system.

Further the (2x2) MIMO-OFDM system implemented on WiMAX network for BPSK modulation depicts lowest SNR (E_b/N_o) ~9 dB at BER 10^{-3} and much better performance of SNR ~5 dB (BR/BW efficiency~ 3.16) compared to lower MIMO (MISO) systems. The MIMO-OFDM system implemented on WLAN, WiMAX and LTE network systems for QPSK modulation shows that the LTE–OFDM network offers lowest SNR (E_b/N_o) ~5.2 dB at BER 10^{-3} and best performance in SNR ~4.8 dB (BR/BW efficiency ~3) compared to other network systems. The best performance of LTE-OFDM network can be attributed to the application of coding techniques such as Turbo coding adopted which gives maximum Error correction in a digital transmission system.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

ACRONYM	**DESCRIPTION**
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CC	Convolution Code
CDMA	Code Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
LTE	Long Term Evolution
LOS	Line Of Sight
MMSE	Minimum Mean Square Error
ML	Maximum Likelihood
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MAC	Medium Access Control layer
NLOS	Non Line Of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OSTBC	Orthogonal Space Time Block Coding
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RS	Reed-Solomon

STBC	Space-Time Block Coding
SNR	Signal to Noise Ratio
SISO	Single Input Single Output
SIMO	Single Input Multiple Output
Wi-Fi	Wireless fidelity
WiMAX	Worldwide interoperability for Microwave Access
WMAN	Wireless Metropolitan Area Network
WLAN	Wireless Local Area Network
ZF	Zero Forcing

CHAPTER – 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

Increasing demand for high-speed multimedia applications and services, along with an increasing repository of internet content is leading to an increased awareness about high-speed communication. This along with the need for flexibility and increased bandwidth impose the use of competent or resourceful mechanisms for transmitting information that would be appropriate to understand the nature and behaviour of channels with wideband capabilities in wireless environments with the demanding requirements. The transmitted signal takes different paths from the source to the destination and these multiple transmissions together are referred to as multipath in the wireless environment. The reduction in signal power occurs due to many factors such as path loss, macroscopic/microscopic fading etc. during the propagation. By using different diversity techniques, fading of the transmitted signal can be reduced. To achieve transmission diversity, the signal must be sent by paths that are different and independent from one another, for example in time, frequency or space and should be combined intelligently at the destination. Multiple Input-Multiple Output (MIMO) exploits the spatial diversity behaviour by using multiple antennas for transmission and reception, both at the source and destination side [5].

MIMO systems are currently used in broadband systems to encounter Inter Symbol Interference (ISI) and frequency-selective fading. Also, MIMO systems can be used for multiplexing information and to exploit spatial diversity behaviour, consequently leading to significant channel capacity enhancements. This enhancement can be increased by combining MIMO with technologies such as Orthogonal Frequency Division Multiplexing (OFDM), Code Division Multiple Access (CDMA), Space Time Block Codes (STBC) or its variants such as Orthogonal Space Time Block Code (OSTBC). OFDM can be employed for transforming channels that exhibit frequency selectivity into corresponding sub channels which exhibit flat-fading. Thus signals on the subcarriers undergo narrowband fading. Broadband communication systems are driven by an increasing need for high data rate multimedia applications. In this context, OFDM systems have grown to become increasingly popular for use with high-speed communication systems. It is a widely held belief that OFDM technology will form a vital part of future wireless communication systems. MIMO can be applied in broadband communication by performing MIMO transmission and detection per subcarrier. MIMO-OFDM is a refined and effective mechanism for high rate data transmission systems especially in environments with multipath fading and where line of sight communication is not available [10][12].

The progress of mobile communications has built the highway for high-speed information exchange. The constantly evolving mobile communications switching from first generation PCS (Personal Communication Services) to 2G Global System for Mobiles (GSM) to the packet data network overlay namely the General Packet Radio Service (GPRS) and EDGE (Enhanced Data for GSM Evolution) has seen a gradual move towards packet switched communication. This is evident in the 3G UMTS (Universal Mobile Telecommunication Systems) and the All-IP networks are in continued development in 4G and 5G networks. Figure 1.1 shows an example of the evolution of the mobile communication systems from circuit switching to packet switching.

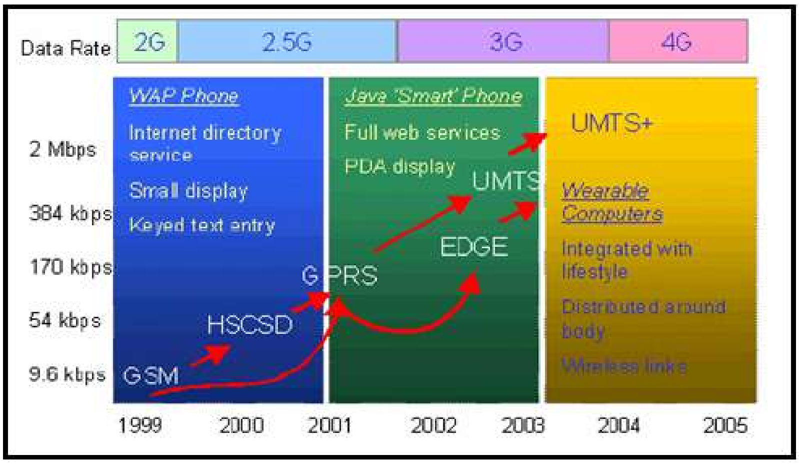


Figure 1.1: Mobile Communication Systems Evolution

1.1 Digital Communication systems

Digital communication engineering represents a wide range of communication methods, including transmission of digital signals and the associated RF components. Digital communication systems utilize the transmission of digital pulses for exchanging information between two or more points. Radio frequency transmission uses analog carriers to transmit digitally modulated pulses result in wireless communication.

A data source generates digital messages leading to the transmission of digital data, for example a keyboard or a computer. An analog signal such as a voice/video signal may also be used, and can be converted into a bit-stream to represent digital information. Pulse Coded Modulation (PCM) systems can be used to represent such data, or more advanced source coding mechanisms can be used to convert analog information to digital data. The codec equipment is used to carry out source coding and decoding.

The basic building blocks of communication system are as shown in figure 1.2.

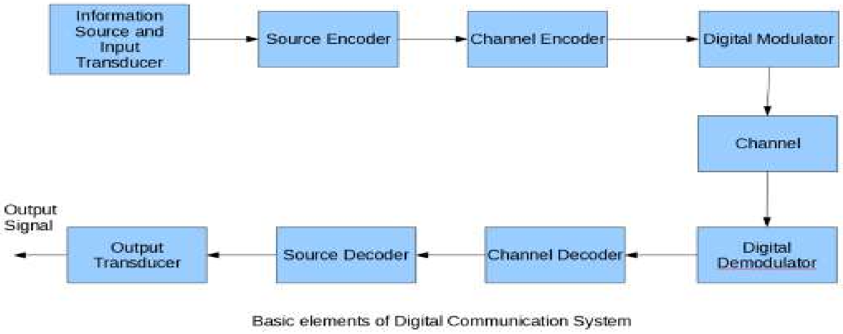


Figure 1.2: Digital Communication System: Basic Building Blocks

The basic building blocks of a digital communication system contains a Data source, an Input transducer, Source encoder and decoder, Channel encoder and decoder, Digital modulator and demodulator, Channel and the Output transducer.

The information source can be analog or digital. In this communication system, the signal produced by the data source is first converted into a digital signal consisting of binary digits. This process of efficiently converting the output of an information source, whether analog or digital is known as source encoding. This operation is performed by a source encoder. The binary sequence from source encoder is then processed by the channel encoder. Digital modulator converts the binary sequences into electric signals that are transmitted over the channel. The communication channel acts as a physical medium for transporting signals from the transmitter to the receiver. Since the channel corrupts the transmitted information, the digital demodulator is used to process the received waveform and to perform an estimation of the data that was transmitted. This data sequence is processed by channel decoding system. The channel decoder then tries to reconstruct the original information transmitted using channel encoder information and its redundancy.

1.2 Multiplexing Techniques

The process by which different information carrying signals can be combined into an individual signal stream is referred to as Multiplexing. The intent is to allocate resources. The multiplexing is responsible for dividing the communication channel from one high-level system to multiple different low-level components. Each logical channel is then used for one data stream or message signals to be transferred. On the receiver side, an opposite process called de-multiplexing is used to extract the original channel structure. Multiple access techniques are used to achieve high subscriber capacity by sharing the available limited spectrum among many subscribers simultaneously, while maintaining the desired quality of communications.

1.2.1 Space–Time Block Code (STBC)

STBC is a multiplexing mechanism that is often used in wireless communication systems. It uses multiple antenna systems to transmit several copies of the message, and exploits diversity to increase the reliability of data transmission. During transmission, the signal encounters different channel propagation effects such as reflection, refraction and scattering. Further, noise is added at the receiver, thus corrupting the received signal. Since multiple antenna systems are used during transmission, several signal copies, but independently corrupted, converge at the destination. This redundancy provides enough information to correctly decode the received signal with a higher probability. Thus STBC can be used to combine multiple copies of a received signal optimally to obtain the best estimate of the transmitted information [17][20].

1.2.2 Code Division Multiple Access (CDMA)

Code Division Multiple Access is a multiple access method used by different communication systems. In CDMA, multiple users can share a single communication channel simultaneously, when using the same channel frequency range. CDMA systems work on the principle of spread spectrum systems, which permits different users to the same communication, but are differentiated through a unique code. Further, CDMA systems use specialized coding mechanisms to reduce interference between end users [38][44].

1.2.3 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a method which encodes information into multiple orthogonal subcarriers. Thus it is a multicarrier multiplexing technique which is used for encoding digital data. OFDM has gained popularity, as it is an efficient scheme for use with wideband communication systems in both wired and wireless communication scenarios. It is increasingly becoming popular in different applications such as satellite television, broadcasting, high-speed Internet, power engineering and voice communication in 4G and 5G system architectures [47].

1.3 Modulation Techniques

Modulation refers to changing the characteristics of a waveform that is periodic (a carrier signal) with reference to a message signal (generally called as a modulating signal). In communication systems, modulation plays an important role of information transmission in an appropriate form for communication over the physical channel. Therefore it performs the necessary operations for converting analog waveforms to digital bit streams and vice versa. Modulation therefore results in the conversion of baseband message signal into an equivalent passband counterpart [15].

1.3.1 Binary Phase-Shift Keying (BPSK)

BPSK is the most basic phase shift keying (PSK) technique and is also referred to as 2PSK. It uses two different phase levels separated by 180° and is simply called 2-PSK. The location of the constellation points themselves do not matter significantly. Therefore it can be easily seen that this type of modulation scheme is very robust against high levels of noise, interference and distortion. Therefore, high noisy environments are necessary to cause the demodulator to generate a wrong decision. The disadvantage of this modulation scheme is that it can only transmit at a rate of 1 bit/symbol and is therefore not appropriate for systems that require high data rates. BPSK is functionally comparable to 2-QAM modulation [50].

1.3.2 Quadrature Phase Shift Keying (QPSK)

QPSK or quadrature phase shift keying (4-PSK, 4-QAM or quadriphase PSK) uses four constellation points which are equally spaced around a circle. QPSK can therefore encode information at a rate of 2 bits/symbol. It can be analytically shown that QPSK improves the data rate performance by a factor of two in comparison with a BPSK system without increasing the required bandwidth of the communication signal. Alternatively, QPSK can be used to maintain the data transmission rate of BPSK, while reducing the bandwidth requirement by exactly 50% [53].

1.3.3 Quadrature Amplitude Modulation (QAM)

QAM is a combination of both an analog modulation scheme and a digital modulation technique. QAM uses amplitude shift keying, which is a modulation technique along with an amplitude modulation scheme (which is an analog modulation method) to transmit two simultaneous digital bit streams and analog message signals. The two message signals are referred to as quadratures, as they are 90° out of phase with each other. These are also referred to as quadrature components. These quadrature components are added together along with phase shift keying resulting in a combination of PSK (digital modulation) and AM (analog modulation). Therefore, at least two amplitudes and two phases are used to identify one simple message. The difference between PSK and QAM is that PSK modulation systems follow the principle of QAM modulators, but that carrier signal remains constant. Digital communication systems therefore extensively employ QAM systems as they exhibit high spectral efficiency and can be used with different constellation sizes. However, it is to be noted that the use of a larger constellation size is only limited by the noise levels in the channel environment [50].

1.4 Multiple Input Multiple Output (MIMO)

MIMO technology has seen many years of development for use with both wired and wireless systems. The use of MIMO systems in wireless communication systems was first introduced by Bell Laboratories in 1984 by Jack Winters. Since then, MIMO has grown in popularity significantly and has become one of the most important areas of wireless communications research. Multiplexing and spatial diversity in wireless systems employ MIMO techniques leading to an inherent increase in the BER performance of the communication system [1][5].

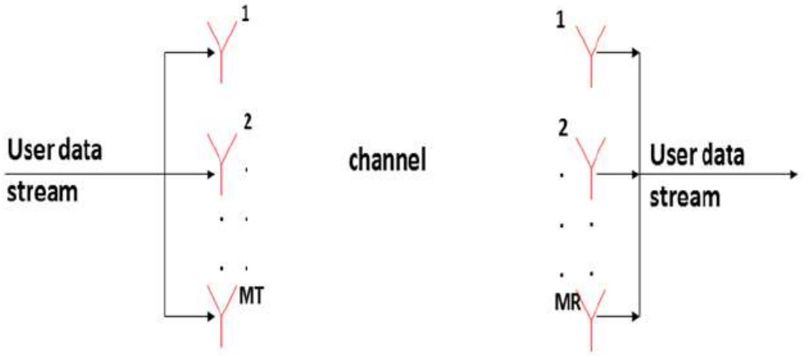


Figure 1.3: MIMO Systems

It is for these reasons that MIMO communication systems are credited with being one of the most important innovations in wireless research. As MIMO can be used to achieve high data-rates using the same available spectrum, it is therefore essential to examine the effect of varying channel conditions on system capacity. Also recently, research and development of multiple-antenna systems have created viable solutions to achieve very high spectral efficiency for wireless networks. An example of communication system with multiple transmit and receive antennas is as shown in the figure 1.3.

1.5 MIMO Functionality

The essential operations performed by MIMO systems can be split up into the following categories. They are: MIMO Precoding, Diversity Coding and Spatial Multiplexing [10].

1.5.1 MIMO Pre-coding

Multi-layer beam forming techniques used in MIMO are referred to as pre-coding. Spatial processing is generally performed at the transmitter. In this particular case, each of the transmitting antennas emit the same signal from a single layer beam forming system such that each antenna has the appropriate tuning with respect to phase and gains. This ensures that the received signal strength is maximised at the receiver input. The use of beam forming leads to combining the incoming signal constructively, so that performance improvements in the form of increased signal gain can be achieved, which can consequently lead to reduced multipath fading. If the beam forming signals are transmitted using predefined directional patterns in a propagation environment without scattering, pre-coding is required in this case since transmit beam forming cannot be used to maximise the incoming signal levels at all receiving antennas. Thus the use of pre-coding necessitates the channel state information knowledge at the transmitting system.

1.5.2 Spatial multiplexing

A dominant technique used to increase channel capacity in the presence of lower signal to noise ratio (SNRs) is spatial multiplexing. Spatial multiplexing can be used to split an individual signal using high data transfer rates to several lower rate signals, and then transmit each low rate signal through multiple antennas using the same frequency channel. Sufficient spatial diversity will ensure that each of these incoming signals will be received at the receiver system from different paths. Each of these received signals will have unique spatial signatures. The maximum number of these parallel streams arriving at the receiving antenna is limited by the total number of antenna systems at the source and destination. Therefore spatial multiplexing does not require the knowledge of the source.

1.5.3 Diversity Coding

In the event that there is no prior information about the channel at the source, diversity coding techniques can be employed. In this process, space time coding is used to encode the signal into a single stream for transmission over the channel. Since the same signal will be sent from each transmit antenna, orthogonal coding will be used. Since each signal is transmitted in independent paths, they will experience fading independently and diversity coding exploits this behaviour to enhance the quality of the received signal. Since the receiver has no knowledge of the channel state at the source, array gain or beam forming gain cannot be achieved using diversity coding techniques. It is also possible to combine recording with spatial multiplexing and the channel state is known at the transmitting system, or it can be combined with diversity coding as the channel state is unknown.

1.6 Types of MIMO Systems

Categories of Multi-Antenna Systems

Multiple antenna MIMO systems (either single user or multi-user MIMO) are developed primarily for use with wireless network architectures such as IEEE 802.11 or WiMAX.

- SISO/SIMO/MISO systems are deteriorating usage conditions of MIMO systems.
- If the receiver uses only one antenna, MISO (Multiple Input Single Output) represents a deteriorating case.
- If the transmitter uses only one antenna, SIMO (Single Input Multiple Output) represents a deteriorating case.
- If both transmitting and receiving systems do not use more than one antenna, the communication system is represented by a SISO (Single Input Single Output) model.

1.7 MIMO Detection Systems

1.7.1 Equalisers

The process of fine tuning electronic signals to create a balance between different frequency components is referred to as equalisation. Although, the use of equalisation in sound engineering is well-known, it has applications in other signal processing industry such as electronics and telecommunication. An electronic circuit called the equaliser is used to achieve this task. Therefore the equaliser is responsible for either increasing or reducing the energy of specific frequency band. Thus equalisers play a vital role in electronic systems such as analog television and radio transmissions. In these applications, it is important to preserve the characteristics of the transmitted waveform, and not just the frequency information. Thus equalisers are used along with filters to cancel out delay effects that directly result in changes in-phase and group delay in communication equipment. Inter-symbol interference can also be reduced through equalisation, and thus allows the recovery of transmitted symbols in digital communication systems. The commonly used equalisation systems in digital communication are [13]:

1.7.1.1 Zero Forcing (ZF) Equalizer

Zero Forcing (ZF) Equalizer computes the counter response of the communication channel. Therefore ZF equalizers use a form of linear equalization algorithm to counteract distortions. This method proposed by Robert Lucky, is used to restore signals received from a noisy channel. Thus ZF equalization is applied to the received signal, by inverting the channel frequency response, and helps to restore the received signal. If this equalizer is used in noise-free environment, which reduces the inter symbol interference to zero. Thus if the channel has a refined frequency response F(x), the zero forcing equalizer can be created by inverting the frequency response as G(x) = 1/F(x) such that the combination of these two frequency responses yield a flat response curve with the linear phase such that F(x)G(x) = 1 [14].

1.7.1.2 Minimum Mean Square Error (MMSE) Equalizer

The method used to minimise the Mean Square Error (MSE) in signal processing is referred to a MMSE estimator. The MMSE estimator therefore provides insights into the quality of the estimation process. This estimation occurs in a Bayesian setting, as the alternative frequency is fixed and does not exist in any estimation system having minimal mean Square error. Training sequences used by MMSE equaliser estimates the multipath characteristics of the channel. These estimates are then used to understand the effects of channel ISI. If these estimators are used to minimise the variance among unbiased estimators, they are then referred to as Minimum Variance Unbiased Estimator (MVUE) [14][15].

1.7.1.3 Maximum Likelihood (ML) Equalizer

Maximum Likelihood Method refers to the process of estimating signal parameters by using a statistical model. The estimation process provides the parameters for the statistical model. Maximum likelihood, then corresponds to one of the most popular methods in statistics. For example, if one is interested in studying the heights of the adult population in a particular city, but constraints with respect to cost or time may prevent them from measuring a little heights of the entire population. In this case, it can be assumed that the heights of the adult population follow a Gaussian distribution with some unknown parameters such as the mean and the variance of the distribution. Here

MLE can be used effectively to estimate the mean and variance of the entire population by using a limited sample of measured heights. This is possible since MLE uses parametric measurements that used the observed samples which are most probable wide estimating the unknown mean and variance of the distribution. Thus for a limited sample set, the maximum likelihood method can be employed as a statistical model for creating a distribution with the necessary model parameters that provides the greatest probability of the observed samples. Thus it can be said that ML estimation maximises the likelihood function while estimating these parameters and provides a single unified approach to statistical estimation, which is applicable not only to Gaussian distributions but many other problems as well [14][15].

1.7.1.4 Monte Carlo Receivers

Monte Carlo methods are widely used algorithms based on the construction of Markov chain models. These methods use a Markov chain model construction technique from a set of samples obtained from the probability distribution. Monte Carlo methods ensure that the Markov chain is an equilibrium distribution based on the desired distribution. The Markov chain state information (generally after performing sufficient iterations) can be used to create a sample of the necessary distribution. The quality of the samples improves over time and as a function of the total number of iterations [8].

The approximation of a given distribution is possible to Monte Carlo Markov Chains, since the starting point of the given distribution always exhibits residual effects. Complex Monte Carlo Markov Chains algorithms can be based on feedback mechanisms which combine current samples with past samples to obtain more accurate information. This creates an additional computational cost while removing the bounds on the run time. These methods ensure that the constructed Markov chain have the integrand at its equilibrium. Therefore Markov chain Monte Carlo methods have found wide usage in diverse fields such as computational physics, computational biology, linguistics and Bayesian statistics, where multidimensional integrals are often used.

1.8 Wireless Networks

Today there is an increasing need for mobility and accessibility in our information society. Associated with this need is the desired for ever increasing data transmission rate. This presents a significant challenge for future generation wireless systems with respect to broadband communication capabilities and providing a very high quality of service (QoS) whenever possible. High data transfer rates and quality of service provisions are essential even in wireless LAN systems in order to implement new applications such as television broadcasting, home entertainment and media streaming. These capabilities were lacking in older IEEE 802.11b or even the IEEE 802.11a/g standards. As an example, a high-quality MPEG 2 video stream requires a bandwidth of 6 Mbps to about 8Mbps, whereas a HDTV MPEG stream requires the bandwidth of about 20 Mbps [66].

The very high bandwidth demand for these applications were continuous transmission of high rate data, while ensuring reliability and uninterrupted service requires high-quality and synchronous connections. Therefore the availability of effective bandwidth plays an important role in mobile radio communication technologies, which is a challenge as the systems operate in a limited bandwidth spectrum. Since available radio spectrum is a precious commodity, methods that effectively exploit these scarce resources are required. Thus a consistent approach towards utilising the offered degrees of freedom is essential in the need for increasing the speed of communication.

One of the important goals of wireless communication is transmissions that are devoid of errors. It is seen that huge amounts of information are transmitted by multimedia apps used over wireless communication systems. The need for error-free communication drives the use of multiple antenna systems, and these can be implemented at both the source and destination along with other signal processing methods such as coding and modulation. It is due to this reason that MIMO systems find increasing use in 4G wireless networks.

1.8.1 Local Area Network (LAN)

A small area such as a house, an office or a campus can be connected using a network of computers, generally a LAN system. An example LAN configuration is as shown in figure 1.4. In comparison to wide area networks, LANs for local area networks operate over a smaller geographic area and generally do not include leased line communications.

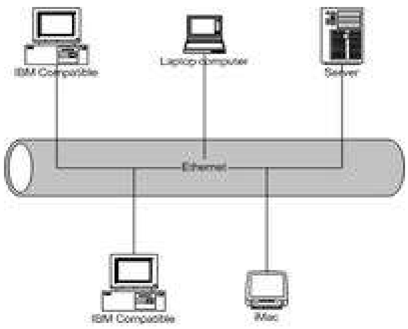


Figure 1.4: An example LAN configuration that uses Ethernet

Similarly, WLAN can be used to wirelessly distribute data between different devices by using a mechanism such as OFDM or spread spectrum techniques. The systems enable connectivity through an access point that connects to the larger networks such as the Internet. WLANs provide the flexibility for users of moving in a fixed coverage area while still retaining network connectivity. Generally, wireless LAN standards use the specifications of the IEEE 802.11 protocols, also known as Wi-Fi.

1.8.2 Wireless Metropolitan Area Network (WMAN)

A Metropolitan Area Network (MAN) usually spans a large geographic area. These networks generally span a large area such as an entire campus, or a part of the city. Metropolitan area networks also interconnect LAN systems and enable them to be part of a larger backbone network. These backbone networks can be build using high-speed fibre-optic communication links and are used to interconnect wide area networks to the larger Internet system.

According to the IEEE 802-2002 standard, a Metropolitan Area Network can be considered to be an optimised version of a LAN system, but for a larger geographic area which may range from several blocks to an entire city. Therefore competition channels with higher capacity and high data rates are used in Metropolitan Area Networks. Thus these networks may not only be owned and operated by single organisations, but also by a community of individuals and small organisations. It is also possible that MANs are owned and operated by federal or governmental entities, and therefore will often provide a mechanism for interconnection and data connectivity with local area networks. The size of the MAN falls between the geographic size of a WAN and a LAN system. Thus Internet connectivity for local area networks can be provided through MANs in a metropolitan coverage area and is therefore useful to connect the smaller networks to wide area networks such as the Internet [75].

1.8.3 Worldwide Interoperability for Microwave Access (WiMAX)

WiMAX networks are standardized by the IEEE 802.16 family of standards that is developed by WiMAX forum. The standards ensure conformance and interoperability with other wireless communication standards. The WiMAX systems enable data transmission rates between 30 to 40 Mbps initially, and with the development of recent standards enable data transmission for fixed wireless nodes of 1Gbps. WiMAX is a standards-based technology that is designed as a replacement for DSL and cable Internet, which is capable of delivering last mile connectivity through wireless broadband access [69].

1.8.4 Long Term Evolution(LTE)

LTE forms the fourth generation standard for wireless data communication, and is a natural evolution of the GSM/UMTS standards. The vision of 4G technology has been to increase link capacities, as well as to use new wireless signal processing techniques and modulation schemes to increase the speed of communication over a mobile wireless network. LTE systems are also tasked with the simplification of existing network architecture and redesign them so that they can be deployed on an IP-based architecture. This consequently leads to a significant reduction in end-to-end delays in comparison to 3G UMTS architectures. Thus the air interface standard designed for LTE systems are incompatible with previous generation 2G and 3G networks. Therefore LTE systems require a different wireless spectrum for operation. Through these advances, LTE has become a common standard for use with high-speed mobile wireless communications and data terminals [68].

1.9 Motivation

MIMO is an advance technology that can be employed to provide efficient solutions to traffic management and capacity issues in networks. MIMO can be used to exploit multipath propagation and use it to increase the reliability of the transmissions. This makes it possible to improve the performance of the wireless communication system, without adding a significant system cost. These reasons have therefore been responsible for an unprecedented success of MIMO communication systems. It has also been a driver of research into other related areas such as information theory, wireless signal processing, antenna engineering and propagation and channel modeling.

Recent technology standards such as 3GPP LTE systems and terrestrial broadcast applications such as digital TV, have advanced significantly by incorporating technologies such as OFDM and CDMA. Since mobile communication systems transmit information over the air using radio channels, that eventually grown to different channel effects such as fading and multipath. These effects lead to the corruption of the transmitted information and create ISI effects. To mitigate these effects, additional signal processing techniques such as equalisation (which requires channel state information) may be required. Further, the channel is to be frequency selective and the mitigation of this selectivity has to be taken into consideration during the design of high speed networks.

1.10 Problem Definition

Mobile communication systems operate in harsh environments and noisy channel conditions. This makes the wireless channel unpredictable and unique in comparison to wired channels, due to a variety of degrading factors such as shadowing, fading, multipath, diffraction and scattering. Additionally mobility causes other challenges associated with doppler spread, delay spread and time dispersion. Therefore the combination of these above factors, along with user mobility creates a wide range of operating environments for the wireless system. Early MIMO propagation models only considered the amplitude and time-varying properties of the channel. Eventually, these models were enhanced by the inclusion of time delay spread information, which is critical for assessing digital transmission performance. The model must also account for the physical geometry of scattering objects around the antennas. The number and locations of these scattering objects are dependent upon the heights of the antennas. Various models have been developed in previous work. In general these models assume uniform scattering around the receive antenna.

Scattering effects of the channel can be an important source of interference leading to low quality of signal reception. To avoid such interference due to scattering, innovative methods such as the use of antenna arrays, and diversity techniques are employed. If the channel conditions are highly dispersive in nature, spatial diversity can be used to mitigate scattering effects. MIMO communication systems take advantage of the channel dispersive nature instead of counteracting it. The MIMO communication system performance can be influenced by signal propagation in indoor environments, where a multiple antenna systems are employed at both ends of the communication system.

The investigation and studies of the MIMO system presented here represent communication over the downlink and system level scenarios. The capacity of the system is influenced by multi-user interference effects. The spatial characteristics of the communication channel, during propagation are responsible for the interference created. It includes line-of-sight areas, far clusters and new models propagation. This makes it feasible to test and evaluate MIMO communication system performance under different channel and propagation conditions. Different environments will also affect the incremental rise in MIMO capacity as the number of antennas is increased.

Therefore, channel modelling for MIMO systems is critical in order to be able to assess the relative performance of the various MIMO architectures. A very promising approach is to use MIMO-OFDM system. MIMO can be integrated with OFDM communication in order to mitigate the frequency selective behaviour of the channel. Due to these reasons, OFDM can be used effectively in broadcasting and wireless LAN applications. Thus, OFDM finds a place in most modern networking standards such as IEEE 802.11, WiMAX and LTE.

1.11 Objectives

The main objectives of the proposed research investigations are as follows:

1) Define a composite MIMO configuration with specifications and modifications in the algorithms for designing an efficient MIMO transceiver system with different modulation, multiplexing techniques and higher MIMO systems at the transmitter end and different detectors and implementation of MIMO system on wireless networks at the receiver end to improve the Bit rate to bandwidth efficiency of the MIMO channel.

2) Development of MIMO transmission system with OSTBC and ALAMOUTI coding for different modulation techniques such as BPSK, QPSK and 16-QAM. Evaluate the SNR performance with BER, for equalizer detections such as ZF-SIC, MMSE-SIC and ML-SIC detector systems.
3) Development of MIMO transmission system with CDMA and OFDM multiplexing for different modulation techniques. Evaluate the SNR performance with BER for different detection systems. Compare the SNR performance of MIMO-CDMA and MIMO-OFDM system with MIMO-OSTBC multiplexing to determine efficient multiplexing and detection system.
4) Development of Higher (3x3) and (4x4) MIMO transmission system for OFDM multiplexing with different modulation techniques and detector systems. Compare the SNR performance with BER of the efficient detection system with the Monte Carlo detection scheme.
5) Implementation of different SISO, SIMO, MISO and MIMO transmission systems with OFDM multiplexing and different modulation techniques on wireless WiMAX Physical layer (IEEE 802.16d-2004) network and evaluate SNR performance with BER.
6) Implementation of MIMO-OFDM transmission system with different modulation techniques on wireless networks such as WLAN (IEEE 802.11n) and Long Term Evolution (LTE) to evaluate the SNR performances with BER. Compare SNR performance of WiMAX (IEEE 802.16m-2009) network with WLAN and LTE networks.

The major part of the thesis work includes design of MIMO transceiver configuration with specifications and the modifications of the software codes for MATLAB-R2013 and conduct simulation studies of the MIMO Transceiver system with different multiplexing, modulation and detection techniques and determination of SNR in terms of E_b/N_0 (where E_b Energy per Bit for transmission and N_o is the AWGN Noise power) and Bit rate to Bandwidth (BR/BW) efficiency at a given BER. Further simulation studies are carried out by implementing the MIMO-OFDM transceiver system on different advanced wireless networks such as WLAN, WiMAX and LTE for achieving more efficient data transmission over the communication systems. In every case the lowest SNR values (E_b/N_0) at a given BER is taken as an important parameter to determine the BR/BW efficiency of the MIMO transceiver system for higher bit rate data transmission.

1.12 Structure of the Thesis

The subject matter of the Thesis has been divided into *Nine* chapters.

Chapter-1: Gives general introduction of Digital Communication, Digital Modulation, MIMO transmission systems, different multiplexing techniques and MIMO detection systems. The chapter outlines the motivation, problem statement of the present research work, main objectives and structuring of the thesis.

Chapter-2: Makes detailed literature survey on the MIMO Concepts, Space Time Block Coding (STBC) and OSTBC with Alamouti scheme, Orthogonal Frequency Division Multiplexing (OFDM) and Code Division Multiple Access (CDMA), MIMO detection techniques and MIMO-OFDM on networks.

Chapter-3: Depicts various designed MIMO configurations, specifications and modifications in the algorithms for developing an efficient MIMO transceiver system with different modulation, multiplexing techniques and higher MIMO system at the transmitter end and different detectors and implementation on various wireless networks at the receiver end.

Chapter-4: Presents mathematical description of MIMO concepts, MIMO working and the channel model. The algorithm developed and methods of implementation schemes of MIMO-OSTBC design, encoding and decoding incorporated for BPSK, QPSK and 16-QAM modulation schemes and ZF, MMSE, ML with SIC detector receiver systems and the performance of MIMO system in different transmission environment.

Chapter-5: Deals with analysis and simulation of (2x2) MIMO performance with different multiplexing techniques such as CDMA and OFDM for different detection systems such as ZF, MMSE and ML with SIC detector receiver systems for BPSK, QPSK and 16-QAM modulation schemes. The performance of (2X2) MIMO for OSTBC, OFDM and CDMA Multiplexing system are evaluated.

Chapter-6: Describes the analysis and simulation of higher (3x3) and (4x4) MIMO-OFDM system performances for different detection systems and modulation schemes. Further the analysis for (4x4) MIMO systems with OFDM multiplexing for Monte Carlo

Detection system has been carried out. The performance of higher order MIMO systems with receiver diversity are investigated.

Chapter-7: Presents the analysis and simulation of lower and (2x2) MIMO-OFDM systems on WiMAX physical layer (IEEE 802.16d-2004) network for different BPSK, QPSK and 16-QAM modulation. Comparison of the WiMAX network SNR performance with BER for different MIMO systems is discussed.

Chapter-8: Illustrates the implementation of MIMO-OFDM transmission system with different modulation techniques on wireless networks such as WiMAX physical layer (IEEE 802.16m-2009), WLAN (IEEE 802.11n), and Long Term Evolution (LTE) networks. Evaluate the SNR performance with BER. The chapter gives a comparison of the WiMAX network SNR performance with WLAN and LTE networks.

Chapter-9: Summarizes the results obtained in the previous chapters for different MIMO systems, modulation, multiplexing and detection techniques. The results of the thesis research investigations are discussed compared with one another and conclusions are drawn. The suggestions for future studies in the area of research are made at the end of the chapter.

CHAPTER 2

LITERATURE SURVEY

CHAPTER 2

LITERATURE SURVEY

2.1 Multiple Input Multiple Output (MIMO)

The earliest idea on MIMO was given by A.R. Kaye and D.A. George [1]. H. Brandenburg and A. D. Wyner [2] discuss the capacity of Gaussian Channel with Memory and the Multivariate cases. Jack Winters and Jack Salz [3] publish several papers which discuss beam forming related applications. A J Paulraj and T Kailath [4] propose the notion of spatial multiplexing technology that uses MIMO. Gregory G Raleigh and John M Cioffi [5] refine new approaches to MIMO technology, while focusing on configurations that use co-located multiple transmit antennas in order to improve the efficiency effectively. G. J. Foshini [6] provide a solution which includes a layered architecture spread across space–time, for wireless communication architectures using multiple antenna systems and operating in a multipath fading environment.

J. H. Winters [7] shows the advantage of using the diversity techniques transmission and reception, in the channel characterised by Rayleigh fading. Multiple delayed versions of the signals are transmitted when transmission diversity is employed. This time delayed versions at the receiver can be employed to reduce the frequency selective fading behaviour, by using equalisation to improve the diversity gain of the system. Simulation techniques such as Monte Carlo methods may be employed to understand the performance of transmit diversity in the Rayleigh fading environments, and estimation at the receiver system may be done using the maximum likelihood method. S. Cui, A. J. Goldsmith and A. Bahai [8] develop the MIMO concept that uses cooperative MIMO to increase the energy-efficiency in Sensor Networks. Sam P. Alex Louay M.A and Jalloul [9] conduct the assessment of MIMO systems which have been surveyed in WiMAX.

Paulraj, et.al [10] present the use of Multiple Input Multiple Output (MIMO) wireless communication systems by employing multiple transmit and receive antennas in a low cost emerging technology that provides a substantial increase in data transmission rates of wireless links by allowing communication up to 1Gbps. S. Mudulodu and A. Paulraj [11] study channel fading performance when space-time coding techniques are employed and show that the incorporation of multiple antennas at the transmitter directly impacts the diversity reception of the system.

Kai-Kit Wong, Ross D. Murch and Khaled Ben Letaief [12] describe the performance of a multiuser MIMO system. By exploiting space diversity, it is shown that the use of multi-user communication in wireless systems leads to an increase in capacity. Nagarajan Sathish Kumar and K. R. Shankar Kumar [13] outlined the issues associated with signal recovery in wireless competition systems that are caused due to fading and interference effects. They also describe a solution to counteract these effects through the use of an equalisation system. The BER performance characteristics of three types of equalizers namely ZF, MMSE and ML equalizers for MIMO wireless receiver are analysed.

Swetamadhab Mahanta, Sakshi Tiwari and Ramesh Bharti [14] explain the importance of MIMO in today’s 4G wireless system and give an analytical examining of signal detection by the use of SIC with ZF, ML, MMSE and QR decomposition for 64-QAM modulation schemes with the help of Rayleigh fading channel is studied under various combinations of transmit/receive antennas. Here, it is concluded that for 64-QAM scheme, ML is the best detection scheme as it is giving low value of Bit Error Rate (BER) for subsequent variation in Signal to Noise Ratio (SNR). Apart from that, as the number of antenna is increasing at the receiver end, i.e. for receive diversity, BER is reducing drastically. Narendra M R [15] describe the performance of (2X2) MIMO antenna systems by providing a performance analysis of transmit diversity. Alamouti Space Time Coding (STBC) techniques is used in combination with various modulation schemes such as BPSK and QPSK to investigate the transmission characteristics of the system. Additionally AWGN channels are used to recreate the characteristics of a noisy channel and flat fading is also used through a Rayleigh distribution. Linear equalisation techniques such as ZF and MLD are used to understand the BER performance.

2.2 Multiple Input Multiple Output-Space Time Coding (MIMO-STBC)

Siavash M. Alamouti [16] deal with the significance of achieving communication improvements by using reference pilot carriers along with inter-symbol guard intervals time periods. Improvements in performance are shown with the use of long time interleaving, in environments which experience deep fading and impulsive noise characteristics. Tianyu Mao and Mehul Motani [17] present the vertical Bell-labs layered space-time (VBLAST) scheme that can be used to exploit the capacity potential provided by multiple transmit antenna systems. In VBLAST systems, detection and decoding are performed layer by layer in a successive way. However, successive processing degrades performance because of the low minimum diversity and error propagation.

Van-Su Pham, et.al [18] propose a low-complexity maximum-likelihood decoding approach based on QR decomposition (QRD) for signal detection in VBLAST-STBC systems, which employ less receive antennas than transmit antennas. Chen Meng and Jamal Tuqan [19] explain about the degradation in the BER performance of the vertical Bell-Labs layered space-time (VBLAST). A hybrid scheme that integrates orthogonal space time block codes (OSTBC) into the lower layers of a VBLAST system has been introduced. STC method that improves BER by increasing the diversity gain and the other is spatial multiplexing (e.g. VBLAST) which focuses on maximizing the channel throughput is studied.

Vahid Tarokh, Nambi Seshadri and A. R. Calderbank [20] develop and construct codes for space–time on high data rate wireless communication and also use multiple antennas across multiple timeslots to distribute a trellis code in order to provide diversity and coding gains. S.M. Alamouti [21] propose a wireless communication system that employs simple transmit diversity. This competition system transmits one block of data at a time in a manner similar to block codes, to provide reduced complexity and increased diversity gains. Marzetta T.L. and Hochwald B.M [22] give a novel idea on how the capacity of the system can be improved in the presence of Rayleigh fading, but mobile system that uses multiple antenna configuration. V. Tarokh and H. Jafarkhani [23] propose detection scheme that is differential in nature, for systems that use diversity at the transmitter, and showed that information about the channel state audit statistics are not essential in the proposed differential space-time coding that are employed.

Vahid Tarokh, Hamid Jafarkhani and A. R. Calderbank [24] describe STBC developed from orthogonal designs makes another major evolution in Information theory. L. Zheng and D. N. C. Tse [25] explain diversity-multiplexing trade-off (DMT) and shows that a trade-off exists between multiplexing and diversity in a MIMO system.

Emre Telatar [26] show that a theoretical upper bound exists for the channel with a defined capacity, and this limits the throughput of the system. The use of a MIMO communication system can increase this limit proportionally depending on the number of transmit and receive antennas employed. Z.Shang, W.Sun and X.Zhou [27] present conditions that are required to ensure that multi-input signals are recovered completely, and is presented in a survey conducted by A. Paulraj, et.al [10] and also explain a vector sampling expansions in shift invariant subspaces in MIMO systems. Gerard J. Foschini and Michael J. Gans [28] present the upper bounds of wireless communication systems under environments which experience fading with use of MIMO antennas.

Quadeer A.A., et.al [29] give a novel idea that an integral part of the receiver design involves estimating the quality of the channel, and show that the use of eye to estimation in the joint channel provides better capabilities for data recovery for Space Time Block Coded MIMO-OFDM systems in environments experiencing fast fading. Weifeng et.al in [30] propose necessary and sufficient condition for any OSTBC to allow transceiver signal.

Luis Miguel Cort´es-Pe˜na [31] present detailed study of diversity coding for MIMO systems. Different STBC schemes including Alamouti's STBC for 2 transmit antennas as well as orthogonal STBC for 3 and 4 transmit antennas are explored. The performance of bit-error rates using BPSK, QPSK, 16-QAM, and 64-QAM modulation schemes is studied. Block codes schemes with different code rates for the cases of 3 and 4 transmit antennas were discussed.

Shubhangi Chaudhary and A.J. Patil, 2012 [32] explain submission results obtained through the use of the simulink modelling tool. The performance of MIMO-STBC with different modulations, such as M-PSK, BPSK, QPSK, 8-PSK and M-QAM, 16-QAM and 64QAM, 256-QAM are studied on the basis of BER, SNR and error probability. The work shows that for systems using space-time block codes, low BER can be achieved through the use of lower order modulation schemes. From the results presented, it is seen that the error performance of a 256-QAM STBC system is much less than that of BPSK for higher errors without STBC.

Lakshmi Prasanna.P and G.Rama Krishna [33] conduct the analysis of STBC and OSTBC codes with respect to BER performance in diversity enabled MIMO systems.

They provide a comparison for space time block codes with and without orthogonality of (2x2) and (8x2) MIMO with maximum likelihood and maximum ratio combining detection systems. Lucian Andrei Perişoară [34] present the analysis of STBC used in MIMO communication can be used to achieve transmit diversity. Similarly the use of maximum ratio combining methods can be employed at the receiver side to provide diversity reception. Also, the number of antenna systems at the transmitter is seen to influence the performance of the system when STBC coding techniques are employed, and the work presents error performance analysis and diversity gains in a wireless communication system that experiences flat fading.

Khoa T. Phan and Chintha Tellambura [35] give an idea of antenna selection for MIMO where only a subset of antennas at the transmitter and/or receiver are activated for signal transmission, a practical technique for the realization of full diversity. The exact closed-form capacity expressions when an OSTBC is employed and N transmit antennas out of total L_t antennas are selected for transmission is derived. The capacity of TAS and OSTBCs for MIMO systems is analysed. The closed-form capacity expression, which avoids the need for numerical integration methods, was derived. The results are sufficiently general to handle systems with an arbitrary number of antennas at both ends of a MIMO link.

Dao and C. Tellambura [36] propose a new method to directly analyze and optimize Symbol Error Rate (SER) performance of Minimum Decoding Complexity (MDC). Additionally, a new signal transformation for rectangular quadrature amplitude modulation is proposed to provide better performance than the existing ones with lower encoding/decoding complexities. Additionally, a new signal transformation to improve the performance of rectangular QAM with less encoding/decoding complexity has been proposed.

2.3 Multiple Input Multiple Output-Code Division Multiple Access (MIMO-CDMA)

Dae-Ki Hong, Young-Jo Lee and Daesik Hong [37] propose frequency offset estimation and combining techniques for Pilot Symbol Assisted (PSA) packet downlink CDMA-MIMO antenna systems. Orthogonal Walsh codes are used for dedicated pilot symbols at the transmit antennas. Discrete Fourier transform (DFT)-based frequency offset estimation is used for simple implementation.

Ruly Lai-U Choi and Ross D Murch [38] propose a system for MIMO that uses direct sequence spread spectrum and CDMA communications that increases the signal-to-interference noise ratio (SINR) in the downlink. This assumes that the MIMO communication system is operating in an environment which exhibits frequency-selective fading. The proposed system implies transmit diversity at the base station through the use of an antenna array, and receiver antenna array at the mobile station. The receiver array implements a set of FIR filters. A MIMO communication system is then used to improve SINR, and a marked improvement in performance is detected in comparison to a conventional CDMA system that uses a Rake receiver or a diversity reception prior to the Rake receiver. Significant improvements in the capacity of the system and performance were shown and the performance of the system improves with the addition of more antennas without saturation. They also showed that the proposed work is a robust and insensitive to channel estimation.

V.Nagarajan and P. Dananjayan [39] discuss a novel method for communication systems with MIMO, where multicarrier detection systems are employed. A chaotic spread spectrum sequence is used to enhance the performance of direct sequence (DS) CDMA communication systems. The system analysis and results are presented for scenarios that involve multi-user communication. The simulation results present a new approach using chaotic spreading codes that can be used to improve the performance of the system and further reduce interference effects in multiple access channels. Further improvements are also suggested the use of Walsh Hadamard spreading code in MIMO MC- DS/CDMA systems.

Peter W. C. Chan and Ernest S. Lo [40] describe the Orthogonal frequency division multiple access (OFDMA) and multicarrier code division multiple access (MCCDMA) which has recently drawn much attention for being potential candidates of future generation cellular systems. The effects of path loss, number of antennas and different user types are studied and insightful results are obtained.

Wan Choi [41] develop a novel system design using antenna partitioning for analyzing MIMO–CDMA system. As the diversity order increases with the number of antennas, the gain of the dynamic antenna-partitioning technique becomes dominant. Since the proposed techniques have low complexity and are similar in principle to current industry systems, it appears that MIMO–CDMA with antenna partitioning is a viable method in increasing the forward-link CDMA system capacity by 100% or more, depending on the number of available antennas.

K. Vishnu Vardhan, Saif K. Mohammed and A. Chockalingam [42] propose a low-complexity detector which achieves uncoded near-exponential diversity performance for hundreds of antennas with an average per bit complexity of just $O(N_tN_r)$, where N_t and N_r denote the number of transmit and receive antennas, respectively. With an outer turbo code, the proposed detector achieves good coded bit error performance. The practical feasibility of the proposed high-performance, low-complexity detector could potentially trigger wide interest in the theory and implementation of large MIMO systems and also illustrates the applicability of the proposed detector in the low-complexity detection of high-rate, non-orthogonal space-time block codes and large multicarrier CDMA (MC-CDMA) systems.

B.Raja Ramesh and Umasankar.Ch [43] present code division multiple access (CDMA) systems where the calculated parity bits are used to select a spreading sequence from a set of mutually orthogonal spreading sequences. This technique was extended to CDMA systems using MIMO techniques. The performance of the two techniques for MIMO-CDMA systems operating on frequency-flat slowly Rayleigh fading channels was compared.

Pritam Som and A. Chockalingam [44] develop high spectral efficiency multicode CDMA systems with large number of users employing single/multiple transmit antennas and higher-order modulation. A local neighbourhood search based multiuser detection algorithm which offers very good performance and complexity, suited for systems with large number of users employing M-QAM/M-PSK is considered.

Karmjeet Singh and Rajbir Kaur [45] illustrate the concept of MC-CDMA and its role in current wireless competition networks. It is shown that CDMA can use multiple antenna systems to improve its performance significantly. An evaluation of E_b/N_0 against average bit error rates of the communication showed that, for multicarrier CDMA communication over Rayleigh channel, the observed BER decreases with respect to the corresponding increase in E_b/N_0. QPSK modulation scheme was used in an AWGN channel environment during the simulation. P. Sreesudha and M. Vijaya Lakshmi [46] explain the important role of CDMA in modern wireless communication systems.

2.4 Multiple Input Multiple Output–Orthogonal Frequency Division multiple access (MIMO-OFDM)

Helmut Bolckset [47] provides an insight into the fundamentals of MIMO-OFDM system. The focus on various signal aspects such as frequency, the design of the receiver and system design that takes into account multiple users. The discussion concludes with an overview of the open areas of research and issues associated with the hardware implementation of about systems.

Orlandos Grigoriadis, H. Srikanth Kamath and Iaeng [48] discuss the use of a Matlab simulation for understanding the BER performance of an OFDM transmission system for varying SNR. The simulation design takes into consideration, channel effects such as multipath propagation, and shows that BER increases with an increase in the number of carriers for a fixed SNR and channel conditions.

Myung-Sun Baek, et.al [49] propose a novel method that involves the combination of signal processing associated with MIMO systems and OFDM is the solution to performance improvements for next generation network architectures. The performance of the wireless communication system that utilises double combination is analysed in both multiple access as well as broadcast network scenarios. Channel estimation techniques for multiple users are
employed along with OFDM training symbols with at least two transmit antennas is analysed and the corresponding results are discussed.

Vineet Sharma, et.al [50] gives an idea that high BER requirements necessitate the need for employing error correction mechanisms such as Forward Error Correction (FEC). The use of such mechanisms reduces the amount of errors especially in the transmission of data over wireless networks. Further, FEC rules the performance of OFDM communication systems that employ BPSK, QPSK and QAM modulation schemes. Also, FEC uses in coding schemes such as convolution codes or Reed Solomon codes or concatenated codes to encode information transmitted over noisy wireless channels. It is shown that by combining two different coding schemes, BER performance improves as these codes can correct for burst errors as well as bit errors caused in an AWGN channel.

Ammar Ali Sahrab and Ion Marghescu [51] show that the use of MIMO-OFDM leads to high data rate communication wirelessly over a broadband channel. This paper provides an in-depth analysis of a MIMO-based OFDM system by using a MATLAB program. The system performance is evaluated to compute the BER and by using MMSE level with Alamouti and SM algorithms. Further performance enhancements can be obtained by using diversity schemes such as ML detection and space time block coding, space frequency block coding etc., at both the transmitter and the receiver systems. The modulation type (BPSK, QPSK, 16QAM and 64QAM) are clearly affecting the performance.

Z. Zhang, W. Zhang and C. Tellambura [52] propose an optimal pilot design and placement for channel estimation in MIMO-OFDM systems considering frequency offsets. Both the single-frequency offset case and the multiple-frequency offset case are treated. P.Sunil Kumar, Dr. M.G.Sumithra, and M.Sarumathi [53] analyse the BER of Rayleigh fading channels in MIMO-OFDM systems using BPSK and QPSK modulation schemes. The radio frequency signals with appropriate statistical properties are simulated. After comparing the simulation results it is seen that the error performance of BPSK modulation is much less in comparison to that of QPSK systems. Therefore it can be seen that BPSK performance is better in channel environment that experiences Rayleigh fading. K.Vidhya and K.R.Shankarkumar [54] provide the channel parameter estimation and BER performance for MIMO-OFDM systems. Using this new communication scheme, BER calculations are computed for 2x2 MIMO by using channel estimation parameters. The proposed work exhibits better performance in comparison to conventional MIMO-OFDM systems for the 2x2 case. The low complexity of the proposed work along with its high-performance, makes it suitable for use with STTC Coding in MIMO-OFDM systems.

Parul Wadhwa and Gaurav Gupta [55] explain the equalization problem for MIMO systems by using numerical results for the simulated performance of the equalization techniques for MIMO systems show that as the number of antennas at the receiver increases, the error performance improves. Equalization technique MMSE is implemented at the receiver. It is observed that BER performance for MIMO-MMSE with Rayleigh flat fading channel is better than ZF equalizer. Simulation analysis presents details about the fixed antenna MIMO antenna configuration and compare the performance with the three types of equalizer based receiver namely MRC, MMSE and ZF. The MMSE equalizer gives minimum BER values for corresponding E_b/N_0 values. The BER performance of MRC systems are found to be much better than that of MMSE equalisers. Simulation results and analytical models show that the MRC equaliser provides better performance in comparison to the other two systems.

Amol Kumbhare, Smita Jolania and Dr.Rajesh Bodade [56] provide a comparison of performance of space time block coding through the use of different equalisation systems such as ZF, MMSE, ML sequence detectors. They evaluate different performance parameters such as system capacity, spectral efficiency for the proposed system configuration. The combination of ZF with ML sequence or combination of MMSE and MLSE is given an additional advantage in equalization. The ZF equalizer improves the performance over channel response and BER performance is further improved by finding ML sequence.

A. Omri and R. Bouallegue [57] propose a new transmission scheme for MIMO-OFDM systems. The new scheme is efficient and suitable especially for symmetric channels such as the link between two base stations or between two antennas on radio beam transmission. Monte-Carlo simulation results show that the proposed scheme has better performance, in terms of bandwidth efficiency and complexity, compared to the conventional MIMO-OFDM scheme methods in the case of a symmetric channel. This contribution introduces a new transmission scheme for MIMO-OFDM systems. The low complexity and high-performance of the proposed work is confirmed by submission results, which compares Alamouti STBC Coding techniques to conventional MIMO-OFDM systems.

Ye (Geoffrey) Li, Jack H. Winters and Nelson R. Sollenberger [58] show that the MIMO-OFDM system uses two independent STC for two sets of two transmit antennas. At the receiver, the independent space–time codes are decoded using prewhitening technique, followed by minimum Euclidean-distance decoding based on successive interference cancellation. Increasing the number of the receive antennas improves the system performance Therefore, MIMO-OFDM is a promising technique for highly spectrally efficient wideband transmission.

2.5 MIMO Detection

Anuj Vadhera and Lavish Kansal [59] present a solution to enhance the performance of MIMO-SM systems. Higher order modulation schemes are employed for (2x2) antenna configuration using different signal detection technique. MIMO-SM techniques are evaluated through the use of higher order modulation schemes leading to an increase in achievable data capacity. The work presents the BER performance in the presence of AWGN and Rayleigh fading channels for high rate communication systems. The signal detection technique used at receiver end is ZF and MMSE. It is shown that SNR increases, and the BER reduces at higher values of SNR, thereby reducing the effect of the distortions introduced by the noisy channel for higher order modulation schemes.

Rohit Gupta and Amit Grover [60] investigate various equalisation mechanisms in order to study the BER performance of MIMO Systems. The studies conducted using various equaliser types such as zero forcing, minimum mean square estimation, maximum likelihood, spear decoding etc. The performance results indicate that the maximum likelihood method outperforms other techniques. Also, spear decoding exhibits the overall best performance, while ensuring a high decoding complexity in comparison to the maximum likelihood method.

Jitendra R.Shishangiya, Ashish Makwana and Dr. Komal R Borisagar [61] explore two types of detectors: Linear and Non-linear detectors implemented at the receiver. Non-linear detector outperform than linear detector. Performance of the non-linear detectors like ML, ZF-SIC and MMSE-SIC are compared and analysed for different BER Vs E_b/N_0 in spatial multiplexing domain. Analysis for different BER for ML, ZF-SIC and MMSE-SIC are compared and also analysed for the MRC. The study confirms that better BER performance is achieved if receiver diversity is more than transmission diversity under the MIMO conditions, therefore MRC gives best results as compared to others.

Ms. Hiral Patel and Dr.MinalSaxena [62] describe an innovative signal detection method known as MIMO detectors, used to improve MIMO performance. MIMO system with V-BLAST architecture along with ML, ZF, MMSE and ordered Successive Interference Cancellation (SIC) detectors are implemented and Rayleigh fading channel is used. The work further analyses MIMO performance using various modulation schemes for the channel impacted by noise and fading. Simulations shows that the performance of a V-BLAST system, shows improvements when combined with detection techniques that use successive interference canceller with ZF or MMSE systems, and can provide the optimal ordering along with reduced system complexity. It is shown that V-BLAST implementations achieve system performance and error rates that are comparable to the maximum likelihood method, while still retaining the reduced complexity in comparison to ML detectors.

Yue Shang and Xiang-Gen Xia [63] discuss the design criterion of embedding complex conjugates in a linear fashion when STBC is employed, in order to achieve full diversity with ZF or MMSE detectors. STBC are constructed by overlapping the Alamouti code. Simulation results indicate that these Alamouti codes that overlapped, provide better performance in comparison to Toeplitz codes, as well as provide a better performance using OSTBC, when the number of antennas is greater than four.

N.Sathish Kumar and Dr. K.R.Shankar Kumar [64] investigate MMSE equalizer based receivers and their performance in MIMO communication systems. Matlab simulation are provided for different transmitter and receiver antenna characteristic to evaluate BER performance. The work shows that the use of an MMSE equaliser is effective for mitigating ISI effects as well as minimising the total noise power in the receiver.

Dhruv Malik and Deepak Batra [65] give suggestion to reduce the complexity of MIMO system and propose detection techniques. BER analysis is presented using different equalizers and then optimum equalization method is suggested. The simulation analysis of MMSE equalizers for 2xn antenna configurations is considered. The error performance improves, as seen from the simulation with an increasing number of antennas at the receiver. This is also consistent with all the three equalisation systems used with the corresponding number of transmit antennas and a MIMO receiver system.

2.6 MIMO-OFDM Implementation on Wireless Networks

Allert van Zelst and Tim C. W. Schenk [66] describe MIMO-OFDM transmitter and receiver scheme. It explains that reference pilot carriers have to be inserted if the minimum level of performance is to be achieved, while making it necessary to have inter-symbol time guard intervals.

Tim C.W. Schenk, Guido Dolmans and Isabella Modonesi [67] illustrate the MIMO-OFDM transmitter and receiver scheme. To achieve acceptable performance the insertion of both reference pilot carriers and inter-symbol time guard intervals are necessary. Performance improvement under deep fading and impulsive noise is usually improved by employing long time interleaving. MIMO-OFDM when generated OFDM signal is transmitted through a number of antennas in order to achieve diversity or to gain higher transmission rate.

Christoph Spiegel, et.al [68] propose the long term evolution (LTE) of UMTS (Universal Mobile Telecommunications System) Terrestrial Radio Access, abbreviated as UTRA LTE, based on OFDM. MIMO are taken into consideration as an alternate method to improve wireless connectivity. The Alamouti and the V-BLAST schemes are used. These two MIMO schemes w.r.t. the achievable performance in the UTRA LTE downlink using up to two transmit and two receive antennas is compared. Furthermore, simulation results showed that both diversity and spatial multiplexing are viable means to improve the data rates.

Mojtaba Seyedzadegan and Mohamed Othman [69] give a technical overview which covers WiMAX overview (Fundamental Concept, Technology, Standard update) and WiMAX architecture (Network and Node Architectures; Physical Layer; MAC Layer).

Wang, Mingxi [70] explain about the WiMAX technology that it has received a lot of attention from the industry during the past two years. This particular technology adopts complex physical layer components such as MIMO-OFDM techniques. A simulation system with LDPC coded MIMO-OFDM is also established to evaluate the performance of the WiMAX transceiver. Simulations show that the iterative receiver structure can achieve good performance.

Prof. LajosHanzo, Dr. Yosef (Jos) Akhtman and Dr. Li Wang [71] describe the conception of parallel transmission of data over dispersive channels. The capacity of the MIMO communication system increases linearly as a number of antennas at the transmitter increases. Further, the use of additional transmit antennas with increased power levels can be used proportionally increase the capacity of the system from the transmitter side.

Manal Al-bzoor and KhaledElleithy [72] depict that WiMAX is an upcoming technology standard that can be used for last mile delivery of broadband services, by providing high data transmission rates and different classes of service leading to a significant improvement in service quality. The unique architecture of the WiMAX MAC and PHY layers that uses OFDMA to allocate multiple channels with different modulation scheme and multiple time slots for each channel allows better adaptation of heterogeneous user's requirements. In this paper a broad study is conducted about WiMAX technology PMP and Mesh deployments from main physical layers features with differentiation of MAC layer features to scheduling and multicasting approaches in both modes of operations.

HardeepKaur and M L Singh [73], J. Mountassir, et.al [74], investigate several modulation techniques for IEEE 802.16 (WiMAX) based OFDM system including BPSK, QPSK, 8PSK and various levels of QAMs. The improvement in system performance is achieved by incorporating a dynamic change in the modulation method depending on the channel conditions. Transmitter and receiver models are simulated according to the parameters established by the standard, to evaluate the performance. Also, convolution coding is used to improve the system performance. Use of adaptive modulation can effectively control the BER of the transmission, as sub carriers that have a poor E_b/N_0 (dB) can be allocated a low modulation scheme such as BPSK. For good E_b/N_0 (dB), the high modulation scheme giving priority to spectral efficiency can be considered. E_b/N_0 of the channel is estimated before the transmission. The modulation scheme is set based on the SNR of the channel.

Yunho Jung, et.al [75] discusses the design and implementation results of a digital MIMO-OFDM WMAN baseband processor with two transmit and two receive antennas. The processor supports two MIMO-OFDM modes of the STBC-OFDM and the SDM-OFDM and the efficient decoding algorithm for each mode is proposed. The PER, link throughput and coverage performance of the MIMO-OFDM WMAN baseband processor with the pro-posed algorithms are also estimated.

Gazi Faisa Ahmad Jubair [76] propose a simulation model based on the IEEE 802.16e OFDM physical layer baseband specification and use various modulation schemes such as BPSK, QPSK, 16-QAM and 64-QAM, and demonstrated different simulation scenarios. The performance evaluation for these modulation schemes by recreating the WiMAX mobile physical layer is presented. The simulation implements a standards compliant OFDMA physical layer specification AWGN channels with Rayleigh fading, and uses SUI model and other signal processing techniques for adaptive modulation and coding.

Simmi Dutta and Devanand Padha [77] present the performance evaluation of IEEE 802.11a OFDM. The channel model simulation to analyse the performance of WLANs based on IEEE 802.11a standard is explained by using indoor environment channel models. IEEE 802.11a uses the basic communication strategy of OFDM which is the base technology for next generation communication systems.

Shau-Yu Cheng, Chueh-An Tsai, and Terng-Yin Hsu [78] elaborate on the wireless broadband applications like WiMAX, Wi-Fi, UWB and WRAN, highly compensating for multipath fading in order to make systems work properly. With the help of a Cyclic Prefix (CP), SISO-OFDM and MIMO-OFDM systems can be easily integrated. In addition, this can help to estimate channels and equalize packets over frequency domains directly. Thus, one of the major challenge for multimode integrations is to make equalizers as compact as possible by linear equalizer.

Jihyung Kim, et.al [79] presents the basic preamble design for channel estimation that features multiple antennas and backward compatibility with 802.11a. It exhibits low overhead and good performance gain because it uses both block type pilot symbols and comb type pilot symbols, both of which are suitable for the WLAN environment.

CHAPTER 3

DESIGN OF MIMO TRANSRECEIEVER CONFIGURATION

CHAPTER 3

DESIGN OF MIMO TRANSRECEIEVER CONFIGURATION

In the present thesis work various configurations for the MIMO transmitter and receiver system have been designed with different MIMO, modulation and multiplexing techniques at the transmitter end and different detectors and wireless networks systems at the receiver end. Algorithms have been modified for each one of the designed MIMO Transceiver configuration. The SNR (E_b/N_0) performance with respect to BER has been evaluated for each designed MIMO configuration to evolve a better MIMO transceiver configuration with maximum Bit rate to Bandwidth efficiency for the wireless network implementation.

In this chapter each one of the designed MIMO transceiver configuration with appropriate block diagram, specifications and necessary modifications made in the algorithms have been summarized for determining the SNR (E_b/N_0) behaviour of the MIMO system with BER. Further in the present work the results obtained for each MIMO configuration have been evaluated to arrive at a more efficient MIMO configuration for implementation on the wireless networks.

3.1 MIMO Transmitter Configuration

From the information source, random sequence of 1’s and 0’s are generated and the data is converted into blocks. The data blocks are modulated using BPSK/QPSK/QAM modulation techniques. Different multiplexing techniques such as OSTBC, CDMA and OFDM are applied to the modulated signal. After multiplexing, the data is transmitted through a transmitter consisting of N transmit antennas. The Rayleigh channel is incorporated at the medium between transmitter and receiver. The same MIMO modulation and multiplexer configuration is adopted for higher MIMO systems such as (3x3) and (4x4) MIMO configurations. The integrated MIMO transmitter configuration is shown in figure 3.1 [35][38][49].

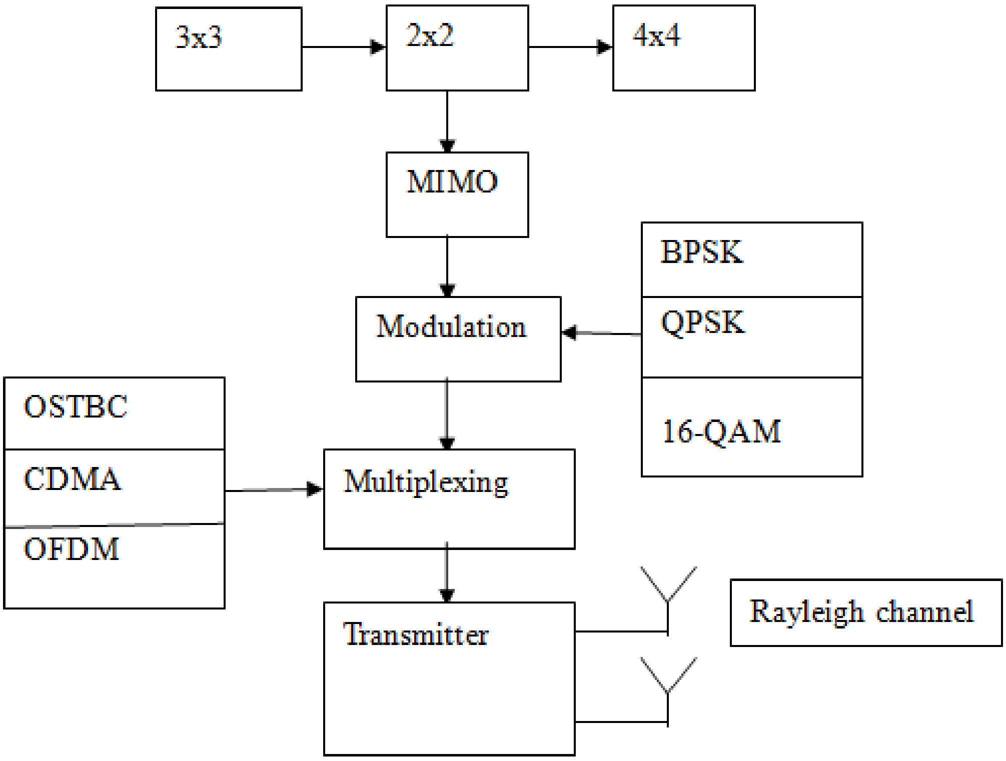


Figure 3.1: MIMO Transmitter Configuration

3.2 MIMO Receiver Configuration

The data modulated and multiplexed signal received from the receiver antennas is demodulated, de-multiplexed and detected using different types of detectors such as ZF, MMSE and ML with SIC detection systems. The received signals after demodulation and de-multiplexing are also implemented on different wireless networks such as WiMAX, WLAN and LTE networks. The integrated MIMO receiver configuration is shown in figure 3.2 [55][56][66].

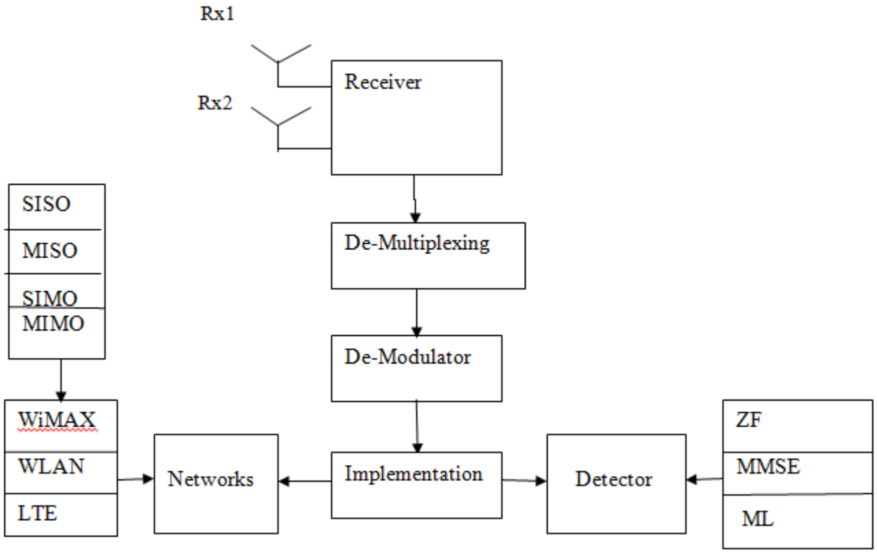


Figure 3.2: MIMO Receiver Configuration

For every combination of the MIMO transceiver system the SNR (E_b/N_0) has been determined as a function of BER to evaluate the Bit rate to Band width efficiency of the MIMO transceiver system.

The Bit rate to Bandwidth efficiency of a transmission channel is given by Shannon theorem

$$\mathbf{H/B_0 = \log_2 (1+ (E_b/N_0)\ (H/B_0)}$$

Where H is channel capacity, B_o is Channel Bandwidth, E_b is the energy/bit and N_0 is the noise power spectral density. (H/B_0) can be defined as Bit rate to Bandwidth efficiency of the transmission Channel and the SNR is defined as

$$\mathbf{SNR = \{(E_b/N_0)\ X\ (Bit\ Rate\ to\ Bandwidth\ Efficiency)\}}$$

In the present thesis work for every designed MIMO configuration with different modulation, multiplexing, detection systems and implementation on different wireless networks, the SNR (E_b/N_0) in dB has been determined as a function of BER. The SNR (E_b/N_0) values at BER $\sim 10^{-3}$ has been compared between various MIMO configurations described in this chapter to evaluate the Bit rate to Band width performance of the MIMO transceiver system.

3.3 (2x2) MIMO Transceiver configuration with different modulations and detector systems for OSTBC Multiplexing

The designed (2x2) MIMO transceiver configuration with BPSK, QPSK and 16-QAM modulation techniques for OSTBC multiplexing at the transmitter end and the ZF, MMSE and ML detectors at the receiving end is shown in figure 3.3 [33] [62].

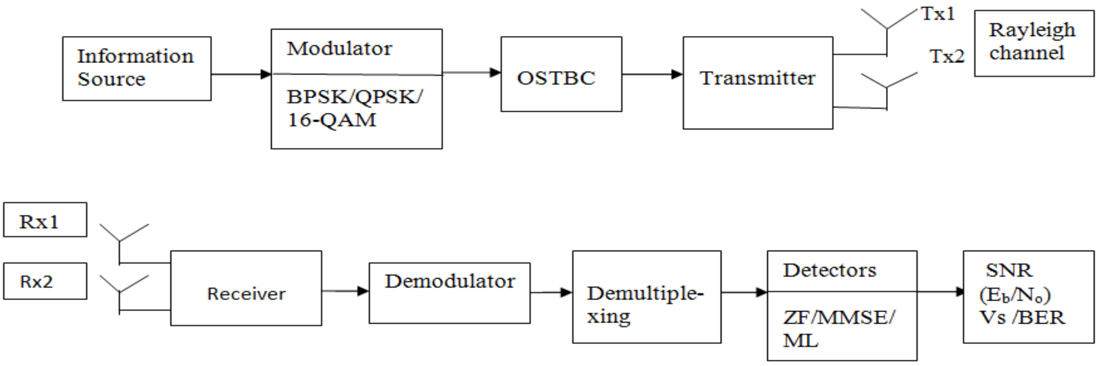


Figure 3.3: (2x2) MIMO Transceiver configuration for OSTBC

For different combinations of the (2x2) MIMO modulations for BPSK, QPSK and 16-QAM and OSTBC multiplexing, the SNR (E_b/N_0) performance as a function of BER is determined for each of the ZF, MMSE and ML-SIC detection systems to evaluate the Bit rate to Bandwidth efficiency of the designed MIMO configuration [63].

3.3.1 Specifications of the MIMO-OSTBC configuration

The specifications for designing the **(**2x2) MIMO Transceiver configuration for different modulation for OSTBC multiplexing and detection system is given in table 3.1

Table 3.1-Specifications of MIMO-OSTBC

Parameters	**Specifications (OSTBC)**
Total Transmitted Bits	10^6
Eb/No Variation	0 – 30dB
Source Data Generator Type	Random Uniform Distribution
Modulation Types Used	BPSK, QPSK, QAM
Equalizers and Detectors	SIC /ZF, ML, MMSE
Decoding	Hard-Decision
Channel Type	Rayleigh Fading
Noise Model	AWGN

The MIMO transceiver configuration is designed for different modulation techniques such as BPSK, QPSK and 16-QAM modulation and OSTBC Multiplexing and detection systems such as ZF, MMSE and ML SIC detection systems for bitrates 10^6 over the range of E_b/N_0 (0-30) dB using a random data generation with uniform distribution and hard decision decoding at the receiver for the Rayleigh channel and AWGN noise model.

3.3.2 Modifications in the Algorithm

This model uses the (2x2) MIMO system employing two transmit and two receive antennas. For different modulation system it employs flat Rayleigh fading over independent transmit-receive links. It uses OSTBC multiplexing technique. At the receiver end, perfect channel knowledge is assumed with no feedback to the transmitter. The code creates two nonlinear interference cancellation methods Zero-Forcing (ZF) and Minimum-Mean-Square-Error (MMSE) with symbol cancellation and compares their performance with the Maximum-Likelihood (ML) optimum receiver.

1. By changing the modulation order, different modulation techniques such as BPSK, QPSK and QAM is employed.
2. Modulated output is applied as input to the Alamouti encoder and two separate symbols (represented by complex numbers). The complex symbols are encoded using the Alamouti code matrix with signed bits, is transmitted through two separate transmit antennas. The input bits were used to decide which of four matrices output was received. The matrices were manually constructed and hard-coded into the simulation.
3. Transmitted output received through Alamouti decoder. Alamouti decoder needs channel knowledge, so a channel estimator is required. The Alamouti Decoder implements a series of equations which combine the channel estimate (the 'h' terms) and the received signals (the 'r' terms) to give an estimate of the symbols that were transmitted.
4. The estimated signal is demodulated by the corresponding demodulator and demultiplexed.
5. The demultiplexed bits are given to the detectors where ZF/MMSE/ML is employed to retrieve an estimate of the original transmitted bits.

Change in the code to generate random bits for BPSK, QPSK and QAM.

randomStr = RandStream('mt19937ar'); is used to generate random bits for BPSK and QPSK.

randomStr = RandStream('swb2712'); is used to generate random bits for QAM.

Details and the results of the MIMO–OSTBC transceiver configuration is discussed in chapter 4.

3.4 (2x2) MIMO Transceiver configuration with different modulations for CDMA and OFDM Multiplexing and different Detector systems

The designed (2x2) MIMO transceiver configuration with BPSK, QPSK and 16-QAM modulation techniques for CDMA and OFDM multiplexing at the transmitter end and for the ZF, MMSE and ML-SIC detection system at the receiving end is shown in figure 3.4.

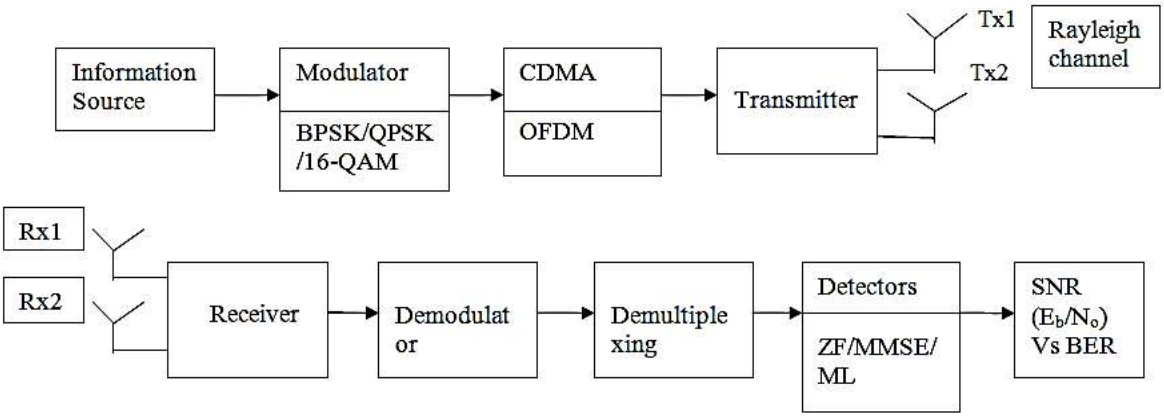


Figure 3.4: (2x2) MIMO Transceiver configuration for CDMA and OFDM

For different combinations of the (2x2) MIMO modulations for BPSK, QPSK and 16-QAM and CDMA and OFDM multiplexing, the SNR (E_b/N_0) performance as a function of BER is determined for each of the ZF, MMSE and ML-SIC detection systems to evaluate the Bit rate to Band width efficiency of the designed MIMO configuration [45][51][55].

3.4.1 Specifications of the MIMO-CDMA and -OFDM configuration

The specifications used in (2x2) MIMO Transceiver configuration for CDMA and OFDM multiplexing and detection system is given in table 3.2.

Table 3.2-Specifications used for MIMO-CDMA and MIMO-OFDM

Parameters	**Specifications**	
	CDMA	**OFDM**
Total Transmitted Bits	10^6	10^6
Eb/No Variation	0 – 30dB	0 – 30dB
Source Data Generator Type	Random Uniform Distribution	Random Uniform Distribution
Modulation Types Used	BPSK, QPSK, QAM	BPSK, QPSK, QAM
Equalizers	ZF, ML, MMSE	ZF, ML, MMSE
Decoding	Hard-Decision	Hard-Decision
Channel Type	Rayleigh Fading	Rayleigh Fading
Noise Model	AWGN	AWGN
	Short code PN sequence = 15 bits, long code PN sequence = 42	FFT size=2048
		Duration of guard interval=0.8µsecs
		Total Symbol duration= 4 µsecs - 3.2 µsecs data interval, 0.8 µsecs guard interval
		OFDM sub carriers =52 - 48 data carriers, 4 pilot carriers
		cyclic prefix length=16 samples, duration 4 µsecs

The MIMO transceiver configuration is designed for different modulation techniques such as BPSK, QPSK and 16-QAM modulation for CDMA and OFDM Multiplexing and detection systems such as ZF, MMSE and ML SIC detection systems for bitrates 10^6 over the range of E_b/N_0 of (0-30 dB) using a random data generation with uniform distribution and hard decision decoding at the receiver for the Rayleigh channel and AWGN noise model.

3.4.2 Modifications in the Algorithm

In CDMA PN sequence is generated and is given to Mod 2 adder. Then serial data stream is interleaved and encoded. A suitable digital modulation technique is used. Finally the signal is transmitted through multiple antennas. At the receiver, the received signal is processed and recovered using the reverse procedure of transmitter.

In OFDM, first a serial data stream is converted into parallel stream and is encoded and interleaved. A suitable digital modulation technique is used. For synchronization pilot bits are added. Then inverse discrete Fourier transform is applied and cyclic prefix is added to include guard bits. Finally the signal will be transmitted through multiple antennas. Received signal is processed and recovered using the reverse process of transmitter at the receiver. Simulation tool used in the project is Matlab. Plot of BER Vs. SNR is obtained for performance analysis.

Details and the results of the MIMO–CDMA and MIMO–OFDM transceiver configuration is discussed in chapter 5.

3.5 Higher MIMO Transceiver configuration with different modulations and OFDM Multiplexing for ML and Monte Carlo receiver system

The MIMO transceiver configuration is designed with higher (3x3) and (4x4) MIMO systems for BPSK, QPSK and 16-QAM modulation techniques with OFDM Multiplexing at the transmitter end and adopting ML-SIC and Monte Carlo detection system at the receiving end. The specifications and the modifications in the algorithms for higher MIMO Transceiver systems are same as the details described in section 3.4 for the MIMO-OFDM transceiver system. The higher MIMO configuration with different modulation and detection system is shown in figure 3.5 [55][57].

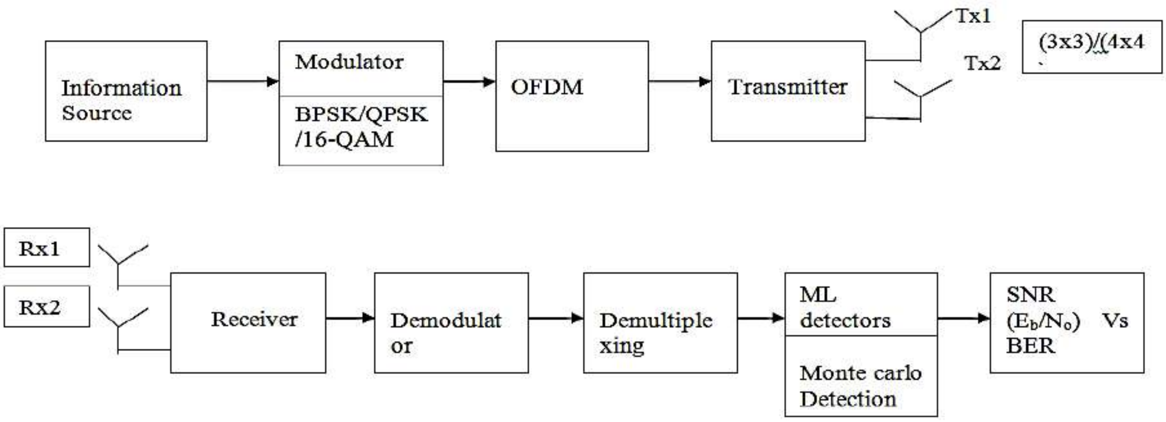


Figure 3.5: Higher MIMO Transceiver configuration for OFDM

For different combinations of the (3x3) and (4x4) MIMO transceiver configurations and different modulation techniques BPSK, QPSK and 16-QAM and for OFDM multiplexing, the SNR (E_b/N_0) performance as a function of BER is determined for ML-SIC and Monte carlo detection system to evaluate the Bit rate to bandwidth efficiency of the designed MIMO configuration [57].

Details and the results of the higher MIMO–OFDM transceiver configuration with ML and Monte Carlo detection systems are discussed in chapter 6.

3.6 MIMO Transceiver configuration with different modulation, OFDM Multiplexing and implementation on WiMAX network

The MIMO transceiver configuration has been designed for lower MIMO systems such as SISO, SIMO, MISO and MIMO with BPSK, QPSK and 16-QAM modulation techniques for OFDM Multiplexing at the transmitter end and implemented on the wireless WiMAX network at the receiving end. The MIMO configuration implemented on WiMAX network is shown in figure 3.6 [69][70].

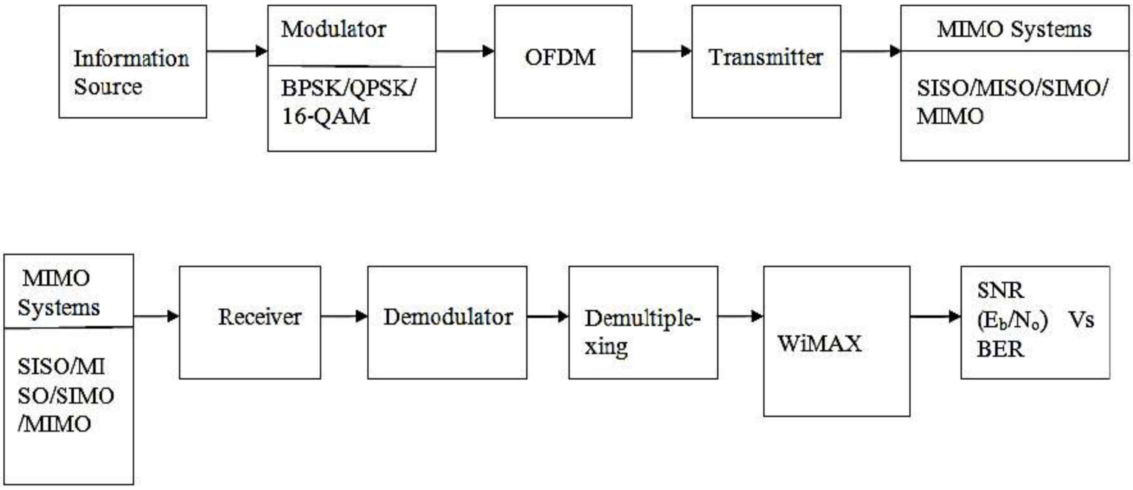


Figure 3.6: Lower MIMO Transceiver configuration for OFDM on WiMAX network

3.6.1 The specifications for MIMO-OFDM on WiMAX N/W (IEEE802.16d-2004)

The specifications used in (2x2) MIMO transceiver configuration for OFDM multiplexing on WiMAX network.

Coding rate 1/2, Bandwidth 10MHz, convolution coding 2/3, interleaving [1;1;0;1], FFT size 256, channel 16, simulation 50,000 bits, Noise AWGN.

The Standard specifications as per the norms are as shown in table 3.3.

Table 3.3: Standard specifications

Parameters	specification
Completed	June 2004
Spectrum	2-11GHz
Propagation/channel conditions	NLOS
Bit Rate	Up to 75MHz (20MHz channelization)
Modulation	256 subcarriers OFDM, BPSK, QPSK, 16QAM, 64QAM, 256QAM.
Mobility	Fixed/Nomadic

3.6.2 Modifications in the Algorithm

The Parameters modified in the block diagram are:

1. Bernoulli binary generator

   Parameters: Probability of a zero: 0.5, Initial seed: 1000, sample time: T_b/Input size, Sample per frame: Input size.
2. Randomization block: PN sequences are generated using a linear feedback shift register (LFSR). The generator polynomial parameter values specify the shift register connections.

   Generator Polynomial: [1000000000000011], Initial seeds:[100101010000000]
3. Coding block: Reed-Solomon (RS) encoder: parameters: Codeword length N=255, Message length K=239 and Convolutional encoder: It uses the poly2trellis function to create a trellis using the constraint length, code generator (octal) and feedback connection (octal) and Parameter: Trellis structure: poly2trellis (7, [171 133]).
4. Modulation block: By changing the modulation order different modulation technique such as BPSK, QPSK and QAM is employed.
5. OFDM symbol assemble block: Generator polynomial [1190], Initial seed: [11111111111], M-ary number: 2, Frame period: 2*T_b.
6. Switching block: Parameters: pulse generator: Number of samples: 2048, pulse width: 2/1, phase delay: 0, sample time: T_b.

7. Rayleigh fading channel: parameter: Maximum Doppler shift (Hz): 1/1000.

For different combinations of the MIMO transceiver system with BPSK, QPSK and 16 QAM modulation and OFDM multiplexing, the SNR (E_b/N_0) performance as a function of BER is determined for each of the lower MIMO system such as SISO, SIMO, MISO and MIMO implemented on WiMAX Network system and evaluation of the Bit rate to Bandwidth efficiency of the designed MIMO system configuration

Details and results of the Lower MIMO–OFDM transceiver configuration implementation on WiMAX networks is discussed in chapter 7.

3.7 (2x2) MIMO Transceiver configuration with QPSK and MQAM modulation, OFDM Multiplexing and implementation on different wireless networks

The MIMO transceiver configuration has been designed with QPSK, 16-QAM and 64-QAM modulation techniques for OFDM Multiplexing at the transmitter end and implemented on the wireless networks such as WiMAX (IEEE 802.16m-2009), WLAN (IEEE 802.11n) and LTE networks at the receiving end. The MIMO configuration implemented on different networks is shown in figure 3.7 [68][74][78].

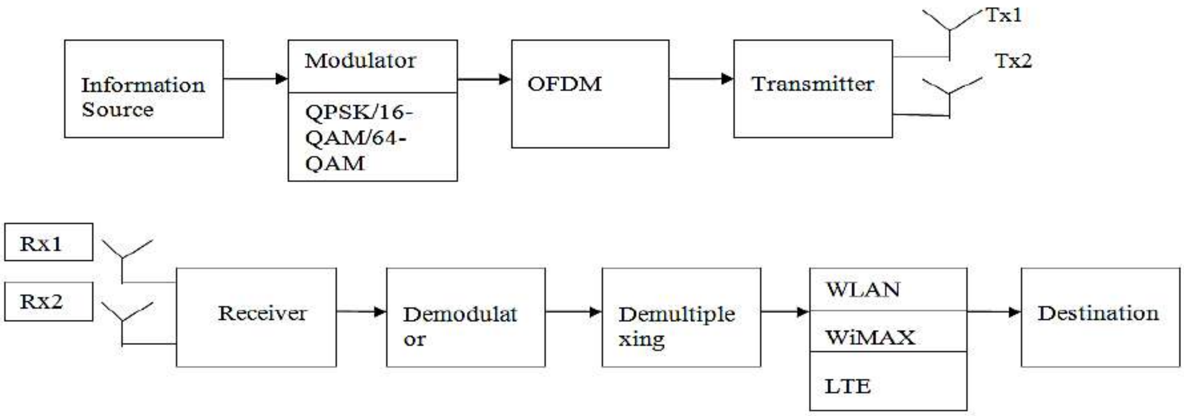


Figure 3.7: (2x2) MIMO Transceiver configuration for OFDM on various networks

3.7.1 Specifications for the WLAN (IEEE 802.11n) Network

The specifications used in (2x2) MIMO-OFDM Transceiver configuration on WLAN is given in table 3.4 [78] [152].

Table 3.4-Specifications for the WLAN network

Parameters	**Specifications**
Data Rates	Upto 320Mbps
Symbol Rate	1kbps
Total Samples	10^6 / Total Antennas (default 2)
No. of Frames	1000
Channel Bandwidth	20MHz and 40 MHz
Equalization	MMSE
Transceiver	STBC with Spatial Mapping
Adaptive Modulation	QPSK, 16-QAM, 64-QAM
Coding Rates	1/2, 2/3, 3/4, 5/6
Transmit Frequency	2.4 GHz and 5GHz
Multiplexing	OFDM

The MIMO-OFDM transceiver configuration implemented on WLAN network is designed for different modulation techniques such as QPSK, 16-QAM and 64-QAM modulation for data rate up to 320 Mbps and symbol rate of 1kbps. Total samples transmitted is 10^6 over the range of 20MHz and 40MHz band width. The coding rates used are ½, 2/3, ¾, 5/6 and a transmit frequency of 2.4GHz and 5GHz.

The Standard specifications as per the norms are as shown in table 3.5.

Table 3.5-Standard specifications for WLAN network

Parameters	**Specifications**
Maximum Data Rate	600 Mbps
RF band	2.4 or 5 GHz
Modulation	CCK, DSSS or OFDM
Number of spatial streams	1,2,3 or 4
Channel width	20 or 40 MHz

3.7.2 Modifications in the Algorithm

The Parameters modified in the block diagram are:

1. Model/channel parameter: Number of OFDM symbols/transmit block: 20, Number of OFDM symbols in training sequence: 4

2. Modulator bank: A suitable digital modulation technique is used.
   BPSK, QPSK, 16-QAM: Number of samples per frame: 960, coding rate ½, Trellis: poly2trellis (7,[133 171]), puncture vector [1].
   BPSK, QPSK, 16-QAM: Number of samples per frame: 960, coding rate **3/4**, Trellis: poly2trellis (7,[133 171]), puncture vector [111001].
3. Pilot block: PN sequence generator: Generator polynomial [10001001], Initial seeds: [1111111].
4. Multipath channel: Fading mode: Flat fading, Max. Doppler shift: 200Hz, SNR (dB) =30.

3.7.3 Specifications of the WiMAX (IEEE 802.16m-2009) Network

The specifications used in **(**2x2) MIMO-OFDM Transceiver configuration on WiMAX network is given in table 3.6 [76] [140].

Table 3.6-Specifications for the WiMAX network

Parameter	**Specification**
Data Rates	100Mbps (Mobile), 1Gbps (Fixed Wireless)
Symbol Rate	1kbps
Total Samples	10^6 / Total Antennas (default 2)
No. of Frames	1000
Channel Bandwidth	1.25MHz to 20MHz
Error Control	HARQ (ARQ + FEC)
Multiplexing	OFDM
Adaptive Modulation	QPSK, 16-QAM, 64-QAM
Coding Rates	1/2, 2/3, ¾
Transmit Frequency	3.5 GHz and 5GHz
Coding	Alamouti Codes
Receiver	Space Time Diversity Combiner

The MIMO-OFDM transceiver configuration implemented on WiMAX network is designed for different modulation techniques such as QPSK, 16-QAM and 64-QAM modulation for data rate up to 1000 Mbps and symbol rate of 1kbps. Total samples transmitted is 10^6 over the range of 1.25MHz to 20MHz band width. The coding rates used are 1/2, 2/3, 3/4, 5/6 and a transmit frequency of 3.5GHz and 5GHz.

The Standard specifications as per the norms are as shown in table 3.7.

Table 3.7-Standard specifications for WiMAX network

Parameters	**Specification**
Completed	May 2009
Spectrum	2-6GHz
Propagation/channel conditions	LOS, NLOS
Bit Rate	Up to 120 Mbps (25 or 28 MHz channelization)
Modulation	Scalable OFDMA, QPSK, 16QAM, 64QAM, 256QAM (optional).
Mobility	Portable/mobile

3.7.4 Modifications in the Algorithm

The Parameters modified in the block diagram are:

1. Model parameters: Channel BW=3.5MHz, Number of OFDM symbols/burst=1, Cyclic prefix factor(G)=1/8.
2. FEC and Modulator block: A suitable digital modulation technique is used.

   BPSK: coding rate=**1/2**, Convolutional encoder is used: parameter: Trellis: poly2trellis (7,[1711 33]), Interleaver: Performs block interleaving- parameters: number of subchannels: 16, number of coded bits/subchannel=192, number of coded bits/subcarrier=1.

   QPSK: coding rate=**1/2**, RS encoder: Output block size N=32, Input block size K=24, Convolutional encoder: Trellis: poly2trellis (7,[1711 33]), Puncture vector: reshape([10;11],4,1), Interleaver: parameters: number of subchannels: 16, number of coded bits/subchannel=384, number of coded bits/subcarrier=2.

   QPSK: coding rate=**3/4**, RS encoder: Output block size N=40, Input block size K=36, Convolutional encoder: Trellis: poly2trellis (7,[1711 33]), Puncture vector: reshape([10101;11010],10,1), Interleaver: parameters: number of subchannels: 16, number of coded bits/subchannel=384, number of coded bits/subcarrier=2.

QAM: coding rate=**1/2**, RS encoder: Output block size N=64, Input block size K=48, Convolutional encoder: Trellis: poly2trellis (7,[1711 33]), Puncture vector: reshape([10;11],4,1), Interleaver: parameters: number of subchannels: 16, number of coded bits/subchannel=768, number of coded bits/subcarrier=4.

QAM: coding rate=**3/4**, RS encoder: Output block size N=80, Input block size K=72, Convolutional encoder: Trellis: poly2trellis (7,[1711 33]), Puncture vector: reshape([10101;11010],10,1), Interleaver: parameters: number of subchannels: 16, number of coded bits/subchannel=768, number of coded bits/subcarrier=4.

3. Multipath fading channel with AWGN: Parameters: Fading mode: Frequency selective fading, K factor:4, delay vector (S): [0 0.4 0.9]*10^{-6}, Gain vector (dB):[0 -15 -20], SNR (dB)=40.
4. Demodulator and FEC bank: Viterbi decoder is used. It uses viterbi algorithm to decode convolutionally encoded input data. Trellis structure: poly2trellis (7,[1711 33]), Decision type: Hard decision.

3.7.5 Specifications for the LTE Network

The specifications used in **(**2x2) MIMO-OFDM Transceiver configuration on LTE network is given in table 3.8.

Table 3.8-Specifications of the LTE Network

Parameters	**Specifications**
Data Rates	1Gbps (Downlink), 500Mbps (Uplink)
Channel Coding	Turbo Coding
Modulation	QPSK, 16-QAM, 64-QAM
Channel Estimation	Least-Squares Approach
Equalizer	MMSE
Multiplexing	OFDM
Scrambling	Bit-Level

Transmit Frequency	1.7 to 2.1GHz
Decision Type	Soft Decision Decoding
Channel Bandwidth	1.4MHz to 20MHz

The MIMO-OFDM transceiver configuration implemented on LTE network is designed for different modulation techniques such as QPSK, 16-QAM and 64-QAM modulation for data rate up to 1 Gbps for downlink and 500Mbps for uplink. Samples are transmitted over the range of 1.4 MHz to 20 MHz band width and a transmit frequency of 1.7 to 2.1 GHz [68][153].

The Standard specifications as per the norms are as shown in table 3.9.

Table 3.9-Standard specifications for LTE network

Parameters	**Specifications**
Standard	3GPP TS 36.101 for the UE (User Equipment) 3GPP TS 36.104 for the eNB(Evolved Node B).
Channel Bandwidth	1.4/3/5/10/15/20 MHz
FFT size	128/256/512/1024/1536/2048
Cyclic Prefix	Normal, Extended
DL multiple access	OFDMA
UL multiple access	SC-FDMA
Duplexing	FDD & TDD
Subcarrier mapping	Localized
Subcarrier hopping	Yes
Data Modulation	QPSK/16QAM/ 64QAM
Subcarrier spacing	15KHz
Channel Coding	convolutional coding and turbo coding
MIMO	2 or 4 at transmit and 2 or 4 at receive side
HARQ	incremental redundancy

3.7.6 Modifications in the Algorithm

The Parameters modified in the block diagram are:

1. Model parameters:_It specifies model parameters for the simulation run. Parameters: Channel BW=10MHz, Number of OFDM per frame=2, Antenna configuration 2x2, SNR=18dB, Block length=2048.
2. Feedback control: Scrambler is used. The source data bits that is transport channel encoded bits are scrambled by a bit-level scrambling sequence.Sample time=10^{-3}, delay length=1.
3. Modulator: A suitable digital modulation technique is used. For QPSK-M-ary number=4, phase offset=pi/4, Input type=bit.

For different combinations of the MIMO transceiver system with QPSK, 16-QAM and 64- QAM modulation and OFDM multiplexing, the SNR (E_b/N_0) performance as a function of BER is determined for (2x2) MIMO system implemented on WLAN, WiMAX and LTE network system for evaluation of the Bit rate to Bandwidth efficiency of the designed MIMO system configuration.

Details and the results of the MIMO–OFDM transceiver configuration implementation on WLAN, WiMAX and LTE networks is discussed in chapter 8.

CHAPTER 4

MIMO-OSTBC TRANSMISSION WITH DIFFERENT MODULATION AND DETECTION SYSTEMS

CHAPTER 4

MIMO-OSTBC TRANSMISSION WITH DIFFERENT MODULATION AND DETECTION SYSTEMS

In recent years, the requirements for high data rate communication in mobile data systems have seen an exponential increase. To satisfy this ever increasing demand for communication, new methods are necessary to exploit the limited resources such as bandwidth and power as efficiently as possible. MIMO competition systems provide an efficient solution for increasing data transmission rates, by employing multiple antenna systems at both the transmitter and the receiver node. STBC systems can exploit diversity transmission by using multiple antennas at the transmitter/receiver to improve the reliability of communication. Two types of STBC coding techniques can be employed, they are, Orthogonal Space-Time Block Codes (OSTBCs) and Non-Orthogonal Space-Time Block Codes (NOSTBCs). The OSTBCs achieve full diversity with low decoding complexity, but at the cost of some loss in data rate [16].

The performance of the system can be substantially improved by using multiple antennas in a wireless competition system at both the transmitting node and the receiving node. This also ensures reliability of the data transmitted. Multiple signal is transmitted from the source, and multiple signal receptions at the destination are combined together to improve the quality of the received signal, while reducing the bit error rates and enhancing performance.

A simple wireless communication system uses a single antenna at both transmission and reception, and is referred to as a single antenna (single-input/single output) system. When multiple antennas are used at both the transmitter and receiver, the system is then referred to as a MIMO system. The difference between these two systems is that in the latter case, multiple parallel streams of information symbols are transmitted, while a single stream of information is transmitted in the first case. Therefore in case of multiple antenna systems, the complexity of the receiving and transmitting systems increases. Thus, a mapping scheme has to be developed in order to map the transmitted streams and the corresponding receiver antennas. The overall system performance will then be dependent upon the optimality of the mapping performed. In this regard, current research focuses on the optimisation of various system parameters such as data transmission rates, reliability of transmission and system complexity. The design objective of the research is then to create both a robust system as well as a wireless system which exhibits low complexity, while providing the highest possible spectral efficiency.

4.1 The MIMO System Model

Relevant signal processing and channel models are required to study multiple input multiple output wireless competition systems. This section presents the necessary background for MIMO models, and an overview of various signal processing techniques and MIMO Channel models [5] [6].

Let us consider a point-to-point MIMO system with n_t transmit and n_r receive antennas as shown in figure 4.1.

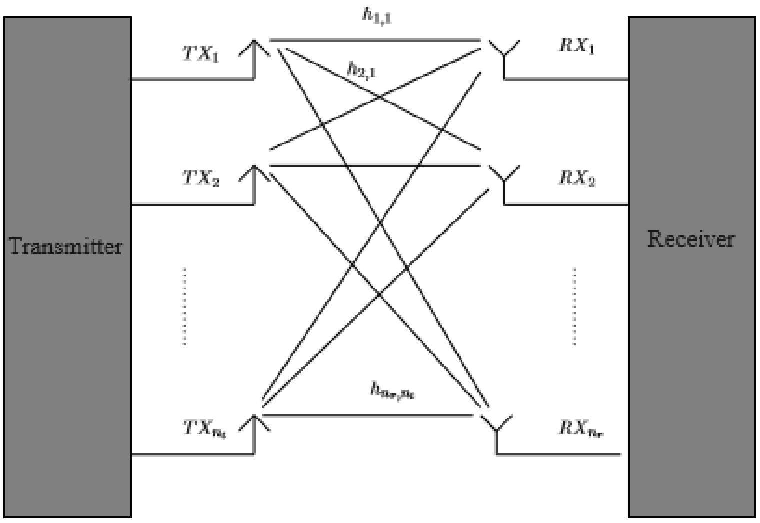


Figure 4.1: MIMO model with n_t transmit antennas and n_r receive antennas

Let $h_{i,j}$ be a complex number corresponding to the channel gain between transmit antenna *j* and receive antenna *i*. If at a certain time instant the complex signals $\{s_1, s_2, \dots, s_{nt}\}$ are transmitted through n_t transmit antennas, the received signal at antenna i can be expressed as:

$$y_i = \sum_{j=1}^{n_t} h_{i,j} s_j + n_i \quad (4.1)$$

where n_i represents the noise component. By integrating the signals received into a single vector y, equation (4.1) can be rewritten as,

$$y = Hs + n \quad (4.2)$$

where y represents a set of received symbol vectors of dimension $n_r \times 1$. The matrix H of dimension $n_r \times n_t$ is referred to as MIMO transfer matrix,

$$H = \begin{bmatrix} h_{1,1} & \cdots & h_{1,n_t} \\ \vdots & \ddots & \vdots \\ h_{n_r,1} & \cdots & h_{n_r n_t} \end{bmatrix} \quad (4.3)$$

The transmit symbol vector s is of $n_t \times 1$ dimension and additive noise vector n is of $n_r \times 1$ dimension. The noise represents the additive white noise characteristic. During the transmission of several symbols, the MIMO channel is assumed to exhibit flat fading behaviour, and that on the channel coefficients are invariant. Flat fading, or frequency non-selective fading is used and this represents the fact that the coherence bandwidth of the channel is much larger than the bandwidth of the transmitted signal. Therefore, all transmitted signals across all frequency components experience the same level of phase shifts and same levels of attenuation during propagation through the channel.

4.2 Definition of SNR and BER

4.2.1 SNR (Signal to Noise ratio): Signal-to-Noise Ratio or simply SNR represents the ratio of the amplitude of the desired signal (analog/digital) with reference to the amplitude of the noise signal. It is assumed that the noise signal is present in the channel, at the time of measurement. SNR is typically measured in decibels (dB) and is expressed in logarithmic scale. SNR represents the quality of the transmission channel, or the quality of the signal communicated over a network. This provides a mechanism to easily identify and isolate the source of noise in the channel, and eventually eliminate these noise signals. Higher signal-to-noise ratio are desirable, as an SNR of zero indicates that both the signal level and the noise levels are equal and one is indistinguishable from the other.

4.2.2 BER (Bit Error Rate): BER represents the total percentage of bits and error in comparison to the total number of bits that were transmitted or received over the channel for a specified period of time. BER is typically expressed as a negative power of 10. For example 20 bits in error for every 1,000,000 bits transmitted would be represented as 20 x 10^{-5}. Bit error rates in digital systems have similar interpretation as SNR in analog communication systems.

4.2.3 E_b/N_0: E_b/N_0 (the energy per bit to noise power spectral density ratio) is an important parameter in digital communication or data transmission. It is a normalized SNR measure and is also known as the SNR per bit. It is particularly useful when comparing the BER performance of different digital modulation schemes without taking bandwidth into account.

E_b/N_0 is a common parameter used to represent the amount of noise, rather than the amount of interference in the communication system employing a specific modulation and coding scheme. N_0 represents the density of white noise and is additive in nature. Before detection, E_b/N_0 is closely related to the SNR. The SNR of the received signal after the receiver filter is given by

$$C/N = E_b/N_0 \cdot \frac{f_b}{B} \tag{4.4}$$

Where, B is available channel bandwidth, and f_b represents the net bit rate or data rate of the channel.

The equivalent expression in logarithmic form (dB) is given by

$$CNR_{dB} = 10 \log_{10}(E_b/N_0) + 10 \log_{10}\left(\frac{f_b}{B}\right) \tag{4.5}$$

According to Shannon–Hartley theorem, there exists a limit to the rate at which the information can be transmitted reliably through channel. This limit depends on the bandwidth of the channel as well as its signal-to-noise, and is given by

$$I < \log_2\left(1 + \frac{S}{N}\right) \tag{4.6}$$

Where I represents the information transmission rate, not taking into consideration the error correcting codes. S/N represents the signal to noise ratio, while B represents the bandwidth of the channel (Hz). C and N represent the total carrier and noise power in the bandwidth respectively.

If we consider the bit rate R (gross rate = information rate I), the equation (4.6) can be rewritten to create a bound on the bit energy to noise ratio E_b/N_0, for the communication system to be deemed reliable. Therefore the average bit energy $E_b = S/R$, with respect to the spectral density of the noise signal, i.e. $N_0 = N/B$, is used to calculate the bandwidth utilisation parameter in terms of bits per second per hertz, or equivalent bits per dimension. In this regard, we define the normalised information rate as $R_l = R/2B$. Combining the above equations, we arrive at the Shannon limit as follows

$$\frac{R}{B} = 2R_l < \log_2\left(1 + 2R_l\frac{E_b}{N_0}\right) \tag{4.7}$$

Shannon-limit bound on E_b/N_0 is given by

$$\frac{E_b}{N_0} > \frac{2^{2R_l} - 1}{2R_l} \tag{4.8}$$

If the bandwidth is larger in comparison to the data transmission rate, then R_l is very close to 0. This represents the bound and also referred to as the ultimate Shannon limit

$$\frac{E_b}{N_0} > \ln(2) \tag{4.9}$$

which is equivalent to –1.59 dB, since

$\ln(2) = 0.693$

$10\log_{10}(0.693) = -1.59$ dB

4.3 Space-Time Coding

Space-Time Codes (STCs) find application not only in wireless networks, but mobile cellular competition systems as well. Since these type of codes can be used in both spatial, as well as temporal domains, Space time coding can introduce redundancy in the transmitted signals, for different antenna systems at different time instants. Without sacrificing bandwidth over spatially uncoded systems, these codes can achieve diversity at both the transmitter and receiver, thereby increasing the gain of the system. In general, the designs of STC amounts to finding transmit matrices that satisfy certain optimality criteria.

Space Time Block Coding (STBC) and Space Time Trellis coding (STTC) are among the two important methods proposed for space-time coding. STTC technique ensures full diversity and provides the advantage of a substantial increase in coding gain, but at an increased cost of higher computational requirement and decoding complexity. To overcome this disadvantage, Alamouti proposed STBC technique, which also ensures full diversity of the code and maximum data rate per channel, and is applicable to a two transmit antenna system. This technique relies on the orthogonality between the transmitted signal vectors of two different antenna systems. Further, the scheme can be generalised for an arbitrary number of antennas, by applying the orthogonal design theory to the latter case. Space-time block codes are thus generalised versions of the base case. When the number of transmit antennas increase more than two, full diversity and data transmission rates does not exist as there are no complex valued space-time block codes. Therefore various coding methods have been designed to provide either full data transmission rates or full diversity [12][20].

4.3.1 Space-Time Block Codes

In terms of implementation complexity, Space–time block codes (STBCs) are efficient since they process an individual block of data at a time to provide diversity gains. Therefore STBC can be represented as a matrix of dimension $\mathrm{n_t} \times \mathrm{N}: \{\mathrm{s_1}, \mathrm{s_2} \dots, \mathrm{s_N}\} \rightarrow \mathrm{S}$, a mapping of a set of complex symbols $\{\mathrm{s_1}, \mathrm{s_2} \dots, \mathrm{s_N}\}$ of dimension $\mathrm{n_N}$ into a matrix of dimension $\mathrm{n_t} \times \mathrm{N}: \{\mathrm{s_1}, \mathrm{s_2} \dots, \mathrm{s_N}\} \rightarrow \mathrm{S}$

An STBC code matrix S is given by,

$$\mathrm{S} = \sum_{n=1}^{n_N} \bar{\mathrm{s}}_\mathrm{n} \mathrm{A_n} + \mathrm{j}\tilde{\mathrm{s}}_\mathrm{n} \mathrm{B_n} \tag{4.10}$$

The set $\{\mathrm{s_1}, \mathrm{s_2} \dots, \mathrm{s_{n_N}}\}$ represents the total number of transmitted symbols such that $\bar{\mathrm{s}}_\mathrm{n} = \mathrm{Re}\ \{\mathrm{s_n}\}$ and $\tilde{\mathrm{s}}_\mathrm{n} = \mathrm{Im}\ \{\mathrm{s_n}\}$. These further represent linear space-time block which have a $\mathrm{n_t}$ x N dimensional fixed size code matrices $\{\mathrm{A_n}, \mathrm{B_n}\}$.

STBCs are generally represented in the matrix form, with each row representing a time slot, and each column represents one antenna's transmissions over time.

$$\begin{array}{cc} & \xrightarrow{\text{transmit antennas}} \\ \text{time-slots}\Big\downarrow & \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n_T} \\ s_{21} & s_{22} & \cdots & s_{2n_T} \\ \vdots & \vdots & & \vdots \\ s_{T1} & s_{T2} & \cdots & s_{Tn_T} \end{bmatrix} \end{array}$$

The modulated symbols, s_{ij} symbols that are transmitted in a given time slot time slot i from a given antenna system j. The total number of time slots is represented by T, and the total number of antennas at the receiver is represented by n_R, with the length of T each.

The total number of symbols transmitted per time slot is found using the code rate of the Space Time Block Code. Therefore, if the encoder outputs a total of k symbols for a given set of time slots T, then the corresponding code rate is r = k/T [24][32].

4.3.2 Alamouti Code

Alamouti codes provide full diversity and full information transmission rates for a system with at least two antennas at the transmitter. The structure of Alamouti encoder or space Time Block coding is as shown in figure 4.2 [21].

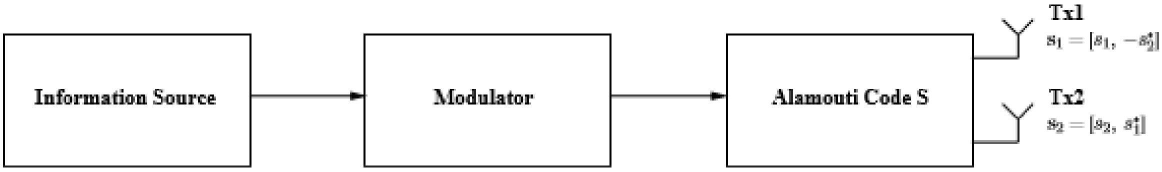


Figure 4.2: Block diagram of Alamouti coding

In order to modulate the information bits, an M-Ary modulation technique is used. In each encoding operation,the encoder takes the block of two modulated symbols s_1 and s_2 and is represented by the code matrix of the transmit antenna as,

$$S = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{4.11}$$

The rows represent the first and the second transmission periods respectively. The symbols namely: s_1 and s_2 are transmitted from each of the two antennas simultaneously during the transmission cycle. The symbol $-s_2^*$ is transmitted from antenna 1 and the symbol s_1^* from transmit antenna 2 during the second transmission period. Space Time Block coding requires encoding to be performed in two different domains namely: the space domain (between multiple transmit antenna systems), and time domain (between two transmission periods). It can be seen that for the matrix S, the columns and rows are orthogonal to each other as well as to the code matrix. This can be represented as,

$$SS^H = \begin{bmatrix} s_1 s_2 \\ -s_2^* s_1^* \end{bmatrix} \begin{bmatrix} s_1^* - s_2 \\ s_2^* s_1 \end{bmatrix}$$

$$= \begin{bmatrix} |s_1|^2 + |s_2|^2 & 0 \\ 0 & |s_1|^2 + |s_2|^2 \end{bmatrix}$$

$$= (|s_1|^2 + |s_2|^2)I_2 \tag{4.12}$$

I_2 represents an identity matrix of dimension (2x2). This identity property aids the receiver in the detection of two signals namely s_1 and s_2, four signal processing technique that is both simple and linear.

If we assume that a single receiver antenna system is used, the channel at any time t can be modelled as a multiplicative distortion that is complex in nature. This distortion can be represented as $h_1(t)$ and $h_2(t)$ for the first and second transmit antennas respectively. Assuming that the fading is constant across two consecutive transmit periods of duration T, $h_1(t)$ and $h_2(t)$ can be represented as:

$$h_1(t) = h_1(t+T) = h_1 = |h_1|e^{j\theta_1} \tag{4.13}$$

$$h_2(t) = h_2(t+T) = h_2 = |h_2|e^{j\theta_2} \tag{4.14}$$

The phase shift and the corresponding gain in amplitude for each transmit antenna path i can be represented by $|h_i|$ and θ_i, $i = 1,2$ at the receiver. The signals that are received at the time instants t and $t + T$ can be written respectively as:

$$r_1 = s_1h_1 + s_2h_2 + n_1 \tag{4.15}$$

$$r_2 = -s_2^*h_1 + s_1^*h_2 + n_2 \tag{4.16}$$

The received signals r_1 and r_2 are obtained at time t and $t + \mathrm{T}$, where the interference and noise at the receiver are represented by two complex random variables namely n_1 and n_2 and can be written in matrix form as

$$\mathrm{r} = \mathrm{Sh} + \mathrm{n} \tag{4.17}$$

Here, the noise vector at the receiver is represented by n, and the complex channel vector is represented by the parameter $\mathrm{h} = [\mathrm{h}_1, \mathrm{h}_2]^{\mathrm{T}}$ [120].

4.3.3 Orthogonal Space Time Block Coding (OSTBC)

Orthogonal STBCs belong to a subclass of linear space-time block codes. These codes ensure that diversity is achieved (of an order$\mathrm{n}_{\mathrm{t}}\mathrm{n}_{\mathrm{r}}$) by decoupling the different transmitted symbols $\{\mathrm{s}_{\mathrm{n}}\}$ when used with a maximum likelihood detector. The possibility of not being able to use more than two antenna systems at the transmitter is one of the main disadvantages of OSTBC techniques, since they result in complex valued signals. Therefore this type of coding exists for code rates that are less than a symbol per time slot [33].

OSTBC techniques represent the linearity property for any space-time block codes S and can be represented using the following property.

$$\mathrm{S}^{\mathrm{H}}\mathrm{S} = \sum_{\mathrm{n}=1}^{\mathrm{N}} |\mathrm{s}_{\mathrm{n}}|^2 \mathrm{I} \tag{4.18}$$

The row i of the space time block code matrix S represent the i^th transmit antenna system and its transmitted symbols during N transmission intervals, while the column j corresponding to the space time matrix S represents symbols that are transmitted from n_{t} antenna systems simultaneously.

Therefore from equation (4.18), it can be seen that the matrix S and its corresponding columns are orthogonal to each other. This implies that each and every block of the signal sequence from any two given transmit antenna systems are orthogonal to each other. Full transmit diversity can therefore be achieved using this orthogonality principle, and at the same time the detection process remains simple and maximum ratio combining can be used for the coupling of the transmitted signals originating from different transmit antennas. This further implies that the decoding process of maximum likelihood detection is simple [24][30].

4.3.4 Rayleigh Channel

In order to approximate the multipath behaviour of the channel in terms of its constructive and destructive properties, a Rayleigh distribution can be employed. Rayleigh distribution can be used to approximate channels that exhibit flat fading, when no line of sight signals are present. Since non-line of sight signals imply that no direct transmission paths exist between the source and destination, the corresponding signal at the receiver can be written as

$$r(t) = s(t) * h(t) + n(t) \tag{4.19}$$

The term $h(t)$ represents a Rayleigh distributed channel matrix that is a random in nature, and is corrupted by additive White Gaussian noise n(t). Another form to represent a Rayleigh distribution is by combining two equal and independent Gaussian random variables that are orthogonal to each other, to obtain the probability density function of the Rayleigh distribution and is written as $p(r) = \frac{r}{\sigma^2} e^{\frac{-r^2}{2\sigma^2}}$ where σ^2 represents the variance of the received signal power [14].

4.4 Modulation Schemes

4.4.1 Binary phase-shift keying (BPSK)

In BPSK, binary symbol 1 and 0 modulate the phase of the carrier. BPSK represents each singular bit as a symbol, which transmits one of two possible phases corresponding to the bit value. The constellation diagram for BPSK modulation scheme is as shown in figure 4.3 [15].

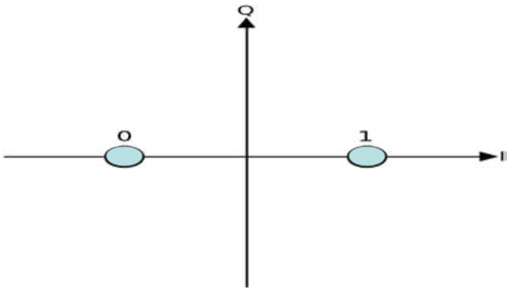


Figure 4.3: BPSK Constellation Points

When the communication channel introduces an arbitrary phase shift, it is difficult to understand which constellation point is present and the de-modulation system will be unable to make a decision. Consequently, to avoid this situation a differential coding scheme can be employed prior to the modulation process.

Implementation

The general form of BPSK (Binary Phase Shift Keying) can be represented as

$$s_n(t) = \sqrt{\frac{2E_b}{T_b}}\cos\big(2\pi f_c t + \pi(1-n)\big), n = 0,1 \tag{4.20}$$

The binary data that is to be transmitted is represented using two different phases namely, 0 and π. Thus the binary data can be represented as two signals, and can be represented mathematically as:

$$s_0(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \pi) = -\sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t) \text{ for binary 0} \tag{4.21}$$

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t) \text{ for binary 1} \tag{4.22}$$

The frequency of the carrier signal is denoted by f_c.

A basis function can be obtained to represent the single signal space, and can be written as:

$$\emptyset\,(t) = \sqrt{\frac{2}{T_b}}\cos(2\pi f_c t) \tag{4.23}$$

Here $\sqrt{E_b \emptyset\,(t)}$ represents the transmitted bit ‘1’ and $-\sqrt{E_b \emptyset\,(t)}$ represents the transmitted bit ‘0’.

Bit Error Rates

In order to find the bit error rate of BPSK modulation in the presence of an AWGN channel, we can use

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \quad \text{or} \quad P_b = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{4.24}$$

4.4.2 Quadrature phase-shift keying (QPSK)

QPSK modulation technique can be employed for mapping digital bits to analog waveforms for transmission over the communication channel. This mapping is performed by pairing data transmission bits in to a set of symbols that are transmitted after modulation using a carrier signal. At the receiver, the modulation will map the waveforms back to the symbol pairs to determine the transmitted bits. In QPSK, two successive bits in the data sequence are grouped together to reduce the bit rate and hence reduces the bandwidth of the channel. The combination of two bits forms four distinct symbols (00, 01, 11 and 10). The symbol is changed to next symbol when the phase of the carrier is changed by 45 degree [15].

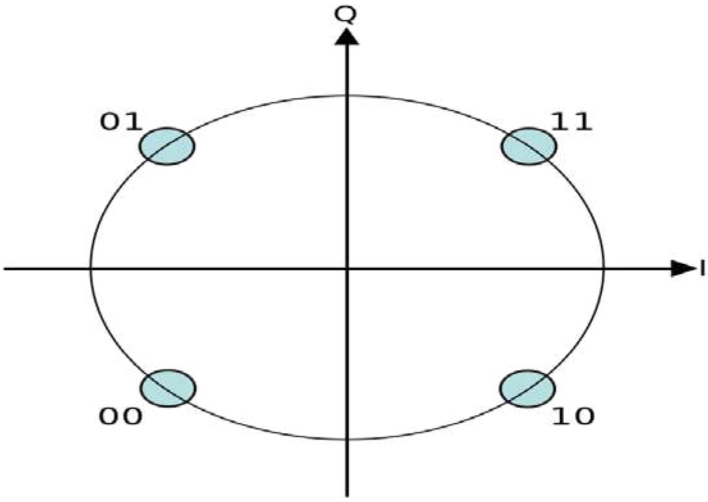


Figure 4.4: Constellation diagram for QPSK

Implementation

The implementations of the system are generic in comparison to that of BPSK modulators, but are representative of a higher order modulation in comparison to BPSK. The symbols are written in the constellation diagram in terms of sine and cosine waves used to transmit them.

$$s_n(t) = \sqrt{\frac{2E_s}{T_s}} \cos\left(2\pi f_c t + (2n-1)\frac{\pi}{4}\right), n = 1,2,3,4 \tag{4.25}$$

This yields the four phases π/4, 3π/4, 5π/4 and 7π/4 as needed.

This results in a two-dimensional signal space with unit basis functions and is given by,

$$\emptyset_1(t) = \sqrt{\frac{2}{T_s}}\cos(2\pi f_c t) \tag{4.26}$$

$$\emptyset_2(t) = \sqrt{\frac{2}{T_s}}\sin(2\pi f_c t) \tag{4.27}$$

The first basis function is used as the in-phase component of the signal and the second as the quadrature component of the signal.

Hence, the signal constellation consists of the signal-space 4 points

$$\left(\pm\sqrt{{E_s}/{2}}, \pm\sqrt{{E_s}/{2}}\right)$$

The factors of 1/2 indicate that the total power is split equally between the two carriers.

Bit error rate

QPSK can be viewed as a quaternary modulation. With this interpretation, the even or odd bits are used to modulate the in-phase component of the carrier, while the odd or even bits are used to modulate the quadrature-phase component of the carrier. As a result, the probability of bit-error for QPSK is the same as for BPSK:

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \tag{4.28}$$

Thus it can be seen that QPSK transmits two bits at a time and requires twice as much power as BPSK, to achieve the same probability of bit errors. The symbol error rate is given by,

$$P_s = 1 - (1 - P_b)^2 \tag{4.29}$$

$$= 2Q\left(\sqrt{\frac{E_s}{N_0}}\right) - \left[Q\left(\sqrt{\frac{E_s}{N_0}}\right)\right]^2 \tag{4.30}$$

It can be seen that the probability of symbol error for high signal-to-noise ratio is given by,

$$P_s \approx 2Q\left(\sqrt{\frac{E_s}{N_0}}\right) \tag{4.31}$$

4.4.3 Quadrature Amplitude Modulation (16-QAM)

The process of integrating and combining two different AM (amplitude modulated) signals into a single channel is referred to as quadrature amplitude modulation (QAM). This results in a effectively doubling the information transmission rate with the same available bandwidth. In wireless system applications, pulse amplitude modulation (PAM) can be used along with quadrature amplitude modulation (QAM). QAM has found wide applications in many wired and wireless digital communication systems for the transmission of data. QAM can be used in many different forms such as 8-QAM, 16, 32, 64 and 256 QAM.

There are two carriers in a QAM signal, both using the same frequencies, but out of phase by one quadrature. The first signal is referred to as the in-phase signal, while the second signal is referred to as quadrature signal. Mathematically, one of the signals can be represented by a sine wave and the other by a cosine wave. These two signals are combined together after modulation at the transmitter. When the signals are received at the destination, first the carrier signals are separated and processed to extract the original data sequence.

QAM systems achieve greater suppression between adjacent constellation points by reducing the distance in the I-Q plane and as a result these points appear to be distributed evenly. Therefore, the constellation points appear to be more distinct from each other, thereby reducing the number of errors associated with symbol detection. Although it is possible to transmit increasing number of bits per symbol, with the constraint of keeping the energy of the transmission constant, constellation points have to be arranged closer together which makes the transmission vulnerable to noise and interference. Therefore lower order quadrature amplitude modulation variants experience higher bit error rates. Thus there is a need to obtain the proper balance between increasing the data transmission rates versus controlling the BER of the data communication. Figure 4.5 shows an example of this effect [15].

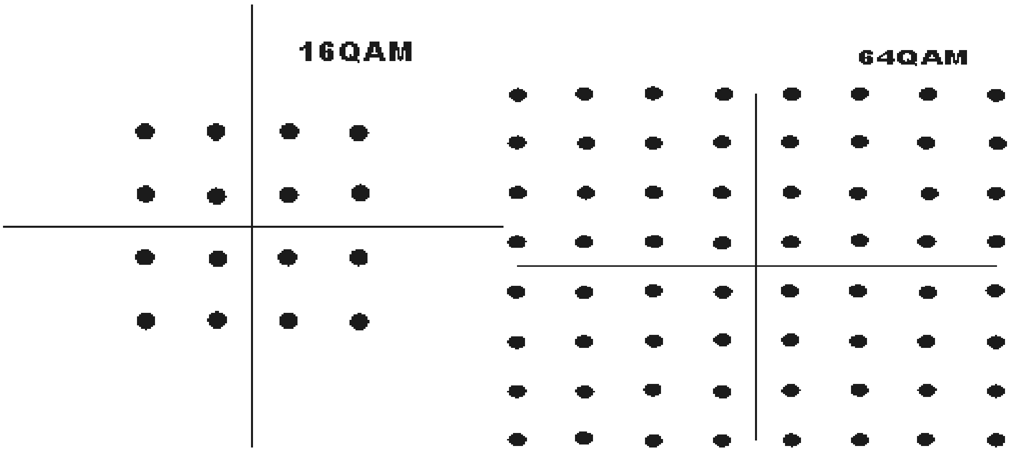


Figure 4.5: Different QAM constellations

Implementation

When transmitting two signals by modulating them with QAM, the transmitted signal will be of the form,

$$s(t) = \Re\{[I(t) + iQ(t)]e^{i2\pi f_0 t}\}$$

$$= I(t)\cos(2\pi f_0 t) - Q(t)\sin(2\pi f_0 t) \qquad (4.32)$$

where $i^2 = -1$, with the in-phase and quadrature components of the modulating signal are represented by $I(t)$and $Q(t)$ respectively, and the carrier frequency of the transmitted signal is represented by f_0. Also, $\Re\{\ \}$represents the real part of the complexity of signal.

A coherent demodulation system can be used to demodulate the two receive signals at the receiver. Multiple copies of two sinusoidal signals that are out of phase with each other by 90° are received at the receiver separately and the detector produces two estimates corresponding to $I(t)$and $Q(t)$respectively. Detection of the modulated signals is now possible independently due to the fact that the carrier signals are out of phase by 90°.

In the ideal case $I(t)$is demodulated by multiplying the transmitted signal with a cosine signal

$$r(t) = s(t)\cos(2\pi f_0 t)$$
$$= I(t)\cos(2\pi f_0 t)\cos(2\pi f_0 t) - Q(t)\sin(2\pi f_0 t)\cos(2\pi f_0 t) \qquad (4.33)$$

Using standard trigonometric identities, equation (4.33) can be written as

$$\mathrm{r(t)} = \frac{1}{2\mathrm{I(t)}[1+\cos(4\pi\mathrm{f_0t})]} - 1/2\mathrm{Q(t)}\sin(4\pi\mathrm{f_0t})$$

$$= \frac{1}{2}\mathrm{I(t)} + 1/2[\mathrm{I(t)}\cos(4\pi\mathrm{f_0t}) - \mathrm{Q(t)}\sin(4\pi\mathrm{f_0t}) \qquad (4.34)$$

Filtering using low-pass filters can then be used to determine the high frequency components (containing the term $4\pi f_0 t$), leaving only the $\mathrm{I(t)}$term. This filtered signal is unaffected by$\mathrm{Q(t)}$, showing that the in-phase component can be received independently of the quadrature component. Similarly, $s(\mathrm{t})$ can be multiplied by a sine wave and then low-pass filter to extract $\mathrm{Q(t)}$.

The phase of the received signal is assumed to be known accurately at the receiver. In order to receive the modulated signal independently, the phase of the received signal should be exactly in sync with the coherent demodulator [85].

4.5 MIMO Receiver Design

Digital communication receiver systems, encounter the problem of signal detection by design, and this is generally due to the measurement of transmitted signals in a noisy environment. Due to the noisy environments, errors occur arbitrarily at the receiver during signal reception. Therefore it is important to design the receiver that can minimise the probability of error, as they provide important performance benefits. Although the design of such systems are possible, they tend to be complex in terms of computational design, and are therefore discarded in favour of receiver designs that are suboptimal in nature. Research into both the system designs have indicated a significant gap in performance under certain circumstances, between suboptimal and the optimal receivers systems.

4.5.1 Detection Using Successive Interference Cancellation

4.5.1.1 Zero forcing (ZF) equalizer

In order to detect each data stream independently, the ZF receiver can be used. The ZF receiver analyses the signals from each transmit antenna and tries to nullify the interfering signal components. The performance of these receivers with reduced drastically in the presence of strong additive noise, and may deteriorate due to the destructive cancellation of the signals from different transmit antenna systems. Since each data stream is detected independently, the ZF receivers exhibit much lower implementation complexity in comparison to the ML receivers [56].

Successive interference cancellation (SIC) can be used to counteract these effects, thereby making an attempt to improve the BER performance of the ZF equalizers. If the channel is assumed to exhibit flat fading behaviour, then the channel can be modeled using a Rayleigh distribution to represent multipath fading. In order to apply successive interference cancellation, the receiver performs the following: first, an estimate of the transmitted symbols x_1 , x_2 are computed using the ZF detector, which is the representation of the MIMO channel system with multiple transmit and receive antennas. In this work, the number of transmit and receive antennas in the MIMO communication system is limited to a (2x2). Further, the multipath Channel is assumed to be flat fading and represented using a Rayleigh distribution and various modulation schemes are employed to evaluate the performance.

In a (2×2) MIMO communication system, the following represents the use of two transmitting antennas. Let us consider a sequence of symbols, $\mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3, \ldots., \mathrm{x}_\mathrm{n}$ for transmission. Normally, during communication the symbols are transmitted sequentially, with x_1 in the first slot, x_2 in the second etc. until all symbols are transmitted. The symbols can be grouped into two individual groups as two transmit antenna systems are used. Therefore we can transmit symbols sequentially using each of the antenna systems and transmit x_1 and x_2 simultaneously during a given time slot. This process can continue until all the symbols are transmitted, and therefore, the amount of time required for transmission is reduced by one half. Since the available symbol sequence are grouped into two groups, only n/2 time slots is needed to transmit the available symbols. This effectively reduces the transmission time by half and also increases the information transmission rate by a factor of two [61].

Zero forcing (ZF) equalizer for (2×2) MIMO channel

Let us now try to understand the process for extracting the two symbols which interfered with each other. In the first time slot, the received signal on the first receive antenna is,

$$y_1 = h_{1,1}x_1 + h_{1,2}x_2 + n_1 = \left[h_{1,1}h_{1,2}\right]\begin{bmatrix}x_1\\x_2\end{bmatrix} + n_1 \qquad (4.35)$$

The received signal on the second receive antenna is,

$$y_2 = h_{2,1}x_1 + h_{2,2}x_2 + n_2 = \left[h_{2,1}h_{2,2}\right]\begin{bmatrix}x_1\\x_2\end{bmatrix} + n_2 \qquad (4.36)$$

Where y_1, y_2 are the received symbol on the first and second antenna, with the channel matrix of the first antenna system given by $h_{1,1}$ and the channel matrix of the first receive antenna due to transmissions from the second transmit antenna is given by $h_{1,2}$ and so on. n_1,n_2 represents the noise on the first and second receive antenna systems respectively.

Assuming that the receiver has a knowledge of $h_{1,1}$, $h_{1,2}$, $h_{2,1}$ and $h_{2,2}$and further the receiver also has a knowledge of y_1 and y_2. Thus there are two unknowns namely $x_1$and x_2. It can be seen that each of the above equations have a pair of unknowns and can be solved using the following. To simplify, we can rewrite the above equation in matrix form as,

$$Y = Hx + n \qquad (4.37)$$

It can be seen from equation (4.37) that the matrix W is necessary in order to ensure that WH = 1, in order to solve for the unknown x. The zero forcing equaliser (linear detector) that satisfies this condition can be represented as

$$W = (H^H H)^{-1} H^H \qquad (4.38)$$

The above matrix is therefore a pseudo inverse matrix of dimension m x n.
The matrix,

$$H^H H = \begin{bmatrix} h_{1,1}^* & h_{2,1}^* \\ h_{1,2}^* & h_{2,2}^* \end{bmatrix}\begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix} = \begin{bmatrix} \left|h_{1,1}\right|^2 + \left|h_{2,1}\right|^2 & h_{1,1}^* h_{1,2} + h_{2,1}^* h_{2,2} \\ h_{1,2}^* h_{1,1} + h_{2,2}^* h_{2,1} & \left|h_{1,2}\right|^2 + \left|h_{2,2}\right|^2 \end{bmatrix} \qquad (4.39)$$

The non-diagonal terms of $H^H H$ matrix are not null. It can be seen that the zero forcing equaliser nullifies the interfering components during equalisation, i.e. while detecting $x_{1,}$ the corresponding interference from x_2 is nullified, and is repeated during the detection of x_2. Since this process can lead to amplification of the noise components, ZF equaliser may not be ideal for this operation. The advantage of this type of equalisation is that it is simple to implement, with low additional complexity.

For BPSK modulation in Rayleigh fading channel, the BER is derived as,

$$P_b = \frac{1}{2}\left(1 - \sqrt{\frac{\left(E_b/N_0\right)}{\left(E_b/N_0\right)+1}}\right) \tag{4.40}$$

4.5.1.2 Minimum Mean Square Error (MMSE) equalizer

The MMSE equaliser offers better compromise between interference of the signal and noise amplification, and tries to minimise the mean squared error of both the transmitter and the received symbols. Therefore MMSE equalisation employs the transmission of data streams along with residual noise and interference. The MMSE equalisation ensures that data streams are independently detected and quantised in a fashion similar to the ZF. For the optimal detection of signals, it may be difficult to obtain accurate noise parameters. Therefore, only a marginal improvement in performance is obtained by using MMSE equalisers in comparison to the ZF equalisers. Due to these reasons, this class of equalisers are not used in practice [64].

Let x be an $n * x_1$ unknown random variable (hidden vector) and let another random variable represented in the vector notation as y equal to $m * x_1$ be used as an observation vector. It is to be noted that both of these vectors need not necessarily correspond to the same dimensionality. Therefore we can construct an estimation system $\hat{x}(y)$ of input vector x which is dependent on the observation vector y.The error vector associated with this type of estimation can be represented by $e = \hat{x} - x$ and its equal and mean squared error (MSE) can be obtained using the trace of the covariance of error matrix as shown in equation (4.41).

$$MSE = tr\left\{E\{(\hat{x} - x)(\hat{x} - x)^T\}\right\} \tag{4.41}$$

where the expected values of both x and y are found. If the vector x is a scalar, then equation (4.41) can be simplified and represented as $E\{(\hat{x} - x)^2\}$.

The estimator achieving the minimum mean Square can now be defined as the MMSE estimator. The determination of the closed form equation of the MMSE estimator is difficult to determine, and therefore the mean square error can be minimized within a particular class (for example, linear estimators) to solve the above problem. The linear MMSE estimator is the estimator achieving minimum MSE among all estimators of the form $AY + b$. If the measurement Y is a random vector, A is a matrix and b is a vector.

Minimum Mean Square Error Equalizers (MMSE)

The Minimum Mean Square Error (MMSE) approach tries to estimate the coefficient W for the equation of y which minimizes the criterion in a way similar to the ZF estimator.

The coefficient W is estimated using the MMSE technique such that the following criterion is minimized,

$$E\left\{[W_{y-x}][W_{y-x}]^H\right\} \tag{4.42}$$

The matrix W is estimated such that it satisfies the condition $WH = I$, to solve for the unknown x. This constraint can be met by a Minimum Mean Square Error (MMSE) detector if the following condition is satisfied,

$$W = [H^H H + N_0 I]^{-1} H^H \tag{4.43}$$

Where W - Equalization Matrix and H - Channel Matrix

We can obtain an estimate of the transmitted symbols x_1, x_2, by the use of a Minimum Mean Square Error (MMSE) equalization and can be represented as:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = [H^H H + N_0 I]^{-1} H^H \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \tag{4.44}$$

In MMSE-SIC, the receiver arbitrarily takes one of the estimated symbols (for example the symbol transmitted in the second spatial dimension, x_2) and subtract its effect from the received symbol y_1 and y_2. Once the effect of $\widehat{x_2}$ is removed, the new channel becomes a one transmit antenna, two receive antenna case and can be optimally equalized by Maximal Ratio Combining (MRC).

4.5.1.3 Maximum Likelihood Detector (ML)

ML detector systems represent the most computationally complex detection algorithms, but this reflects an increase in system performance. This type of detector system transforms on the transmitted signals through the use of a known MIMO Channel matrix as a function in order to compute all available received signals that are noiseless nature. Next the Euclidean distance is minimized for each of the received signals, by performing a search process. If the signals are not corrupted by noise, then the minimum distance can be achieved and the signal can be considered to be the most likely possibility of the transmitted signal [60][61][106].

MIMO with ML-SIC equalization

The estimate $\hat{x}$ that minimises the equation $J = |y - H\hat{x}|^2$, is found using the ML receiver system and therefore we have,

$$J = \left|\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} - \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix}\right|^2 \tag{4.45}$$

In case of QPSK modulation the signal variables x_1 or x_2 can take two possible values namely +1 or -1. Therefore it is necessary to find the minimum value from all the four possible combinations of x_1 and x_2 in order to find a maximum likelihood (ML) solution.The minimum value of the above four combinations can be chosen based on the four possibilities namely $J_{+1,+1}$ denoted by [1 1] , if it is minimum; $J_{+1,-1}$ denoted by [1 0], if it is minimum; $J_{-1,+1}$ denoted by [0 1], if it is minimum; and $J_{-1,-1}$ denoted by [0 0], if it is minimum.

The minimum values of four possible symbol combinations during transmission are included in the assimilation. This is based on the minimum estimate of the transmitted symbol, and is repeated for different variations of E_b/N_o.

4.6 MIMO implementation with OSTBC and BPSK

The proposed scheme is assumed for two transmit and two receiving antennas as shown in figure 4.6. BPSK modulator and demodulator techniques are used in respective ends. Alamouti encoding and decoding techniques are applied and ML estimation is assumed at the end. MATLAB simulation is used for programming of the proposed model and simulation and synthesis results are obtained [63].

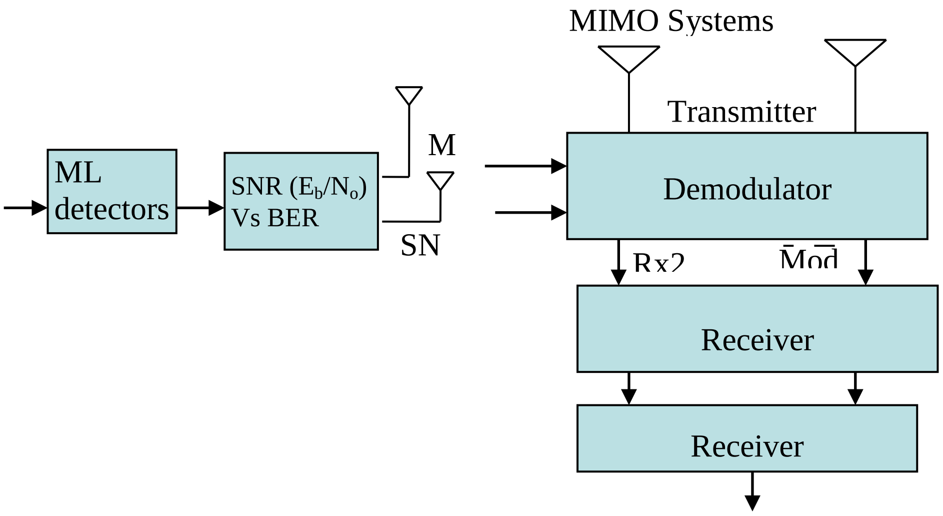


Figure 4.6: Proposed (2X2) OSTBC Scheme

MIMO-OSTBC Algorithm

- The working principle of the proposed system has been split into various steps.
- Modulate the data block using BPSK/QPSK/QAM constellation with 16 bit out of which 8 bits of real part and 8 bits of imaginary Part.
- Modulated output is applied as input to the Alamouti encoder and two separate symbols (represented by complex numbers), the complex symbols are encoded using the Alamouti code matrix with signed bits is transmitted through two separate transmit antennas. The input bits were used to decide which of four matrices output was received. The matrices were manually constructed and hard-coded into the simulation.
- Transmitted output received through Alamouti decoder. Alamouti decoder needs channel knowledge, so a channel estimator is required. The Alamouti Decoder implements a series of equations which combine the channel estimate (the 'h' terms) and the received signals (the 'r' terms) to give an estimate of the symbols that were transmitted. It is a "Soft decision" decoder.
- The estimated signal is demodulated by the corresponding demodulator to retrieve an estimate of the original raw transmitted bits.

4.7 FLOW CHART for MIMO-OSTBC

The flow chart for MIMO-OSTBC is as shown in figure 4.7.

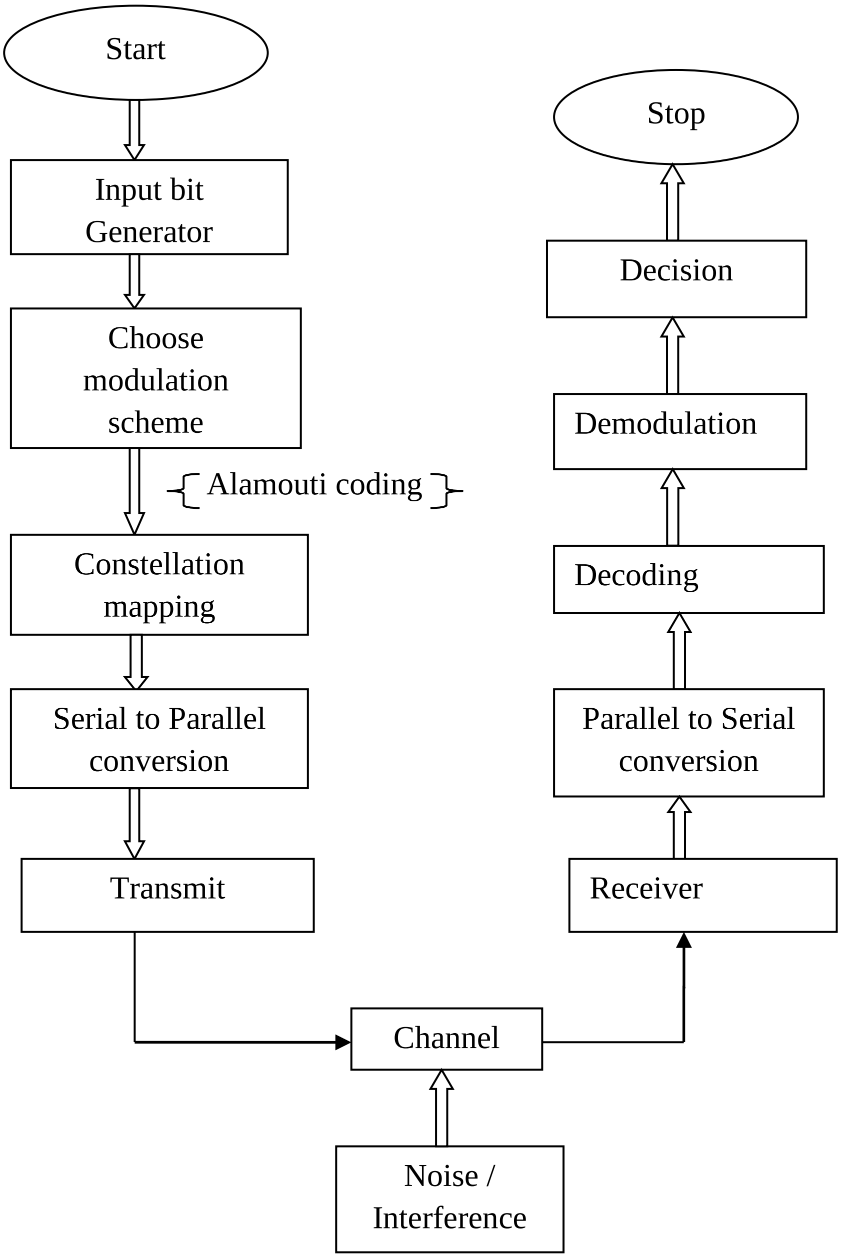


Figure 4.7: Flow Chart for MIMO-OSTBC

4.8 Results and Discussions

The performance analysis of MIMO-OSTBC communication system and their results, for various modulation techniques such as BPSK, QPSK and 16-QAM modulation are discussed in this section. The communication channel is assumed to exhibit multipath fading behaviour, with the fading assumed to be flat and modelled using a Rayleigh distribution, when Additive White Gaussian Noise (AWGN) is present in the channel. The system performance is analysed using different detector types and results are computed through MATLAB simulations. The SNR (E_b/N_0) values as a function of BER are determined by combining the SIC techniques with ZF, MMSE and ML detector systems and modulation schemes for studying their relative performances with digital modulation. The SNR values are determined as a function of BER for each BPSK, QPSK and 16-QAM modulation schemes [33][34].

The SNR values derived as a function of BER of (2x2) MIMO-OSTBC multiplexing system for the three detector systems are shown in figure 4.8 for BPSK modulation.

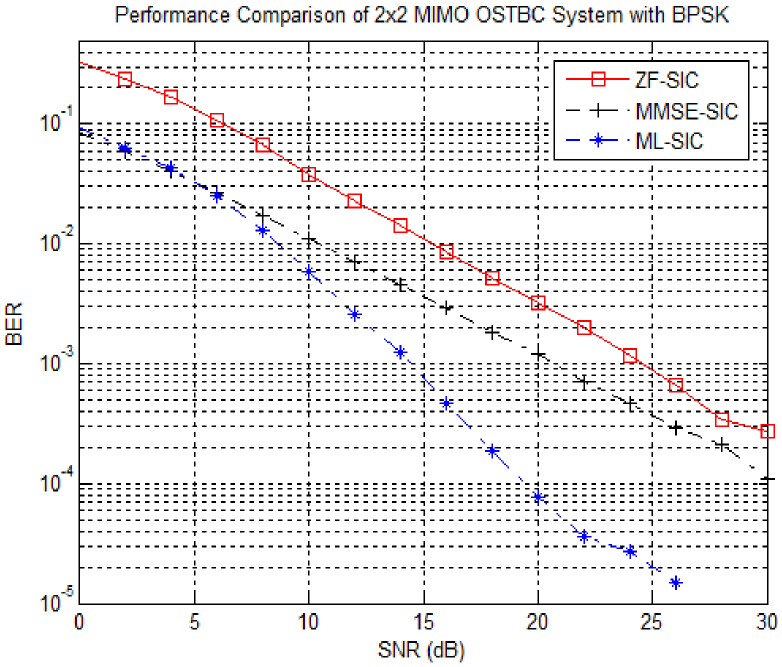


Figure 4.8: SNR Vs. BER performance for a (2x2) MIMO-OSTBC system with BPSK

The figure 4.8 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3}, the signal to noise ratio for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 24.4 dB, 20.6 dB and 14.46 dB respectively when BPSK modulation system is used. From the performance plot, it can be seen that the difference in SNR between ML-SIC detector and ZF-SIC detector systems ~10 dB for BPSK modulation. For the ML detection system that employs successive interference cancellation, the least value of the signal-to-noise ratio is obtained at ~14.46 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detectors for use with a MIMO-OSTBC communication system that employs BPSK modulation.

The SNR values derived as a function of BER of (2x2) MIMO-OSTBC multiplexing system for the three detector systems are shown in figure 4.9 for QPSK modulation.

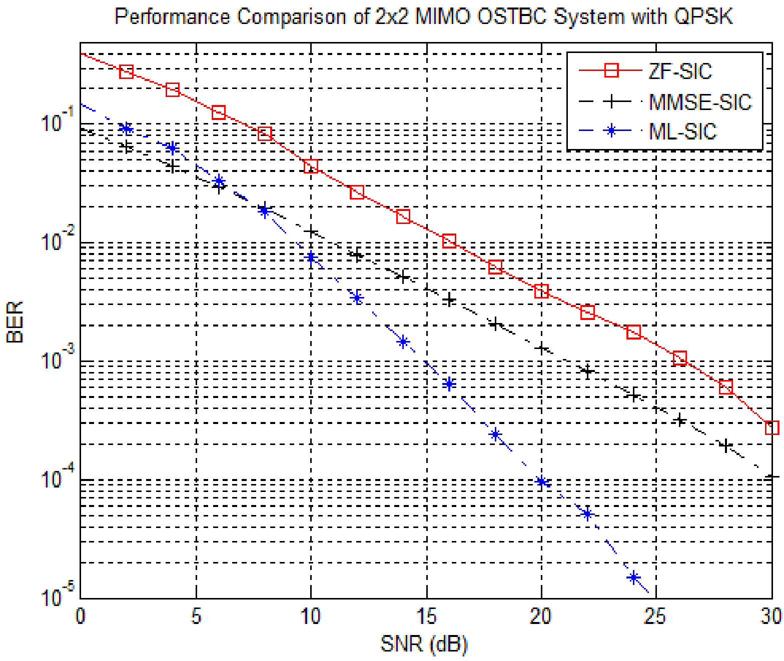


Figure 4.9: SNR Vs. BER performance for a (2×2) MIMO-OSTBC system with QPSK

From the figure 4.9, it is clearly evident that for all the three types of detection systems, as signal-to-noise ratio increases, the corresponding BER decreases. At the threshold level of BER equal to approximately 10^{-3}, each of the detection systems namely ZF, MMSE and ML detectors with successive interference cancellation, the signal-to-noise ratio is measured at approximately 26.1 dB, 21.1 dB and 14.8 dB respectively when QPSK modulation system is used. From the performance plots, it can be seen that for ML and ZF systems employing successive interference cancellation, the SNR difference is approximately 11.3 dB. The SNR values are found to be lowest ~14.8 dB for ML-SIC detector suggests that ML-SIC detectors are more efficient for MIMO-OSTBC transmission for QPSK modulation.

The SNR values derived as a function of BER of (2x2) MIMO-OSTBC multiplexing system for the three detector systems are shown in figure 4.10 for 16-QAM modulation.

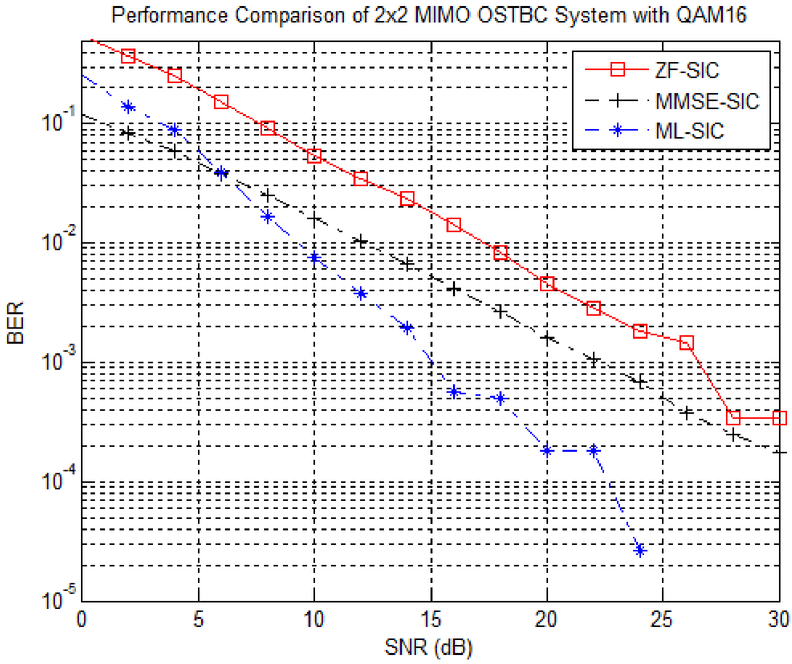


Figure 4.10: SNR Vs. BER performance for a (2×2) MIMO-OSTBC system with 16-QAM

The figure 4.10 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3}, the signal to noise ratios for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 26.4 dB, 22.0 dB and 15.1 dB respectively when 16-QAM modulation system is used. From the performance plot, it can be seen that the difference in SNR between ML-SIC detector and ZF-SIC detector systems ~11.3 dB for 16-QAM modulation. For the ML detection system that employs successive interference cancellation, the least value of the signal-to-noise ratio is obtained at ~15.1 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detectors for use with a MIMO-OSTBC communication system that employs 16-QAM modulation.

The performance results of the simulation at a BER threshold of ~10^{-3} , and the corresponding signal-to-noise ratio values for a (2x2) MIMO-OSTBC communication system is tabulated for three different detectors namely ZF, MMSE and ML with successive interference cancellation (SIC) and for three different modulation schemes such as BPSK, QPSK and 16-QAM are summarized in Table 4.1.

Table 4.1- Comparison table of SNR Values of (2x2) MIMO-OSTBC with ZF, MMSE and ML detectors each with SIC, for various modulation schemes at BER threshold of ~10^{-3} .

Modulation/ Detectors with SIC	BPSK SNR(dB)	QPSK SNR(dB)	16-QAM SNR(dB)
ZF	24.4	26.1	26.4
MMSE	20.6	21.1	22.0
ML	14.4	14.8	15.1

It is evident from the table 4.1 that at BER ~10^{-3} , all the three detectors depicts as expected similar behaviour and SNR values increases ~2 dB as we go from lower BPSK to higher 16-QAM modulation scheme. Further it is clearly depicted in the table that the SNR (E_b/N_0) values for the ML–SIC detector at BER ~10^{-3} shows lowest values ~14.4 dB for BPSK modulation displays better performance of SNR ~10 dB (BR/BW efficiency ~10) compared to other detector systems. It can be concluded from the simulation results that the MIMO-OSTBC transmission system offers better SNR performances for BPSK modulation with ML-SIC detection system. Similar results are reported by Weifeng Su, Stella N. Batalama, Dimitris A. Pados [30].

The results presented in the chapter of the thesis have been published in the international journal paper:

Bhagya.R, Dr. A G Ananth," Transmission Characteristics of 2x2 MIMO system Using OSTBC Multiplexing for Different Detector Systems", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE), Volume-3, Issue-7, July 2014, Pages 10423- 10431. (Impact factor 1.686).

CHAPTER 5

MIMO-CDMA AND OFDM MULTIPLEXING FOR DIFFERENT MODULATION AND DETECTION SYSTEMS

CHAPTER 5

MIMO-CDMA AND OFDM MULTIPLEXING FOR DIFFERENT MODULATION AND DETECTION SYSTEMS

5.1 Code Division Multiplexing (CDMA)

The Code Division Multiple Access (CDMA) is an upcoming technology for next generation multimedia information of real-time and non-real-time traffic and various multi-source multi-traffic communication environments. MIMO is a system to increase data rate significantly with multiple antennas at both the transmitter and receiver. MIMO takes the benefit of random fading and multipath delay spread. In order to be effective, MIMO systems will need to function reliably in interference limited environment. The combination of MIMO and CDMA can further improve the system transmission rate over the traditional CDMA system. Various mobile communication standards such as IS-95 (CDMAOne), CDMA2000 and WCDMA (the 3G standard used by GSM carriers) which are often referred to as merely CDMA.

5.2 CDMA Fundamentals

DSSS (Direct Sequence Spread Spectrum) forms one of the important components of the CDMA system. DSSS is a transmission mechanism which results in information transmission that looks similar to the presence of white noise or the entire bandwidth of a given channel. Information is first scrambled using a spreading sequence, and the received signal is required to be processed using descrambling code for extraction of transmitted information. In CDMA transmission that employs the spread spectrum technique, the message data signal is directly multiplied by a spreading sequence (or chip code) to scramble the transmitted information. Therefore the resulting spread sequence requires a data rate that is higher than the message data signal. An exclusive OR function is used to multiply the data with the spread sequence as shown in figure 5.1.

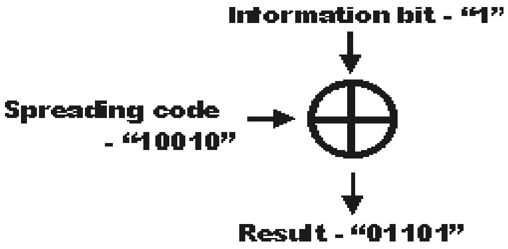


Figure 5.1: Data spreading

5.2.1 Spreading in CDMA

In CDMA systems, a chip refers to a spreading sequence which is much smaller than an information bit. The process of data spreading in CDMA systems are shown in figure 5.2. The final output of the spreading system results in a data rate that is similar to the spreading sequence (or chip sequence). The data transmission rate of such a signal is then referred to as the chip rate, and is measured as the ratio of the number of chips per second.

In order to spread the signal over a large bandwidth, the baseband information stream is modulated using a carrier signal. This is because, signals with high data rates occupy wider signal bandwidths than those with low data rates.

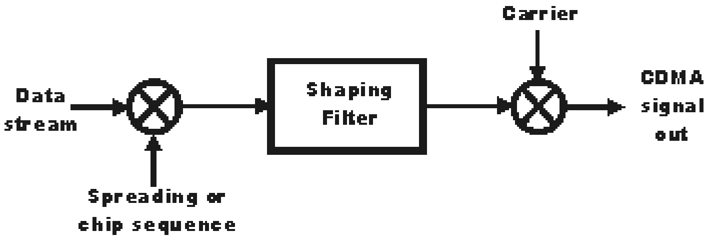


Figure 5.2: CDMA data spreading

5.2.2 CDMA spread spectrum generation

The CDMA signal first undergoes demodulation, which results in the reconstitution of the input data stream. This is the first step prior to the decoding of the original data. Once the received signal is decoded, it is then multiplied with the spreading code, and correlation is employed to determine if it is the original transmitted information. After multiplying, then only the data that was generated with the same spreading code is regenerated, all the other data that is generated from different spreading code streams is ignored as shown in figure 5.3.

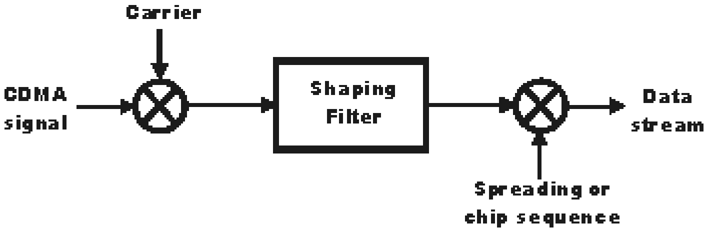


Figure 5.3: CDMA data despreading

5.2.3 CDMA Spread System Gain

Since the bandwidth of the spread signal will be much larger in comparison to the transmitted information stream, the parameter spreading gain can be used to measure this relative increase in bandwidth. If the number of input data bits is a period equal and to 1/R, and if W represents the bandwidth of the spread signal, then the spreading gain is given by,

$$\text{Spreading gain} = W/\ R$$

When the spreading gain of the CDMA communication system is large, the overall performance of the system tends to be more effective. This is due to the fact that the signal becomes larger than the transmitted signal. Due to this reason, the data created by any other spreading codes appear as the noise signal to the receiver side processing, and can be completely discarded. But, if the same scrambling sequence is used at the receiver, the data will remain unchanged and can be successfully decoded from the CDMA transmission. If different scrambling codes are used during transmission and reception, signals that are representative of noise and interference are generated, and these can be discarded during processing.

5.3 MIMO-CDMA Transceiver System

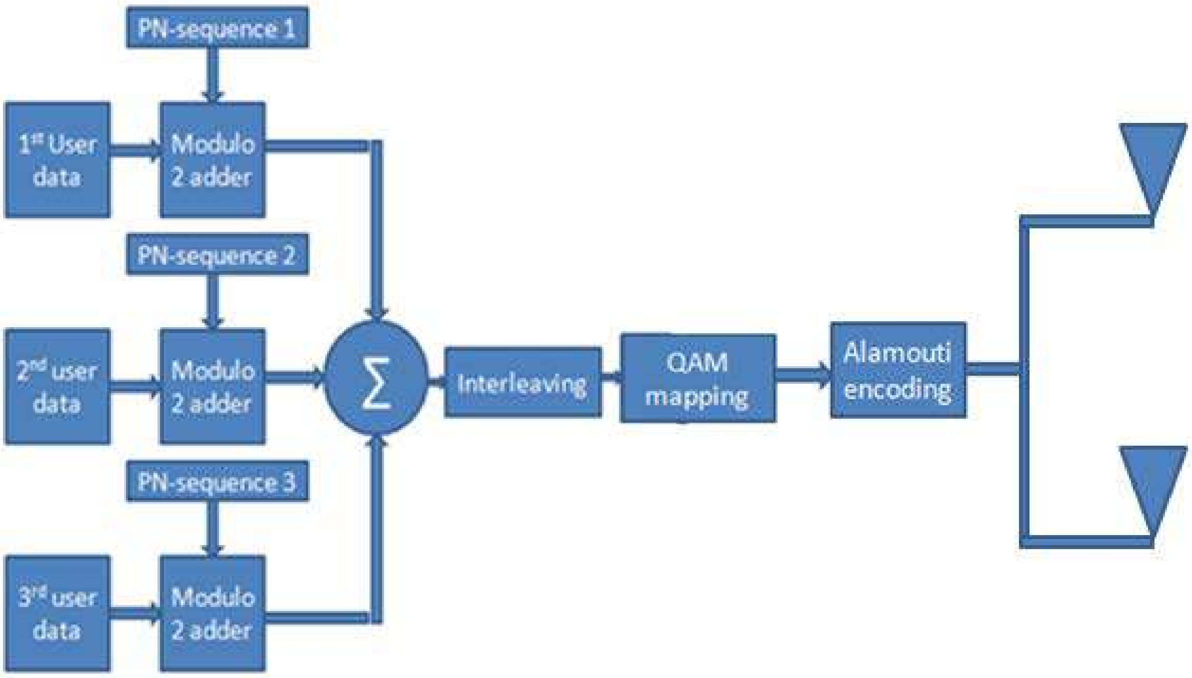


Figure 5.4: Block diagram of MIMO-CDMA Transmitter system

In order to achieve diversity or high data transmission rates, resulting CDMA signal must be transmitted to the number of antenna systems. The system is then referred to as a MIMO-CDMA system. Similar to other communication system that employ MIMO-CDMA system also have more than one transmit and receive antennas at the corresponding nodes. In order to mitigate multipath fading, diversity reception can be used where the same signal is transmitted through multiple antenna systems so that multiple signals are received at the receiver, with each signal taking an independent path. If each of these paths are independent of each other, the entire set of received signals would have passed through an equal and uncorrelated channel. Thus in order to increase capacity, MIMO can be used to transmit different sequences of information through a number of antennas and the same number of antennas will receive the signals in the receiving end. The increase in capacity will then be directly correlated to the total number of antennas used. The spacing of such antenna systems should be given careful consideration, with a spacing of at least one half wavelength of the transmitting signal for MIMO communication to work effectively [39].

All the user data is summed after spreading through respective PN-sequences. Then serial data stream is interleaved and encoded. A suitable digital modulation technique is used. Finally the signal is transmitted through multiple antennas as shown in figure 5.4. An exact opposite sequence of operations is performed at the receiver during receiver side processing.

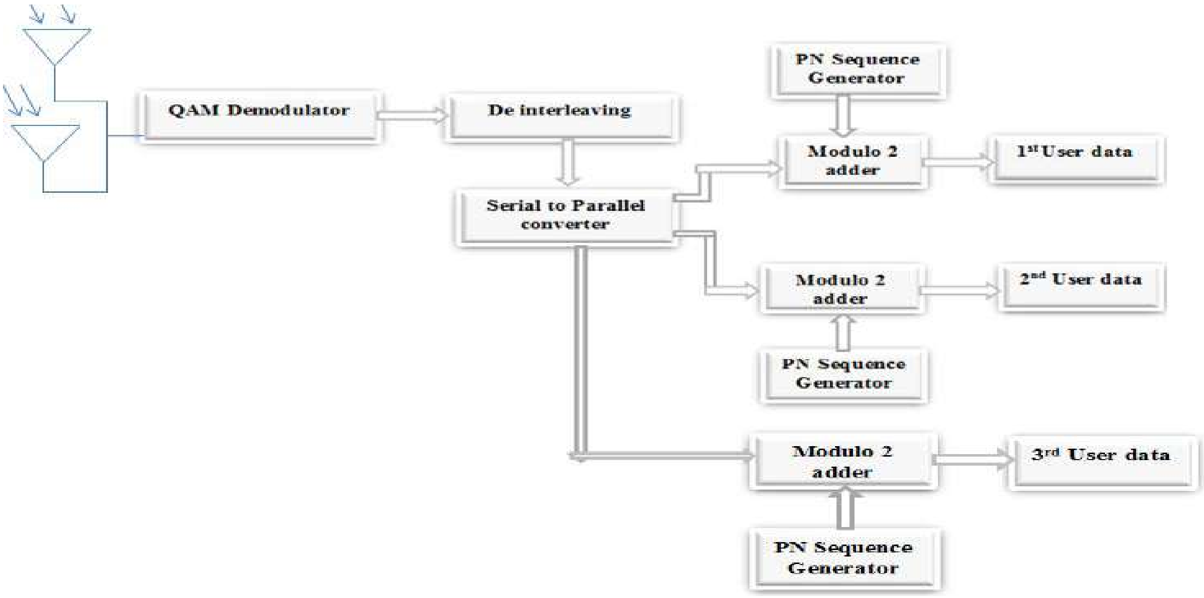


Figure 5.5: Block diagram of MIMO-CDMA receiver system

The signals that are transmitted are received by the receiver antennas as shown in figure 5.5. The received RF signal is first down converted to the carrier frequencies. Then the receiver must do the synchronization that will help to adjust the symbol timings. Subsequently, demodulation is done where the signal is de-spread by using 16-QAM demodulator. Here, the zero forcing detector is used to detect the received signal. The detection of MIMO signals must be performed for every CDMA subcarrier used. Thus for each subcarrier, the received signals are processed through a MIMO detection system in order to recover the transmitted information on that subcarrier.

The output of the demodulator is fed to the de-interleaving block. Because to achieve acceptable performance, the interleaving block at the transmitter insert both reference pilot carriers and inter-symbol guard time interval. By employing long time interleaving, performance improvement under deep fading and impulsive noise is usually improved. So in de-interleaving block, it removes those reference pilot carriers and inter-symbol time guard intervals. The output of the de-interleaving block is fed to the serial to parallel converter. This converter converts the sequential symbols to parallel symbols for multiple users to receive the symbols simultaneously. The output of this converter is fed to different modulo-2 adder simultaneously. The modulo-2 adder performs the logic XOR operation between the output of the converter and the pseudo noise (PN) code generated by the PN sequence generator. Here, the PN sequence generator used is same as that used at the transmitter side. The output of the modulo-2 adder is the original transmitted data. The output of the different modulo-2 adder is used by multiple users simultaneously [43].

5.4 Flow chart for MIMO-CDMA

The flow chart for MIMO-CDMA is as shown in figure 5.6.

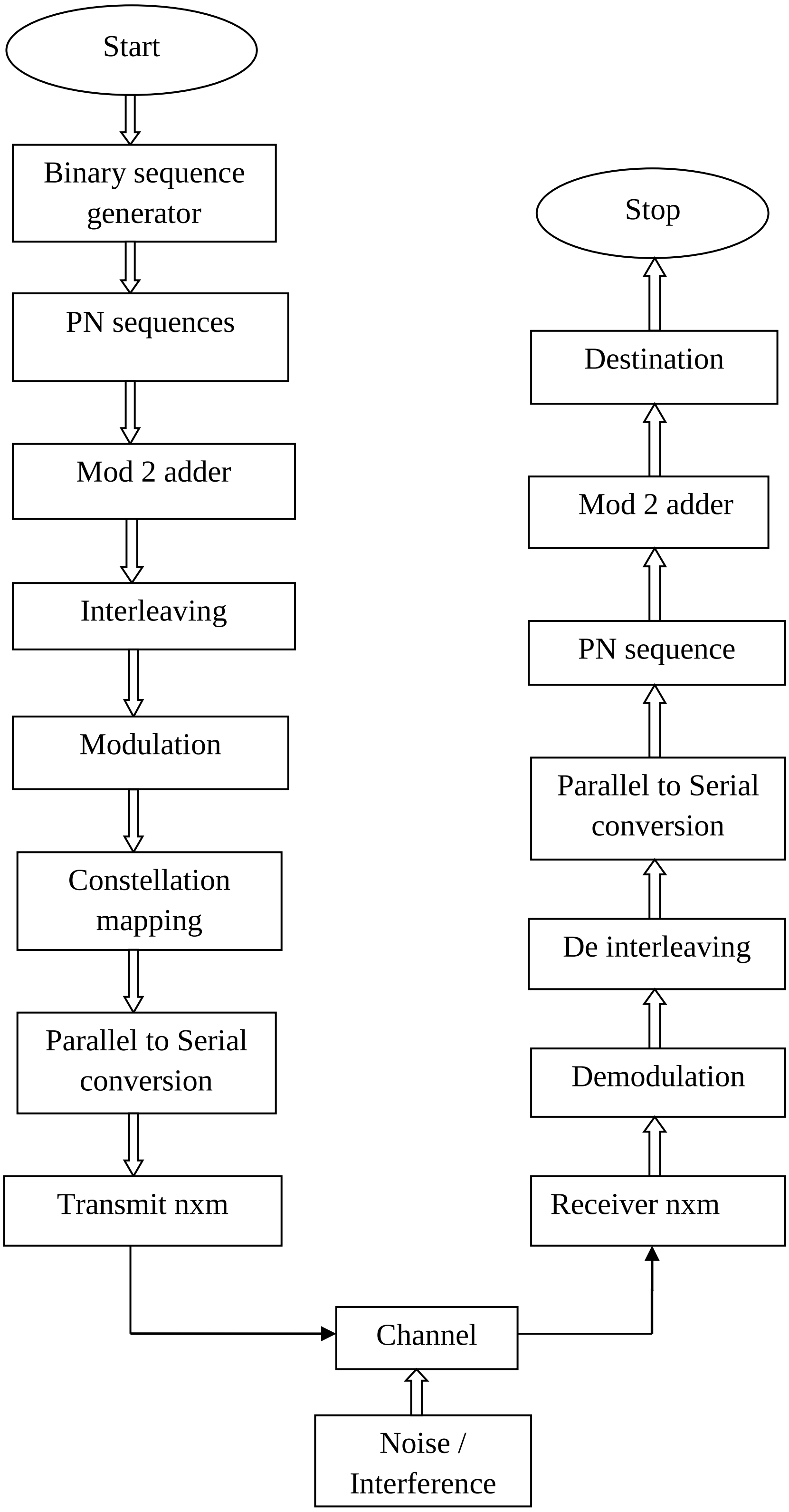


Figure 5.6: Flow Chart for MIMO-CDMA

5.5 Results and Discussions

The performance analysis of MIMO-CDMA communication systems and its results, for various modulation techniques such as BPSK, QPSK and 16-QAM modulation are discussed in this section. The communication channel is assumed to exhibit multipath fading behaviour, with the fading assumed to be flat and modelled using a Rayleigh distribution, when Additive White Gaussian Noise (AWGN) is present in the channel. The system performance is analysed using different detector types and results are computed through MATLAB simulations. The BER values as a function of SNR (E_b/N_0) are determined by combining the SIC techniques with ZF, MMSE and ML detector systems and modulation schemes for studying their relative performances in digital modulation. The SNR values are determined as a function of BER for each BPSK, QPSK and 16-QAM modulation schemes [45][46].

The SNR values derived as a function of BER for (2x2) MIMO-CDMA multiplexing system for the three detection systems are shown in figure 5.7 for BPSK modulation.

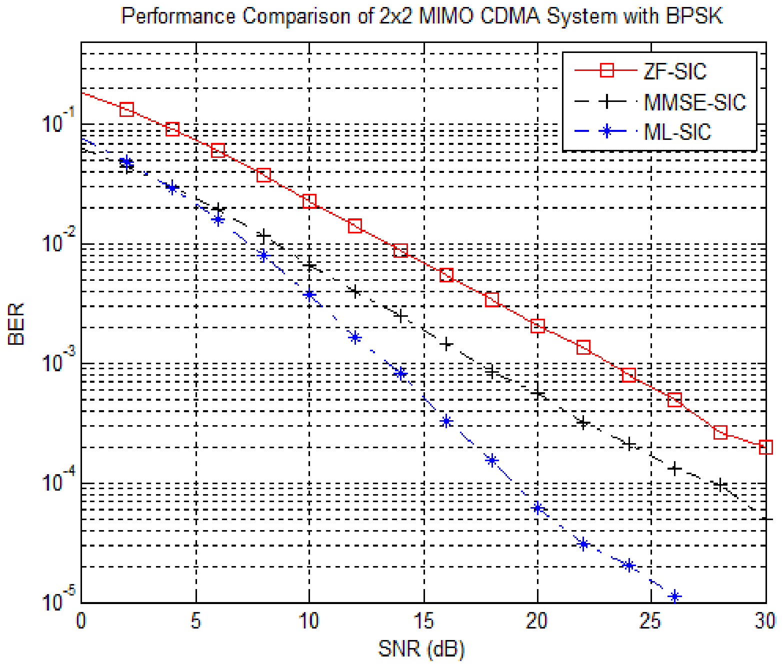


Figure 5.7: SNR Vs. BER performance for a (2×2) MIMO-CDMA system with BPSK

The figure 5.7 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3}, the signal to noise ratio for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 23.09 dB, 17.53 dB and 13.35 dB respectively when BPSK modulation system is used. From the performance plot, it can be seen that the difference in SNR between ML-SIC detector and ZF-SIC detector systems ~9.74 dB for BPSK modulation. For the ML detection system that employs successive interference cancellation, the least value of the signal-to-noise ratio is obtained at ~13.35 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detectors for use with a MIMO-CDMA communication system that employs BPSK modulation.

The SNR values derived as a function of BER for (2x2) MIMO-CDMA multiplexing system for the three detection procedures shown in figure 5.8 for QPSK modulation.

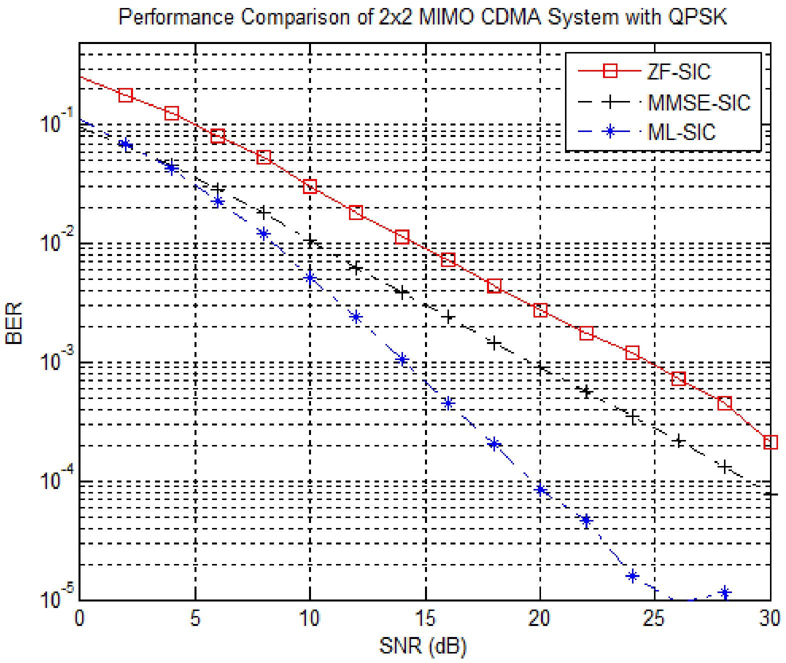


Figure 5.8: SNR Vs. BER performance for a (2x2) MIMO-CDMA system with QPSK

From the figure 5.8, it is clearly evident that for all the three types of detection systems, as signal-to-noise ratio increases, the corresponding BER decreases. At the threshold level of BER equal to approximately 10^{-3} , each of the detection systems namely ZF, MMSE and ML detectors with successive interference cancellation, the signal-to-noise ratio is measured at approximately 24.68 dB, 19.46 dB and 14.07 dB respectively when QPSK modulation system is used. From the performance plots it can be seen that for ML and ZF systems employing successive interference cancellation, the SNR difference is approximately 10.61 dB. Further, the SNR values are found to be lowest ~14.07 dB for ML-SIC detector suggests that ML-SIC detectors are more efficient for MIMO-CDMA transmission systems for QPSK modulation.

The SNR values derived as a function of BER for (2x2) MIMO-CDMA multiplexing system for the three detection procedures shown in figure 5.9 for 16-QAM modulation.

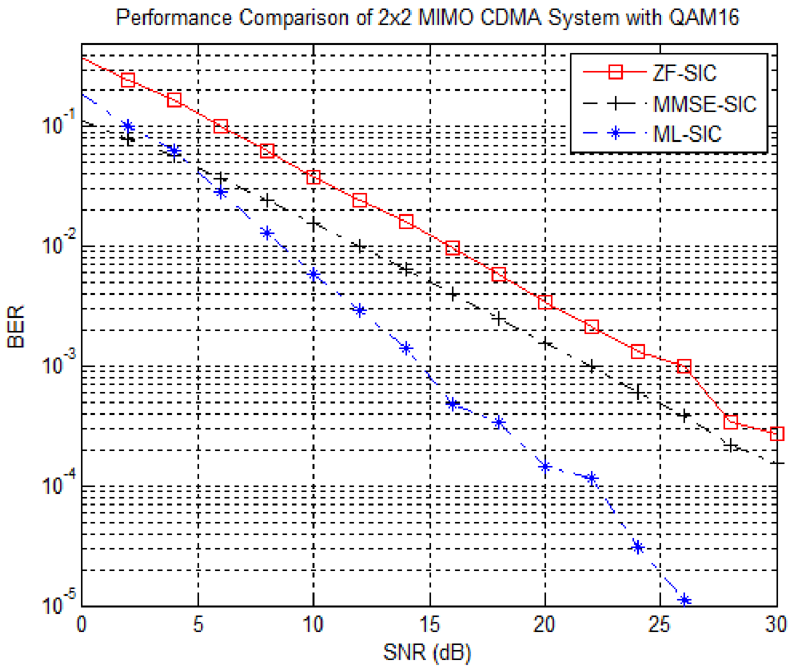


Figure 5.9: SNR Vs. BER performance for a (2x2) MIMO-CDMA system with 16-QAM

The figure 5.9 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3} , the signal to noise ratio for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 25.56 dB, 21.99 dB and 14.58 dB respectively when 16-QAM modulation system is used. From the performance plot, it can be seen that the difference in SNR between ML-SIC detector and ZF-SIC detector systems ~10.98 dB for 16-QAM modulation. For the ML detection system that employs successive interference cancellation, the least value of signal-to-noise ratio is obtained at approximately 14.58 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detector for use with a MIMO-CDMA communication system that employs 16-QAM modulation.

The performance results of the simulation at a BER threshold of ~10^{-3} , and the corresponding signal-to-noise ratio values for a (2x2) MIMO-CDMA communication system is tabulated for three different detectors namely ZF, MMSE and ML with successive interference cancellation (SIC) and for three different modulation schemes such as BPSK, QPSK and 16-QAM are summarized in Table 5.1.

Table 5.1- Comparison table of SNR Values of (2x2) MIMO-CDMA with ZF, MMSE and ML detectors each with SIC, for various modulation schemes at BER threshold of ~10^{-3}.

Modulation Detector	BPSK SNR(dB)	QPSK SNR(dB)	16-QAM SNR(dB)
ZF-SIC	23.09	24.68	25.56
MMSE-SIC	17.53	19.46	21.99
ML-SIC	13.35	14.07	14.58

It is shown in the Table 5.1 that at BER ~10^{-3} , all the three detectors depicts similar behaviour as expected and the SNR values for ML-SIC detector increases ~1.23 dB as we go from lower BPSK to higher 16-QAM modulation scheme. Further it is clearly depicted in the table that the SNR (E_b/N_0) values for the ML–SIC detector at BER ~10^{-3} shows lowest values ~13.35 dB for BPSK modulation compared to other detection systems. It can be concluded from the simulation results that the MIMO-CDMA transmission system offers better SNR performance for BPSK modulation with ML-SIC detection system.

5.6 MIMO with Orthogonal Frequency Division Multiplexing (OFDM)

Data transmission rates of several hundred megabits per second can be achieved in indoor wireless systems. This implies that the overall spectral efficiencies can be improved significantly by employing MIMO-OFDM system to several bits/Hz/s. The corresponding improvement in spectral efficiency and data transmission rates is due to the use of parallel transmission mechanisms in MIMO-OFDM, in both frequency domains and space domains respectively [47].

A very promising approach is to use MIMO system. MIMO can be combined with OFDM in order to deal with the frequency selective nature of wideband wireless channels.

5.6.1 Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) has become a popular technology for use with high-speed communication systems. Orthogonal means that the signals are totally/completely independent of each other. It is achieved by ensuring that the carriers are placed exactly at the nulls in the modulation spectra of each other. OFDM distributes the data of a large number of carriers that are spaced apart at precise frequencies. This spacing provides orthogonality. The principle of orthogonality is as shown in figure 5.10. Figure shows that for OFDM spectral efficiency, measured in bits/sec/Hz is due to the drop in the signal level at the band is fundamentally because of single carrier which is of low data rate channel. Further the power spectral density of the signal in OFDM can assume a rectangular shape [48].

Spectral efficiency = log 2 M bits/s/Hz

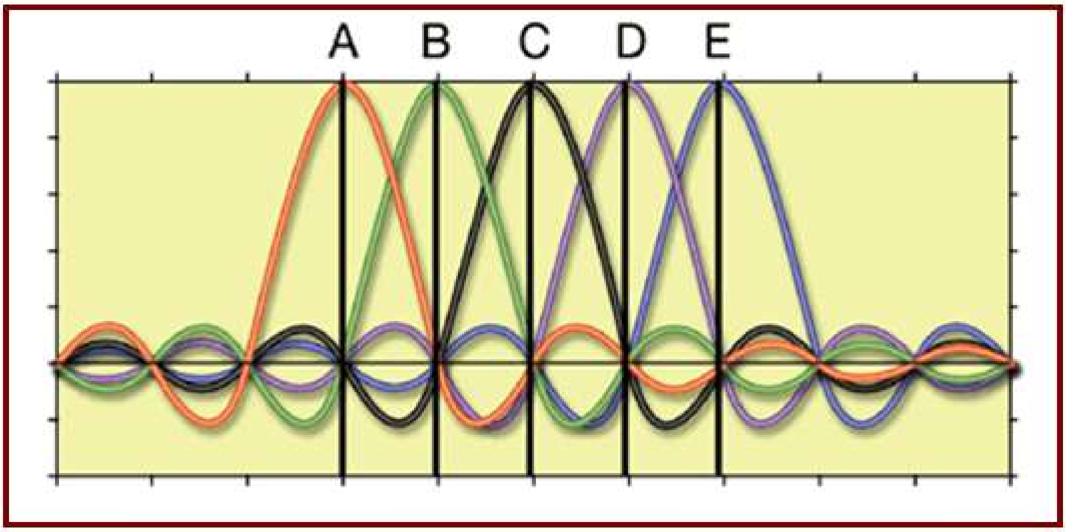


Figure 5.10: Principle of Orthogonality

5.6.2 Parallel Transmission Scheme

OFDM is also known as discrete multi-tone modulation (DMT) which is based upon the principle of frequency division multiplexing (FDM), but it is utilized as a digital modulation scheme. The bit stream that is to be transmitted is split into several parallel bit streams. The broadband channel can be divided into multiple parallel sub channels during OFDM modulation, and is demonstrated in figure 5.11. This creates an efficient mechanism for transmission of signals through wireless channels that exhibit multipath behaviour.

The available frequency spectrum is divided into sub-channels and each low rate bit stream is transmitted over one sub channel by modulating sub carrier using a standard modulation scheme, for example BPSK, QPSK, QAM. The sub-carrier frequencies are chosen so that the modulated data streams are orthogonal to each other which mean that cross talk between the sub channels is eliminated. By replacing the fast modulated wideband signal, with the narrowband signal slow modulation, the channel equalisation characteristics are vastly improved. Therefore the fundamental advantage of an OFDM communication system is its inherent ability to mitigate severe channel effects such as interference and multipath fading without the use of complex equalisers.

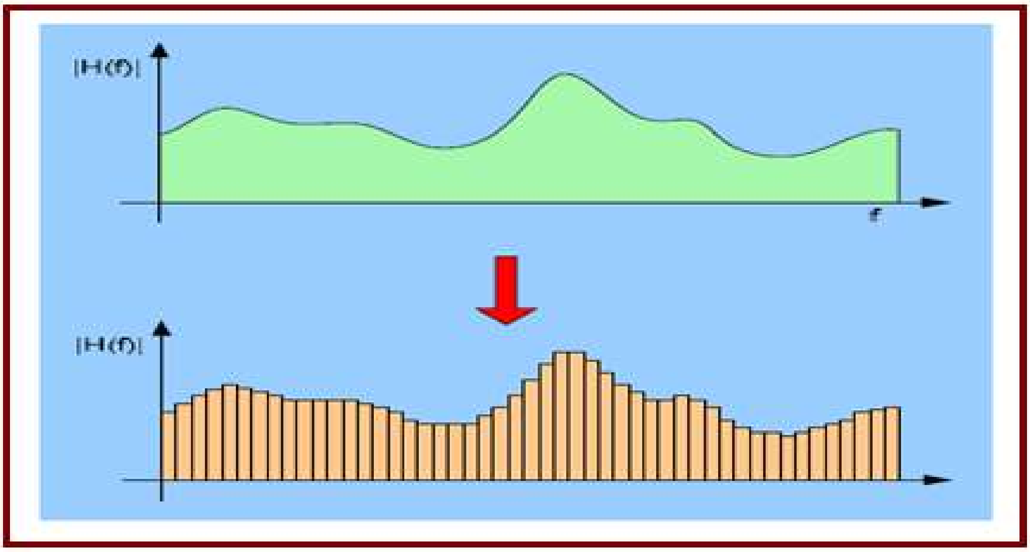


Figure 5.11: A broadband channel divided into many parallel narrowband channels

5.7 MIMO-OFDM Communication Systems

Since OFDM communication systems support the use of multiple antennas to support larger bandwidths, it is advantageous to combine MIMO with OFDM. This combination greatly simplifies the system design and removes the need for channel equalisation.

5.7.1 MIMO-OFDM Transmitter

The transmission system that uses MIMO-OFDM is made up of N_t bits. Multiplexing is then performed on these incoming bits and next the parallel encoding and interleaving is performed. After interleaving, modulation maps each set of bit to the corresponding symbol and then inverse discrete Fourier transformation is computed for each symbol. The cycle prefixes is added to each encoded block prior to transmission. During transmission the signal is up converted to RF frequency range and is transmitted as shown in figure 5.12.

The input data is converted from a serial stream to parallel sets by the transmitter. The data encoding can be performed on a per branch basis, or jointly over all the transmitter branches. By employing long time interleaving, performance improvement under deep fading and impulsive noise can be improved. QAM modulation involves sending digital information by periodically adjusting the phase and amplitude of a sinusoidal electromagnetic wave.

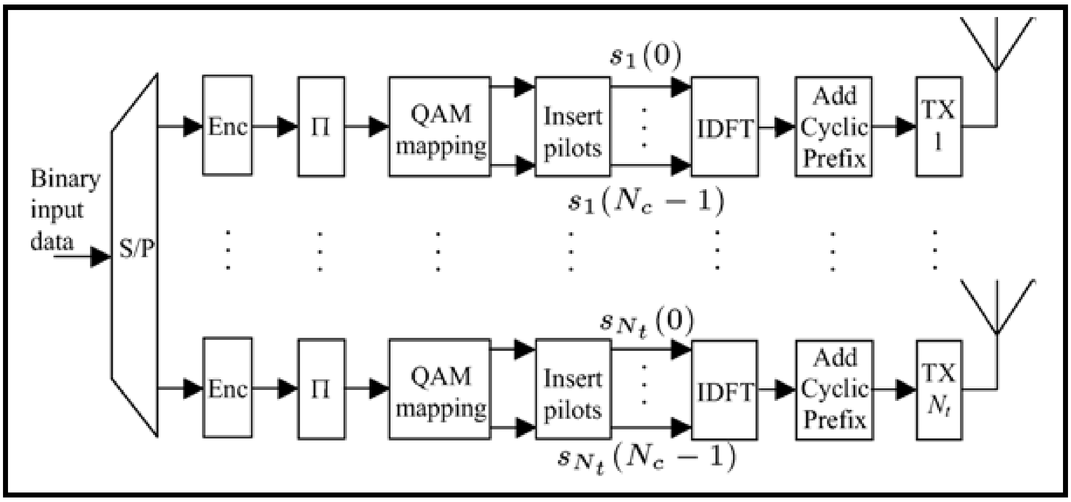


Figure 5.12: Block Diagram of MIMO-OFDM Transmitter

By applying an inverse Fourier transform to the binary data, the binary information is spread over several consecutive symbols. An inverse Fourier transform converts the frequency domain data set into samples of the corresponding time domain representation of this data. Specifically, the IFFT is useful for OFDM because it generates samples of a waveform with orthogonal frequency components. During each guard interval, the transmitter sends the cyclic prefix information thereby reducing the sensitivity of the communication system to problems such as timing synchronisation.

Generally, it is essential for the receiver to know the state of the wireless channel behaviour for reliable detection and keeps track of phase and amplitude drifts. The transmitter occasionally sends known training symbols to enable channel estimation in a wireless communication system. Moreover, pilot symbols are inserted into every MIMO-OFDM data symbol on predefined subcarriers to track the phase drift [48][50].

5.7.2 MIMO-OFDM Receiver

Through the use of training symbols in the preamble, the frequency offset information and the symbol timing information must be accurately estimated by the receiver. After this estimation, the cycle prefixes is discarded and an N-point DFT (Discrete Fourier Transform) is applied. For each OFDM subcarrier, MIMO detection is performed by routing received signal to the corresponding ith MIMO detector. This leads to the recovery of N_t data signals from the subcarrier's transmission. Additional operations such as mapping, de-interleaving and decoding are performed on the transmitted streams on it per symbol basis and combined together to retrieve the binary output information. The entire process is as shown in figure 5.13 [51] [53].

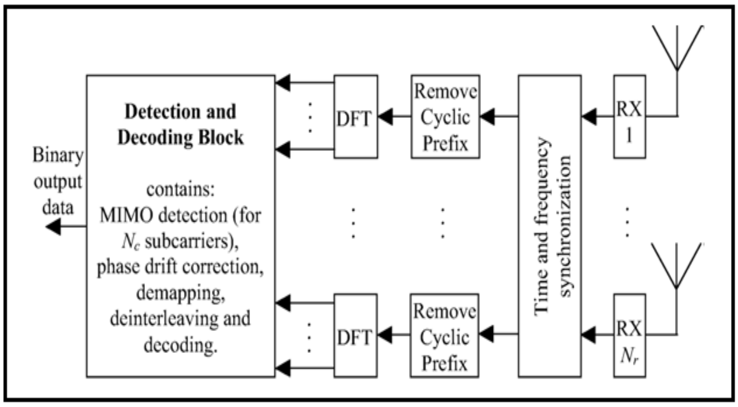


Figure 5.13: Block Diagram of MIMO-OFDM Receiver

5.8 Flow chart for MIMO-OFDM

The flow chart for MIMO-OFDM is as shown in figure 5.14.

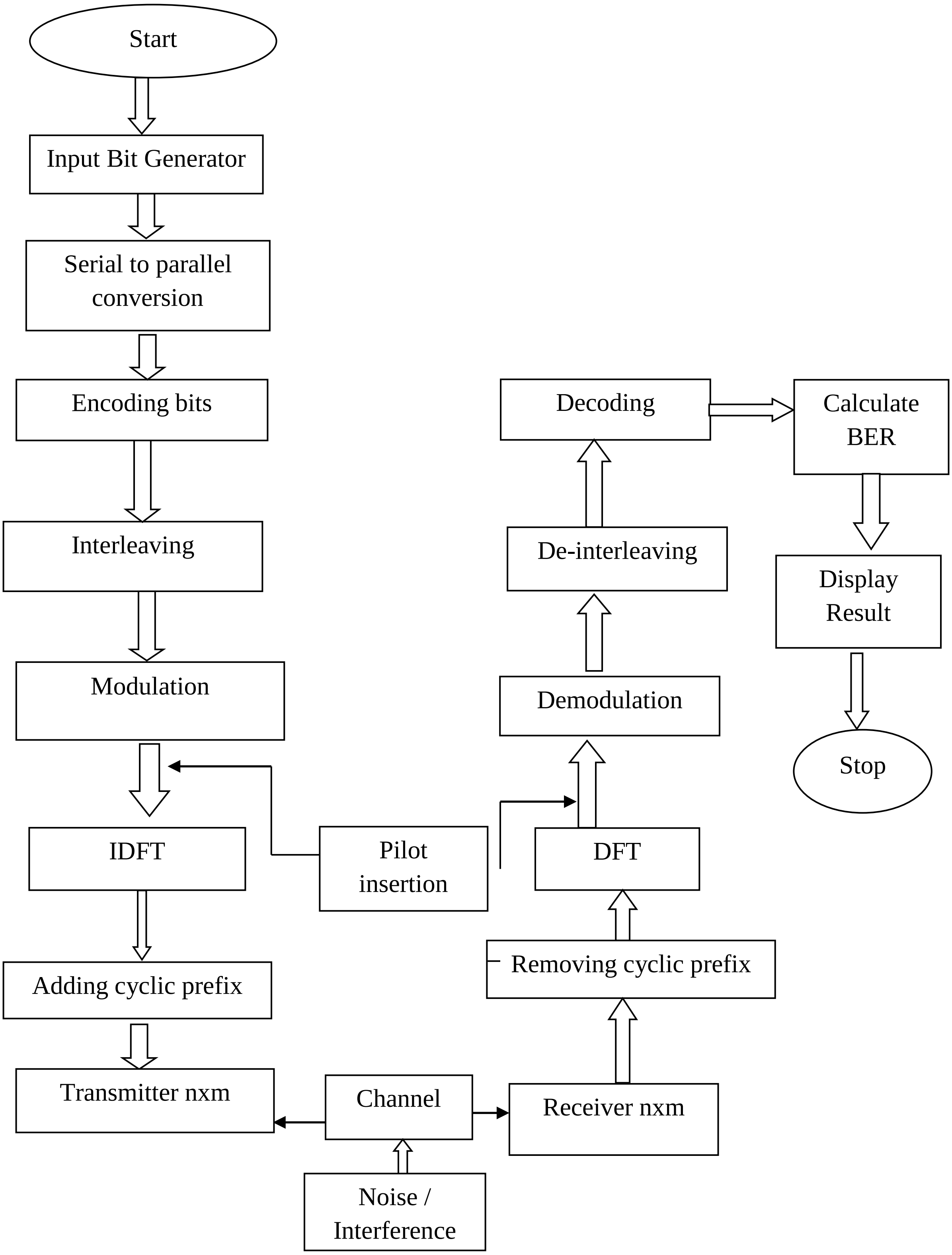


Figure 5.14: Flow chart for MIMO-OFDM System

5.9 Results and Discussions

The transmit and receive procedures for a (2x2) MIMO communication system is described as follows. First, the sequential data stream is converted into parallel data and then each parallel data stream undergoes an encoding and interleaving process. Digital modulation is then performed on this data, with synchronisation requiring the addition of a few pilot bits. In order to include guard bits and cyclic prefix, IDFT (inverse discrete Fourier transform) is applied. The resulting signal is transmitted through a MIMO system and the receiver side processing uses the exact opposite process of the transmitter. This type of communication system design assumes the use of (2x2) antenna system that is operating in a flat fading environment. The performance of MIMO-OFDM and the simulation results for different modulation presuming AWGN channel for the flat fading environment modelled by a Rayleigh distribution is done using MATLAB.

The performance analysis of MIMO-OFDM communication systems and its results, for various modulation techniques such as BPSK, QPSK and 16-QAM modulation are discussed in this section. The communication channel is assumed to exhibit multipath fading behaviour, with the fading assumed to be flat and modelled using a Rayleigh distribution, when Additive White Gaussian Noise (AWGN) is present in the channel. The system performance is analysed using different detector types and results are computed through MATLAB simulations. The BER values as a function of SNR (E_b/N_o) are determined by combining the SIC techniques with ZF, MMSE and ML detector systems and modulation schemes for studying their relative performances in digital modulation.

The SNR values derived as a function of BER for (2x2) MIMO-OFDM multiplexing system for the three detector systems are shown in figure 5.15 for BPSK modulation.

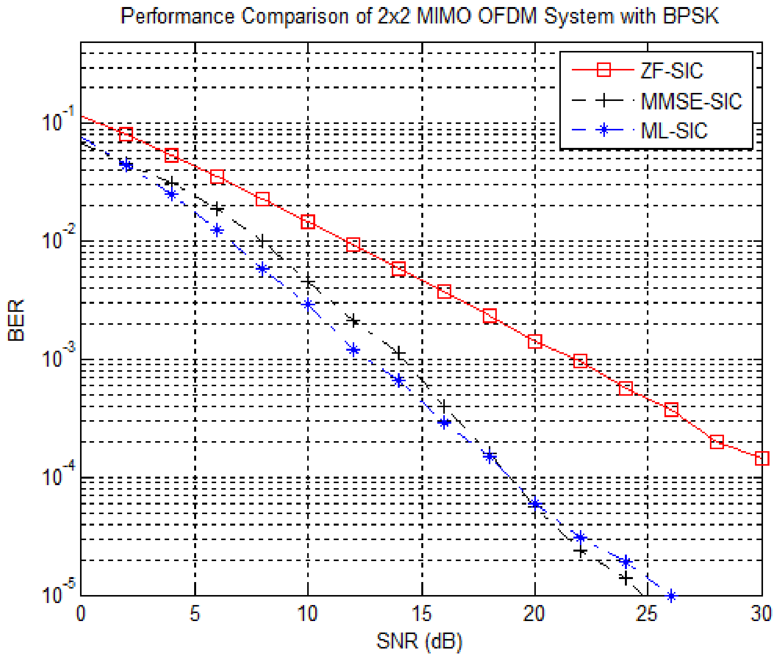


Figure 5.15: SNR Vs. BER performance for a (2x2) MIMO-OFDM system with BPSK

The figure 5.15 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3} , the signal to noise ratio for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 21.67 dB, 14.14 dB and 12.6 dB respectively when BPSK modulation system is used. From the performance plot, it can be seen that the difference in SNR between ML-SIC detector and ZF-SIC detector systems ~9.07 dB for BPSK modulation. For the ML detection system that employs successive interference cancellation, the least value of the signal-to-noise ratio is obtained at ~12.6 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detectors for use with a MIMO-OFDM communication system that employs BPSK modulation.

The SNR values derived as a function of BER for (2x2) MIMO-OFDM multiplexing system for the three detector systems are shown in figure 5.16 for QPSK modulation.

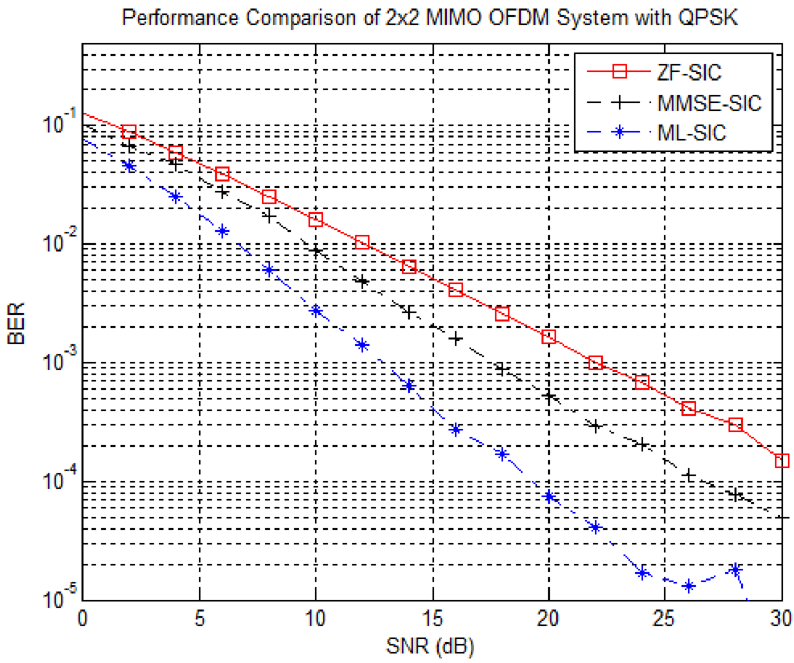


Figure 5.16: SNR Vs. BER performance for a (2×2) MIMO-OFDM system with QPSK

From the figure 5.16, it is clearly evident that for all the three types of detection systems, as signal-to-noise ratio increases, the corresponding BER decreases. At the threshold level of BER equal to approximately 10^{-3} , each of the detection systems namely ZF, MMSE and ML detectors with successive interference cancellation, the signal-to-noise ratio is measured at approximately 22.08 dB, 17.63 dB and 12.75 dB respectively when QPSK modulation system is used. From the performance plots it can be seen that the difference in SNR between ML-SIC detector and ZF-SIC detector systems ~9.33 dB for QPSK modulation. Further, when ML-SIC detection system is employed, the least value of the signal-to-noise ratio is obtained at approximately 12.75 dB. Thus it can be seen that ML detection systems when used with MIMO-OFDM communication system and QPSK modulation performs most efficiently.

The SNR values derived as a function of BER for (2x2) MIMO-OFDM multiplexing system for the three detector systems are shown in figure 5.17 for 16 QAM modulation.

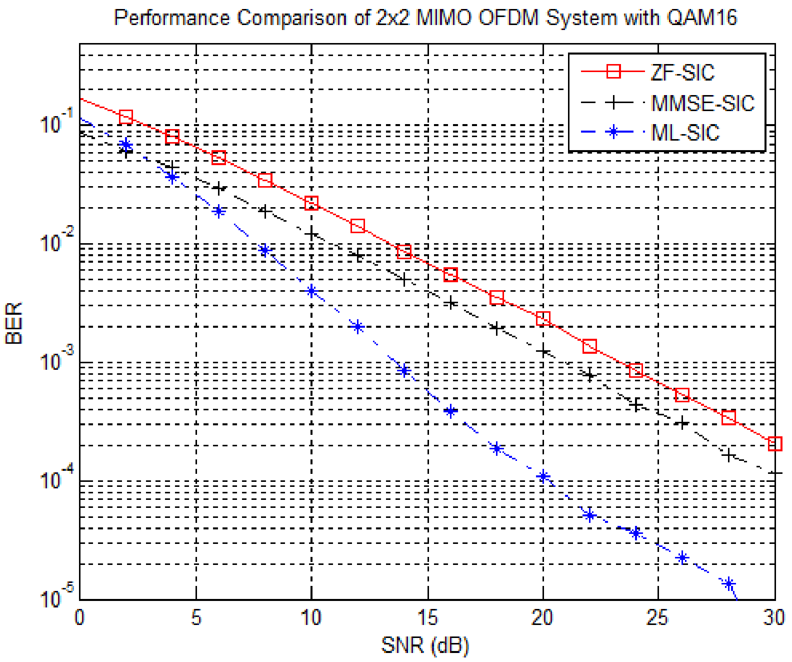


Figure 5.17: SNR Vs. BER performance for a (2×2) MIMO-OFDM system with 16-QAM

The figure 5.17 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3} , the signal to noise ratios for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 23.26 dB, 20.81 dB and 13.58 dB respectively when 16-QAM modulation system is used. From the performance plot, it can be seen that the difference in SNR between ML-SIC detector and ZF-SIC detector systems approximately 9.68 dB for 16-QAM modulation. For the ML detection system that employs successive interference cancellation, the least value of the signal-to-noise ratio is obtained at ~13.58 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detector for use with a MIMO-OFDM communication system that employs 16-QAM modulation.

The performance results of the simulation at a BER threshold of ~10^{-3} , and the corresponding signal-to-noise ratio values for a MIMO-OFDM communication system with (2x2) is tabulated for three different detectors namely ZF, MMSE and ML with successive interference cancellation (SIC), and three different modulation schemes namely BPSK, QPSK and 16-QAM are summarized in Table 5.2.

Table 5.2- Comparison table of SNR Values of (2x2) MIMO-OFDM with ZF, MMSE and ML detectors each with SIC, for various modulation schemes at BER threshold of ~10^{-3}.

Modulation/ Detector	BPSK SNR(dB)	QPSK SNR(dB)	16-QAM SNR(dB)
ZF-SIC	21.67	22.08	23.26
MMSE-SIC	14.14	17.63	20.81
ML-SIC	12.6	12.75	13.58

For all three detection systems at BER threshold of ~10^{-3} , the system performance exhibits similar behaviour with increasing SNR values. Signal-to-noise ratio values is increased by approximately 1 dB on the when the modulation scheme is changed from the lower order BPSK to a higher-order 16-QAM modulation. Further from the table, it can be seen that the signal-to-noise ratio SNR (E_b/N_0) values for the ML detection system shows the lowest value of approximately ~12.6 dB at a BER threshold of ~10^{-3} . Thus it can be summarised that for a MIMO-OFDM communication system, the results show that the performance of SNR vs. BER is most efficient for a ML-SIC detection system.

The results presented from the simulation analysis of (2x2) MIMO-CDMA transmission system with different detection procedures and modulation techniques clearly suggests that for CDMA multiplexing at BER~10^{-3}, for BPSK Modulation, the ML-SIC detector shows lowest SNR (E_b/N_0) values ~13.35 dB. Similarly the results for the (2x2) MIMO-OFDM transmission system with different detection and modulation techniques suggests that for OFDM Multiplexing at BER~10^{-3} for BPSK Modulation, the ML-SIC detector shows lowest SNR (E_b/N_0) values ~12.6 dB and better performance of SNR ~1.86 dB (BR/BW efficiency ~ 1.53) compared to OSTBC and CDMA multiplexing systems. The SNR values determined as a function of BER for CDMA and OFDM multiplexing for BPSK, QPSK and 16-QAM modulation schemes has been presented by Parul Wadhwa , Gaurav Gupta [55] and N.Sathish Kumar, Dr.K.R.Shankar Kumar [64].

The analysis and the results demonstrate that a MIMO-OFDM communication system offers better performances in comparison to a CDMA system when BPSK modulation is used.

The results presented in the chapter of the thesis have been published in the international journal papers:

1. **R Bhagya, A G Ananth, "Study Of Transmission Characteristics Of 2x2 MIMO System for OFDM Multiplexing and BPSK modulation with ZF Equalizer And MMSE Receivers", International Journal of Soft Computing and Engineering (IJSCE), Volume-2, Issue-3, July 2012, Pages 37-40. (Impact factor 0.52).**
2. **Bhagya.R, Dr. A G Ananth," Performance Studies Of 2x2 MIMO System For Different Modulation and OFDM Multiplexing Techniques using ML Detector", International Journal of Electronics and Communication Engineering (IJECE), Vol. 3, Issue 5, Sep 2014, 11-22 © IASET.(Impact Factor 3.2029)**

CHAPTER 6

HIGHER ORDER MIMO-OFDM MULTIPLEXING SYSTEM FOR DIFFERENT DETECTOR AND MODULATION SYSTEM

CHAPTER 6

HIGHER ORDER MIMO-OFDM MULTIPLEXING SYSTEM FOR DIFFERENT DETECTOR AND MODULATION SYSTEM

At the transmitter, diversity coding techniques are used when there is no channel knowledge. In diversity methods a single stream is transmitted but the signal is coded using techniques called Space Time Code. Through the use of full (or near) orthogonal coding, the signal is emitted from each of the transmit antennas. In the case of multiple antenna links, the diversity behaviour can be exploited for each independent fading signal. In order to increase the SNR at the receiver, redundant data is transmitted over space time domains on multiple antennas by using different modulation schemes. Since the need for wireless technologies with high data rate capabilities is essential, the performance of OFDM with different modulation schemes is studied.

Higher order modulation can be used in MIMO-OFDM communication systems to achieve large data capacity. The increase in modulation order leads to the corresponding increase in BER. Therefore, by increasing the SNR of the signal, the above problem can be solved, and thus the amount of distortions introduced by the channel can be decreased. This consequently leads to the results that BER will eventually decrease at higher values of SNR.

The performance of the MIMO-OFDM technique at higher modulation levels and for higher antenna configuration that is (3x3) and (4x4) using different detection techniques is presented. In order to construct radio communications more robust several different diversity modes are used, with varying channel conditions. The diversity techniques include frequency diversity (using different channels, spectrum and OFDM), time diversity utilising timeslots and channel coding and spatial diversity which utilises multiple transmit and receive antenna systems.

6.1 Diversity Techniques

Diversity coding can be employed in wireless communication systems with MIMO antennas. These channels suffer from wireless propagation effects such as fading and multipath resulting in unreliable data transmission and decoding. In order to improve the quality of reception as well as decoding quality, multiple redundant copies of the same information is transmitted through multiple antennas at the transmitter. This redundancy results in better decoding and recovery of the transmitted data [65].

It can also been seen that multiple propagation paths frequently exists between the transmitter and the receiver, due the occurrence of scattering by different obstacles present in the signal propagation path. Therefore different copies of the same signal information undergo varying degrees of attenuation and are affected by noise and interference leading to distortion, time delays and changes in phase. These effects that occur in the wireless channel due to propagation is referred to as multipath fading. Thus it can be seen that the system performance and the corresponding property of error can be seriously affected by multipath fading. Therefore in mobile communication systems, performance is affected not only by multipath fading, but also due to the time varying nature of the communication channel. The result is a time-varying fading channel. Communication through these channels can be difficult hence particular techniques may be required to achieve satisfactory performance.

Diversity reception techniques can be employed to mitigate adverse channel effects such as fading and multipath, thereby improving the performance of the system. It can be used to reduce the outage probability by decreasing the error rate. This is achieved by transmitting the information signal multiple times through independent channel paths. This implies that, of the transmitted signals at least one of the replicas will be received correctly or one of the diversity branches will be received with sufficient signal-to-noise ratio so that the transmitted signal is to be decoded reliably and ensure that the system outage probability is reduced [97].

6.2 (3x3) and (4x4) MIMO Transmission System using ZF, MMSE and ML detectors with successive interference cancellation

If it is assumed a BPSK modulation scheme, 1 bit would be mapped into one symbol that is 1 and 0. Thus, BER can be defined as the ratio of the total number of bits in error to the total number of transmitted bits. BER is expressed as a percentage and is an important performance metric.

The transmission of signals with high power levels, or choosing a lower order modulation/coding scheme can result in the improvement of BER. Also, forward error correction schemes may be employed to transmit redundant data to increase the reliability.

The BER of the transmission system is the number of detected bits that are incorrect before error correction to the total number of transmitted bits. This is approximately equal to the decoding error probability and represents the total number of decoded bits which are corrupted even after the error correction. Generally, the BER of the transmission system is much larger than the BER of transmitted information, since the latter is influenced by the use of forward error correction codes.

If it is assumed that a bit 0 is transmitted and there is some noise in the system, the decoding part decodes the bits to 1 instead of the actual bits of 0. The bit error is 1 since the bits in the symbol is not the correct bit.

An analysis of OFDM for (3X3) and (4x4) MIMO systems in channel environment that experiences Rayleigh fading is performed. Different detection systems such as ZF, MMSE, and ML detectors along with successive interference cancellation receivers are used to minimize the bit error rates. The system is tested for different modulation schemes such as BPSK, QPSK and QAM techniques. The system design is optimized to minimize BER, while improving the overall performance of the MIMO communication system. The performance study is conducted for different configurations of transmit and receive antennas. The performance study is presented to compare the advantages and disadvantages of the above-mentioned detection systems in terms of SNR with reference to BER.

6.3 Bit Error Rate (BER) for BPSK modulation (Rayleigh channel)

With BPSK, the binary digits 1 and 0 may be represented by the analog levels $+\sqrt{E_b}$ and$-\sqrt{E_b}$ respectively. The system model is as shown in the figure 6.1.

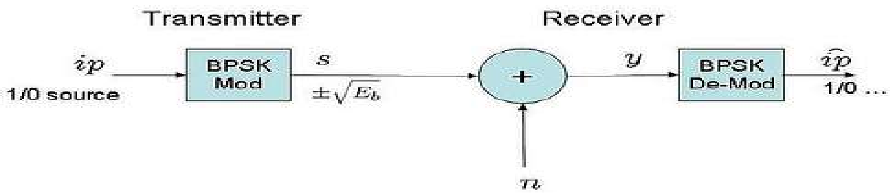


Figure 6.1: Simplified block diagram with BPSK transmitter-receiver

In Rayleigh channel, a circularly symmetric complex Gaussian random variable is of the form,

$$h = h_{re} + jh_{im} \tag{6.1}$$

where real and imaginary parts are zero mean independent and identically distributed (i.i.d) Gaussian random variables with mean 0 and variance σ^2.

The magnitude $|h|$ which has a probability density is given by,

$$p(h) = \frac{h}{\sigma^2} e^{\frac{-h^2}{2\sigma^2}}, z \geq 0$$

6.4 Results and Discussions

The performance analysis of MIMO-OFDM communication systems and its results, for various modulation techniques such as BPSK, QPSK and 16-QAM modulation are discussed in this section. The communication channel is assumed to exhibit multipath fading behaviour, with the fading assumed to be flat and modelled using a Rayleigh distribution, when Additive White Gaussian Noise (AWGN) is present in the channel. The system performance is analysed using different detector types and results are computed through MATLAB simulations. The BER values as a function of SNR (E_b/N_0) are determined by combining the SIC techniques with ZF, MMSE and ML detector systems and modulation schemes for studying their relative performances in digital modulation. The SNR values are determined as a function of BER for each BPSK, QPSK and 16-QAM modulation schemes [134].

6.4.1 (3x 3) MIMO-OFDM system

A MIMO-OFDM communication system that employs multiplexing is analysed and the corresponding performance analysis of SNR Vs. BER for (3x3) communication system for the three different detection systems are evaluated for BPSK modulation. The performance analysis is as shown in figure 6.2.

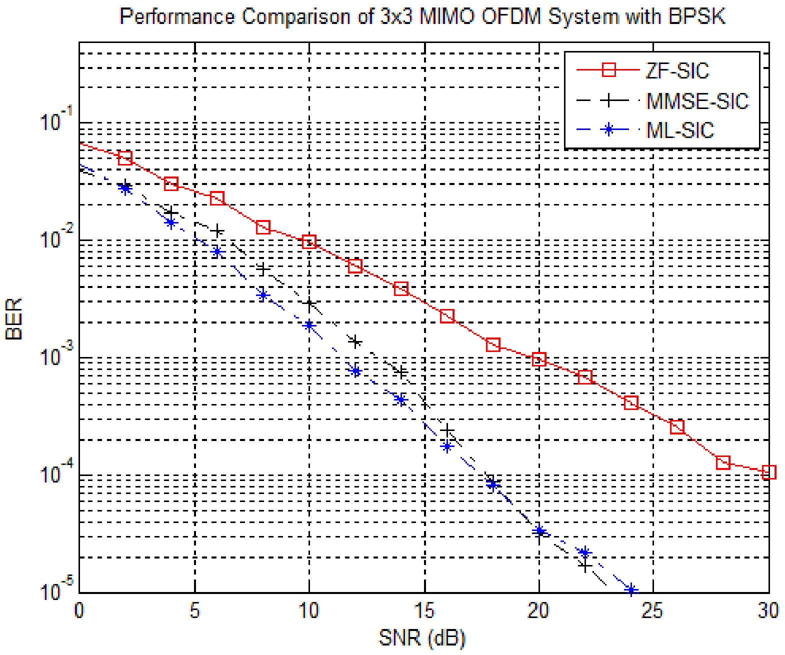


Figure 6.2: SNR Vs. BER performance for a (3x3) MIMO-OFDM system with BPSK

The figure 6.2 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3}, the signal to noise ratio for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 19.43 dB, 12.88 dB and 11.45 dB respectively when BPSK modulation system is used. From the performance plot, it can be seen that the difference in SNR between ML-SIC detector and ZF-SIC detector systems ~7.98 dB for BPSK modulation. For the ML detection system that employs successive interference cancellation, the least value of signal-to-noise ratio is obtained at ~11.45 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detectors for use with a MIMO-OFDM communication system that employs BPSK modulation.

The SNR values derived as a function of BER for (3x3) MIMO-OFDM multiplexing system for the three detector systems are shown in figure 6.3 for QPSK modulation.

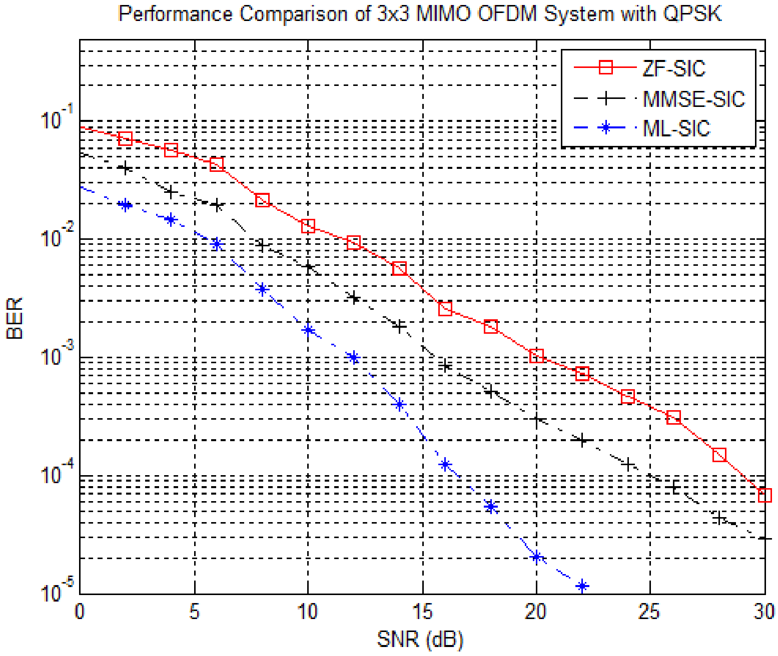


Figure 6.3: SNR Vs. BER performance for a (3x3) MIMO-OFDM system with QPSK

From the figure 6.3, it is clearly evident that for all the three types of detection systems, as signal-to-noise ratio increases, the corresponding BER decreases. At the threshold level of BER equal to approximately 10^{-3} , each of the detection systems namely ZF, MMSE and ML detectors with successive interference cancellation, the signal-to-noise ratio is measured at approximately 20.13 dB, 15.62 dB and 11.9 dB respectively when QPSK modulation system is used. From the performance plots it can be seen that for ML and ZF systems employing successive interference cancellation, the SNR difference is approximately 8.14 dB. Further, when ML-SIC detection system is employed, the least value of the signal-to-noise ratio is obtained at approximately 11.9 dB. Thus it can be seen that ML detection systems when used with (3x3) MIMO-OFDM communication system and QPSK modulation performs most efficiently.

The SNR values derived as a function of BER for (3x3) MIMO-OFDM multiplexing system for the three detector systems are shown in figure 6.4 for 16-QAM modulation.

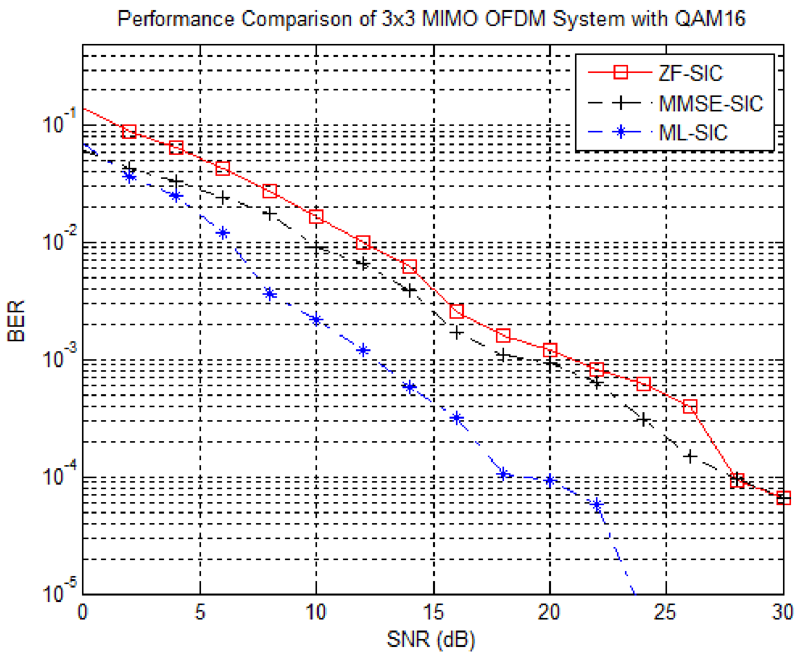


Figure 6.4: SNR Vs. BER performance for a (3x3) MIMO-OFDM system with 16-QAM

The figure 6.4 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3}, the signal to noise ratios for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 20.81 dB, 18.78 dB and 12.45 dB respectively when 16-QAM modulation system is used. From the performance plot, it can be seen that the SNR differences between the different detection systems (namely ZF and ML) is approximately 8.36 decibels. For the ML detection system that employs successive interference cancellation, the least value of the signal-to-noise ratio is are obtained at approximately 12.45 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detectors for use with a (3x3) MIMO-OFDM communication system that employs 16-QAM modulation.

6.4.2 (4 x 4) MIMO-OFDM system

A MIMO-OFDM communication system that employs multiplexing is analysed and the corresponding performance analysis of SNR Vs. BER for (4x4) communication system with three different detection systems are employed for BPSK modulation scheme. The performance analysis is as shown in figure 6.5.

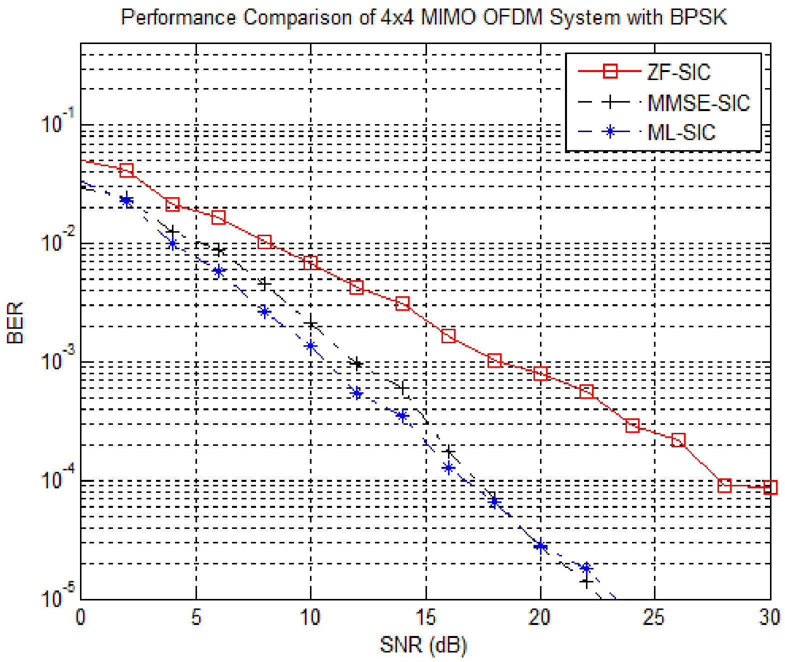


Figure 6.5: SNR Vs. BER performance for a (4x4) MIMO-OFDM system with BPSK

The figure 6.5 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3} , the signal to noise ratios for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 18.25 dB, 11.9 dB and 10.5 dB respectively when BPSK modulation system is used. From the performance plot, it can be seen that the SNR differences between ML-SIC detector and ZF-SIC is approximately 7.68 decibels. For the ML detection system that employs successive interference cancellation, signal-to-noise ratio values are found to be the lowest at ~10.57 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detectors for use with a (4x4) MIMO-OFDM communication system that employs BPSK modulation.

The SNR values derived as a function of BER for (4x4) MIMO-OFDM multiplexing system for the three detector systems are shown in figure 6.6 for QPSK modulation.

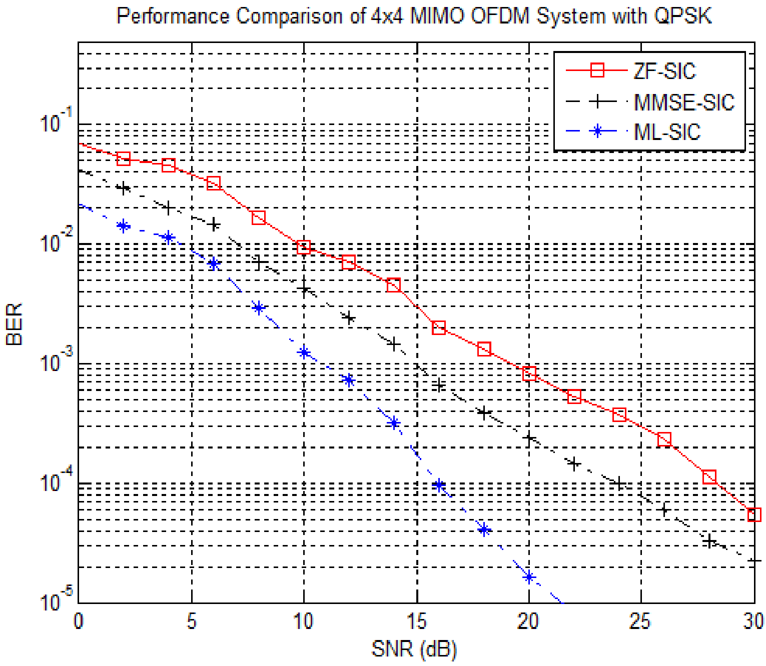


Figure 6.6: SNR Vs. BER performance for a (4x4) MIMO-OFDM system with QPSK

From the figure 6.6, it is clearly evident that for all the three types of detection systems, as signal-to-noise ratio increases, the corresponding BER decreases. At the threshold level of BER equal to approximately 10^{-3} , each of the detection systems namely ZF, MMSE and ML detectors with successive interference cancellation, the signal-to-noise ratio is measured at approximately 19.15 dB, 14.95 dB and 10.82 dB respectively when QPSK modulation system is used. From the performance plots it can be seen that for ML and ZF systems employing successive interference cancellation, the SNR difference is approximately 8.3 dB. Further, when ML-SIC detection system is employed, the least value of the signal-to-noise ratio is obtained at approximately 10.82 dB. Thus it can be seen that ML detector when used with (4x4) MIMO-OFDM communication system and QPSK modulation performs most efficiently.

The SNR values derived as a function of BER for (4x4) MIMO-OFDM multiplexing system for the three detector systems are shown in figure 6.7 for 16-QAM modulation.

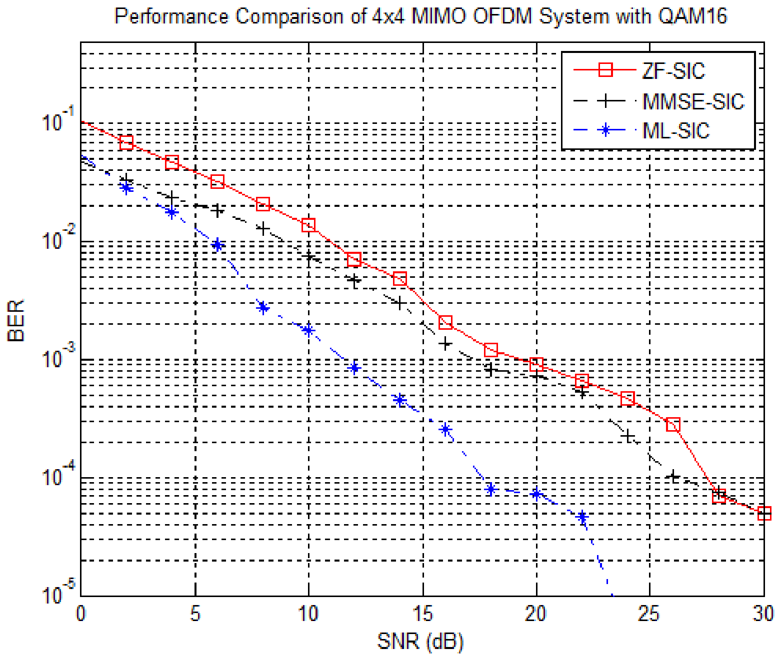


Figure 6.7: SNR Vs. BER performance for a (4x4) MIMO-OFDM system with 16-QAM

The figure 6.7 clearly shows that signal-to-noise ratio increases as BER decreases, in the case of all the three detection systems. Further, at a BER of approximately 10^{-3} , the signal to noise ratios for ZF, MMSE and ML detection systems using successive interference cancellation are approximately 19.67 dB, 17.05 dB and 11.51 dB respectively when 16-QAM modulation system is used. From the performance plot, it can be seen that the SNR differences between the different detection systems (namely ZF and ML) is approximately 8.16 decibels. For the ML detection system that employs successive interference cancellation, the least value of the signal-to-noise ratio is obtained at ~11.51 dB. This clearly shows that the ML-SIC detection systems are the most efficient type of detectors for use with a (4x4) MIMO-OFDM communication system that employs 16-QAM modulation.

The performance results of the simulation at a BER threshold of ~10^{-3} , and the corresponding signal-to-noise ratio values for (2x2), (3x3) and (4x4) MIMO-OFDM communication system is tabulated for three different detectors namely ZF, MMSE and ML with successive interference cancellation (SIC) for three different modulation schemes namely BPSK, QPSK and 16-QAM are summarized in Table 6.1

Table 6.1-Comparison table of SNR Values of (2x2), (3x3), (4x4), for different modulation techniques at BER ~10^{-3} for MIMO-OFDM system for various detectors.

Modulation/ Detector	(2x2) MIMO SNR(dB)	(3x3) MIMO SNR(dB)	(4x4) MIMO SNR(dB)
ZF-SIC	**21.67**	**19.43**	**18.25**
MMSE-SIC	**14.14**	**12.88**	**11.9**
ML-SIC	**12.6**	**11.45**	**10.57**

It is clearly seen from table 6.1 that at a BER threshold of approximately 10^{-3}, all the three detectors shows SNR values decreasing when switching to higher (4x4) MIMO systems from lower (2x2) MIMO system. The (4x4) MIMO indicates SNR ~2 dB improvement compared to (2x2) MIMO for ML-SIC detection system. Further it is clearly depicted in the table that the SNR measurements for the ML detector with SIC at BER threshold ~10^{-3} shows for (4x4) MIMO–OFDM system lowest SNR (E_b/N_0) values ~10.57 dB for BPSK modulation and improved performance of SNR ~2.03 dB (BR/BW efficiency ~1.58) compared to lower (2x2) MIMO-OFDM system.

It can be concluded from the simulation results that the (4x4) MIMO transmission system offers better SNR performance for BPSK modulation with ML-SIC detection system.

6.5 A 4x4 MIMO-OFDM System with a Markov Chain Monte Carlo Receiver

A detailed performance analysis of a (4x4) MIMO-OFDM communication system is discussed in this section. The various modulation mechanisms namely BPSK, QPSK and QAM are used to study the characteristics of the transmitter. The wireless channel is assumed to be of AWGN type. A Markov Chain Monte Carlo (MCMC) system is used at the destination to study the BER performance. The performance results of the simulation at a BER threshold of ~10^{-3} dB, shows that higher signal-to-noise ratio is achieved. Further for the three modulation mechanisms namely BPSK and 16-QAM, the signal-to-noise ratio is approximately ~6.9 dB and 10.8 dB, showing an overall improvement of about 4 dB. The performance comparison of the MIMO-OFDM system that employs a

MCMC receiver clearly shows that this type of MIMO-OFDM Multiplexing System with BPSK modulation demonstrates a much better BER performance.

6.5.1 Markov chain Monte Carlo (MCMC)

The construction of Markov chain with a desired set of properties is not complex. The complexity lies in the determination of the total number of steps that are required in order to converge to the stationary distribution with a defined error threshold. A good Markov chain design will exhibit rapid mixing properties so that the stationary distribution can quickly conversed a solution from an arbitrary starting position as described by the mixing time of the Markov chain.

Multidimensional integrals are the most common type of MCMC algorithms used for computation. These methods rely on a co-operative group of “walkers” to converge to a solution. At each step, the integrand value at that particular point of the walker (which moves randomly) is counted. Thus, such a walker then may require an arbitrary number of steps around the defined area while looking for high convergence of the integral to move to the next step. Monte Carlo method that employs random simulation in the form of random walk models can be employed here. It is generally seen that Monte Carlo integration techniques that employ random samples and conventional computations are statistically independent, whereas those used in MCMC are correlated samples.

6.5.2 MIMO-OFDM and MCMC Receiver

Through the use of training symbols in the preamble, the frequency offset information and the symbol timing information must be accurately estimated by the receiver. After this estimation, the cycle prefix is discarded and an N-point DFT (Discrete Fourier Transform) is applied. For each OFDM subcarrier, MIMO detection is performed by routing received signal to the corresponding i^{th} MIMO detector. This leads to the recovery of N_t data signals from the subcarrier’s transmission. Additional operations such as mapping, de-interleaving and decoding are performed on the transmitted streams that is for the N_t parallel streams and combined together to retrieve the binary output information.

6.5.3 MCMC Detector

As N increases, the total number of transmit antennas increases, and the dimensionality of d rapidly increases and therefore the summation become cumbersome. In order to use computationally efficient schemes for the computation of P (d_k= | y, λ_2^e), Monte Carlo integration methods can be employed with the use of a Gibbs sampling type procedure.

Further the performance of higher order MIMO systems with MCMC receiver has been investigated. The performance analysis of MIMO-OFDM system for different modulation schemes and using AWGN channel are obtained using MATLAB Simulation. The SNR values are plotted against BER for BPSK and 16-QAM modulation systems.

The SNR values are computed through MATLAB simulation and plotted against BER for BPSK modulation. The figure 6.8 represents the performance of (4x4) MIMO communication system with OFDM when Monte Carlo detector and BPSK modulation is employed.

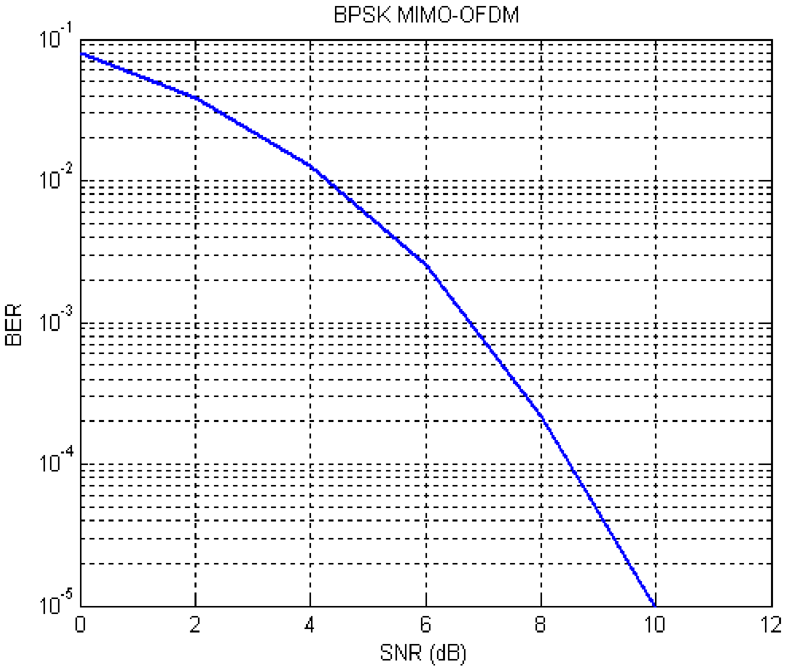


Figure 6.8: SNR Vs. BER performance of (4×4) MIMO-OFDM and MCMC Detector (BPSK)

The figure 6.8 shows that at a BER threshold of approximately 10^{-3}, the SNR value is ~6.9 dB for BPSK modulation with Monte Carlo detector.

The SNR values are computed through MATLAB simulation and plotted against BER for 16-QAM modulation. The figure 6.9 represents the performance of (4x4) MIMO communication system with OFDM when Monte Carlo detector and 16-QAM modulation is employed.

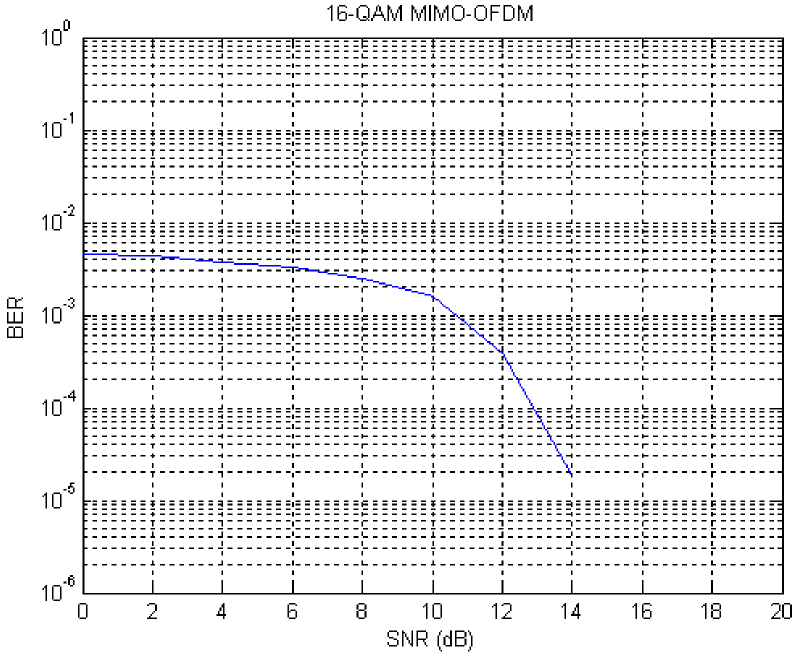


Figure 6.9: SNR Vs. BER performance of (4×4) MIMO-OFDM and MCMC Detector (16-QAM)

The figure 6.9 depicts that at BER ~10^{-3} , the SNR value is ~10.8 dB for 16-QAM modulation with Monte Carlo detector. The performance of (4x4) MIMO-OFDM system at BER ~10^{-3} derived for ML-SIC and Monte Carlo detectors for QPSK and 16 QAM modulations are summarized in Table 6.2.

Table 6.2-Comparison table of SNR Values (4x4) MIMO-OFDM transmission with ML-SIC and Monte Carlo detectors for various modulation schemes at BER ~10^{-3}.

Modulation/ Detector /	BPSK SNR(dB)	16-QAM SNR(dB)
ML-SIC	10.57	11.51
Monte Carlo	6.9	10.8

It is evident from the table 6.2 that the (4x4) MIMO-OFDM system with Monte Carlo detection system and ML-SIC detection system at BER threshold of ~10^{-3} shows an large improvement of SNR approximately 3.6 dB (BR/BW efficiency ~2.29) compared to ML detection system. The present results obtained for higher order MIMO systems exhibit SNR improvement of about approximately 2 dB for ML detectors compared to the results reported in the papers Damith Senaratne, Chintha Tellambura, Himal A. Suraweera [138] and Navjot Kaur, Lavish Kansal [150].

The results suggest that the performance of higher MIMO system can be drastically improved by using complex detection systems such as Monte Carlo detection.

The results presented in the chapter of the thesis have been published in the international journal paper:

1. **R Bhagya, Pramodini D V, A G Ananth, "Transmission characteristics of 4x4 MIMO system with OFDM multiplexing and Markov Chain Monte Carlo Receiver", International Journal of Soft Computing and Engineering (IJSCE), Vol-1, November 2011, Pages 233-237. (Impact factor 0.52).**

CHAPTER 7

IMPLEMENTATION OF MIMO-OFDM COMMUNICATION SYSTEM ON WIRELESS NETWORKS

CHAPTER 7

IMPLEMENTATION OF MIMO-OFDM COMMUNICATION SYSTEM ON WIRELESS NETWORKS

Wireless communication is the transfer of information from one place to another without using cables. In earlier time the smoke signal, semaphore and drums were used, but nowadays telecommunication make use of electronic devices such as telephone, television, radio or computer. Radio and TV are used for one way communication and mobile phones are used for two way communication. Due to the seamless mobility nature in wireless networks, anytime and anywhere connectivity is possible to access network services. The limitation of wired networks, where services can only be used in fixed area is overcomed in wireless networks. The need for anytime and anywhere connectivity has increased with the availability of broadband services and therefore is driving the need for fast wireless systems. The standards 802.11 and 802.16 were developed by IEEE for wireless LAN, and MAN. The standards of wireless communication are developed all over the world [48].

7.1 WiMAX

WiMAX–Worldwide Inter-operability for Microwave Access is a technology which provides wireless data communication and can provide data communication up to 72 Mbps. It supports the architecture of point to multi-point data transmission. WiMAX name raised after WiMAX forum formed in 2001 to ensure and enhance interoperability of the standard. WiMAX forum generated two documented releases to provide technical standard and information for deployment of WiMAX, and those two releases were release 1.0 and release 1.5. WiMAX forum is also responsible for future analysis research and modelling carry out in this standard of IEEE 802.16 (WiMAX). WiMAX based on 802.16 ratification intent end to provide services to metropolitan area networks (MANs), recognise as wireless broad band access (BWA). Its aim to provide broad band wireless access (BWA) over long range for different applications. WiMAX provide broadband wireless access (BWA) capabilities for a range of 30 miles for fixed subscriber and a range of 3-10 mile for mobile user in contrast with Wi-Fi 802.11 provide services up to 100-300 feet [69].

WiMAX is used as a wireless access technology for broadband systems. It is a standard based technology that enables broadband wireless access, and has been designed as a replacement for traditional digital subscriber line and cable Internet. The message is conveyed between residential buildings and commercial places by using WiMAX system is economically efficient. Different standards of WiMAX have been introduced over time by IEEE. IEEE 802.16d and IEEE 802.16e which represent fixed WiMAX and mobile WiMAX are the most commonly used standards.

The WiMAX technology standard can be classified under Wireless Metropolitan Area Networks (WMANs). The technology is standardised and developed by the IEEE 802.16 working group. This working group specialises in the development of WMAN standards for point to multi-point wireless communication supporting broadband capabilities. The initial WiMAX standard i.e. 802.16a, has been further enhanced and releases supporting fixed wireless access such as IEEE 802.16d or 802.16-2004 standard was developed. Also support for mobility and roaming was introduced in the IEEE 802.16e or 802.16-2005 standard. The WiMAX standard utilizes some key technology enablers to support high speed wireless data communication. Some of these technology enablers are discussed below:

- **Orthogonal Frequency Division Multiplexing (OFDM):** WiMAX adopts orthogonal frequency division multiplexing to provide high speed data and to mitigate various channel effects such as frequency selective fading and multipath. OFDM communication systems utilise a larger set of high-data rate modulated carrier signals that are spaced very close to each other. By making these closely spaced signals orthogonal to each other, any mutual interference effects can be nullified. In order to provide reliability and resilience against channel propagation effects such as frequency selective fading and multipath, the transmitted data is divided across each of these carrier signals.

- **Multiple Input Multiple Output (MIMO):** In order to exploit the benefits of multiple propagation in the channel, the WiMAX standard uses MIMO communication. The use of MIMO antenna systems ensures that signal processing operations are possible at lower received signal strengths, thereby supporting higher data rates. The propagation channel limitations such as interference due to multipath and limited data throughput can be overcome by using MIMO. Thus MIMO systems provide an effective mechanism for exploiting multipath signals in order to improve the data transmission rates on a given communication channel. Although the use of MIMO systems increase the complexity of the signal crossing system, MIMO can be used to enable the transmission of multiple data streams, and leads to an increased channel capacity.

7.2 WiMAX-Protocol Layers

For the IEEE 802.16d-2004 specification, the WiMAX standard defines the air interface working in the frequency band 2-11 GHz. The medium access control (MAC) layer and the physical layer specification are defined in the air interface standard [70].

The IEEE 802.16 standard is structured in the form of a protocol stack with well-defined interfaces. The MAC layer is formed with three sub layers as shown in figure 7.1.

- Service Specific Convergence Sub-layer (CS)
- MAC Common Part Sub-layer (CPS) and
- Privacy Sub-layer.

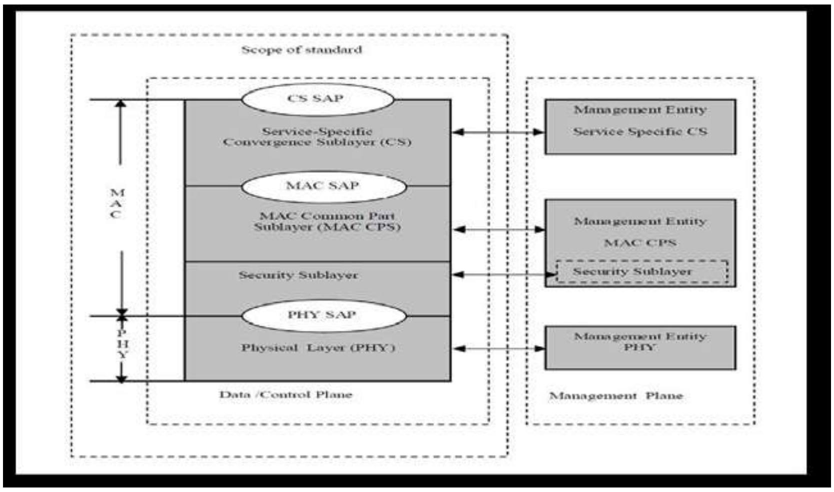


Figure 7.1: WiMAX Protocol Stack

The MAC CS receives higher level data through CS SAP and provides transformation and mapping into MAC SDU. The WiMAX specification describes two types of traffic transports through IEEE 802.16 networks: ATM and Packets. Therefore, interfacing on various protocols is available for multiple CS specification.

7.2.1 Physical (PHY) layer

The connection between the communicating devices is set up by the Physical layer. The function of this layer is to transmit a bit sequence and also specifies the modulation and coding systems, along with the other specifications of the transmitter. The physical layer of the IEEE 802.16 WiMAX uses two transmission mechanisms in the form of OFDM and OFDMA. It has support for two duplexing techniques namely TDD and FDD, and operates in the 11 GHz frequency spectrum. For use with multimedia services that require higher data rate communications such as video streaming/conferencing services, OFDM can be used as a viable option to maintain high data rates in channels characterised by NLOS and multipath.

The IEEE 802.16-2004 standard defines three different PHYs that can be used in conjunction with the MAC layer to provide a reliable end-to-end link. These PHY specifications are:

- A single carrier SC modulated air interface.
- A 256-point FFT OFDM multiplexing scheme.
- A 2048-point FFT OFDMA scheme.

Although air interfaces with single carrier is used for LoS communication, the two OFDM-based systems are better suited for NLOS communication, since they utilise a simple equalisation method to process multiple carrier signals. The OFDM WiMAX physical layer standard for fixed subscribers specified user profiles that utilise 256-point FFT operations. This further enables fixed WiMAX systems to service a coverage area of about 5 kms. This allows maximum data transfer rates of up to 70 Mbps the service area by using the channel bandwidth of 20 MHz. Therefore the system can be used to offer wireless broadband connectivity in NLoS environments for end users.

Similarly the OFDM physical layer specification for mobile WiMAX specifies the use of 2048-point FFT in user profiles. This enables the mobile WiMAX systems to service a coverage area of about 1.6 to 5 kms in range. Therefore data transmission rates of up to 5 Mbps are possible in mobile WiMAX with user mobility by using the channel bandwidth of 1.75 MHz. To ensure reliable communication, additional features such as power saving mechanisms and handoff capabilities were introduced. The two critical issues for mobile applications are battery life and handoff. On one hand, maximizing battery life implies minimizing the mobile station power usage. On the other hand, handoff and handovers are necessary to enable the MS to shift from one cell to another at vehicular speeds without disconnecting the connection [123].

7.2.2 PHY Layer Adaptation

WiMAX technology is an IEEE 802.16 standard, which is responsible for providing the Broadband Wireless Access (BWA) to the users as an alternative of the wired broadband. WiMAX provides broadband connectivity using wireless communication to different network types such as fixed networks, portable networks, roaming networks and mobile wireless networks.

WiMAX technology supports adaptive modulation to regulate the Signal Modulation Scheme which depends on the SNR state of the radio link. When the radio link is soaring in quality, the highest modulation scheme is opted which is offering the system to avail additional capacity and when the radio link is poor, the WiMAX system can move to a lower modulation scheme to keep the connection stability [74].

The current channel condition report is send to the BS via reverse signal strength indicator (RSSI) and based on this report, a specific coding rate is opted for the data transmissions thus, users who are having the bad channel condition, will be provided the optimal coding rate that gives the maximum efficiency and better throughput.

7.3 MIMO-OFDM on WiMAX

The equalization complexities are reduced by ensuring that data is transmitted on different parts of the spectrum, thereby increasing the spectral efficiency of the system. This also leads to better error performance, and more reliable recovery. Also communication in non-line of sight (NLOS) conditions is now possible by integrating OFDM systems with MIMO. Thus the diversity is achieved by using MIMO-OFDM technique. The parameters namely frequency, time and space are used by OFDM, STC and MIMO systems respectively. The current and main application of MIMO-OFDM is IEEE 802.16 (WiMAX) which will gain high popularity and the researcher‘s attraction for further development and improvement [73].

Consider a wireless system that uses MIMO-OFDM system, and has N transmit and M receive antennas as shown in figure 7.2. A spatial multiplexing technique is employed with this type of MIMO system. Information coding is performed on each individual antenna system at the transmitter (referred to as PAC (per antenna coding)). Therefore, N parallel branches exist for N transmit antenna systems that uses OFDM. The transmitted information is then split into N parallel streams while processing. A separate OFDM transmitter performs the operations such as coding, modulation, interleaving and IFFT on the data stream. Additional operations such as the addition of cycle prefixes and guard intervals are used for the conversion of OFDM symbols for transmission over the communication link.

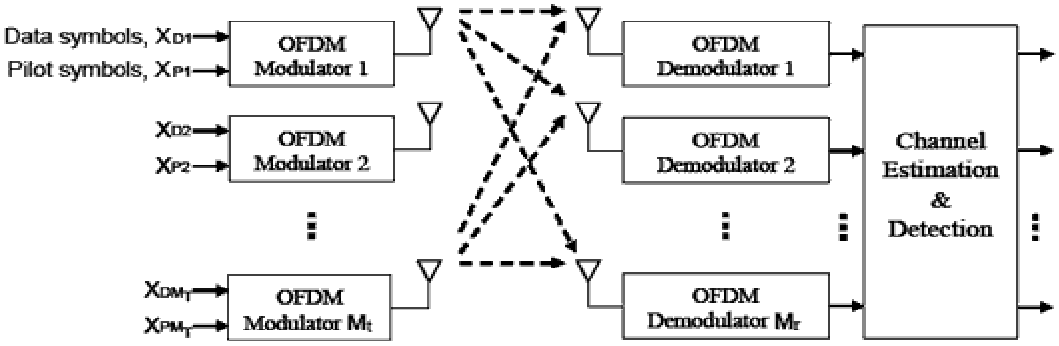


Figure 7.2: MIMO-OFDM system

In order to ensure the reliability of communication, the receiver system should have knowledge of the transmitted symbols as well as the channel estimate. The transmitter therefore sends an initial training sequence periodically to aid the receiver in proper decoding of the received data. This ensures that the receiver has a knowledge of channel variations. Further the OFDM system uses pilot symbols in order to track of amplitude variations and the signal phase drift.

The limitations of MIMO-OFDM system include limitations on antenna size, increased receiver complexity, and increased cost of RF systems. The limitation of antenna size and antenna spacing poses serious design concerns, especially in the design of mobile phone systems to battery power constraints and mutual coupling effects between antennas.

MIMO-OFDM techniques are primarily driven through the need for mobile and wireless broad band access. Due to its support to high speed wireless broad band access, low complexities (in respect of equalization at receiver), spectral efficiency and flexibilities, it is considered to be prominent and promising candidate for further wireless technologies. Example are LTE, 4G, IEEE 802.16 (WiMAX) and IEEE 802.11n.

7.4 Implementation of MIMO-OFDM on WiMAX PHY Layer

The aim is to implement all features of the WiMAX MIMO-OFDM physical layer specified in IEEE 802.16d-2004 using Matlab Simulink. Adaptive modulation and coding mechanisms can be employed to mitigate the variations in channel quality due to temporal effects of multipath fading channel. Adaptive modulation and coding employs multiple modulation and coding schemes that are dynamically adapted depending on channel conditions and variations in the signal-to-noise ratio of the channel. Therefore adaptive modulation and coding can be employed to maximize system performance by increasing throughput and BER performance. This gives an overview of the performance of a MIMO-OFDM WiMAX transmitter and receiver and also explains the SNR Vs BER performance for different BPSK, QPSK and 16-QAM modulation schemes.

The physical layer model of the WiMAX system is built from the IEEE standard documentation. The model is built under the defined parameters. The modeling is created on Matlab 7.9.0 (R2009b), Simulink 9 in Windows operating system environment. Matlab 7.9.0 (R2009b) simulink includes the mandatory requirements as specified by the WiMAX standard. The Model includes three significant components namely: the transmitter system, the receiver system and the channel model as shown in figure 7.3. Transmitter consists of channel coding, modulation and sub-components and channel is modulated on AWGN and multipath Rayleigh Fading channel [72] [73].

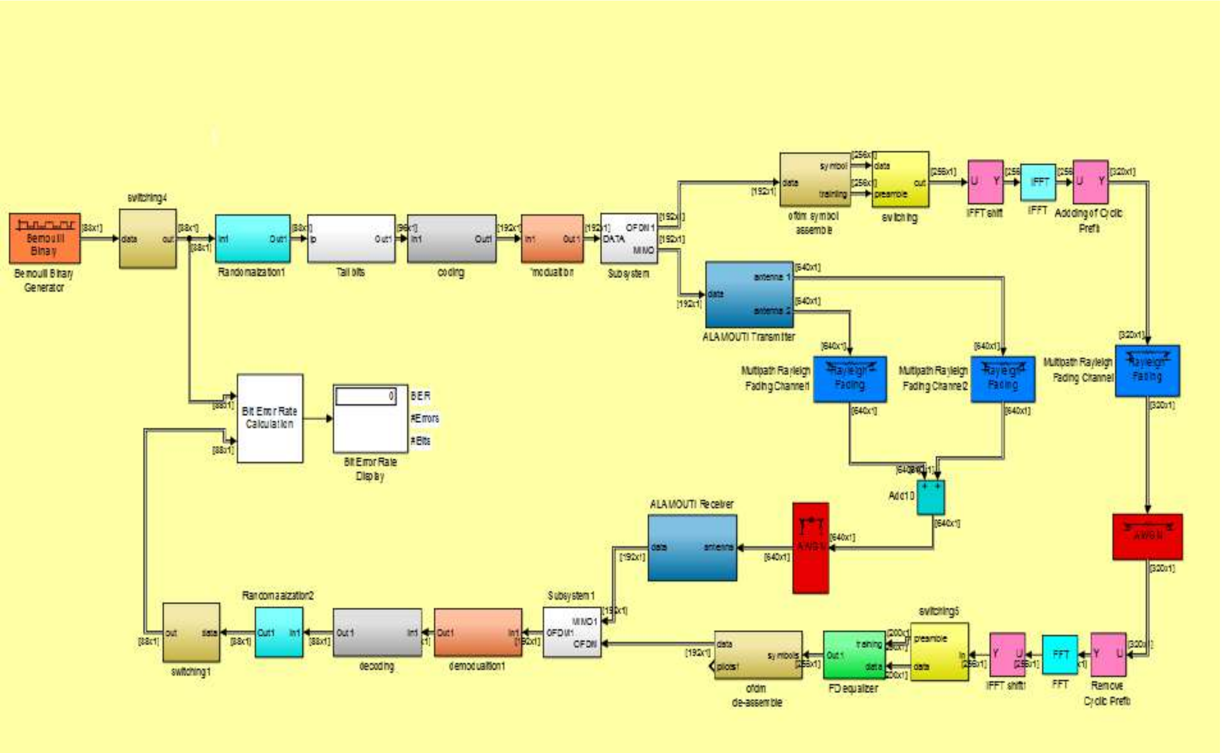


Figure 7.3: Simulink Implementation

7.4.1 Transmitter

This section contains the different steps of the transmitter which should be performed before transmitting the data. The blocks representations of the WiMAX transmitter simulator are as shown in figure 7.4.

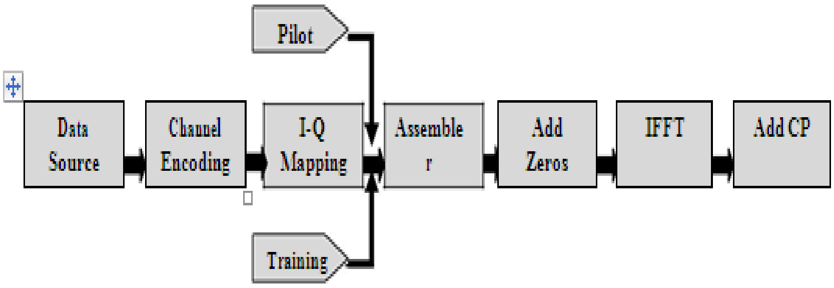


Figure 7.4: Transmitter of the WiMAX system

The data source is generated from the source is obtained from the binary random generator and is coded and modulated to obtain QAM symbols. The OFDM physical layer utilises 256 subcarriers during transmission. A total of 192 data subcarriers, one

DC subcarrier and eight pilot subcarriers constitute the OFDM symbol. It also includes a total of fifty five guard carriers. So, the procedure of collecting the zero DC subcarrier, data and pilots is needed to build the symbols. Moreover, preambles consist of training sequences that would be appended at the starting on each burst. These training sequences are used for analysing the channel estimation.

7.4.2 Channel coding

In WiMAX system channel coding is performed in three steps-

- Randomization
- Forward Error Correction
    - R-S Encoding
    - Convolution Encoding
- Interleaver.

7.4.2.1 Randomisation

The randomiser is used to completely randomise the input source data during each burst and data allocation cycle, in order to ensure that the continuous sequence of zeros and ones are avoided. A pseudo random binary sequence generator is used to generate this random sequence, and the implementation uses a 15 stage binary shift register, with an associated generator polynomial and digital logic to create a feedback mechanism as in figure 7.5.

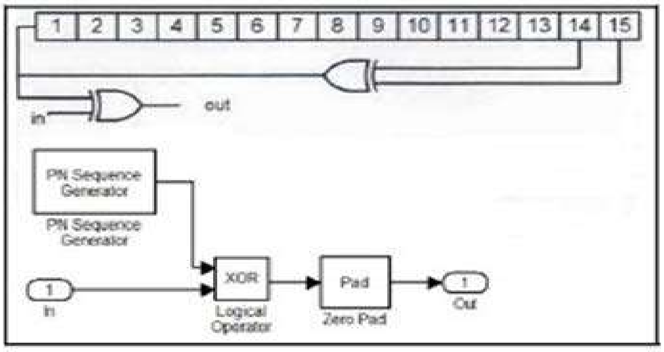


Figure 7.5: Randomizer

7.4.2.2 Forward Error Correction

The channel encoder carries out error-control coding for the purpose of protecting information against error incurred as it progresses through the noise channel. This is achieved by including additional information such that the channel decoder is able to accurately recover the source information despite the presence of errors. Forward Error Correction is applicable to both transmit and receive bursts, and employs R-S encoding and convolution encoding that improves the Bit Error Rate (BER) performance.

7.4.2.3 Reed-Solomon Encoding

A Galois Field computational technique is used by the Reed Solomon encoder to compute redundant bits transmissions. In order to represent data, Galois fields are employed in error control coding. A Reed Solomon encoding technique is used by WiMAX, which is based on the GF(28) method. This method uses 255 transmitted bytes, with K = 239 and with a total of eight corrected bytes (T = 8). Eight tail bits are added to the data sequence prior to the encoding stage. Two code generation polynomial functions namely the generator polynomial g(x) and field generator polynomial p(x) are used during this stage. A Galois Field Array is generated using the code generation polynomial, while the field generator polynomial is employed to compute the amount of redundant data bits that need to be appended to the transmitted data sequence. The standard defines the use of the following polynomial function:

$p(x) = x8+x4+x3+x2+1$ and $g(x) = (x + \lambda.0)\,(x + \lambda.1)\,(x + \lambda\,2)\,(x + \lambda 3)$

Reed Solomon encoding process exhibits properties that make them appropriate for use with the correction of burst errors. This encoding mechanism corrects errors through the construction of the polynomial function that is obtained from the transmitted data symbols. An oversampled polynomial is being transmitted in place of the original data symbols. An RS (n, k, t) represents a Reed Solomon code that can process symbols of one bit each. The encoder requires an input of length k (data symbols of one bit each), and constructs n symbol code with the redundancy of 2t parity bits. The parameter n represents the number of bytes after encoding, k represents the total number of data bytes prior to encoding and t represents the total number of data bytes that can be corrected. The ability of the RS code to correct errors can be found using (n − k), indicating the block redundancy measure.

7.4.2.4 Convolution Encoding

The outer block of the Reed Solomon encoder is input to the binary convolution coding system. Binary convolution codes can be used to correct data transmission errors that occur randomly. If the specified convolution coding is represented by CC (m, n, k), then this type of coding is referred to as forward error correction (FEC). In this case, each m-bit data symbol is encoded and transformed into a symbol of length n-bits. The code rate is now represented by m/n, and this can be used as a function that transforms the last k data symbols. The constraint length of the code is then represented by the parameter k.

7.4.2.5 Interleaver

To scatter error bursts, data interleaving is generally used. The most basic form can be defined as a randomizer and that it does not change the state of the bits but it works on the position of bits and thus reduce the error concentration to be corrected with the purpose of increasing the efficiency of FEC by spreading burst errors which is introduced by the transmission channel over a longer time.

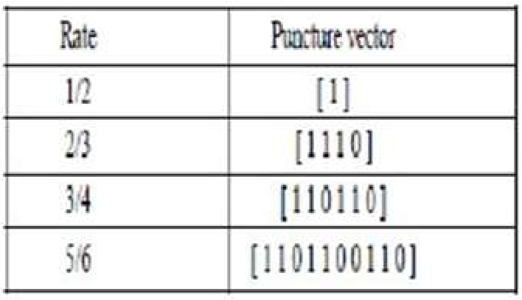
The interleaving of data bits is done prior to the transmission of the symbols. The input data at the source is first randomised by the interleaving, by employing a permutation technique that involves two iterations. The first iteration of the permutation is tasked with mapping non- adjacent subcarriers to the adjacent bits. The second iteration then ensures the mapping of a LSB or MSBs to the constellation points, thereby avoiding long run-lengths of bits that exhibit lower reliability.

A block interleaving system is then used to encode all information bits and interleaved them to create encoded OFDM symbol. The choice of the modulation scheme is used to decide the total number of coded bits in the symbol in the physical layer. Since an adaptive modulation and coding is supported by IEEE 802.16 WiMAX standard, the choice of a particular scheme is entirely based on data rate requirements and channel conditions.

7.4.3 Data Puncturing

The method that is employed to systematically remove data bits from information stream is referred to as puncturing. This process involves low rate encoding, which is used to reduce data transmission, thereby creating a high rate code. It can be seen that variable coding rates can be achieved through the use of the puncturing process, and variable coding rates are required to provide different levels of protection to the system users. This puncturing process uses different code rates namely: 1/2, 2/3, 3/4, and 5/6. The different coding rates and the corresponding puncture bits are as indicated in the table 7.1.

Table 7.1 Puncture bits



Rate	Puncture vector
1/2	[1]
2/3	[1110]
3/4	[110110]
5/6	[1101100110]

A block interleaver is used to interleave the encoded data by a Reed Solomon convolution encoder. The total number of bits encoded per sub channel is used to decide the block size in OFDM.

7.4.4 Modulation

A variety of modulation schemes such as BPSK, QPSK etc. is employed depending on size of the data symbols. Modulation can be performed by dividing the total number of incoming bits and individual groups of size i. Thus 2i constellation points exist. Each constellation point represents the total number of bits that are mapped to a particular symbol dependingt on the modulation scheme. For example, BPSK, QPSK and 16-QAM have a total of 2, 4 and 16 constellation points respectively. Additional information is needed to correctly demodulate the symbols, and are transmitted in the form of Pilot carriers and Guard bands.

7.4.5 Inverse FFT

The IFFT block is used to convert the OFDM symbol from frequency domain symbols per time domain symbols. The basic function of IFFT receives the N number of sinusoidal and N symbols at a time, if N number of subcarriers is chosen for the system to evaluate the performance of WiMAX.

7.4.6 Cyclic Prefix Insertion

To maintain the frequency orthogonal, cyclic prefix is added in OFDM signals and the delay is reduced due to multipath propagation. CP is added at the beginning of the signal before transmitting. When the CP length L is greater than multipath delay, the ISI is totally eliminated. The reverse operation of the transmitter block is performed by the receiver. During communication over the wireless channel, it is to be noted that the received signal cannot be modelled as the combination of the signal transmitted and channel noise. In order to successfully retrieve the transmitted information bits at the receiver, decoding as well as de-interleaving mechanisms are employed at the receiver.

7.5 Bit Error Rate Calculation

Error rate calculation block performs the comparison between the data transmitted from the source with the data received at the receiver. The error rate in this case is calculated as a continuous statistic, and this is obtained by dividing the total data elements in unequal pairs with respect to the total data elements from the source. The figure 7.6 shows the error rate calculation mechanism and can be used to compute BER or symbol error rate for different data inputs. If the inputs from the source are of the form of bits, BER is computed, else symbol error rates are computed for the input symbols.

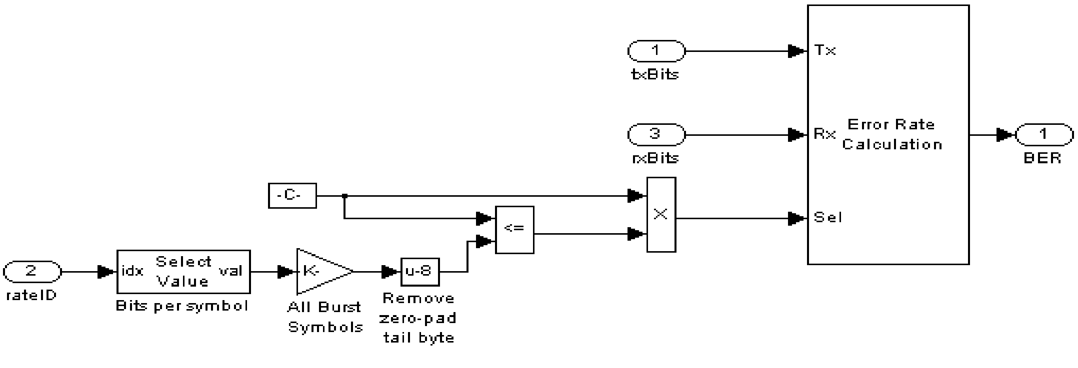


Figure 7.6: Bit/Symbol Error Rate Computations

7.6 Results and Discussion

The performance of a MIMO-OFDM WiMAX transmitter and receiver for various modulation mechanisms such as BPSK, QPSK and QAM are analysed. Implementation of different MIMO (SISO, SIMO, MISO)-OFDM systems on WiMAX networks is examined and the system performance evaluation is presented along with the simulated results.

The signal bandwidth sent through the system by the transmitter spectrum scheme is shown in figure 7.7.

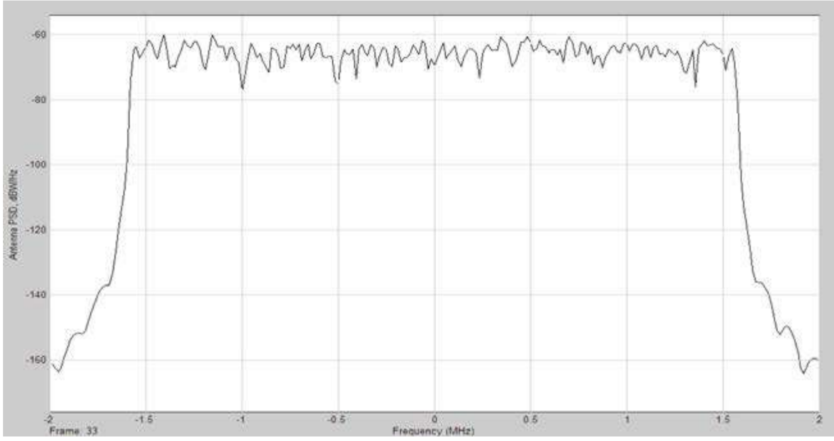


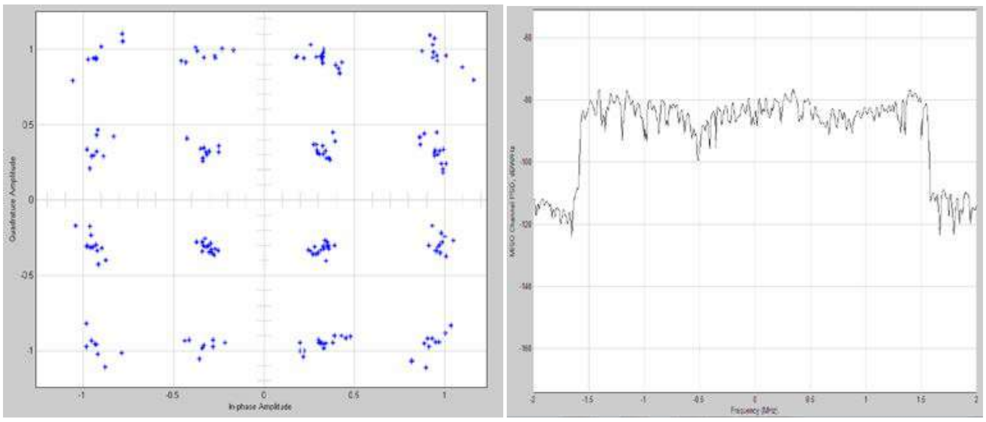
Figure 7.7: Transmitter Spectrum

Figure 7.7 shows bandwidth which is calculated by subtracting the upper filtering frequency from the lower filtering frequency. The power spectral density (PSD) is merely the (overall level) ^2 divided by the bandwidth.

Constellation diagram is used by digital modulation schemes to accurately represent the complex plane of the modulation. The complex plane is employed to represent complex numbers to the associated modulation symbols. Gray coding sequences are generally employed to represent these constellation points. These type of codes use binary sequences in such a way that the difference between two successive codes changed only by one bit. The use of such codes ensures production in bit error rates. The in phase and quadrature components are represented by the real axis and the imaginary axis of the complex plane. The rectangular arrangement is generally employed for the arrangement of the constellation points to create a two-dimensional grid.

During the decision process at the receiver, the demodulation system finds the constellation point that is closest to the received symbol in order to make a decision. This distance is referred to as the Euclidean distance is computed from the received signal. It is therefore possible to pack more bits per symbol depending on the Euclidean distance between two adjacent constellation points. Such a process not only doubles the noise and interference, but also results in an increase in BER, since the constellation points are closer.

Figure 7.8 shows that the symbols are represented as complex numbers. They are visualized as points on the complex plane. The real and imaginary axes are often called the in phase or I-axis and the quadrature or Q-axis. Plotting several symbols in a scatter diagram produces the constellation diagram. The points on a constellation diagram are called constellation points. The constellation diagram and the channel spectrum are shown in figure 7.8



(a) (b)

Figure 7.8: (a) Constellation and (b) Channel spectrum

Figure 7.8 (b) shows the signal time series and its power distribution over the channel for different frequencies.

7.6.1 MIMO-OFDM Network Implementation

The degree of diversity achieved for the communication system is represented by the BER curves and its slope. This degree represents the total performance improvement in the BER of the system, expressed in decibels. It can be seen that for a SISO communication system, the error probability improves by a factor of 10 i.e. by one for a

10 day increase in signal to noise ratio. Therefore the degree of diversity indicates the presence of no diversity. Similarly for a (1×2) or MISO (2×1) communication system, the degree of diversity of two is achieved. Finally for a MIMO (2×2) communication system, a degree of diversity of four can be achieved.

The results of the performance of MIMO-OFDM system on WiMAX physical layer when different modulation schemes such as BPSK, QPSK and QAM are employed, with the wireless channel modelled using a Rayleigh distribution are analysed using MATLAB simulation. The SNR is plotted as a function of BER and analysed for different MIMO (SISO, SIMO, MISO)-OFDM systems on WiMAX physical layer to study their relative behaviour and performance. The SNR (E_b/N_0) is first computed for each modulation scheme namely: BPSK, QPSK and 16-QAM and the corresponding BER values are obtained. The SNR performance as a function of BER for different MIMO-OFDM communication system on WiMAX physical layer is shown in figure 7.9 for BPSK modulation. The parameters selected include coding rate 1/2, Bandwidth 10MHz, convolution coding 2/3, interleaving [1;1;0;1], FFT size 256, channel 16, simulation 50,000 bits, Noise AWGN.

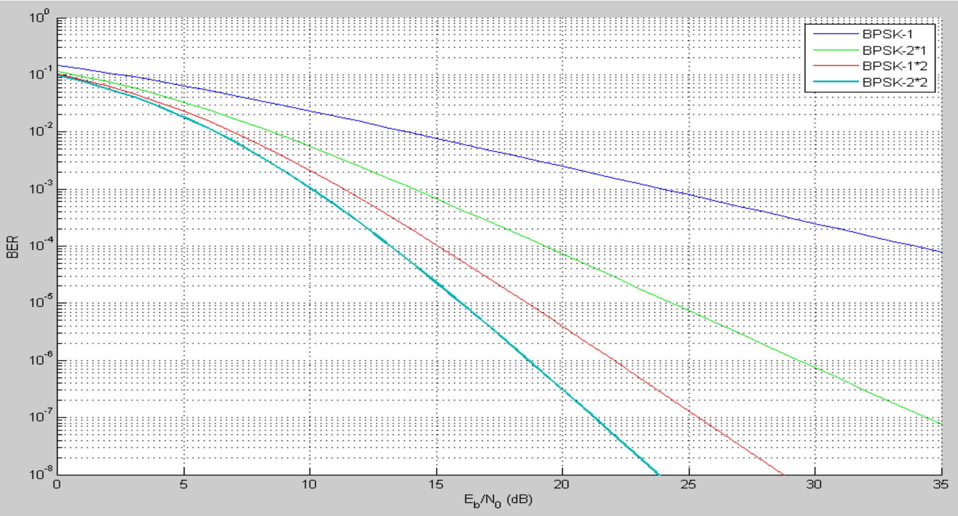


Figure 7.9: SNR Vs. BER performance analysis of (2x2) MIMO-OFDM system on WiMAX networks for BPSK modulation

It is shown in the figure 7.9 that with the increase of signal-to-noise ratio, the value of BER decreases for each of the four MIMO communication systems. Further, at a BER of approximately 10^{-3} , the signal-to-noise ratios for SISO (1x1), MISO (2x1), SIMO (1x2) and MIMO (2x2) systems are approximately 23.5 dB, 14.5dB, 11 dB and 9 dB respectively when BPSK modulation system is used. Further it is seen that there is a large improvement in SNR from SISO to MIMO system ~14.5 dB. For the MIMO system that employs BPSK modulation, the least value of the signal-to-noise ratio is obtained at ~9 dB. This clearly shows that the MIMO (2x2) systems are the most efficient type for use with a MIMO-OFDM communication for WiMAX with BPSK modulation.

The SNR values are computed with reference to BER, as a function of various MIMO-OFDM communication system models on WiMAX PHY as shown in figure 7.10 for QPSK modulation. The parameters selected include coding rate 1/2, Bandwidth 10MHz, convolution coding 2/3, interleaving [1;1;0;1], FFT size 256, channel 16, simulation 50,000 bits, Noise AWGN.

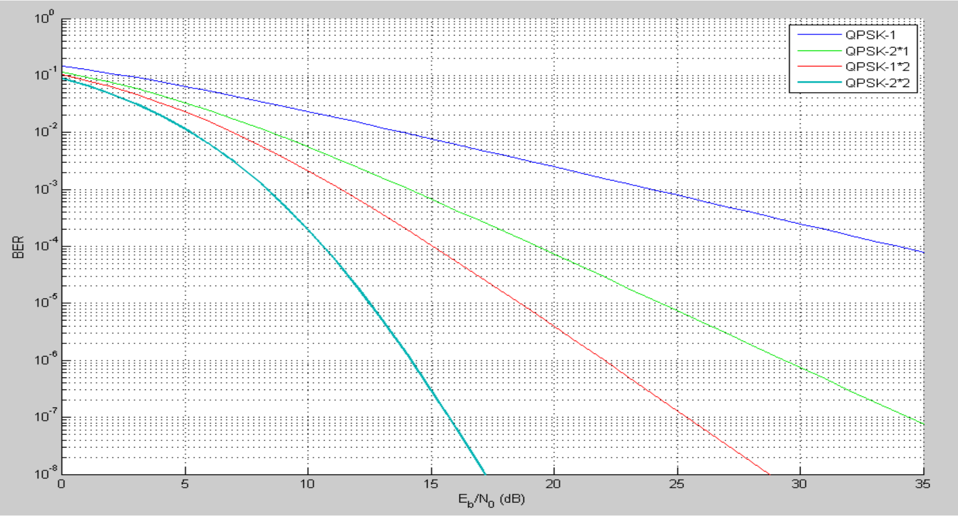


Figure 7.10: SNR Vs. BER performance analysis of (2x2) MIMO-OFDM system on WiMAX networks for QPSK modulation

It is shown in the figure 7.10 that with the increase of signal-to-noise ratio, the value of BER decreases for each of the four MIMO communication systems. Further, at a BER of approximately 10^{-3} , the signal to noise ratios for SISO (1x1), MISO (2x1), SIMO (1x2) and MIMO (2x2) systems are approximately 24.2 dB, 14.6 dB, 11.5 dB and 9.5 dB respectively when QPSK modulation system is used. Further it is seen that there is a large improvement in SNR from SISO to MIMO system ~14.7 dB. For the MIMO system that employs QPSK modulation, the least value of the signal-to-noise ratio is obtained at ~9.5 dB. This clearly shows that the MIMO (2x2) systems are the most efficient type for use with a MIMO-OFDM communication for WiMAX with QPSK modulation.

The SNR values are computed with reference to BER, as a function of various MIMO-OFDM communication system models on WiMAX PHY as shown in figure 7.11 for 16-QAM modulation. The parameters selected include coding rate 1/2, Bandwidth 10MHz, convolution coding 2/3, interleaving [1;1;0;1], FFT size 256, channel 16, simulation 50,000 bits, Noise AWGN are used for each of the four MIMO communication systems.

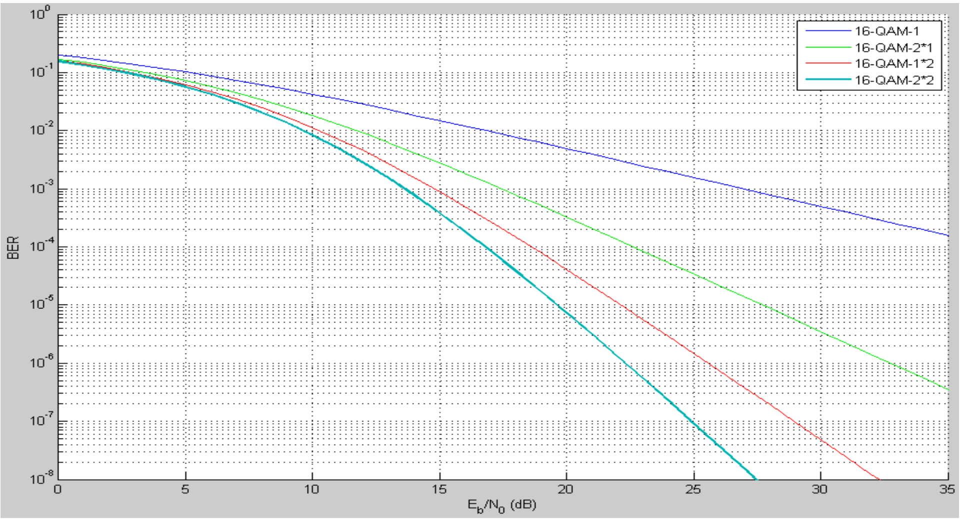


Figure 7.11: SNR Vs. BER performance analysis of (2x2) MIMO-OFDM system on WiMAX networks for 16-QAM modulation

Further, at a BER of approximately 10^{-3} , the signal to noise ratios for SISO (1x1), MISO (2x1), SIMO (1x2) and MIMO (2x2) systems are approximately 26.5 dB, 17 dB, ~14.8 dB and 13.4 dB respectively when 16-QAM modulation system is used. Further it is seen that there is a large improvement in SNR from SISO to MIMO system ~12.5 dB. For the MIMO system that employs 16-QAM modulation, the least value of the signal-to-noise ratio is obtained at ~13.4 dB. This clearly shows that the MIMO (2x2) systems are the most efficient type for use with a MIMO-OFDM communication for WiMAX with 16-QAM modulation.

The performance results of the simulation for different MIMO–OFDM implementation on WiMAX network with different modulation techniques are as shown in the Table 7.2.

Table 7.2-Comparison table of SNR Values of MIMO systems with implementation on Wi-MAX network, for different modulation techniques at BER ~10^{-3} using Reed-Solomon (RS) encoder with Convolution encoder.

MODULATION MIMO SYSTEMS	BPSK SNR(dB)	QPSK SNR(dB)	16-QAM SNR(dB)
SISO	**23.7**	**24**	**27**
MISO	**14**	**14.3**	**17.5**
SIMO	**11.3**	**12**	**14.9**
MIMO	**9**	**10**	**13.4**

It is seen that from Table 7.2, at a BER threshold of approximately 10^{-3} , each of the four MIMO–OFDM systems depicts similar behaviour that SNR increasing from lower BPSK to higher 16-QAM modulation is expected from theoretical considerations. Further it clearly displays improvement in SNR performance ~5 dB for lower MIMO (MISO) systems. The implementation of (2x2) MIMO-OFDM system on WiMAX network exhibits the lowest SNR (E_b/N_o) ~9 dB at BER ~10^{-3} for BPSK modulation and indicates a better performance of SNR ~5 dB (BR/BW efficiency~ 3.16) compared to lower MIMO (MISO) systems.

In order to show the SNR improvement achieved by implementation on network a comparison of the SNR values obtained at BER threshold of approximately 10^{-3} for (2x2) MIMO-OFDM system for BPSK, QPSK and 16-QAM modulation with and without implementation on WiMAX network are displayed in Table 7.3.

Table-7.3-Comparison table of SNR Values of (2x2) MIMO-OFDM system with and without implementation on WiMAX network, for different modulation techniques at BER ~10^{-3}.

MIMO-OFDM / MODULATION	BPSK SNR(dB)	QPSK SNR(dB)	16-QAM SNR(dB)
WITHOUT IMPLEMENTATION ON NETWORK	12.6	12.75	13.58
WITH IMPLEMENTATION ON NETWORK	9	10	13.4

It is seen that from Table 7.3, at a BER threshold of approximately $10^{-3,}$ the signal-to-noise ratio increases for a change to higher order modulation from BPSK to 16-QAM modulation as expected from theoretical considerations. Further the table shows that performance of the MIMO-OFDM implementation on WiMAX network for BPSK modulation shows a large improvement in SNR ~3.6 dB, SNR ~2.75 dB for QPSK modulation and SNR ~0.18 dB for 16-QAM Modulation. The results show that the (2x2) MIMO-OFDM systems are efficiently implementable on WiMAX network (Physical layer IEEE 802.16d-2004) and exhibit a much better SNR (E_b/N_0) performance ~9 dB with BPSK modulation for transmission of higher data rates. Similar implementation of different MIMO systems on WiMAX networks performance shows improvement in SNR for the MIMO-OFDM WiMAX networks as reported by Mojtaba Seyedzadegan and Mohamed Othman [69] and Wang, Mingxi [70].

The results presented in the chapter of the thesis have been published in the international journal paper:

1. **Bhagya.R, Dr. A G Ananth," MIMO Performance on WiMAX Networks for Different Modulation Schemes", International Journal of Advance Engineering and Research Development (IJAERD), Volume 1, Issue 8, August-2014. (Impact factor 3.134).**

CHAPTER 8

IMPLEMENTATION OF MIMO-OFDM ON DIFFERENT WIRELESS NETWORKS

CHAPTER 8

IMPLEMENTATION OF MIMO-OFDM ON DIFFERENT WIRELESS NETWORKS

MIMO-OFDM communication systems have found an important place in the air interface standard implementations of 4th and 5th generation of wireless broadband technologies. In order to ensure the reliability during high speed data transfers, multiple input multiple output (MIMO) communication systems are combined with OFDM, in order to divide the available radio spectrum in the multiple sub channels that are closely spaced to each other. This combination is referred to as MIMO-OFDM system which forms the backbone of current and next-generation wireless networks such as WLAN (wireless local area networks), since their incorporation results in the achievement of higher spectral efficiency, system capacity and increased throughput of the system [77].

8.1 Wireless Local Area Networks (WLAN)

Wireless Local Area Networks (WLANs) were conceived as a duplex, high data rate communication system, with a fixed transmission range. These WLAN systems can be employed as a network to extend or replace existing LAN systems. Since WLAN systems utilise the air interface as the communication medium, it provides the advantage of user mobility. This results in the availability of a shared access medium for LAN users without the necessity of plugging in to a wired system.

8.2 Wireless LAN Architecture

The logical architecture of a wireless LAN is illustrated in figure 8.1. The WLAN functions are the Physical layer and the Medium Access Control layer. The transmission of data bits, specifications associated with the various procedures, electrical and mechanical systems are outlined in the physical layer specification. The seizures associated with the correction of errors, and synchronisation parameters between two systems are outlined in the MAC layer specification. The medium access control (MAC) and logical Link control (LLC) together form the data link layer and is as shown in figure 8.1. The MAC layer technology of WLAN systems enables shared access of the competition medium through the use of a carrier sensing protocol. The logical link control layer on the other hand is similar to Ethernet systems, and is tasked with link level transmissions of PDUs (packet data units). When different clients or stations, have to be addressed in the communication medium, the procedures outlined in the LLC specifications are utilised for exchange of control information between end users [79].

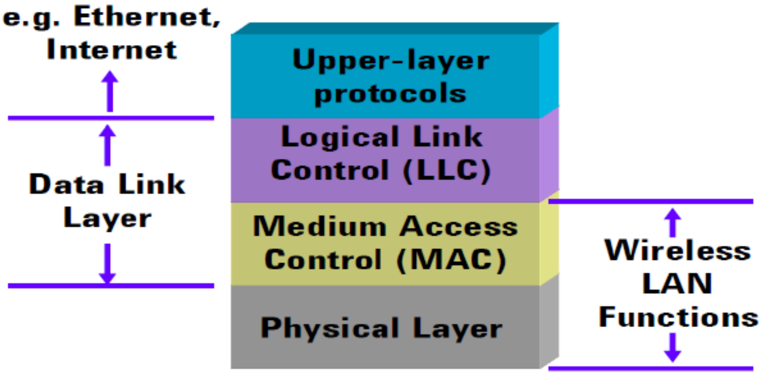


Figure 8.1: Wireless LAN Architecture Protocol Layers

8.3 802.11 Physical Layer Functions

The IEEE 802.11 physical layer specification is required to perform various operations including carrier sensing, transceiver functions etc.This applies to all physical layer types, except that they perform these functions differently and offer varying levels of performance.

Carrier-sense functions

The physical layer implements a carrier-sense operation by directing the PMD to check whether the medium is busy or idle. This involves activating a receiver that receives and demodulates radio frequency signals at specific frequencies.

Transmit Function

After receiving notice from the MAC layer the PLCP switches the PMD to transmit mode indicating a start of transmission. The MAC layer sends the number of octets which is needed for transmission and the data rate instruction along with this request.

The PMD react by sending the preamble of the frame along with the remaining physical layer header and MSDU.

Receive Function

If the clear channel assessment finds a busy medium and valid preamble of an incoming frame, the PLCP will monitor the header of frame. If the PLCP determines the physical layer header is error free, the PLCP will send a receive indication to the MAC layer to provide notification of an incoming frame. The PLCP sends the information such as the number of octets and data rate which is present in the frame header.

8.4 IEEE 802.11 standard

In this thesis IEEE 802.11n standard is considered. The 802.11n amendment, which specifies MIMO technology to extend data rates into the hundreds of megabits per second in the 2.4GHz and 5GHz bands, was ratified in 2009. 802.11n is backward compatible with 802.11a and 802.11b/g. Because of the much higher data rate and flexibility of 802.11n, most new deployments today are based on 802.11n.

8.5 Implementation of MIMO-OFDM on WLAN Network (IEEE 802.11n)

The model contains components that employ the essential features of the WLAN 802.11n standard. The top row of blocks contains the transmitter components while the bottom row contains the receiver components. The block diagram of the MIMO-OFDM implementation on WLAN network is as shown in figure 8.2 [111] [152].

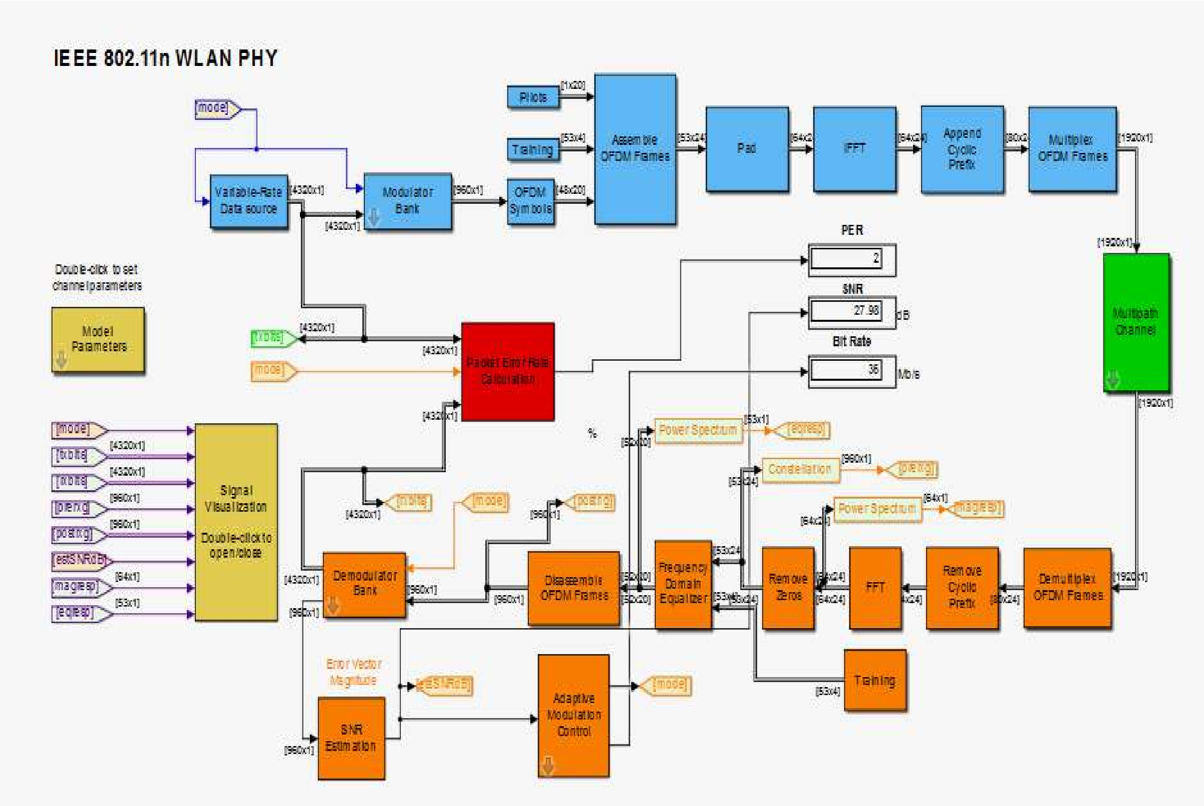


Figure 8.2: Block diagram of (2x2) MIMO-OFDM on IEEE 802.11n WLAN PHY

The communication system in this simulation performs the following tasks:

Random data's are generated at a bit rate that varies during the simulation. The varying data rate is accomplished by enabling a source block periodically for a duration that depends on the desired data rate. Coding, interleaving and modulation schemes are employed which is specified in the standard. Each modulator block in the bank performs these tasks:

- Convolutional coding and puncturing using code rates of 1/2, 2/3, and 3/4
- Data interleaving
- QPSK, 16-QAM and 64-QAM modulation

OFDM transmission uses 52 data subcarriers, 4 pilots, 64-point FFTs and a 16-sample cyclic prefix. PLCP (physical layer convergence protocol) preamble modeled as four long training sequences. Dispersive multipath fading channel is used and we can configure channel properties using the Multipath Channel block. The receiver uses an equalization block which utilizes Viterbi decoding. A configuration block called Model

Parameters enables us to set parameters such as the composition of each OFDM frame, and trace back depth for the Viterbi decoder. One parameter of particular interest for the adaptive modulation and coding in this simulation is the Low-SNR thresholds parameter. This is a seven-element vector that indicates how the simulation should choose a data rate based on the SNR estimate.

The model has eight modes, each associated with a particular modulation scheme and convolutional code. The seven thresholds are the boundaries between eight adjacent regions corresponding to eight different modes. The simulation should then apply the mode with the highest throughput in order to obtain the necessary error performance. Determining appropriate thresholds often involves running the simulation multiple times, varying the values of the Low-SNR thresholds parameter.

The following numerical results are displayed in the simulation:

- The total percentage of packet error is as shown in the PER block
- An estimate of the signal-to-noise ratio based on EVM (error vector magnitude), is depicted in the SNR block. Similarly the signal-to-noise ratio at the receiver is also shown.
- The bit rate of the current transmission or communication is shown in the Bit Rate block. This corresponds to a set of bit rates specified in the standard [130].

8.6 Results and Discussions

The performance analysis of (2x2) MIMO-OFDM communication systems and the results, when different modulation schemes such as BPSK, QPSK and 16-QAM modulation are used is discussed in this section. We first determine the signal-to-noise ratio (SNR) and its variation as a function of bit error rate (BER) when different modulation techniques such as QPSK, 16-QAM and 64-QAM are employed. A MIMO-OFDM communication system that employs multiplexing is analysed and the corresponding performance analysis of SNR Vs. BER for (2x2) communication system for WLAN network is computed. The performance analysis is as shown in figure 8.3.

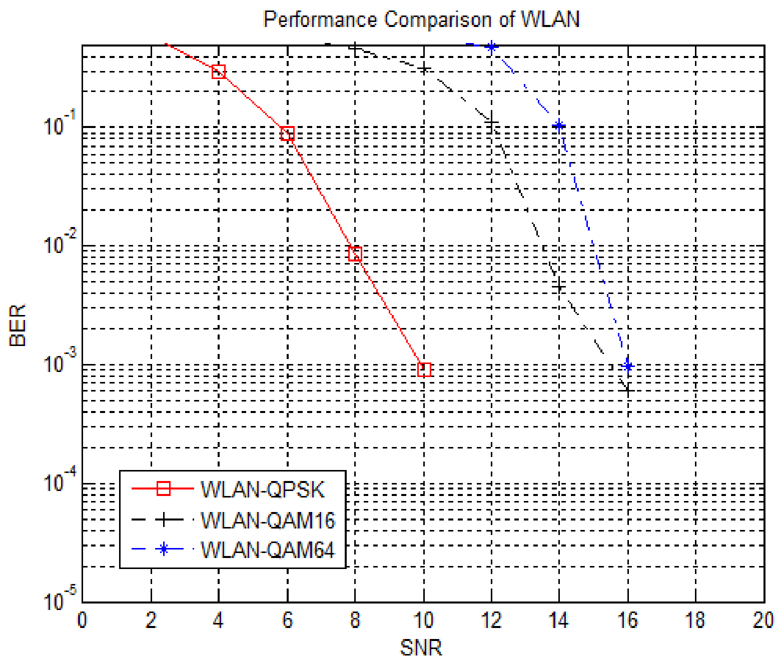


Figure 8.3: SNR Vs. BER performance analysis of (2x2) MIMO-OFDM system on WLAN network for different modulation schemes

It is shown in the figure 8.3 that with the increase of signal-to-noise ratio, the value of BER decreases for different modulation schemes. The figure indicates that implementation of MIMO-OFDM system on the WLAN network at BER ~10^{-3} depicts that for QPSK modulation SNR ~10 dB, 16-QAM modulation SNR ~15.5 dB and 64-QAM modulation SNR ~16 dB are achievable. The simulation results of (2x2) MIMO-OFDM communication system at BER threshold of approximately 10^{-3} indicates a large improvement in SNR ~6 dB between QPSK and 64-QAM modulation. The (2x2) MIMO-OFDM implementation on WLAN network shows lowest SNR ~10 dB for QPSK modulation. The results suggest that the (2x2) MIMO-OFDM implementation with QPSK modulation is very efficient on WLAN networks.

8.7 IEEE 802.16m-2009 WiMAX NETWORK

8.7.1 WiMAX Physical Layer

The WiMAX physical layer is based on OFDM. OFDM is the transmission scheme of choice to enable high-speed data, video and multimedia communications and is used by a variety of commercial broadband systems including DSL, Wi-Fi, DigitalVideo Broadcast-Handheld (DVB-H) and MediaFLO besides WiMAX.

8.8 Implementation of MIMO-OFDM on WiMAX Network (IEEE 802.16m-2009)

The simulation model shown in figure 8.4 is an end-to-end baseband model of the physical layer of a WiMAX, according to the IEEE 802.16m-2009 standard. Particularly, it models the OFDM-based physical layer called Wireless MAN-OFDM supporting all the mandatory coding and modulation options. It also illustrates STBC, an optional transmit diversity scheme specified for use on the downlink. Finally, it illustrates the use of digital pre-distortion, a technique for extending the linear range of a nonlinear amplifier [72].

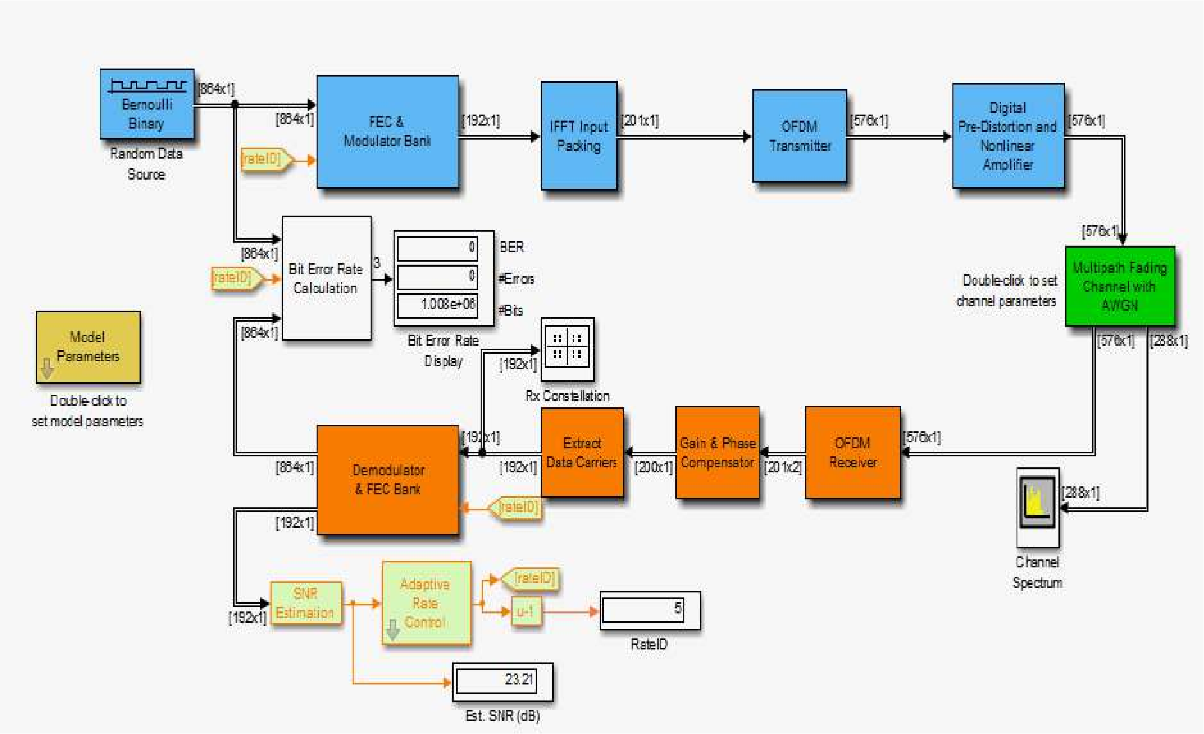


Figure 8.4: Block diagram of (2x2) MIMO-OFDM on IEEE 802.16 WiMAX

The following operations are performed by the communication system model. In order to model a downlink burst, the random information bits are generated at the source, and used to create a set of OFDM symbols. A Reed Solomon encoding scheme concatenated with the convolutional code is used for forward error correction. This incorporates the rate adaptable convolution coding in the inner loop. For each of the corresponding modulation schemes namely BPSK, QPSK, 16-QAM or 64-QAM, interleaving of the data rates are performed according to the standards specification.

A 256-point FFT based OFDM transmission is utilized along with the variable cyclic prefix length. Among the 256 subcarriers, 192 are for data, 8 are for pilots, 28 are left guard band, 27 are right guard band and 1 is DC null. The burst preamble uses an OFDM symbol with a single preamble. An optional memoryless nonlinearity that can be driven at several backoff levels is used with an optional digital pre-distortion capability that corrects for the nonlinearity of the signal transmission.

The simulation model incorporates the channel behavior through the use of a MIMO multipath fading channel, with the noise model represented by AWGN. The channel model is assumed to be of the flat fading type with dispersion and multipath components. The inserted preambles are used for estimating the channel conditions at the OFDM receiver system.

Decoding is performed using Reed Solomon and Viterbi decoders at the receiver side. A hard-decision demodulation follows a de-interleaving module. The two decoding models utilize a rate adaptive mechanism that takes into account the signal-to-noise ratio at the receiver to dynamically adapt the data transmission rate depending on channel conditions. The code rate is represented by the Rate_ID parameter, and is chosen from one of the seven specified code rates in the OFDM physical layer standard specification.

Furthermore, the simulation model includes mechanisms for the display measurement of BER information after error control coding has been performed at the receiver. Spectrum Analyzer blocks display the spectra of both the OFDM transmitter output and the faded AWGN channel output. Also, two Constellation Diagram blocks display the AM/AM and AM/PM characteristics of the signal at the output of the memory less nonlinearity. Finally, a constellation diagram block is used to display the channel impairments of the received signal and helps in the visualization of adaptive modulation and coding during the simulation run time.

8.9 Results and Discussions

The performance of a MIMO-OFDM WiMAX transmitter and receiver for different QPSK, 16-QAM and 64-QAM modulation schemes are analysed. The Implementation of different MIMO-OFDM systems on WiMAX networks is examined and performance of the system is evaluated with the presentation of simulation results.

The SNR is measured with reference to the BER computed for a WiMAX network for different modulation schemes in order to study their modulation performance. The signal-to-noise ratio i.e. SNR (E_b/N_0) is computed for the variations in BER for modulation schemes such as QPSK, 16-QAM and 64-QAM. Figure 8.5 shows the SNR performance of WiMAX network that incorporates a (2x2) MIMO-OFDM multiplexing system is computed for varying BER values when different modulation schemes are used.

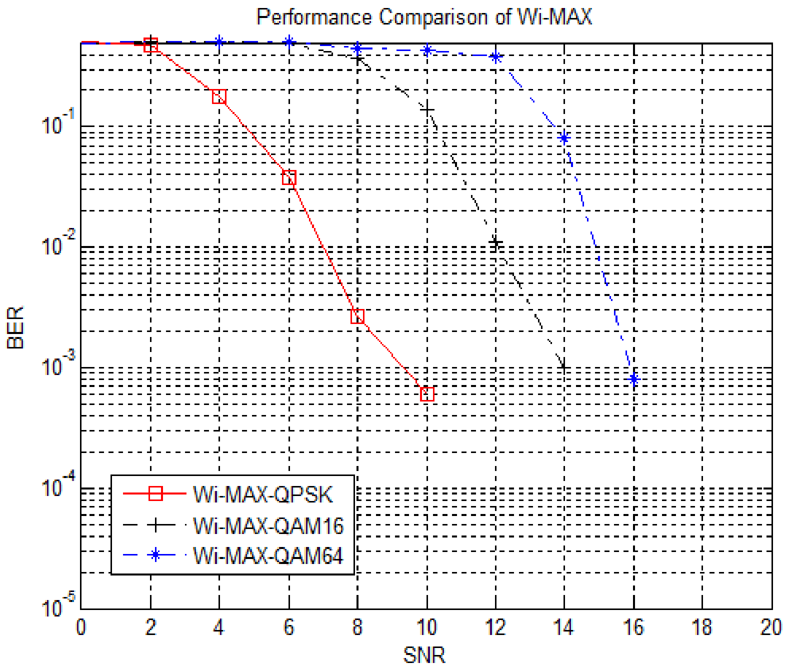


Figure 8.5: SNR Vs. BER performance analysis of (2x2) MIMO-OFDM system on WiMAX network for different modulation schemes

It is shown in the figure 8.5 that with the increase of signal-to-noise ratio, the value of BER decreases for different modulation schemes. The figure indicates that for MIMO-OFDM system at BER ~10^{-3} , the WiMAX network depicts that for QPSK modulation SNR ~9.1 dB, 16-QAM modulation SNR ~14 dB and 64-QAM modulation SNR ~15.7 dB are achievable. The simulation result of (2x2) MIMO-OFDM communication system at a BER threshold of approximately 10^{-3} shows a large improvement in SNR ~6.6 dB between QPSK and 64-QAM modulation. The (2x2) MIMO-OFDM implementation on WiMAX network shows lowest SNR ~9.1 dB for

QPSK modulation. The results suggest that, the (2x2) MIMO-OFDM implementation with QPSK modulation is more efficient on WiMAX networks.

8.10 Long Term Evaluation (LTE)

LTE systems were first introduced in 2004 by NTT DOCOMO, and the standardization effort started in 2005. The new alliance was founded in May 2007, namely the LTE/SAE Trial Initiative (LSTI), which was responsible for the rapid introduction of the LTE technology worldwide. The technology was standardized in December 2008, and LTE was available as a service publicly in December 2009 when it was launched in Oslo and Stockholm by TeliaSonera, as a data service on a portable USB dongle. Since then, the service was launched by major carriers across North America, with the first LTE Mobile device launched by Samsung (the SCH R900) in September 2010. The launch of an LTE smartphone namely the Samsung Galaxy indulge became the world's first LTE smartphone offering the services. Since then, all major carriers have announced the migration to the technology. The LTE technology revolution is represented by the LTE advanced technology and was standardized in March 2011.

The LTE standard specification offers a peak data transmission rate of 300 Mbps on the downlink, and a peak data transmission rate of 75 Mbps on the uplink along with QOS provisions that ensures a data transfer delay in the radio access network of about 5 ms. LTE also supports faster mobility along with both broadcast and multicast communication. The use of carrier bandwidths ranging from 1.4 MHz to 20 MHz enables LTE to support dynamically scalable bandwidths. LTE uses frequency division duplexing and time division duplexing to this effect. LTE incorporates an evolved packet core (EPC), which is an all IP network architecture designed as a replacement for the 2.5G GPRS networks, while supporting both voice and data handoffs in a seamless manner. LTE handovers are backward compatible with older technology standards such as GSM, CDMA2000 and UMTS networks. The architectural design is flat leading to a simpler and less expensive system, with the capacity of about four times as that supported by the third generation HSPA standard [68].

8.11 LTE Network Architecture

The LTE network architecture, its network elements and interfaces is as shown in figure 7.6. The LTE network consists of the core network represented by the EPC and the access network represented by the E-UTRAN. The core network or CN is composed of various logical nodes, along with an evolved node B (eNodeB) which acts as a first point of contact to UEs. Standardised interfaces interconnect these network elements and a low compatibility and interoperability between different vendors. This allows network operators to obtain and source network elements manufactured by different vendors. It is therefore possible to combine or split the implementation of network entities by network operators for economical reasons. The figure 8.6 represents this functional split.

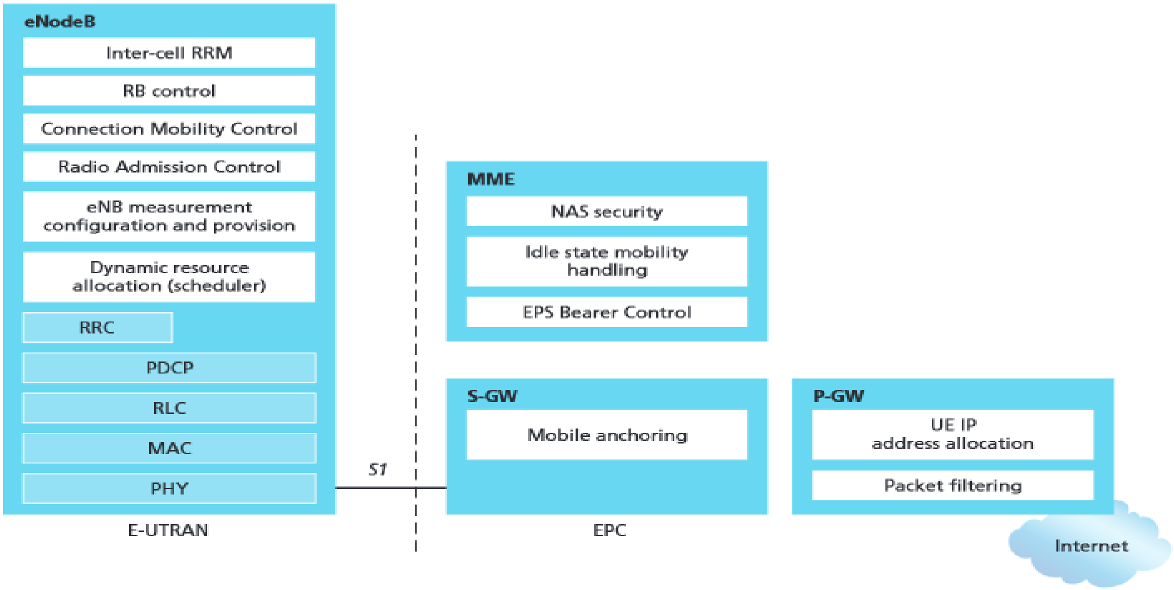


Figure 8.6: Functional split between E-UTRAN and EPC

8.12 Implementation of MIMO-OFDM on LTE Network

The simulation model shown in figure 8.7 is an end-to-end baseband model of the physical layer of a LTE standard [153].

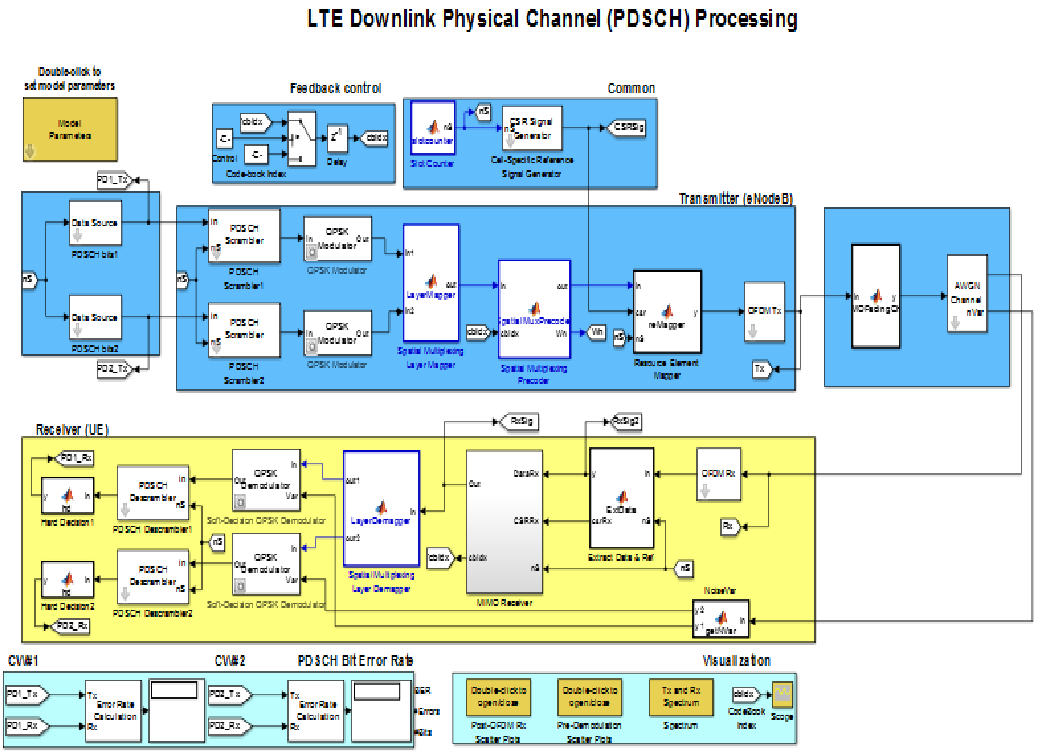


Figure 8.7: Bloch diagram of LTE Downlink Physical Channel

Physical Channel (PDSCH) Processing

A physical channel corresponds to a set of time-frequency resources used for transmission of a particular transport channel. The Physical Downlink Shared Channel (PDSCH) is the main physical channel used for the transmission of unicast data. This example uses a single-codeword transmit diversity transmission over two or four transmit antennas. The physical downlink channel processing includes various modules such as:

Scrambling

The information bits from the source are first scrambled using a scrambling sequence prior to transmission. To ensure interference randomization between cells the scrambling sequence depends on the physical layer cell identity. The simulation assumes downlink transmission in a single cell, with the single user and with a defined cell ID.

Data Modulation

The scrambled bits are converted into complex modulated symbols by Downlink data modulation. The set of modulation schemes supported include QPSK, 16QAM and

64QAM corresponding to two, four and six bits per modulation symbol respectively. We can select the different modulation schemes using the PDSCH parameters for different modulation types in the simulation.

Layer Mapping and Precoding

The LTE Encode function combines the transmit diversity layer mapping and precoding as per the LTE Standard. This function uses complex notation for signals and employs the OSTBC Encoder System to implement the space-frequency block coding specified for LTE. For both two and four antenna schemes, the LTE specifications make use of the basic Alamouti code, applied over space and frequency dimensions with no rate reduction.

OFDM Transmission

A per-antenna code (PAC) is generated using complex valued time domain signal from a fully populated resource grid, and is used with OFDM modulation system. Based on the LTE standard specified channel bandwidth, the total number of FFT points are chosen. In one time slot, 7 OFDM symbols are transmitted, each with a different cyclic prefix length.

MIMO Channel

The simulator uses the MIMO Channel to model the Rayleigh fading over multiple links. We can select from a choice of frequency-flat static characteristic to one where the Maximum Doppler shift, path gains, path delays and correlation levels can be individually specified for each link. The path delays are constrained to be integer multiples of the channel input sample time.

Receiver Side Processing (at the UE)

The receiver side processing (processing of the user equipment) mainly includes the OFDM receiver. The effects of unequal cyclic prefix lengths are remote by the austere receiver on it per symbol basis in each and every time slot. It then converts the symbols into a time/frequency domain grid structure by using the demodulation system of the OFDM receiver.

Channel Estimation

Channel estimation when selected, applies averaging based least-squares estimation technique to reduce noise in each sub frame. This is performed by employing linear interpolation and reference signals for each subcarrier. CSR signals are used in this case for the purpose of channel estimation. As an alternative, an ideal channel estimation scheme is also provided which uses the channel gains from the MIMO fading channel. This ideal scheme can be used as a reference for performance evaluation of the actual estimation scheme.

Transmit Diversity (TD) Combining

TD combining for the multiple transmitted signals is folded into the TD Combine function which is similar to the encoder and uses complex notation for signals and employs the OSTBC Combiner. The combined data stream is further demodulated and descrambled to get the received data bits.

8.13 Results and Discussion

The variation of signal-to-noise ratio with reference to BER is computed for LTE network for different modulation schemes to evaluate their modulation performance. The SNR is computed with reference to BER for different modulation schemes namely QPSK, 16-QAM and 64-QAM. Figure 8.8 shows the SNR performance of LTE network computed for varying BER, when different modulation schemes are used with a (2x2) MIMO-OFDM communication system.

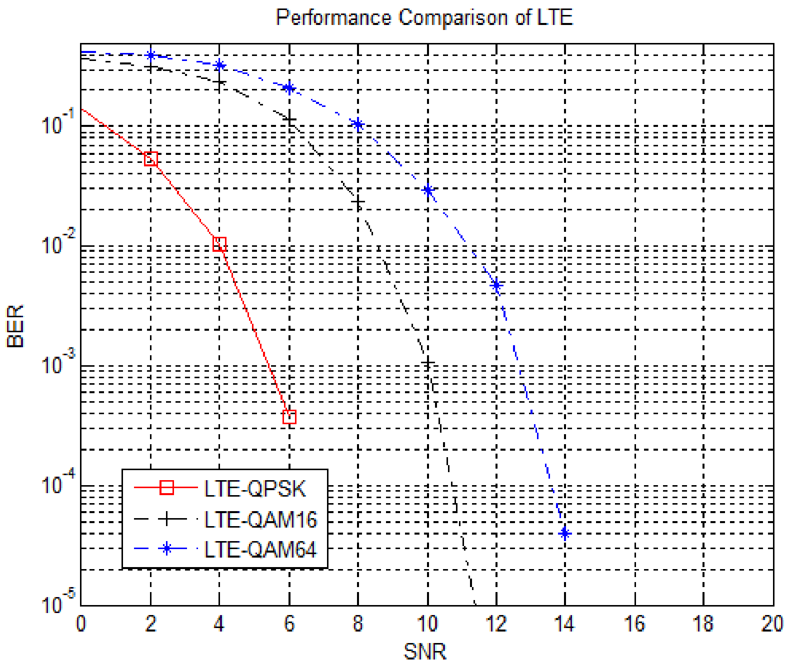


Figure 8.8: SNR Vs. BER performance analysis on WiMAX network for different modulation schemes

It is depicted in the figure 8.10 that for increasing values of SNR, BER decreases for different modulation schemes. The figure indicates that for MIMO-OFDM system at BER ~10^{-3} , the LTE network depicts that for QPSK modulation SNR ~5.2 dB, 16-QAM modulation SNR ~10 dB and 64-QAM modulation SNR ~12.8 dB are achievable. The simulation results of (2x2) MIMO-OFDM communication system at BER threshold of approximately 10^{-3} indicate that there is a large improvement in SNR ~7.6 dB and between QPSK and 64-QAM modulation. The (2x2) MIMO-OFDM implementation on LTE networks shows lowest SNR.

The results of the analysis suggest that the (2x2) MIMO-OFDM implementation with QPSK modulation is very efficient on LTE networks.

In order to find the improvement in the SNR values (2x2) MIMO-OFDM system on different wireless networks a comparison of the SNR values obtained for different networks at BER ~10^{-3} with and without Implementing (2x2) MIMO-OFDM system on different wireless networks for QPSK modulation has been summarised in Table 8.1

Table 8.1-Comparison table of SNR Values of (2x2) MIMO-OFDM system with and without implementation on WLAN, WiMAX and LTE networks, for QPSK modulation technique at BER ~10^{-3} .

NETWORK	**WLAN SNR(dB)**	**WiMAX SNR(dB)**	**LTE SNR(dB)**
WITHOUT MIMO-OFDM NETWORK IMPLEMENTATION	**12.75**	**12.75**	**12.75**
WITH MIMO-OFDM NETWORK IMPLEMENTATION	**10**	**9.1**	**5.2**
DIFFERENCE (SNR)	**2.75**	**3.75**	**7.55**

It can be clearly seen from the table 8.1, that at a BER threshold of approximately 10^{-3} the simulation results show that implementation of MIMO-OFDM transmission on WLAN networks for QPSK modulation there is significant improvement in SNR ~2.75 dB. Similarly the implementation on WiMAX networks shows an improvement in SNR ~3.65 dB and implementation on LTE networks shows an improvement in SNR ~7.55

dB. The results show that the (2x2) MIMO-OFDM systems are efficiently implementable on LTE networks and exhibit a much better SNR (E_b/N_0) performance ~5.2 dB with QPSK modulation The MIMO-OFDM transmission system implementation on LTE networks at BER ~10^{-3} for QPSK modulation displays lowest SNR (E_b/N_0) ~5.2 dB and better performance in SNR ~4.8 dB (BR/BW efficiency ~3) for transmission of higher data rates.

The results presented in the chapter of the thesis have been published in the international journal paper:

R Bhagya and A.G.Ananth Performance of MIMO-OFDM Transmission System on Wireless Networks" has been accepted for publication in International Journal of Innovative Research in Computer Science & Technology (IJIRCST),Volume 3, Issue 1, pp 31-36, January 2015 with impact factor 2.08.

CHAPTER 9

DISCUSSION, CONCLUSIONS AND FUTURE SCOPE

CHAPTER 9

DISCUSSION, CONCLUSIONS AND FUTURE SCOPE

9.1 Discussion

The simulation results of MIMO transceiver communication systems for higher bit rate transmission with different multiplexing, modulation and detection system have been presented in the previous chapters. Further the implementations of MIMO-OFDM system on different wireless networks with different modulation schemes are also presented. The SNR (E_b/N_0) performance with BER has been used as an important parameter for measuring the channel efficiency (capability) of the MIMO transceiver system for higher bit rate transmission. Further the lowest SNR (E_b/N_0) values are used for determining the Bit rate to Band Width efficiency (BWR/BW) of the designed MIMO transceiver configuration. In the present chapter the most significant results obtained in the previous chapters are highlighted to make final conclusions on the work carried out in the thesis. The futures scope of the research work carried out in the thesis is also presented in the chapter.

The SNR values derived at BER ~10^{-3} for MIMO-OFDM communication system for different BPSK, QPSK and 16-QAM modulation schemes using ML-SIC detection system are shown in figure 9.1.

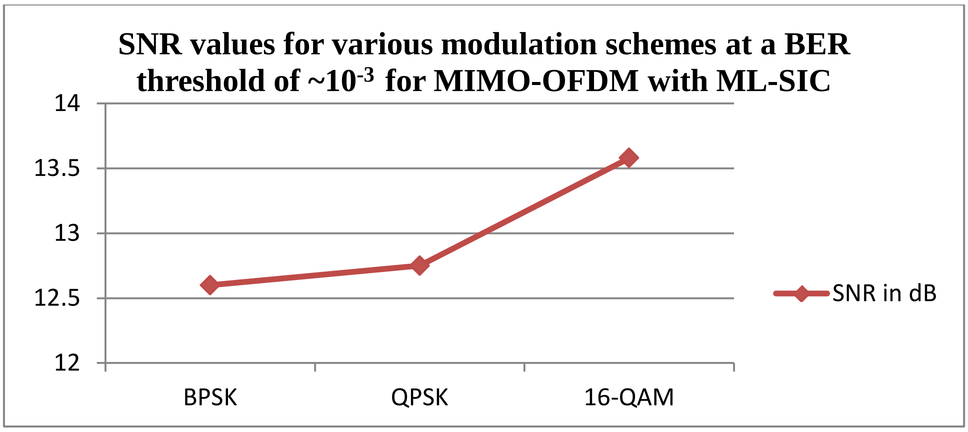


Figure 9.1: SNR values for various modulation schemes at a BER threshold of ~10^{-3} for (2x2) MIMO-OFDM with ML-SIC

Figure 9.1 shows that the SNR increases with higher modulation as per modulation theory and shows highest SNR values ~13.58 dB for 16-QAM modulation and lowest SNR values ~12.6 dB for BPSK when ML detection is used with successive interference cancellation. The result suggests that the SNR values of MIMO-OFDM system with ML-SIC detection gives improved performance of SNR ~ 0.98 dB for BPSK modulation.

The SNR values derived at BER ~10^{-3} for MIMO-OFDM communication system with BPSK modulation for different detection systems namely ZF, MMSE and ML detectors along with successive interference cancellation are shown in figure 9.2.

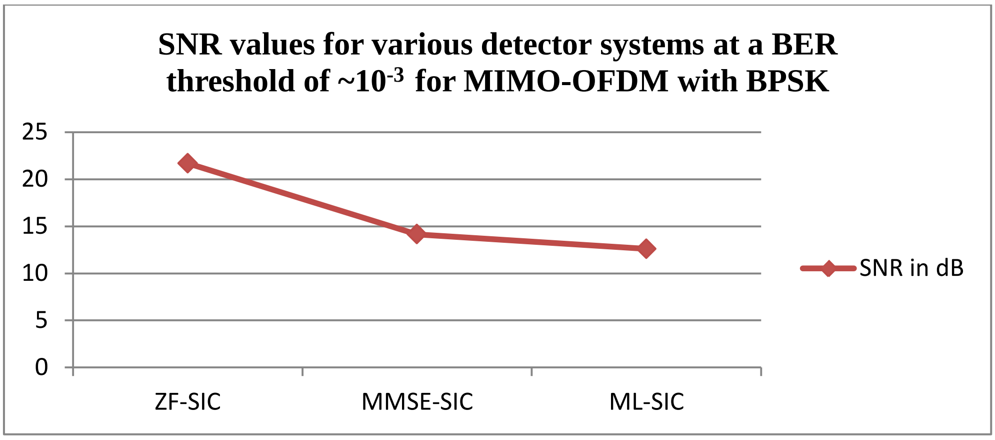


Figure 9.2: SNR values for various detector systems at a BER threshold of ~10^{-3} for (2x2) MIMO-OFDM with BPSK

The figure 9.2 depicts that the SNR decreases with different detection systems and shows highest SNR values ~21.67 dB for ZF-SIC detector system and lowest SNR values ~12.6 dB for ML-SIC detection system. The results suggest that the SNR values of MIMO-OFDM with BPSK Modulation gives improved performance of SNR ~9.07 dB for ML-SIC detection system.

The SNR values derived at BER ~10^{-3} for MIMO-Communication system with BPSK modulation and ML–SIC detection system for different OSTBC, CDMA and OFDM multiplexing techniques are shown in figure 9.3.

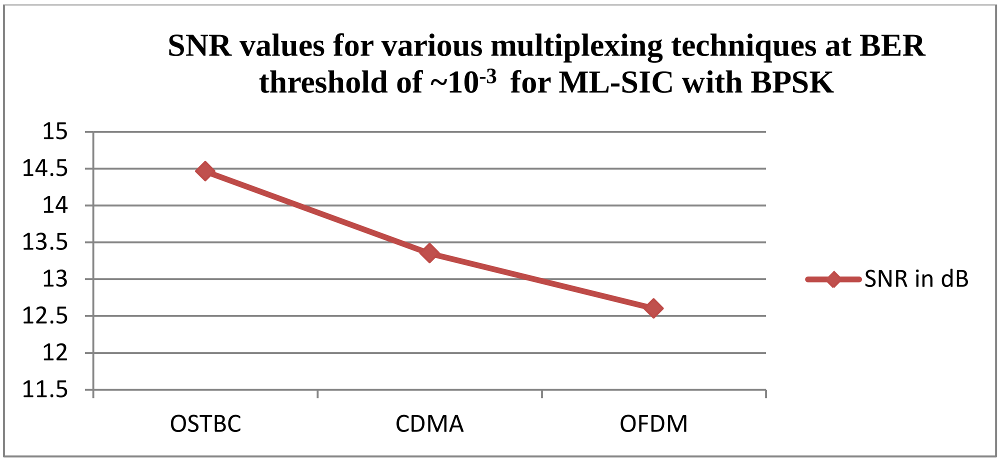


Figure 9.3: SNR values for various multiplexing schemes at BER threshold of ~10^{-3} for ML-SIC with BPSK

The figure 9.3 illustrates that the SNR decreases with different multiplexing systems and shows highest SNR values ~14.46 dB for OSTBC multiplexing and lowest SNR values ~ 12.6 dB for OFDM Multiplexing system. The results suggest that the SNR values of MIMO-OFDM gives improved performance of SNR ~1.86 dB with BPSK Modulation for OFDM multiplexing system.

The SNR values derived at BER threshold of ~10^{-3} for MIMO-OFDM communication system with BPSK modulation and ML-SIC detection system for Higher MIMO system and Monte Carlo receiver is shown in figure 9.4.

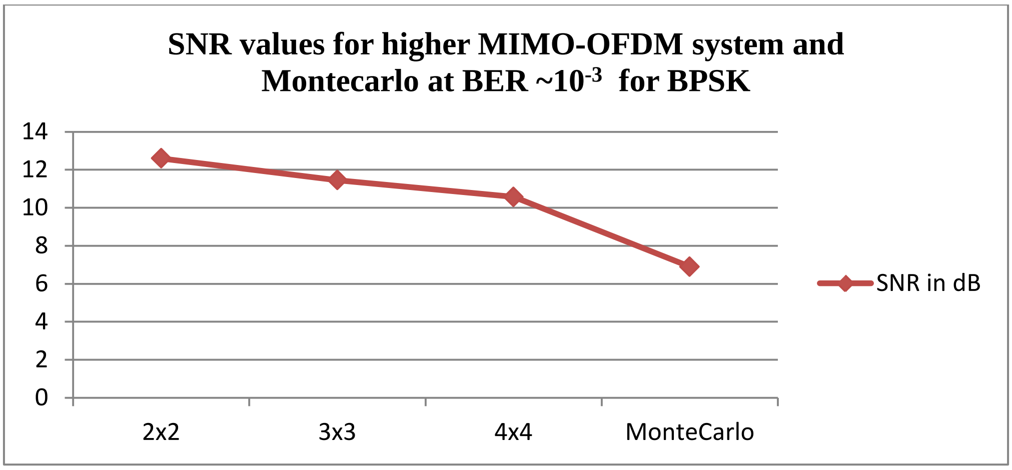


Figure 9.4: SNR values for Higher MIMO-OFDM system at BER 10^{-3} with ML-SIC detector for BPSK modulation

It is evident in the figure 9.4 that the SNR decreases with different MIMO-OFDM systems and shows higher SNR values ~12.6 dB for (2x2) MIMO system and lowest SNR values ~10.57 dB for (4x4) MIMO system with BPSK modulation for ML-SIC detection system. The results suggest that the SNR values of (4x4) MIMO-OFDM gives improved performance of SNR ~2.03 dB for ML-SIC detection system.

Further it can be seen from the figure 9.4 that the (4x4) MIMO-OFDM system performances with Monte Carlo detection system shows lowest SNR ~6.9 dB and indicates further improvement in SNR~3.6 dB against ML-SIC Detection system for BPSK modulation. These suggest that the SNR performance for higher MIMO system can be largely improved using Monte Carlo detection.

The SNR values derived at BER ~10^{-3} for MIMO-OFDM communication system implementation on WiMAX (IEEE 802.16d-2004) wireless network with BPSK modulation for different MIMO-systems with both transmission and receiver diversity namely SISO, MISO, SIMO and MIMO are shown in figure 9.5.

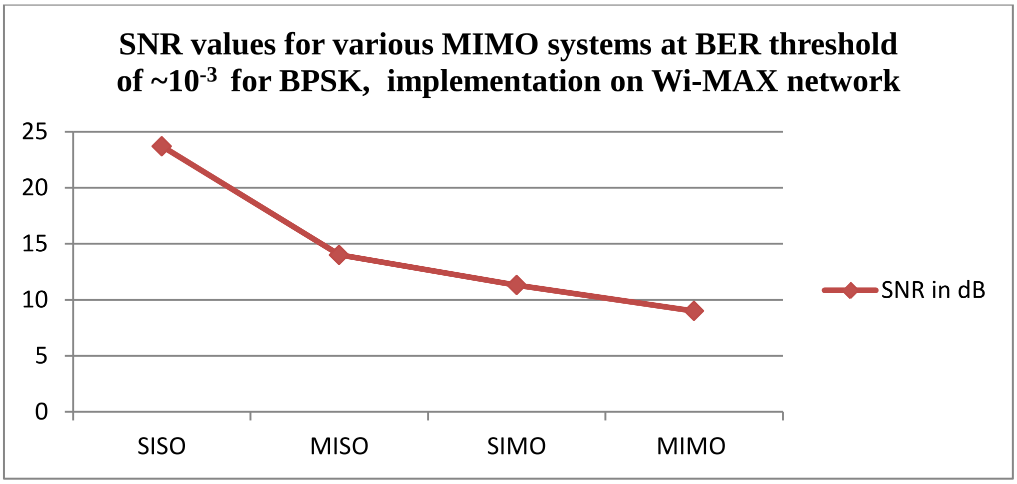


Figure 9.5: SNR values for various MIMO systems at BER threshold of ~10^{-3} for BPSK, implementation on WiMAX network

It is seen in figure 9.5 that the SNR decreases with different MIMO-OFDM systems and indicates highest SNR values ~23.7 dB for (1x1) SISO system and lowest SNR values ~9 dB for (2x2) MIMO system. The results suggest that the (2x2) MIMO-OFDM implementation on WiMAX networks show much better performance in SNR ~3.7 dB with BPSK Modulation compared to lower MIMO (SISO) system.

The SNR values derived at BER ~10^{-3} for (2x2) MIMO-OFDM communication system implementation on WiMAX (IEEE 802.16m-2009) wireless network for different QPSK, 16-QAM and 64-QAM modulation schemes shown in figure 9.6.

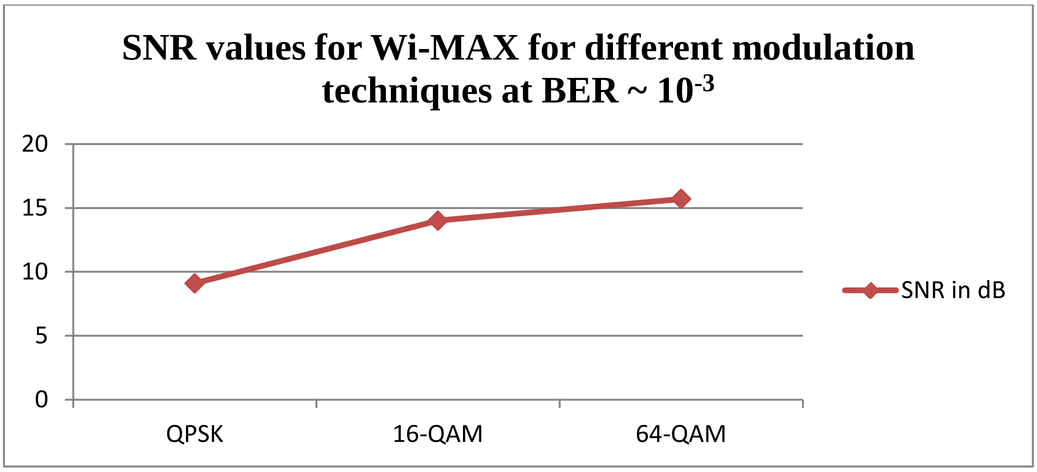


Figure 9.6: SNR variation for MIMO-OFDM implementation on WiMAX networks for different modulation scheme

The figure 9.6 shows that for the MIMO-OFDM implementation on WiMAX Networks the SNR increases for higher modulation schemes. The MIMO-OFDM system implementation on WiMAX network shows highest SNR values ~15.7 dB for 64-QAM modulation and lowest SNR values ~9.1 dB for QPSK modulation system. The results suggest that the SNR values of QPSK modulation gives improved performance of SNR ~6.6 dB for WiMAX network implementation

The SNR values derived at BER ~10^{-3} for (2x2) MIMO-OFDM communication system implementation on different wireless networks namely WLAN, WiMAX and LTE for QPSK modulation scheme are compared in figure 9.7.

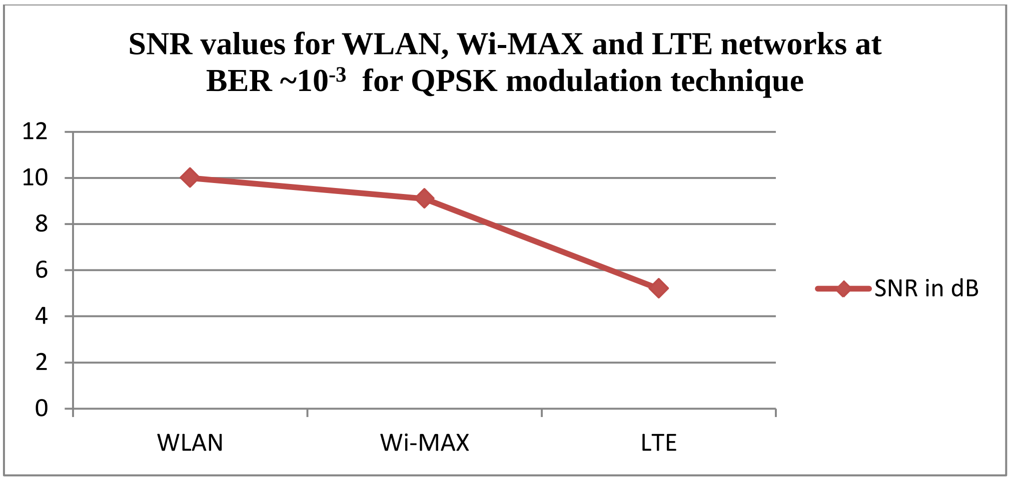


Figure 9.7: SNR values for WLAN, WiMAX and LTE networks at BER ~10^{-3} for QPSK modulation technique

The figure 9.7 depicts that for the MIMO-OFDM implementation on wireless Networks the SNR varies with different networks. The MIMO-OFDM system implementation on different networks shows highest SNR values ~10 dB for WLAN network and lowest SNR values ~5.2 dB for LTE network for QPSK modulation. The results suggest that the SNR values for (2x2) MIMO-OFDM system on LTE network shows improved performance SNR ~4.8 dB for network implementation.

As WLAN, WiMAX and LTE networks use different error coding techniques, the SNR values derived at BER ~10^{-3} for the (2x2) MIMO-OFDM implementation on the WLAN, WiMAX and LTE networks for different coding schemes and modulation techniques are summarized in table 9.1.

Table 9.1-Comparison table of SNR values for WLAN, Wi-MAX and LTE for different modulation schemes at BER ~ 10^{-3} with different coding techniques.

CODING TECHNIQUE USED	NETWORKS / MODULATION	QPSK SNR (dB)	16-QAM SNR (dB)	64-QAM SNR (dB)
CONVOLUTION CODING	WLAN (IEEE 802.11n)	10	15.5	16
REED-SOLOMON WITH CONVOLUTION CODING	WiMAX (IEEE 802.16-2009)	9.1	14	15.7
TURBO CODING	LTE	5.2	10	12.8

It can be seen clearly from the table 9.1 that at a BER threshold of approximately ~10^{-3}, the SNR values increases when modulation is changed from QPSK to 64-QAM modulation for all the three networks is consistent with theoretical considerations. Further the table shows that implementation of the MIMO-OFDM transmission on LTE networks for QPSK modulation shows lowest SNR ~5.2 dB compared to other networks. The LTE implementation of (2x2) MIMO–OFDM network indicates a large improvement in SNR ~4.8 dB compared to WLAN network and SNR ~3.9 dB compared to WiMAX networks. The (2x2) MIMO-OFDM implementation on the three networks indicates that the SNR values are very sensitive to the error coding techniques used by the networks. The lowest SNR ~5.2 dB values and the better SNR performance displayed by LTE network compared to WLAN and WiMAX networks can be attributed to the efficient Turbo coding schemes adopted by LTE networks.

In the present thesis work investigations on various MIMO systems has been carried out by studying the SNR performance as s function of BER. The lowest SNR values determined at BER threshold of ~10^{-3} for evaluating the performance of various MIMO-Multiplexing high bit rate transmission systems and implementation of MIMO systems on different wireless networks with different modulation schemes are summarized in Table 9.2

Table 9.2-Comparison table of SNR (E_b/N_0) Values for MIMO transmission systems with different modulation techniques at BER ~10^{-3} .

SL NO	MIMO TRANSMISSION SYSTEMS	BPSK SNR (dB)	QPSK SNR (dB)	16-QAM SNR (dB)
1	(2x2) MIMO-OSTBC system With ML-SIC Detection.	14.46	14.8	15.15
2	(2x2) MIMO-OFDM system with ML -SIC Detection.	12.6	12.75	13.58
3	Higher (4x4) MIMO–OFDM system with ML–SIC Detection.	10.57	10.82	11.51
4	Higher (4x4) MIMO–OFDM system with Monte Carlo detection	6.9	---	10.8
		QPSK SNR (dB)	16-QAM SNR (dB)	64-QAM SNR (dB)

5	**(2x2) MIMO-OFDM System Implemented on Wi-LAN (IEEE 802.16-2004) Networks**	**10**	**15.5**	**16**
6	**(2x2) MIMO-OFDM System Implemented on WiMAX (IEEE 802.16-2004) Networks.**	**9.1**	**14**	**15.7**
7	**(2x2) MIMO-OFDM System Implemented on LTE Networks.**	**5.2**	**10**	**12.8**

It is clearly indicated in the table 9.2 that the SNR performance of MIMO systems with different detection, multiplexing, higher MIMO systems and MIMO implementation on networks with BPSK, QPSK, 16-QAM and 64-QAM modulation system shows that in all the cases the SNR values increases from lower modulation to higher modulation schemes at BER ~10^{-3} as per theoretical considerations.

The studies on MIMO-OSTBC system carried out using different detection systems shows that and the ML-SIC detection and BPSK modulation offers lowest SNR ~14.46 dB at BER ~10^{-3} suggesting that it is an efficient system for higher bit rate transmission. Similar studies carried on MIMO-OFDM system using different detection systems shows that with ML-SIC detection system and BPSK modulation offers lowest SNR ~12.6 dB at BER ~10^{-3} indicating that it is an efficient system for higher bit rate transmission. The studies on the higher (4x4) MIMO-OFDM systems with ML-SIC and Monte Carlo detection system indicated that the higher MIMO system with Monte Carlo detection dipicts the lowest SNR ~ 6.9 dB at BER ~10^{-3} for BPSK modulation is a very efficient system for higher bit rate transmission. Further implementation of (2x2) MIMO-OFDM system on WLAN, WiMAX (IEEE 802.16-2009) and LTE networks with different coding techniques clearly demonstrated that the LTE network with turbo coding exhibit the lowest SNR ~5.2 dB at BER ~10^{-3} for QPSK modulation is the most efficient system for higher bit rate transmission.

9.2 Conclusions

From the detailed presentation of the results and discussions carried out in the thesis the following conclusions can be drawn:

1. The MIMO-OSTBC transceiver system shows increase in SNR (E_b/N_0) values with BER for lower BPSK to higher 16-QAM modulation system as per the theoretical considerations.
2. The MIMO-OFDM transceiver system for different modulation schemes displays the lowest SNR (E_b/N_0) for BPSK modulation and found to be more efficient compared to higher 16-QAM modulation schemes.
3. The MIMO-OFDM transceiver system for different detection systems for BPSK modulation shows the lowest SNR (E_b/N_0) ~14.46 dB at BER 10^{-3} and displays better performance of SNR ~10 dB (BR/BW efficiency ~10) compared to ZF-SIC detector systems. The MIMO-OSTBC system with BPSK modulation for ML detector system is found to be most efficient compared to other detection systems.
4. The MIMO-OFDM transceiver system shows that for BPSK modulation, indicate the lowest SNR (E_b/N_0) ~12.6 dB at BER 10^{-3} and better performance of SNR ~1.86 dB (BR/BW efficiency ~1.53) compared to OSTBC multiplexing systems. The MIMO-OFDM system is found to be more efficient compared to other multiplexing techniques.
5. The (4x4) MIMO-OFDM transceiver system indicate that for BPSK modulation, with ML detection system the lowest SNR (E_b/N_0) ~10.57 dB at BER ~10^{-3} and improved performance of SNR ~2.03 dB (BR/BW efficiency ~1.58) compared to lower (2x2) MIMO-OFDM system. The (4x4) MIMO-OFDM system with ML detection system is found to be more efficient compared to lower (2x2) MIMO systems.
6. The performance of higher (4x4) MIMO-OFDM transceiver system using Monte Carlo detection system with BPSK modulation indicates lowest SNR (E_b/N_0) ~ 6.9 dB at BER ~10^{-3} and improved performance of SNR ~ 3.6 dB (BR/BW efficiency ~2.29) compared to ML detection system. The (4x4) MIMO-OFDM

system with Monte Carlo detection system is found to be more efficient compared to ML detection system.

7. The MIMO-OFDM transceiver system implementation on WiMAX (IEEE 802.16d-2004) network for both MIMO transmission and receiving diversity shows that for BPSK modulation, depicts the lowest SNR (E_b/N_0) ~9 dB at BER ~10^{-3} and better performance of SNR ~5 dB (BR/BW efficiency ~ 3.16) compared to lower MIMO (MISO) systems. The (2x2) MIMO-OFDM system is implemented on WiMAX networks found to be more efficient compared to lower MIMO systems.

8. The MIMO-OFDM transceiver system implemented on WLAN, WiMAX and LTE network systems for QPSK modulation shows that the LTE–OFDM network offers lowest SNR (E_b/N_0) ~5.2 dB at BER ~10^{-3} and better performance in SNR ~4.8 dB (BR/BW efficiency ~3) compared to WLAN other network systems. The (2x2) MIMO–OFDM system implemented on LTE networks is found to be the most efficient system for higher bit rate transmission.

9. The MIMO-OFDM transceiver system implementation on LTE networks for QPSK modulation displays lowest SNR (E_b/N_0) ~5.2 dB at BER ~10^{-3} and better performance in SNR ~4.8 dB (BR/BW efficiency ~3) higher efficiency for bit rate transmission can be attributed to the advanced Turbo coding scheme adopted in the LTE network.

9.3 Future scope of the Research work

The future scope of this study is immense since it can be extended to test the performance of many upcoming transceiver techniques and new coding methods for MIMO-OFDM and the simulation can be easily modified to include more parameters. It can also be seen that parallel systems can be used to support multiple architectures, thereby enabling the ability to create high data rate OFDM communication system.

Additionally, it is necessary and significant to understand the performance of detection systems, and their associated complexity especially when higher order MIMO algorithms are employed. Their effect on problems such as estimation of the channel and its synchronisation should also be studied with respect to the performance. The studies will provide additional perspectives at the system level, and answer open research questions on the implementation of detection systems in OFDM.

The use of MIMO and OFDM next-generation networks can be used to support the ever increasing customer demand for high-speed wireless broadband communication networks that can serve a variety of applications such as gaming, on-demand video and other multimedia applications.

Further, it can be clearly seen that OFDM systems have some unique advantages over other access technologies such as CDMA and TDMA that are employed in previous generation mobile cellular networks. OFDM is a robust technology that provides significant performance improvements in dense areas, with multipath channel conditions.

Also, a wide range of challenges can be addressed through the use of OFDM technology such as spectrum limitations, bandwidth demands and power constraints. There is a clear need to develop new solutions that can provide even better spectral efficiency, while providing an ability to increase the overall throughput of the wireless channel. It should not only support multiple users within the smaller coverage area, but also simultaneously enhance the end-user experience, while reducing the transport network cost of the carrier. This can create an efficient and flexible system that can cater to the ever-changing needs of the wireless consumer.

MIMO-OFDM systems when incorporated in mobile communication systems are useful in achieving high-spectral efficiency. This can be used to transform mobile systems since these systems have limited capabilities with respect to radio resources and data transmission rates. With increasing spectrum requirements, efficient usage of available spectrum is an essential and ever increasing need in existing and next generation wireless networks and communications systems. MIMO-OFDM has become a default candidate in many wireless networking standards and in addition to improving spectral efficiency, it can also be useful in improving coverage ranges of cellular systems. Future work can focus on upcoming multiple access schemes like single carrier frequency division multiple access (SC-FDMA) and also evaluating the performance of OFDM and SC-FDMA systems in next-generation wireless networks like IEEE 802.11ac and IEEE802.11ad systems, 3GPP Long Term Evolution Advanced (LTE-A) and other newer standards. Also novel channel estimation techniques can be evaluated to further improve the efficiency of MIMO-OFDM systems.

REFERENCES

[1] A R Kaye and D.A. George,” Transmission of multiplexed PAM signals over multiple channels and diversity systems”, IEEE transactions on Communication technology, Vol.COM-18, pp 520-525, October 1970.

[2] Branderburg, Wyner,” The Capacity of the Gaussian Channel with Memory and the Multivariate Case”, Vol. 53, No. 5, pp 745–778, May/June 1974 (1975, 1976).

[3] Jack Winters and Jack Salz at Bell Laboratories published in the journal J. Salz, “Digital transmission over cross-coupled linear channels”, AT&T Technical Journal, Vol. 64, No. 6, pp 1147–1159, July–August 1985.

[4] A J Paulraj and T Kailath,” Increasing capacity in wireless broadcast systems using distributed transmission/directional reception”, U.S.Patent 5345599, 1994.

[5] Gregory G Raleigh and John M Cioffi,” Spatial-temporal coding for wireless communications”, IEEE transactions on communications, Vol. 46, No. 3, pp 357-366, March 1998.

[6] G. J. Foschini, “Layered space–time architecture for wireless communication in a fading environment when using multiple antennas,” Bell Labs Syst. Tech. J., Vol. 1, pp 41–59, Autumn 1996.

[7] J. H. Winters, “The diversity gain of transmit diversity in wireless systems with Rayleigh fading”, IEEE Trans. Veh. Technol., Vol. 47, No. 1, pp. 119–123, February 1998.

[8] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and Cooperative MIMO in Sensor Networks". IEEE J. Select. Areas of Communication 22 (6): 1089–1098, August, 2004.

[9] Sam P. Alex and Louay M.A. Jalloul, "Performance Evaluation of MIMO in IEEE802.16e/WiMAX", IEEE J. of Selected Topics in Signal Processing, Vol. 2, No. 2, April, 2008.

[10] A. J. Paulraj, D. Gore, R. U. Nabar, and H. B¨olcskei, “An Overview of MIMO Communications - A Key to Gigabit Wireless”, IEEE LI, November 15, 2006.

[11] S. Mudulodu and A. Paulraj, “A Transmit Diversity Scheme for Frequency Selective Fading Channels,” Proceedings of the IEEE Global Telecommunications Conference 2000, Vol. 2, pp 1089-1093, November 27, 2000.

[12] Kai-Kit Wong, Ross D. Murch, Khaled Ben Letaief, ” Performance Enhancement of Multiuser MIMO Wireless Communication Systems”, IEEE Transactions On Communications, Vol. 50, No. 12, pp 1960-1970, December 2002.

[13] Nagarajan Sathish Kumar, K. R. Shankar Kumar, “BER Performance Analysis of ZF, ML and MMSE Equalizers for MIMO Wireless Communication Receiver”, European Journal of Scientific Research, Vol. 59, No. 4, pp. 522-532, Inc 2011.

[14] Swetamadhab Mahanta, Sakshi Tiwari, Ramesh Bharti,” BER Analysis of MIMO System Detection Using Rayleigh Channel”, International Journal of Modern Communication Technologies & Research (IJMCTR), Vol. 2, Issue 5, pp 27-30, May 2014.

[15] Narendra M R,” Study of Transmission Characteristics of MIMO System for Different Modulation Techniques”, International Journal of Innovative Technology and Exploring Engineering (IJITEE), Vol. 3, Issue 1, pp 151-154, June 2013.

[16] Siavash M. Alamouti,” A simple Receiver Diversity Techniques for wireless communications , IEEE Journal on Select Areas in Communications, Vol. 16, No.8, pp 1451-1458, October 2008.

[17] Tianyu Mao and Mehul Motani, “STBC-VBLAST for MIMO Wireless Communication Systems”, IEEE Transactions On Broadcasting, Vol. 50, No. 4, December 2010.

[18] Van-Su Pham, Minh-Tuan Le, Linh Mai, and Giwan Yoon, “Low Complexity Maximum-likelihood Decoder for VBLAST-STBC scheme in MIMO Wireless Communication Systems”, IEEE Communications Letters, Vol. 2, June 2012.

[19] Chen Meng and Jamal Tuqan, “Precoded STBC-VBLAST for MIMO Wireless Communication Systems”, pp 337-340, ICASSP 2007.

[20] V. Tarokh, N. Seshadri, and A. R. Calderbank, “Space-time codes for high data rate wireless communication: performance criterion and code construction,” IEEE Trans. Inform. Theory, Vol. 44, No. 2, pp 744–765, March 1998.

[21] S.M. Alamouti, "A simple transmit diversity technique for wireless communications". IEEE Journal on Selected Areas in Communications 16 (8): 1451–1458, October 1998.

[22] Marzetta, T.L. and Hochwald, B.M, "Capacity of a mobile multiple-antenna communication link in Rayleigh flat fading". IEEE Transactions of Information Theory 45 (1): 139–157, January 1999.

[23] V. Tarokh and H. Jafarkhani, "A Differential Detection Scheme for Transmit Diversity". IEEE Journal on Selected Areas in Communications 18 (7): 1169–1174, July 2000.

[24] Vahid Tarokh, Hamid Jafarkhani, A. R. Calderbank,”Space–Time Block Codes from Orthogonal Designs”, IEEE Transactions On Information Theory, Vol. 45, No. 5, pp 1456-1467, July 1999.

[25] L. Zheng and D. N. C. Tse,"Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels". IEEE Trans. Inf. Th. 49 (5): 1073–1096, May 2003.

[26] I. Emre Telatar "Capacity of multi-antenna gaussian channels".European Transactions on Telecommunications, 10 (6): 585–595, November 1999.

[27] Z. Shang, W. Sun and X. Zhou, "Vector sampling expansions in shift invariant subspaces expansions in shift invariant subspaces". Journal of Mathematical Analysis and Applications 325 (2): 898–919, January 2007.

[28] G. J. Foschini and M. J. Gans, “On limits of wireless communications in a fading environment when using multiple antennas,” Wireless Personal Commun., Vol. 6, No. 3, pp 311–335, March 1998.

[29] Quadeer, A.A., Dhahran, Sohail, M.S,” Enhanced channel estimation using Cyclic Prefix in MIMO STBC OFDM systems”, 2010.

[30] Weifeng Su, Stella N. Batalama, Dimitris A. Pados,” On Orthogonal Space-Time Block Codes and Transceiver Signal Linearization”, IEEE Communications Letters, Vol. 10, No. 2, pp 91-93, February 2006.

[31] Luis Miguel Cort´es-Pe˜na,” MIMO Space-Time Block Coding (STBC): Simulations and Results”, Design Project: Personal and Mobile Communications, Georgia Tech (Ece6604), pp 1-8, April 2009.

[32] Shubhangi Chaudhary, A.J. Patil,” Performance Analysis of MIMO-Space Time Block Coding With Different Modulation Techniques by, ICTACT Journal On Communication Technology, Vol. 3, Issue 1, pp 510-514, March 2012.

[33] Lakshmi Prasanna.P, G.Rama Krishna,” Diversity analysis in MIMO systems using OSTBC (Orthogonal Space Time Block Codes)”, International Journal of Emerging Technology and Advanced Engineering (IJETAE), Vol. 2, Issue 9, pp 243-247, September 2012.

[34] Lucian Andrei Perişoară,” BER Analysis of STBC Codes for MIMO Rayleigh Flat Fading Channels”, Telfor Journal, Vol. 4, No. 2, pp 78-82, 2012.

[35] Khoa T. Phan, Chintha Tellambura,” Capacity Analysis for Transmit Antenna Selection Using Orthogonal Space-Time Block Codes”, IEEE Communications Letters, Vol. 11, No. 5, pp 423-425, May 2007.

[36] Dao and C. Tellambura, "Quasi-orthogonal STBC with minimum decoding complexity: performance analysis, optimal signal transformations, and antenna selection diversity," IEEE Transactions on Communications, Vol. 56, No. 6, pp. 849-853, June 2008.

[37] Dae-Ki Hong, Young-Jo Lee, Daesik Hong, ”Robust Frequency Offset Estimation for Pilot Symbol Assisted Packet CDMA With MIMO Antenna Systems”, IEEE Communications Letters, Vol. 6, June 2012.

[38] Ruly Lai-U Choi, Ross D. Murch, “MIMO CDMA Antenna System for SINR Enhancement”, IEEE Transactions On Wireless Communications, Vol. 2, No. 2, March 2003.

[39] V.Nagarajan and P. Dananjayan ,” Performance Analysis of MIMO MC-DS/CDMA System Using Chaotic Spreading Sequence”, International Journal of Computer and Electrical Engineering, Vol. 2, No. 2, pp 329-333, April, 2010.

[40] Peter W. C. Chan, Ernest S. Lo, “Performance Comparison of Downlink Multiuser MIMO-OFDMA and MIMO-MC-CDMA withTransmit Side Information-Multi-Cell Analysis”, IEEE Transactions On Broadcasting, Vol. 50, No. 4, December 2010.

[41] Wan Choi, “Multiuser Antenna Partitioning for Cellular MIMO–CDMA systems”, IEEE Communications Letters, Vol. 12, June 2007.

[42] K. Vishnu Vardhan, Saif K. Mohammed, A. Chockalingam, “A Low Complexity Detector for Large MIMO Systems and Multicarrier CDMA Systems”, IEEE Journal On Selected Areas In Communications, Vol. 26, No. 3, pp 473-485, April 2008.

[43] B.Raja Ramesh,Umasankar.Ch,” A Performance Evaluation of CDMA/MIMO Communication System using permutation Spreading”, International Journal of Engineering Trends and Technology (IJETT), Vol. 4, Issue 6, pp 2283-2287, June 2013.

[44] Pritam Som ,A. Chockalingam,” Multiuser Detection in Large-Dimension Multicode MIMO-CDMA Systems with Higher-Order Modulation”, The 2011 Military Communications Conference - Track 1 - Waveforms and Signal Processing, pp 364-370, IEEE 2011.

[45] Karmjeet Singh, Rajbir Kaur,” Performance Analysis of MIMO Multi-Carrier CDMA with QPSK Modulation in Rayleigh Channel”, International Journal of Engineering Research and Applications (IJERA), Vol. 3, Issue 4, pp.2562-2565, July-August 2013.

[46] P. Sreesudha, M. Vijaya Lakshmi,” BER Enhancement of MIMO-CDMA based on Space-Time Block Codes”, David Bracewell, et al. (Eds): AIAA 2011, CS & IT 03, pp. 21–26, 2011, © CS & IT-CSCP 2011.

[47] H. B¨olcskei,“ MIMO-OFDM wireless systems: Basics, perspectives, and challenges”, IEEE Journal on Wireless Communications, Vol. 13, No. 4, pp 31-37, August 2006.

[48] Orlandos Grigoriadis, H. Srikanth Kamath, Iaeng, “BER Calculation Using Matlab Simulation For OFDM Transmission”, Proceedings of the International Multi-Conference of Engineers and Computer Scientists 2008, Vol. 2 IMECS, pp 19-21, March 2008.

[49] Myung-Sun Baek, Mi-Jeong Kim, Young-Hwan You and Hyoung-Kyu Song, “Semi-Blind Channel Estimation and PAR Reduction for MIMO-OFDM System with Multiple Antennas”, IEEE Transactions On Broadcasting, Vol. 50, No. 4, December 2004.

[50] Vineet Sharma, Anuraj Shrivastav, Anjana Jain, Alok Panday," BER performance of OFDM-BPSK,-QPSK,-QAM over AWGN channel using forward Error correcting code", International Journal of Engineering Research and Applications (IJERA), Vol. 2, Issue 3, pp 1619-1624, May-June 2012.

[51] Ammar Ali Sahrab, Ion Marghescu," MIMO-OFDM: Maximum Diversity Using Maximum Likelihood Detector", pp 1-4, 978-1-4799-2385-4/14/$31.00 ©2014 IEEE.

[52] Z. Zhang, W. Zhang and C. Tellambura, "MIMO-OFDM Channel Estimation in the Presence of Frequency Offsets," IEEE Transactions on Wireless Communications, Vol. 7, No. 6, pp 2329-2339, June 2008.

[53] P.Sunil Kumar, Dr. M.G.Sumithra, M.Sarumathi," Performance Analysis of Rayleigh Fading Channels in MIMO-OFDM Systems using BPSK and QPSK Modulation Schemes", The SIJ Transactions on Computer Networks & Communication Engineering (CNCE), Vol. 1, No. 1, pp 12-17, March-April 2013.

[54] K.Vidhya , K.R.Shankarkumar," BER Performance of MIMO-OFDM System using STTC", International Journal of Scientific and Research Publications, Volume 3, Issue 2, pp 1-5, February 2013.

[55] Parul Wadhwa , Gaurav Gupta," BER Analysis & Comparison of Different Equalization Techniques for MIMO-OFDM System", International Journal of Advanced Research in Computer Science and Software Engineering, Vol. 3, Issue 6, pp 1682-1688, June 2013.

[56] Amol Kumbhare, Smita Jolania, DR Rajesh Bodade, "BER Performance Comparison of MIMO OFDM with Channel Equalizers", International Journal of Advanced Research in Computer Science and Software Engineering, Vol. 4, Issue 2, February 2014.

[57] A. Omri and R. Bouallegue,” New Transmission Scheme for MIMO-OFDM System”, International Journal of Next-Generation Networks (IJNGN), Vol.3, No.1, pp 11-19, March 2011.

[58] Ye (Geoffrey) Li, Jack H. Winters, Nelson R. Sollenberger,” MIMO-OFDM for Wireless Communications: Signal Detection With Enhanced Channel Estimation”, IEEE Transactions On Communications, Vol. 50, No. 9, pp 1471-1477, September 2002.

[59] Anuj Vadhera, Lavish Kansal,” BER Analysis of 2x2 Spatial Multiplexing under AWGN and Rayleigh Channels for Different Modulations”, Global Journal of Researches in Engineering, Vol. 13, Issue 11, version 1, 2013.

[60] Rohit Gupta, Amit Grover,” BER Performance Analysis of MIMO Systems Using Equalization Techniques”, Innovative Systems Design and Engineering, Vol. 3, No 10, pp 11-25, 2012.

[61] Jitendra R.Shishangiya, Ashish Makwana, Dr. Komal R Borisagar,” Performance Comparison Of Non-Linear Detectors For MIMO System In Spatial Multiplexing”, Journal Of Information, Knowledge And Research In Electronics And Communication Engineering, ,Vol. 2, Issue 2, pp 714-717, November 12 - October 13.

[62] Ms. Hiral Patel, Dr.MinalSaxena,” An Efficient Comparison of MIMO-OFDM Detection using Spatial Multiplexing techniques”, International Journal of Computational Engineering, Vol, 03, Issue, 6, pp 48-53, June 2013.

[63] Yue Shang, Xiang-Gen Xia,” Space–Time Block Codes Achieving Full Diversity With Linear Receivers”, IEEE Transactions On Information Theory, Vol. 54, No. 10, pp 4528- 4546, October 2008.

[64] N.Sathish Kumar, Dr.K.R.Shankar Kumar,” Performance Analysis of M*N Equalizer based Minimum Mean Square Error (MMSE) Receiver for MIMO Wireless Channel”, International Journal of Computer Applications, Vol. 16– No.7, pp 47-50, February 2011.

[65] Dhruv Malik, Deepak Batra," Comparison of various detection algorithms in a MIMO wireless communication receiver", International Journal of Electronics and Computer Science Engineering, ISSN- 2277-1956, Vol. 1, No.3, pp 1678-1685.

[66] Allert van Zelst, and Tim C. W. Schenk, "Implementation of a MIMO OFDM-Based Wireless LAN System", IEEE Transaction on Signal Processing, Vol.52, No. 2, pp 483-494, February 2004.

[67] Tim C.W. Schenk, Guido Dolmans and Isabella Modonesi "Throughput of a MIMO OFDM based WLAN system" Proc. Symposium IEEE Benelux Chapter on Communications and Vehicular Technology, 2004.

[68] Christoph Spiegel, Jens Berkmann, Zijian Bai, Tobias Scholand, Christian Drewes," MIMO Schemes In UTRA LTE, A Comparison", IEEE 2008, pp 2228-2232, 2008.

[69] Mojtaba Seyedzadegan and Mohamed Othman, "IEEE 802.16: WiMAX Overview, WiMAX Architecture," International Journal of Computer Theory and Engineering Vol. 5, No. 5, pp 784-787, 2013.

[70] Wang, Mingxi, "WiMAX physical layer: Specifications overview and performance evaluation," Consumer Communications and Networking Conference (CCNC), 2011 IEEE, pp 9-12, January 2011.

[71] Prof. LajosHanzo, Dr. Yosef (Jos) Akhtman and Dr. Li Wang, "MIMO-OFDM for LTE, Wi-Fi and WiMAX Coherent versus Non-coherent and Cooperative Turbo-transceivers," 2011.

[72] Manal Al-bzoor and KhaledElleithy, "Wimax Basics from Phy Layer to Scheduling and Multicasting Approaches," International Journal of Computer Science & Engineering Survey (IJCSES), Vol.2, No.1, February 2011.

[73] HardeepKaur and M L Singh, "Bit Error Rate Evaluation of IEEE 802.16 (WiMAX) in OFDM System," International Journal of Computer Applications, 10-13 February 2012, pp 40(12). Published by Foundation of Computer Science, New York, USA.

[74] J. Mountassir, H. Balta, M. Oltean, M. Kovaci and A. Isar, “A physical layer simulator for WiMAX in Rayleigh fading channel,” 6th IEEE International Symposium on Applied Computational Intelligence and Informatics (SACI) 2011, pp 281-284, 2011.

[75] Yunho Jung, Jiho Kim, Seongjoo Lee, Hongil Yoon, and Jaeseok Kim, “Design and Implementation of MIMO-OFDM Baseband Processor for Wireless MANs”, IEEE Transactions on circuits and systems-II Express Briefs, Vol. 54, No. 7, July 2007.

[76] Gazi Faisal Ahmad Jubair; “Performance Evaluation of IEEE 802.16e (Mobile WiMAX) in OFDM Physical Layer”, ME Thesis of Blekinge Institute of Technology 2009.

[77] Simmi Dutta and Devanand Padha,“ Performance Evaluation Simulation of IEEE 802.11a OFDM Using Indoor Environment Channel Models”, IETE Journal Of Research, Vol. 57, Issue 1, January-February 2011.

[78] Shau-Yu Cheng, Chueh-An Tsai, and Terng-Yin Hsu,“ Channel Estimator and Aliasing Canceller for Equalizing and Decoding Non-Cyclic Prefixed Single-Carrier Block Transmission via MIMO-OFDM Modem”, IEEE Transactions On Very Large Scale Integration (Vlsi) Systems, Vol. 19, No. 1, January 2011.

[79] Jihyung Kim, Sangho Nam, Dong Seung Kwon and Daesik Hong, “Efficient Preamble Structures for MIMO OFDM-based WLAN Systems”, IEEE 2007.

[80] S. B. Weinstein, “Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform”, IEEE Transactions on Communication Technology, Vol. 19, Issue 5, October 1971.

[81] B. Sklar, “Rayleigh fading channels in mobile digital communication systems .i. characterization”, IEEE Commun. Mag., Vol. 35, No. 7, pp 90–100, 1997.

[82] D. P. Taylor, G. M. Vitetta, B. D. Hart, and A. Mämmelä, “Wireless channel equalization”, Eur. Trans. Telecom., Vol. 9, No. 2, pp 117–143, March–April 1998.

[83] Heidi Steendam, Marc Moeneclaey, “Optimization of OFDM on Frequency-Selective Time Selective Fading Channels”, IEEE Trans. Signal Processing, Vol. 32, No. 10, pp 1431–1441, September 1998.

[84] P. F. Driessen and G. J. Foschini, “On the capacity formula for multi- ple input multiple output wireless channels: A geometric interpretation”, IEEE Trans. Commun., Vol. 47, No. 2, pp 173–176, February. 1999.

[85] J. Lu, K. B. Letaief, J. C. Chuang, and M. L. Liou, “M-PSK and M-QAM BER computation using signal-space concepts”, IEEE Trans. Commun., Vol. 47, pp 181–184, February 1999.

[86] Vahid Tarokh, Hamid Jafarkhani, A. Robert Calderbank, “Space–Time Block Coding for Wireless Communications: Performance Results”, IEEE Journal On Selected Areas In Communications, Vol. 17, No. 3, pp 451-460, March 1999.

[87] C. Komninakis, C. Fragouli, A. H. Sayed, and R. D. Wesel, “Channel estimation and equalization in fading”, in Proc. 33rd Asilomar Conf. Signals, Syst., Comput., pp 1159–1163, October 1999.

[88] D.-S. Shiu, G. J. Foschini, M. J. Gans, and J. M. Kahn, “Fading correlation and its effect on the capacity of multielement antenna systems”, IEEE Trans. Commun., Vol. 48, No. 3, pp 502–513, March 2000.

[89] I. E. Telatar and D. N. C. Tse, “Capacity and mutual information of wideband multipath fading channels,” IEEE Trans. Information Theory, Vol. 46, No. 4, pp 1384–1400, July 2000.

[90] T A. Chen, M. P. Fitz, W.Y. Kuo, M. P. Fitz, M. D. Zoltowski, J. H. Grimm, “A space-time model for frequency nonselective Rayleigh fading channels with applications

to space-time modems", IEEE J. Select. Areas Commun., Vol. 18, pp 1175–1190, July 2000.

[91] H. Bolcskei and A. J. Paulraj, "Space-Frequency Coded Broadband OFDM systems", Proceedings of the IEEE Wireless Communications and Networking Conference, Vol. 1, pp 1-6, September 2000.

[92] David R. Pauluzzi and Norman C. Beaulieu, "A Comparison of SNR Estimation Techniques for the AWGN Channel", IEEE Transactions on Communications, Vol. 48, Issue 10, October 2000.

[93] D.W. Bliss, K.W. Forsythe, A.O. Hero, and A.L. Swindlehurst, "MIMO Environmental Capacity Sensitivity", Thirty- Fourth Asilomar Conf. on Signals, Systems & Computers 1, Pacific Grove, Calif., pp 764–768, 29 October –1 November 2000.

[94] Sriram Vishwanath, Nihar Jindal, Andrea Goldsmith," On the Capacity of Multiple Input Multiple Output Broadcast Channels", pp 1444-1450, IEEE 2002.

[95] W. Henkel, G. Taubock, P. Olding, "The cyclic prefix of OFDM/DMT – an analysis," International Zürich Seminar on Broadband Commu. Zürich, Switzerland, February 2002.

[96] A. F. Molisch, M. Steinbauer, M. Toeltsch, E. Bonek, and R. S. Thom¨ a, "Capacity of MIMO systems based on measured wireless channels", IEEE J. Select. Areas Commun., Vol. 20, No. 3, pp 561–569, April 2002.

[97] Christos Komninakis, Christina Fragouli, Ali H. Sayed, Richard D. Wesel," Multi-Input Multi-Output Fading Channel Tracking and Equalization Using Kalman Estimation", IEEE Transactions On Signal Processing, Vol. 50, No. 5, pp 1065-1076, May 2002.

[98] L. Dong, R. W. Heath, and H. Ling, "MIMO wireless handheld terminals using antenna pattern diversity", submitted to IEEE Trans. Wireless Commun., June 2002.

[99] A. Stamoulis, S. N. Diggavi, and N. Al-Dhahir, “Intercarrier interference in MIMO OFDM”, IEEE Transactions on Signal Processing, Vol. 50, pp 2451–2464, October 2002.

[100] B. Muquet, Z. Wang, G. B. Giannakis, M. de Courville, and P. Duhamel, “Cyclic prefixing or zero padding for wireless multicarrier transmissions”, IEEE Trans. Commun., Vol. 50, No. 12, pp 2136–2148, December 2002.

[101] David J. Love, Robert W. Heath,” Equal Gain Transmission in Multiple-Input Multiple-Output Wireless Systems”, IEEE Transactions on Communications, Vol. 51, No. 7, pp 1102-1110, July 2003.

[102] David Gesbert, Mansoor Shafi, Da-shan Shui, Peter J. Smith, Ayman Naguib. From theory to practice: An overview of MIMO space-time coded wireless systems. IEEE journal on selected areas in communications 2003; 21(3):281.

[104] Arogyaswami J. Paulraj, Dhananjay A. Gore , Rohit U. Nabar, Helmut Bölcskei,” An Overview of MIMO Communication-A Key to Gigabit Wireless”, Proceedings of the IEEE 2004;92(2):205-207.

[105] Z. Chen, J. Yuan, B. Vucetic, and Z. Zhou, “Performance of Alamouti scheme with transmit antenna selection”, IEEE Int. Symposium on Personal, Indoor and Mobile Radio Commun. (PIMRC), Vol. 2, pp 1135–1141, September 2004.

[106] T. Cui and C. Tellambura, "Approximate ML detection for MIMO systems using multistage sphere decoding", IEEE Signal Processing Letters, Vol. 12, No. 3, pp 222-225, March 2005.

[107] Z. Chen, “Asymptotic performance of transmit antenna selection with maximal-ratio combining for generalized selection criterion”, IEEE Commun. Lett., Vol. 8, pp 247–249, April 2005.

[108] Z. Chen, J. Yuan, and B. Vucetic, “Analysis of transmit antenna selection/maximal-ratio combining in Rayleigh fading channels”, IEEE Trans. Veh. Technol., Vol. 54, No. 4, pp 1312 – 1321, July 2005.

[109] Kyung Won Park and Yong Soo Cho," An MIMO-OFDM technique for high-speed mobile channels", IEEE Communications Letters, Volume 9, No. 7, pp 604 – 606, July 2005.

[110] D. Dao and C. Tellambura, " Intercarrier interference self-cancellation space-frequency codes for MIMO-OFDM", IEEE Transactions on Vehicular Technology, Vol. 54, No. 5, pp 1729-1738, September 2005.

[111] S. Yang, and F. Kaltenberger, “MIMO Algorithms for Wireless LAN”, Proceedings Wireless Congress, Munich, Germany, October 2005.

[112] D. J. Love, “On the probability of error of antenna-subset selection with space-time block codes”, IEEE Trans. Commun., Vol. 53, pp 1799–1803, November 2005.

[113] M. Biguesh, and A.B. Gershman, “Training-based MIMO channel estimation: a study of estimator tradeoffs and optimal training signals”, IEEE Trans. Signal Process, Vol.54, No.3, pp 884- 893, March 2006.

[114] B. Farhang-Boroujeny, H. zhu, and Z. Shi, “Markov chain monte carlo Algorithms for CDMA and MIMO communication systems”, IEEE Trans. Signal Process., Vol. 54, No. 5, pp 1896-1909, May 2006.

[115] Katalinic R. Nagy and R. Zentnerl “Benefits of MIMO Systems in Practice: Increased Capacity, Reliability and Spectrum Efficiency”, 48th International Symposium ELMAR, Zadar, Croatia, June 2006.

[116] Hanan Weingarten, Yossef Steinberg, Shlomo Shamai (Shitz),” The Capacity Region of the Gaussian Multiple-Input Multiple-Output Broadcast Channel”, IEEE Transactions On Information Theory, Vol. 52, No. 9, pp 3936-3964, September 2006.

[117] S. Kaviani and C. Tellambura, “Closed-form BER analysis for antenna selection using orthogonal space-time block codes,” IEEE Commun. Lett., Vol. 10, pp 704–706, October 2006.

[118] M.Cicerone,O.Simeone and U.Spagnolini,“ Channel Estimation for MIMO-OFDM Systems by Modal Analysis/Filtering”, IEEE Transaction on Communication, Vol.54, No.11, pp 2062-2074, November 2006.

[119] L. Yang and J. Qin, “Performance of Alamouti scheme with transmit antenna selection for M-ary signals,” IEEE Trans. Wireless Commun., Vol. 5, No. 12, pp 3365–3369, December 2006.

[120] Khoa T. Phan, Chintha Tellambura,” Capacity Analysis for Transmit Antenna Selection Using Orthogonal Space-Time Block Codes”, IEEE Communications Letters, Vol. 11, No. 5, pp 423-425, May 2007.

[121] Andreas M¨uller and Joachim Speidel,” Orthogonal STBC in General Nakagami-m Fading Channels: BER Analysis and Optimal Power Allocation”, IEEE Vehicular Technology Conference (VTC), Dublin, Ireland, pp 1698, April 2007.

[122] T. Cui, C. Tellambura and Y. Wu, "Constrained Detection for Spatial-multiplexing Multiple-Input Multiple-Output Systems," IEEE Transactions on Vehicular Technology, Vol. 57, No. 3, pp 1537-1547, May 2008.

[123] K. Etemad, “Overview of Mobile WiMAX Technology and Evolution”, IEEE Communication Mag., Vol. 46, No. 10, pp 31–40, October 2008.

[124] F. S. Al-Kamali, M. I. Dessouky, B. M. Sallam ,F. E. A. El-Samie,” Frequency Domain Interference Cancellation For Single Carrier Cyclic Prefix CDMA Systems”, Progress In Electromagnetics Research B, Vol. 3, pp 255–269, 2008.

[125] Pitchaiah, V. Erceg, D. Baum, R. Krishnamoorthy and A. Paulraj, “Modeling of Multiple-Input Multiple-Output (MIMO) radio channel based on outdoor measurements conducted at 2.5GHz for fixed BWA applications”, Proc. Int. Conf. Communications, 2008.

[126] Wan Choi, Jeffrey G. Andrews and Robert W. Heath, Jr, “Antenna Partitioning for Multiuser MIMO-CDMA”, IEEE Transactions On Wireless Communications, Vol. 2, No. 2, March 2009.

[127] Shailendra Mishra, D.S.Chauhan,” Link Level Performance of Multiple input Multiple Output (MIMO) System”, International Journal of Control and Automation, Vol.2, No.3, pp 29-41, September 2009.

[128] Jian Xu, Sang-Jin Lee, Woo-Seok Kang and Jong-Soo Seo, “Adaptive Resource Allocation for MIMO-OFDM Based Wireless Multicast Systems”, IEEE Transactions on Broadcasting, Vol. 56, No. 1, March 2010.

[129] J. S. Baek, and J. S. Seo, “Effective symbol timing recovery based on pilot-aided channel estimation for MISO transmission mode of DVBT2 system”, IEEE Trans. Broadcast., Vol. 7, No. 2, pp 2603–2611, June 2010.

[130] V. K. Jain D. Divakaran,” Channel Estimation for a New High Performance MIMO STC-OFDM WLAN System”, IEEE Communications Letters, Vol. 6, June 2010.

[131] G. Caire, N. Jindal, M. Kobayashi, and N. Ravindran,” Multiuser MIMO achievable rates with downlink training and channel state feedback”, IEEE Trans. Inf. Theory, 56(6):2845–2866, 2010.

[132] Emil Bjöorson, Björn Ottersten,” A framework for training-based estimation in arbitrary correlated Racian MIMO channels with Racian disturbance”, IEEE transaction on signal processing 2010; 58(3)1807.

[133] I-Wei Lai, Gerd Ascheid, Heinrich Meyr and Tzi-Dar Chiueh, “Efficient Channel Adaptive MIMO Detection Using Just-Acceptable Error Rate”, IEEE Transactions On Wireless Communications, Vol. 10, No. 1, January 2011.

[134] J. Goldberger and A. Leshem, “MIMO detection for high-order QAM based on a Gaussian tree approximation”, IEEE Trans. Inform. Theory, Vol. 57, No. 8, pp 4973-4982, August 2011.

[135] P. Som, T. Datta, N. Srinidhi, A. Chockalingam, and B. S. Rajan,“ Low-complexity detection in large-dimension MIMO-ISI channelsusing graphical Models”, IEEE Jl. Sel. Topics in Signal Processing(JSTSP): Special issue on Soft Detection for Wireless Transmission, Vol. 5, No. 8, pp 1497-1511, December 2011.

[136] John W. M. Rogers, Dave G. Rahn, Mark S. Cavin, Foster F. Dai, Neric Fong, Richard Griffith, JoseMacedo, David Moore and Mike Toner, “A Fully Integrated Multi-Band MIMO WLAN Transceiver RFIC”, IEEE Transactions On Broadcasting, Vol. 50, No. 4, December 2011.

[137] D. Senaratne and C. Tellambura, "Spatial Multipath Resolution for MIMO Systems", IEEE Wireless Communications Letters, Vol. 1, No. 1, pp 10-13, February 2012.

[138] Damith Senaratne, Chintha Tellambura, Himal A. Suraweera,” Performance Analysis of MIMO Channel Inversion in Rayleigh Fading”, IEEE Transactions On Vehicular Technology, Vol. 61, No. 3, pp 1188-1196, March 2012.

[140] Nuzhat Tasneem Awon, Md. Mizanur Rahman, Md. Ashraful Islam, A.Z.M. Touhidul Islam,” Effect of AWGN & Fading (Raleigh & Rician) channels on BER performance of a WiMAX communication System”, (IJCSIS) International Journal of Computer Science and Information Security,Vol. 10, No. 8, August 2012, pp 11-17.

[141] Daniel Sacristan-Murga, Miquel Payaro and Antonio Pascual-Iserte, “Transceiver Design Framework for Multiuser MIMO OFDM Broadcast Systems with Channel Gram

Matrix Feedback", IEEE Transactions on Wireless Communications, Vol. 11, No. 5, MAY 2012.

[142] Sakshi Gupta, Himanshu Sharma, "Performance Investigation for Different Modulation Techniques in WCDMA with Multipath Fading Channels", International Journal of Advanced Research in Computer Science and Software Engineering, Vol. 2, Issue 7, July 2012 .

[143] Nazia Parveen, D.S.Venkateswarlu," Implementation of Space-Time Block Coding (STBC) Using 2 Transmit and 2 Receive Antennas", International Journal of Emerging Technology and Advanced Engineering (IJETAE), Vol. 2, Issue 10, October 2012.

[144] Hsin-Lei Lin, Robert C. Chang, "Implementation of Synchronization for 2×2 MIMO WLAN System", IEEE Transactions On Broadcasting, Vol. 52, No. 14, December 2012.

[145] R.O. Abolade , Z. K. Adeyemo," Adaptive Modulation Performance In MIMO-OSTBC Over Rayleigh Fading Channel" , International Journal of Engineering & Computer Science IJECS-IJENS, Vol. 12, No. 6, pp 21-25, December 2012.

[146] A. G. R. G. Hanna and A. H. Zekry, "Development of WiMAX physical layer building blocks", Third International Conference on Intelligent Systems Modeling and Simulation 2012, pp 537-541, 2012.

[147] Gurpreet Singh, Priyanka Mishra, Rahul Vij," BER Analysis Of V-Blast MIMO Systems Under Various Channel Modulation Techniques In Mobile Radio Channels", 2012 International Conference on Computer Technology and Science (ICCTS 2012) IPCSIT, Vol. 47 (2012) © (2012) IACSIT Press, pp 123-127, Singapore.

[148] Rohit Gupta, Amit Grover," BER Performance Analysis of MIMO Systems Using Equalization Techniques", Innovative Systems Design and Engineering, Vol. 3, No. 10, pp 11-25, 2012.

[149] S.P.Premnath, J.R.Jenifer, C.Arunachalaperumal," Performance Enhancement Of MIMO Systems Using Antenna Selection Algorithm", International Journal of Emerging Technology and Advanced Engineering, Vol. 3, Special Issue 1, pp 229-233, January 2013.

[150] Navjot Kaur, Lavish Kansal," Performance Analysis of MIMO Systems over AWGN Channel with Antenna Selection using Zero Forcing Receivers", International Journal of Computer Applications, Vol. 63,No.14, pp 26-30, February 2013.

[151] R. Kanimozhi, A. Bhuvaneswari," Bit Error Performance Analysis of STBC Achieving Full Diversity with ZF Receiver Using MISO", International Journal of Advanced Information Science and Technology (IJAIST) ISSN: 2319:2682 Vol.18, No.18, pp 94-99, October 2013.

[152] Weihua Helen Xi, Alistair Munro, Michael Barton," Link Adaptation Algorithm for the IEEE 802.11n MIMO System", pp 1-12.

[153] Guangxiang Yuan, Xiang Zhang and Wenbo Wang, Yang Yang, "Carrier Aggregation for LTE-Advanced Mobile Communication Systems", IEEE Communications Magazine February 2010, pp88-93.