



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

**Performance Analysis and Investigation of Digital Symbol
Detection Techniques for Single and Multi-carrier Modulations**

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*A Thesis Submitted to the School of Graduate Studies of Addis Ababa University
in Partial Fulfillment of the Requirements for the Degree of
Masters of Science In Electrical and Computer Engineering (Communication Engineering)*

Oct 2017, Addis Ababa

ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA
UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTERS OF SCIENCE IN ELECTRICAL AND COMPUTER ENGINEERING
(COMMUNICATION ENGINEERING)

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Declaration

I, the undersigned, declare that this MSc thesis is my original work, has not been presented for fulfillment of a degree in this or any other university, and all sources and materials used for the thesis have been acknowledged.

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This thesis work has been submitted for examination with my approval as a university advisor.

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Abstract

During symbol transmission we may use single carrier or multi-carrier modulation. In case of single carrier transmission all users share the same transmission medium and this causes the problem of Inter Symbol Interference (ISI) which leads to error in reception. In case of multi-carrier transmission there is Multiple Access Interference (MAI). In several digital communication problems, the received signal is given by a linear combination of the data symbols corrupted by channel effects. So the received symbol may be affected by transmission channel noise, interference, distortion, bit synchronization problems, attenuation, and wireless multipath-fading. Therefore efficient demodulation and symbol detection strategies are very necessary.

This thesis work on symbol detection is done as per the request of Information Networks Security Agency (INSA) of Ethiopia. The industry wants to implement advanced digital receiver for local use. So the industry main aim is to review, investigate, and implement efficient symbol detection algorithms.

In this paper we have considered a class of single carrier and multi-carrier symbol detection algorithms and compare their performance in terms of Bit Error Rate (BER) and Signal to Noise Ratio (SNR) of various modulation type and order. M-ary PSK and M-ary QAM have been simulated with optimum and sub-optimum detectors like Maximum-Likelihood (ML), Minimum Mean Square Error (MMSE) and Zero Forcing (ZF) detector.

From our findings, for the single carrier single user case for additive White Gaussian Noise (AWGN) channel the BER at 15dB is 10^{-3} , which is acceptable. Again for the case of Rayleigh Fading channel at 35dB still we have a BER of 10^{-3} . In the case of multicarrier multi user (MC-CDMA) detection over Rayleigh fading channel, we have been shown how the three different detectors behave in performance and complexity analysis. Finally, it can be seen that the most complex and the best performing detector, is the Maximum Likelihood detector.

Index Terms—Symbol detection, Single user, Single-carrier, Multi-carrier, Multi-user, M-ary Modulation, maximum likelihood detection, optimal and sub-optimal detectors, BER, SNR, Complexity analysis, MATLAB

Acknowledgment

First of all I would like to thank the almighty God for his love, guidance and protection. Next I would like to express my great thanks to my advisor Dr. -Ing. Dereje Hailemariam for his advice, cooperation, and fellowship. He was always available to share us his deep insights, wide knowledge and extensive experience. His advices have value lasting much beyond this thesis work. We consider it a blessing to be supervised under him.

I am highly thankful towards the examining committee Dr. Yehnew, Dr. Ephrem, Dr. Binyam, Mr. Garma (MSc) and all ECE staff members for giving us constructive ideas starting from the progress presentation till the completion of this thesis work.

This work has been funded by Information Network Security Agency (INSA) which highly motivates us to deal with real time and local problems so our deep gratitude pass to INSA coordinators and friends.

I would like to thank all my friends and especially my classmates for all the thoughtful and mind stimulating discussions we had, which prompted me to think beyond the obvious. Last but not least I would like to thank my family for their contribution in one way or the other.

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Abbreviations

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CE	Channel Estimation
CP	Cyclic Prefix
DAB	Digital Audio Broadcasting
DAC	Digital to Analog Converter
DDCE	Decision Directed Based Channel Estimation
DFT	Discrete Fourier Transform
DVB	Digital Video Broadcasting
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
INSA	Information Network Security Agency
ISI	Inter Symbol Interference
LS	Least square
MAI	Multiple Access Interference
MAP	Maximum A Posteriori Probability
MC	Multi Carrier
MCM	Multi Carrier Modulation
MIMO	Multi Input Multi Output
MMSE	Minimum Mean Square Error
ML	Maximum Likelihood
MUD	Multiuser Detection
OFDM	Orthogonal Frequency Division Multiplexing
PAM	Pulse Amplitude Modulation
PAR	Peak to Average Ratio

PDF	Probability Density Function
PSD	Power Spectral Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
SC	Single Carrier
SNR	Signal to Noise Ratio
SP	Serial to Parallel
SUD	Single User Detection
ZF	Zero Forcing

Chapter One

Introduction

1.1 Background

As the digital communications industry continues to grow and evolve, the signal processing applications related to this field continue to grow as well. It needs advanced data transmission, channel modeling and data reception. Data reception in turn, has spawned an increasing need to seek automated methods of efficient demodulation and digital symbol detection algorithms. The data to be transmitted can be mapped in to “M” symbols. The Demodulator converts the received waveform into an N-dimensional vector. Therefore symbol detection is the process of deciding which of the “M” possible symbols are transmitted based on the received vector components. Without the noise and channel effects we would receive what we sent, but the noise and channel effects like multipath propagation, interference from other users, and the time selectivity of a channel can transform one symbol into another [1 and 2].

During symbol transmission we may use single carrier or multi-carrier modulation. Both carrier types have their own advantages and disadvantages. As per the type of carrier modulation we will have single carrier and multi-carrier symbol detection techniques [1 and 3]. In case of single carrier transmission all users share the same transmission medium. Each user transmits information over the common transmission medium. Therefore there is the problem of inter symbol interference (ISI) and as the signal powers of the users are different, information of the user that has weak signal is obtained with much errors, this situation is called as the near-far problem. So the solution of this problem is to use multi-carrier transmission with orthogonal codes followed by Multiuser Detection (MUD). Multi-carrier transmission overcomes the problem of time dispersion (caused by multi-path propagation) of the radio channel.

As we have single and multi-carrier modulations we have also single and multiuser detection techniques. The single carrier single user detection is simply the optimal detection and multi-carrier symbol detection can be Orthogonal Frequency Division Multiplexing (OFDM), Code Division Multiple Access (CDMA), Multiple Input Multiple Output- Orthogonal Frequency Division Multiplexing (MIMO-OFDM) or Multi-Carrier Code Division Multiple Access (MC-CDMA) based. Single user detection refers to detection of data symbols in the absence of interfering users whereas multiuser detection refers to the scenario in which a single receiver jointly detects multiple simultaneous transmissions [4-6].

There are three types of multiuser detectors with in single or multi-carrier transmission, namely the linear, non-linear and adaptive detectors [4]. Decorrelating detector and the minimum mean square error (MMSE) detector are the two main classes of linear detectors [7]. They are highly analogous to the zero-forcing and MMSE equalizers used to combat ISI in a single carrier channel [8]. Decorrelating detector attempts to completely eliminate the Multiple Access Interference (MAI) for all users. The MMSE detector instead tries to minimize the square of the residual noise plus interference. Hence the decorrelating detector is simply the special case of the MMSE detector, when the noise is zero. The decorrelating detector often results in unacceptable noise enhancement. Furthermore it is not practical as it is difficult to drive the interference to zero in this situation. For these reasons attention will be restricted to the more general and practical MMSE detector, in comparison to the decorrelating detector [9-11].

The linear detection schemes described earlier are viable in the sense of bit error rate (BER), but superior performance can be obtained by applying non-linear detection schemes namely, maximum likelihood and successive interference cancellation symbol detection algorithms [4,9 and 11].

So for this thesis work, single carrier single user and MC-CDMA based multi-carrier symbol detection algorithms have been implemented with various modulation type and order. The performance of the considered detection techniques have been compared in terms of BER and SNR. M-ary PSK and M-ary QAM have been simulated with the optimum and sub-optimum

detectors like Maximum-Likelihood (ML), Minimum Mean Square Error (MMSE) and Zero Forcing (ZF) detector. Because ML detection is optimal in terms of performance but uses exhaustive search, so the complexity is very high and MMSE have near optimal performance but with considerably less complexity. So finally we will propose less complex optimal and sub-optimal detectors based on the performance analysis for the industry practical use.

1.2 Statement of the Problem

Digital communication technologies have evolved to a more dynamic applications in a couple of decades and are expected to continue in the future. Due to the rapid growth of multi-rate voice, data and multimedia services, there is an even increasing demand for error free and more reliable reception. But practically it is well known that the wireless multi-path channel causes time dispersion, attenuation, and phase shift, known as fading, in the received signal. Again the channel impairments like noise, interference, distortion, bit synchronization problems, attenuation, and wireless multipath-fading are the major factors limiting the performance of a digital communications system. This all causes to increase probability of making an error and reduces the reliability of digital communication systems. In order to address these requirements (error free reception and reliability), next generation communication need advanced symbol detection algorithms.

Most of the researchers working on equalization, estimation and detection problems investigate and propose different techniques for different applications but, during practical implementations the algorithms are not considered. So there is a gap during real implementation of concepts.

Information Networks Security Agency (INSA) of Ethiopia is working on an industrial project that aims to implement efficient receiver to mitigate the effects of multipath channel on the transmitted signal for a certain application. INSA requests us the implementation of symbol detection algorithms for their own practical use. So here in this thesis work our intense is to show analysis and implementation of theoretical concepts is possible. Basically we are going to implement efficient symbol detection algorithms for single and multi-carrier cases and recommend the best

symbol detection techniques for practical implementation. Therefore, the great opportunity here is to adopt the implementation of the existing algorithms as per the local need of the industry.

1.3 Objective of the study

The thesis is aimed to achieve the following general and specific objectives.

1.3.1 General Objective

- ❖ To investigate, analyse and implement symbol detection algorithms for single and multicarrier systems having an acceptable bit error rate performance and feasible computational complexity.

1.3.2 Specific Objectives

The specific objectives of this thesis can be summarized as follows:

- ✓ To review and investigate efficient symbol detection algorithms for single and multi-carrier cases.
- ✓ To implement the selected symbol detection algorithms for various modulation type and order.
- ✓ Compare performance of the considered detection techniques in terms of bit error rate (BER) and signal to noise ratio (SNR) of various modulation type and order.
- ✓ To recommend the best detection techniques for practical implementation.

1.4 Literature Survey

Due to the demand of error free and more reliable reception, a lot of researches have been done which most of them have mainly focused on performance comparison of single and multiuser

symbol detection algorithms. We review some of the works in demodulation, channel estimation and symbol detection algorithms related to our study.

Christian V., had a thesis work on “Efficient Data Detection Algorithms in Single and Multi-Carrier Systems without the Necessity of a Guard Period” proposes high data rate transmissions over wireless channels without the necessity of guard periods. This ought to increase information data rate and the transmit power per datum is decreased. However he never considered the performance and computational complexity trade-off due to multiple access interference (MAI) [2].

A.A. Khan, who was doing on Symbol detection in spatial multiplexing systems using particle swarm optimization, proposes the particle swarm optimization in order to reduce the search space of the maximum likelihood (ML) detector and the computational complexity of symbol detection in spatial multiplexing systems. The particle swarm optimization algorithm is also compared to some heuristic approaches, such as the genetic algorithm and differential evolution algorithm [12]. But he got near optimal, significantly less complexity and closer to the optimal solution in performance.

Asmamaw G., had his thesis work on “Genetic Algorithm-Based Joint Channel Estimation and Data Detection for Multi-User MIMO”, He tries to introduce different CE and MUD methods used at the receiver of a base station. Least square (LS), minimum mean square error (MMSE), and decision directed based channel estimation (DDCE) methods are some of the channel estimation algorithms. Zero Forcing (ZF), minimum mean square error, and maximum likelihood (ML) are the main multiuser detection methods [10]. So his intense was to drive an algorithm for overloaded Multi Input Multi Output (MIMO) base station receiver, but not real time implementation of the algorithms with optimal performance.

Felip Riera-Palou, Guillem Femenias, Jaume Ramis, had their thesis work on “Performance Analysis of Multiuser Detectors for Uplink Quasi-synchronous MC-CDMA Systems”. They analysis and compares the average BER of different multiuser detectors in the uplink of MC-

CDMA system like maximum likelihood, zero-forcing, minimum mean-square error and interference cancellation-based multiuser detectors [11]. But they didn't show any direction on the real time implementation of the symbol detectors.

In [13 and 14] several techniques for multiuser detection were discussed. These techniques include optimum detector and suboptimum detectors such as decorrelating detector, linear minimum mean-square error detector, decision-feedback detector, blind multiuser detector and interference cancellation detectors. Optimum detectors are near-far resistant and can improve the system performance significantly. However, its complexity increases exponentially with the number of users. On the other hand, the complexity of suboptimum detectors increases linearly with the number of users and can achieve near-optimum performance.

After reviewing most relevant works, we propose to implement the best performance symbol detection algorithms for single and multicarrier systems with a random and real recorded voice signal input having an acceptable BER performance and computational complexity.

1.5 Thesis Contribution

Most of the thesis works we have reviewed are mainly done on performance analysis of symbol detectors with random generated input test signals and no considerations on the real inputs. The contributions of this thesis are outlined as follows:

- ❖ In this paper we have considered a class of single carrier and multi-carrier symbol detection algorithms and Compare their performance in terms of bit error rate (BER) and signal to noise ratio (SNR) for various modulation type and order. In addition to this we had complexity analysis of different channel symbol detection algorithms.
- ❖ The final work of this thesis is an input to a practical implementation of digital receiver project for local use at Information Networks Security Agency (INSA) of Ethiopia.
- ❖ This thesis also contributes choice of best symbol detection techniques for practical implementation based on performance and complexity.

- ❖ Finally, this work creates an opportunity and gives a clue to researchers who are interested to work on digital symbol detection with some of the future works.

1.6 Methodology

The following methodologies have been used to achieve the objectives of this thesis work:

- Literature review: Include reading books, journals, articles, simulation tools, and other resources related to symbol detection algorithms for single and multicarrier systems
- System modeling: Involves modeling of the overall system for both single and multicarrier systems.
- Simulation: Simulating the modeled system using MATLAB, and then integrating the implementation parameters of each algorithm.
- Performance comparison: Comparative analysis in terms of BER and SNR, computational complexity of the detection algorithms.
- Analysis and interpretation of the results: Finally, the results are interpreted and conclusion and future work are drawn based on the results obtained.

1.7 Thesis Organization

This thesis work is organized in to five chapters. Chapter one presents the introduction and objectives of this work and in Chapter two we have seen some theoretical parts of symbol detection fundamentals which are useful to understand the thesis work, like detection theory and optimum receivers, classification of symbol detection techniques and theoretical BER Performance have been described and Chapter three concerns about the system model, implementation algorithms, parameters and assumptions with the implementation of single user single carrier (optimum) symbol detector and its results and then Chapter four concerns MC-CDMA system model, symbol detectors, parameters and simulation results of implementation of multi-carrier multiuser detection, assumptions and results. Finally, Chapter five resumes this thesis and presents perspectives for future work.

Chapter Two

Literature Review on Symbol Detection Fundamentals

2.1 What is Symbol Detection?

At a digital transmitter, we can transmit at each time one of a set of symbols $S_i(t)$, where $i=0 \dots M-1$. This transmission conveys to us which of M symbols we want to send, that is, $k = \log_2 M$ bits of information. Each symbol sent every T seconds, where T is the symbol period for the discrete data transmission system. Thus, symbols are sent at the symbol rate of $1/T$ symbols per second. The number of symbols that can be sent is often measured in bits so that $k = \log_2 M$ bits are sent at every symbol period. Thus, the data rate is $R = k/T$ bits per second. At the receiver, for a single carrier case we assume we received symbol $S_i(t)$ corrupted by noise [1 and 15].

$$r(t) = S_i(t) + n(t) \quad (2.1)$$

How do we decide which symbol $i \in \{0 \dots M-1\}$ was transmitted? We split the task into correlation or matched filter reception, and detection, as shown in Figure 2.1.

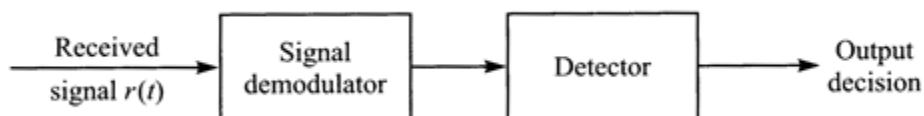


Figure 2.1 A block diagram of the receiver block

Given the signal space diagram of the transmitted symbols and the received signal space vector “ r ”, what rules should we have to decide on i ? This is the topic of detection. Optimal detection uses rules designed to minimize the probability that a symbol error will occur. By error, we mean that a different symbol was detected than the one that was sent [16]. Therefore Symbol detection is the process of decision making which of the M possible signal waveforms/ symbols are transmitted based on the received vector.

In the case of Multicarrier transmission different users transmit their information over multiple subcarriers. One of the key challenges in designing Multi-user Multicarrier communication systems is mitigating interference due to multi-user data streams reached at the receiver at the same time. The receiver may wish to demodulate and detect a subset of two or more signals from a larger

subcarrier signals. In that case, the receiver jointly detects the subset of desired signals while suppressing the interfering signals [10].

For multiuser Multi-carrier transmission with user information \mathbf{S}_i , where $i=0, \dots, M-1$, the received signal \mathbf{Y} is given by,

$$\mathbf{Y} = \mathbf{H}\mathbf{C}\mathbf{S}_i + \mathbf{N} \quad (2.2)$$

Where, $\mathbf{S}_i = [s_0, s_1, \dots, s_{M-1}]$ and $\mathbf{Y} = [y_1, y_2, \dots, y_N]$ denote the transmit symbol from the M^{th} subcarrier and the received signal at the N^{th} receiver respectively, \mathbf{H} stands for the channel transfer matrix, \mathbf{C} stands for spreading sequence and \mathbf{N} denotes the white Gaussian noise with a variance of δ^2_n . Then the MUD mitigates the effect of ISI and delay spread and a single receiver jointly detects multiple simultaneous transmissions by suppressing the channel effects while increasing the probability of reception [10].

2.2 Performance of the M-ary Modulators

The performance of modulation schemes is often measured in terms of its power efficiency, bandwidth efficiency, and bit error rate (BER) [17].

Power efficiency describes the ability of modulation techniques to preserve the fidelity of the digital message at low power levels. This measures how favourably this trade-off between fidelity and signal power is made and is expressed by the ratio signal energy per bit to noise power spectral density (E_b/N_0) required at the receiver in put for a certain probability of error.

Bandwidth efficiency describes the ability of modulation schemes to accommodate data within a limited bandwidth. Increasing the data rate implies decreasing the pulse width of digital symbol which increase the bandwidth of the signal. Bandwidth efficiency reflects how efficiently the bandwidth is utilized and defines as the ratio of throughput data rate per hertz in a given bandwidth. The system capacity of digital communication system is directly proportional with the bandwidth efficiency of the modulation scheme since modulation with greater bandwidth efficiency will transmit more data in a given spectrum allocation.

The transmission BER is the number of detected bits that are incorrect before error correction, divided by the total number of transferred bits (including redundant error codes). The information BER, approximately equal to the decoding error probability, is the number of decoded bits that remain incorrect after the error correction, divided by the total number of decoded bits (the useful information). Normally the transmission BER is larger than the information BER. In a communication system, the receiver side BER may be affected by transmission channel noise, interference, distortion, bit synchronization problems, attenuation, and wireless multipath-fading. The BER may be improved by choosing a strong signal strength (unless this causes cross-talk and more bit errors), by choosing a slow and robust modulation scheme or line coding scheme, and by applying channel coding schemes such as redundant forward error correction codes.

The SNR is the ratio of the received signal power over the noise power in the frequency range of the process. SNR is inversely related to BER, that is high BER causes low SNR. High BER causes an increase in packet loss, enhance in delay and decrease throughput. SNR is an indicator usually measures the clarity of the signal in a circuit or a wired/wireless transmission channel and measure in decibel (dB). The signal to noise ratio (SNR) is the ratio between the wanted signal and the unwanted background noise.

There are several digital modulation schemes that have been proposed for digital communication systems. These digital modulation schemes include basic schemes such as M-ary Phase Shift Keying (M-PSK), M-ary Pulse Amplitude Modulation (M-PAM), M-ary Quadrature Amplitude Modulation (M-QAM), and M-ary Frequency Shift Keying (M-FSK). Other more advanced digital modulation techniques that build on these basic schemes include Gaussian Minimum Shift Keying (GMSK) which is used in the GSM cellular standard, Spread Spectrum Modulation which is used in the UMTS cellular standard, and Orthogonal Frequency Division Modulation (OFDM). Here the theoretical BER performances analysis revision will be done for M-ary PAM, M-ary PSK and M-ary QAM for AWGN channel [15, 17 and 18].

2.3 Detection Theory and Optimum Receivers

The reception process may be divided into two components; namely, signal demodulation and detection. The Demodulator Converts the received waveform into an N-dimensional vector $\mathbf{r} = [r_1, r_2, r_3 \dots r_N]$ and Detector decides which of the M possible signal waveforms are transmitted based on the vector “ \mathbf{r} ”. In optimal symbol detection, the whole received signal is used in the detection of each symbol separately. As we have the received signal components given by “ \mathbf{r} ”, and we assume the channel effects and we shall focus on the detection of one of the N transmitted symbols. Thus the detection process consists of attempting to find the most likely value of “ S_i ” given the received signal components [19].

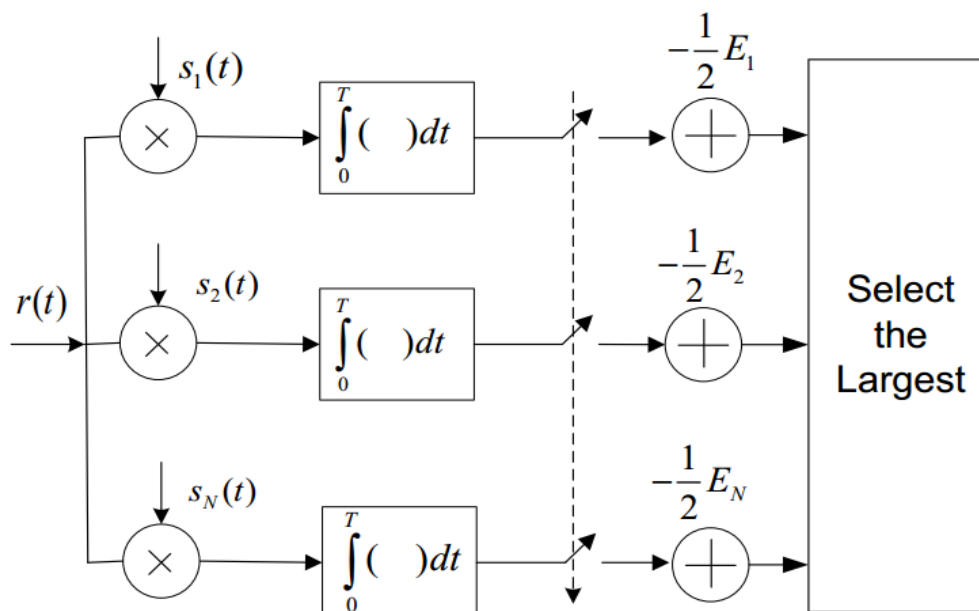


Figure 2.2 Reception processes [19]

2.3.1 Demodulator types

There are two kinds of demodulators i.e., signal correlator and matched filter.

2.3.1.1 Correlation demodulator:

Suppose a set of N basis functions $\{f_n(t), n = 1, 2, \dots, N\}$ span the signal space and therefore are enough to decompose the received signal into N-dimensional vector. The received signal is passed through a parallel bank of N cross correlator's, which transfers the waveform into vector element

(the projection of $r(t)$ on to $\{f_n(t), n = 1, 2, \dots, N\}$).

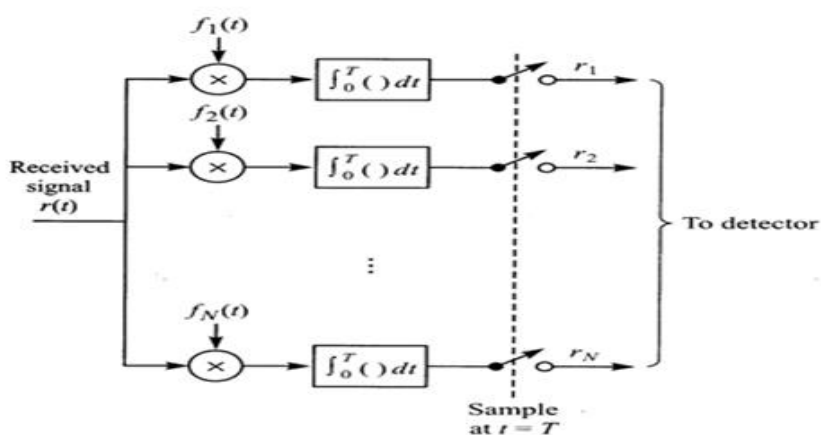


Figure 2.3 Correlation type demodulator [19, 16]

Thus, we have at the output of the integrator

$$\int_0^T r(t) f_k(t) dt = \int_0^T [s_m(t) + n(t)] f_k(t) dt \quad (2.3)$$

$$r_k = s_{mk} + n_k, k = 1, 2, \dots, N \quad (2.4)$$

Where,

$$s_{mk} = \int_0^T s_m(t) f_k(t) dt, k = 1, 2, \dots, N \quad (2.5)$$

$$n_k = \int_0^T n(t) f_k(t) dt, k = 1, 2, \dots, N \quad (2.6)$$

Note that $s_{mk}, k = 1, 2, \dots, N$ are deterministic and form the vectors \mathbf{s}_m , however, n_k is a random variable. The received signal in the interval $0 \leq t \leq T$ can be expressed by

$$r(t) = \sum_{k=1}^N s_{mk} f_k(t) + \sum_{k=1}^N n_k f_k(t) + n'(t) = \sum_{k=1}^N r_k f_k(t) + n'(t) \quad (2.7)$$

The term $n'(t)$ defined below is a zero-mean Gaussian process. In the following, it is shown that $n'(t)$ is irrelevant to the decision as to which signal was transmitted. Consequently, the decision may be based entirely on the correlators' output signal and noise components $r_k = s_{mk} + n_k, k = 1, 2, \dots, N$.

$$n'(t) = n(t) - \sum_{k=1}^N n_k f_k(t) \quad (2.8)$$

The means of n_k for all n are

$$E(n_k) = \int_0^T E[n(t)]f_k(t)dt = 0 \quad (2.9)$$

Their variances are

$$\begin{aligned} E(n_k n_m) &= \int_0^T \int_0^T E[n(t)]f_k(t)dtd\tau = \frac{1}{2}N_0 \int_0^T \int_0^T \delta(t - \tau) f_k(t)f_m(\tau)dtd\tau = \\ &\frac{1}{2}N_0 \int_0^T f_k(t)f_m(\tau)dtd\tau = \frac{1}{2}N_0\delta_{mk} \end{aligned} \quad (2.10)$$

$$\text{Where } \delta_{mk} = \begin{cases} 1, & m=k \\ 0, & m \neq k \end{cases} \quad (2.11)$$

Therefore, the N noise components $\{n_k\}$ are zero-mean uncorrelated Gaussian random variables with a common variance $\delta_n^2 = \frac{1}{2}N_0$.

Conditioned on $s_m(t)$, the correlator output is a Gaussian random variable with mean

$$E(r_k) = E(s_{mk} + n_k) = s_{mk} \quad (2.12)$$

And equal variance, $\delta_r^2 = \delta_n^2 = \frac{1}{2}N_0$ since $\{n_k\}$ are uncorrelated Gaussian random variables, they are also statistically independent, therefore, $\{r_k\}$ are statistically independent Gaussian random variables. The probability density function (pdf) of $\mathbf{r} = [r_1 \ r_2 \ \dots \ r_N]$ conditioned on \mathbf{s}_m is

$$p(\mathbf{r} | \mathbf{s}_m) = \prod_{k=1}^N p(r_k | s_{mk}), m = 1, 2, \dots, M \quad (2.13)$$

Where

$$p(r_k | s_{mk}) = \frac{1}{\sqrt{\pi N_0}} \exp\left[-\frac{(r_k - s_{mk})^2}{N_0}\right], k = 1, 2, \dots, N \quad (2.14)$$

Hence the joint conditional probability density function (pdf) is

$$p(\mathbf{r} | \mathbf{s}_m) = \frac{1}{(\pi N_0)^{N/2}} \exp\left[-\sum_{k=1}^N \frac{(r_k - s_{mk})^2}{N_0}\right], m = 1, 2, \dots, M \quad (2.15)$$

Next, the correlator outputs $\{r_k\}$ can be shown to be sufficient statistics, in other words, it suffices to demonstrate $n'(t)$ offers no additional information for detection, or to show $n'(t)$ is uncorrelated with the N correlator outputs $\{r_k\}$. Since $n'(t)$ and $\{r_k\}$ are Gaussian and uncorrelated, they are statistically independent and $n'(t)$ can be ignored [16 and 19].

2.3.1.2 Matched filter demodulator:

Instead of using a bank of “N” correlators to generate the variables $\{r_k\}$, we may use a bank of “N” linear filters. Suppose that the impulse responses of the N linear filters are

$$h_k(t) = \begin{cases} f_k(T-t), & 0 \leq t \leq T \\ 0, & \text{otherwise} \end{cases} \quad (2.16)$$

Where $\{f_k(t)\}$ are the N basis functions, the outputs of these filters will be

$$y_k(t) = \int_0^T r(\tau) h_k(t - \tau) d\tau = \int_0^T r(\tau) f_k(T - t + \tau) d\tau, k = 1, 2, \dots, N \quad (2.17)$$

Sampling the outputs of these filters at $t = T$, we obtain

$$y_k(T) = \int_0^T r(\tau) f_k(\tau) d\tau = r_k, k = 1, 2, \dots, N \quad (2.18)$$

The result at $t = T$ is the same as that obtained from the linear correlators. However, this is not to conclude both type demodulators are all the same any time. Indeed, it emphasizes that the equality holds only at the time instant $t = T$. A matched filter to the signal $s(t)$ is that its impulse response is $h(t) = s(T - t)$, where $s(t)$ is assumed to be confined to the time interval $0 \leq t \leq T$. Figure below demonstrates the matched filter demodulator that generates the observed variables $\{r_k\}$ [16 and 19].

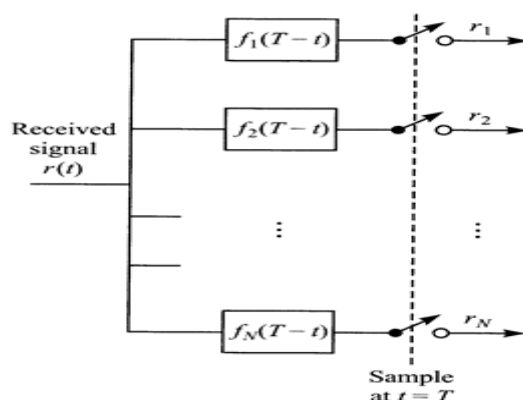


Figure 2.4 Matched filter demodulator [16 and 19].

2.4 Classification of Symbol Detection Techniques

In this section, we review detection in digital communications in the presence of additive white Gaussian noise. This topic is of particular interest in determining an optimum design of a receiver.

Detection theory provides a set of rules for a decision-making method, which is used to observe the received signals and predict the transmitted symbols. The results of detection are subject to transmission errors. However, the goal of the detection theory is to deal with transmission error such that an acceptable quality of performance can be obtained at the receiver, thereby leading to an optimum receiver. As we have single and multi-carriers modulations we have also single and multiuser detection techniques [4, 14 and 20].

Single user detection refers to detection of data symbols in the absence of interfering users whereas Multiuser detection refers to the scenario in which a single receiver jointly detects multiple simultaneous transmissions. the key challenges in designing multi-user communication systems is mitigating interference due to multi-user data streams reached at the receiver at the same time.

The modulation and detection techniques combination can be summarized as in the table below.

Table 2.1 Classification of detection techniques [4, 14 and 20].

Possible User and Carrier Combination	Multiplexing Technique	Possible Symbol Detector Algorithm	Implementation Concepts
Single user -Single carrier	-	ML, MAP	Optimum receiver implementation
Single user- Multi-carrier	OFDM	ML, MMSE, Decorrelating	OFDM Modulation, Demodulation, and detection.
Single carrier -multiuser	CDMA	ML, MMSE, Decorrelating, SIC, PIC, Sphere decoding	CDMA based Modulation, Demodulation, and detection.

Multi-carrier multiuser	CDMA, OFDM, MIMO-OFDM and MC-CDMA	ML, MMSE, Decorrelating, SIC, PIC, Sphere decoding, V-Blast MMSE /V-Blast ZF	CDMA, OFDM, MIMO-OFDM, MC-CDMA Modulation, Demodulation, and detection.
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2.4.1 Single user Single carrier Symbol Detection

Here the possible types of symbol detection techniques are MAP and ML.

2.4.1.1 MAP Detector:

The posterior probabilities is defined as

$$p(\text{symbol } s_m \text{ was transmitted } | r) = p(s_m | r), m = 1, 2, \dots, M \quad (2.19)$$

The decision criterion is based on selecting the signal corresponding to the maximum of the set of posterior probabilities $\{p(s_m | r)\}$; hence, such a criterion is called as maximum a posteriori probability (MAP) criterion. The posterior probabilities can be expressed by

$$p(s_m | r) = \frac{p(r | s_m)p(s_m)}{p(r)} \quad (2.20)$$

Where $p(r | s_m)$ is the conditional PDF of the observed vector given s_m , and $p(s_m)$ is the a priori probability of the m^{th} signal being transmitted. The denominator can be written as

$$p(r) = \sum_{m=1}^M p(r | s_m)p(s_m) \quad (2.21)$$

Therefore, to compute the posterior probabilities $p(s_m | r)$ requires knowledge of the a priori probabilities $p(s_m)$ and the conditional PDFs $p(r | s_m)$ for $m = 1, 2, \dots, M$. We observe that the denominator above is independent of which signal is transmitted [1, 16 and 19].

2.4.1.2 ML Detector

In this section, we review how to design and implement the symbol-by-symbol maximum likelihood (ML) detector to make the probability of correct decision maximum. Suppose the M signals are equally likely, that is, the a priori probability is $p(s_m) = 1/M$ for all M . Consequently, to maximize $p(s_m | r)$ is equivalent to maximizing $p(r | s_m)$. The conditional PDF $p(r | s_m)$ or any monotonic function of it is usually called the likelihood function. The decision criterion based on the maximum of the likelihood function, $p(r | s_m)$ over the M signals is called the maximum-likelihood (ML) criterion. Where $p(r | s_m)$ is given by [1, 16 & 19].

$$p(r | s_m) = \frac{1}{(\Pi N_0)^{N/2}} \exp\left[-\sum_{k=1}^N \frac{(r_k - s_{mk})^2}{N_0}\right], m = 1, 2, \dots, M \quad (2.22)$$

To simplify the computation, we take natural logarithm both sides as

$$\ln p(r | s_m) = -\frac{1}{2} N \ln(\Pi N_0) - \frac{1}{N_0} \sum_{k=1}^N (r_k - s_{mk})^2 \quad (2.23)$$

Apparently, the maximum of $p(r | s_m)$ over s_m is equivalent to finding the signal s_m that minimizes the Euclidean distance

$$D(r, s_m) = \sum_{k=1}^N (r_k - s_{mk})^2 \quad (2.24)$$

$D(r, s_m)$ is called the distance metrics. As a result, this decision rule is called as minimum distance detection. This can be expanded as

$$D(r, s_m) = \sum_{k=1}^N (r_k)^2 - 2 \sum_{k=1}^N r_k s_{mk} + \sum_{k=1}^N s_{mk}^2 = \|r\|^2 - 2r \cdot s_m + \|s_m\|^2 \quad (2.25)$$

The term $\|r\|^2$ can be ignored in the computation of the metrics since it is common to all distance metrics. The modified distance metrics are

$$D'(r, s_m) = -2r \cdot s_m + \|s_m\|^2 \quad (2.26)$$

To minimize $D'(r, s_m)$ is equivalent to maximizing $c(r, s_m)$, as below

$$c(r, s_m) = 2r \cdot s_m + \|s_m\|^2 \quad (2.27)$$

Notes:

- (1). the term $r \cdot s_m$ represents the projection of the received signal vector onto each of the M possible transmitted signals vectors. The projection is a measure of the correlation between

the received vector and the m^{th} signal, therefore, $c(r, s_m)$ is called the correlation metrics for deciding which of the M signals was transmitted.

(2). the term $\|s_m\|^2 = E_m$, $m = 1, 2, \dots, M$ may be viewed as bias for signal sets that have unequal energies. Accordingly, for signals with same energy, this term can be ignored. The correlation metrics $C(\mathbf{r}, \mathbf{s}_m)$, $m = 1, 2, \dots, M$ can be expressed as

$$c(r, s_m) = 2 \int_0^T r(t) s_m(t) dt - E_m \quad (2.28)$$

Therefore, this can be generated by a demodulator that cross-correlates the received signal $r(t)$ with each of the M possible transmitted signals with the individual energy. As a result, the MAP criterion can be simplified to the ML criterion when all signals have same energy. On the other hand, if the energies of signals are unequal, the MAP criterion should be adopted [1, 16 & 19].

For the case of Rayleigh channel the likelihood function again can be derive as that of AWGN. Suppose the M signals are equally likely, that is, the a priori probability is $p(s_m) = 1/M$ for all M . Consequently, to maximize $p(s_m | y, H)$ is equivalent to maximizing $p(y | s_m, H)$, where $y = h * s_i + n$, Note that minimizing the probability of error is equivalent to maximizing the probability of correctly estimating s_m . Further, note that the probability density of the white Gaussian noise V , is given by:

$$f_v(v) = \frac{1}{(\pi\delta^2)^n} \text{Exp}\left(-\frac{1}{\delta^2} \|v\|^2\right) \quad (2.29)$$

Thus, the likelihood of $\hat{\mathbf{S}}_m$ is obtained by substituting \mathbf{V} with $\mathbf{y}_k - \mathbf{H}\mathbf{s}_{mk}$ in the above. By observing that $f_v(v)$ is maximized by minimizing $\|v\|^2$. Therefore the ML estimate of \mathbf{S} , i.e. $\hat{\mathbf{S}}_m$, is given by:

$$\hat{s}_m = \min \sum_{k=1}^N (y_k - H s_{mk})^2 \quad (2.30)$$

2.4.2 Single user Multi-carrier Symbol Detection

Reliably and efficiently transmitting signals with high-speed data over imperfectly wired and wireless channels is still one of the central problems of signal processing in digital communications. Recently, one successful approach to achieving high-speed data transmission either over a wired or a wireless channel uses a channel partitioning method to divide the transmission channel into a number of orthogonal sub-channels or subcarriers. The channel partitioning method constructs a set of parallel sub-channels, which are largely independent. The channel partitioning method is often referred to as multicarrier modulation (MCM) and is also called multichannel modulation [3].

In digital communications, MCM can be classified as discrete multi-tone (DMT) or orthogonal frequency division multiplexing (OFDM), depending on the applications in wired or wireless channels, respectively. Both DMT and OFDM have the same channel partitioning where their carrier spacing is selected in such a way that each of the subcarriers is orthogonal to the other subcarriers. The difference between DMT and OFDM is that DMT usually uses a dynamic loading algorithm to assign a proportionately large fraction of the digital information to sub-channel signals with the largest signal-to-noise ratio (SNR) of the sub-channel output, while OFDM carries a fixed number of bits on all sub-channels [6].

2.4.3 Single carrier Multiuser Symbol Detection

Multi-user detection methods are classified on the basis of their performance as optimal, suboptimal and near optimal Algorithms, where the names define their performance characteristics. Many algorithms have been proposed in the literature to implement efficient and less complex receivers which are broadly classified into linear and non-linear detection techniques [4, 20] see the Figure 2.5, below.

Maximum likelihood (ML) detection is optimal in terms of performance but uses exhaustive search, so the complexity is very high. Suboptimal algorithms have low complexity but at the same time, their performance is not reliable for bad channels. E.g. Zero Forcing, Minimum Mean Square Error (MMSE) Method, Successive Interference Cancellation (SIC). Near optimal algorithms have

a performance of very close to optimal algorithms, But with considerably less complexity. E.g. Sphere decoding.

Single carrier multiuser detection, which is demodulation of users in the presence of MAI, is therefore central to efficient operation of a CDMA system. This focuses on the design and analysis of optimal and near-optimal multiuser detection with feasible computational complexity. Efficient signal processing for CDMA based systems is, therefore, of great interest. CDMA allows all users to use both time and frequency resources simultaneously. Users distinguish themselves by modulating their information onto a user-specific spreading sequence. By selecting mutually orthogonal spreading sequences, each user can be perfectly separated at the common receiver. However, Orthogonality is impossible to maintain in a real-world wireless mobile environment and so, the users suffer multiple access interference (MAI) [5].

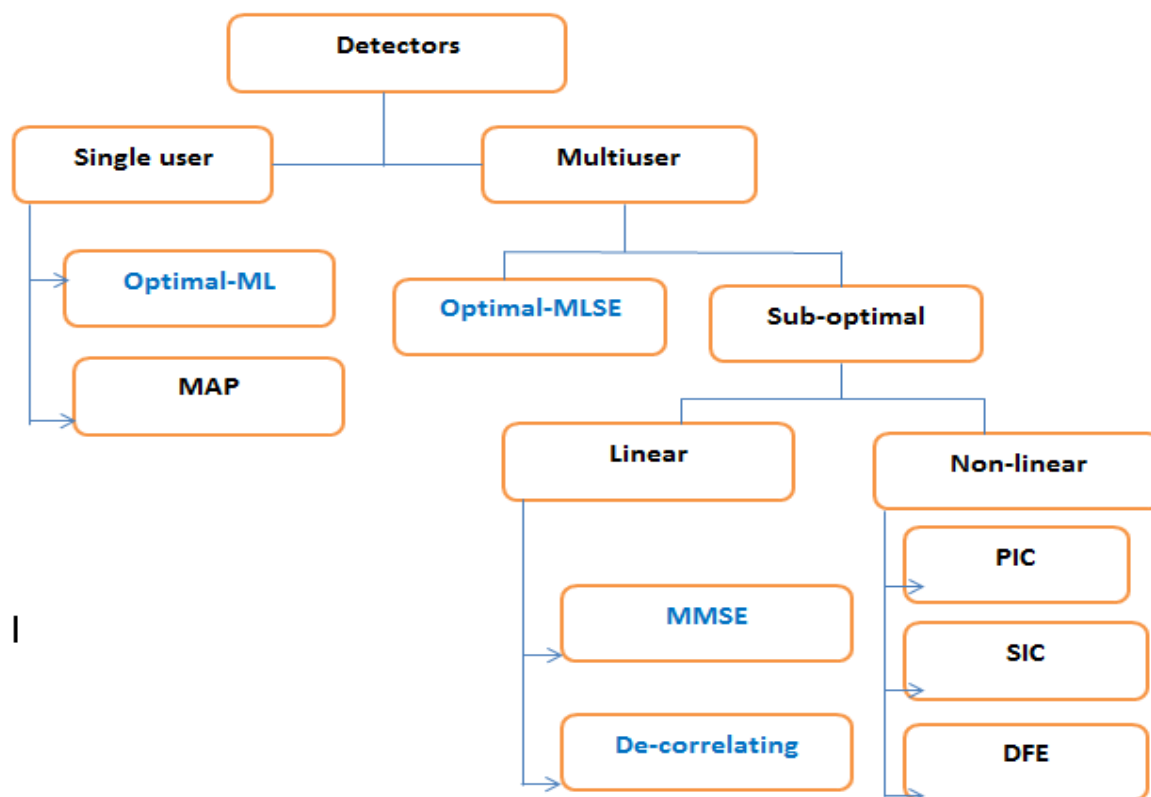


Figure 2.5 Multiuser detection classification diagrams [13].

2.4.4 Multi-carrier Multiuser Symbol Detection

All what we will consider here is the multiple access type (OFDM or CDMA or MC-CDMA), but the multiuser detectors are what we have discussed in 2.4.3. Basically OFDM has orthogonal sub-carrier and the serial-parallel converter, OFDM converts the serial data into parallel data that is modulated onto different sub-carriers which share system bandwidth, and achieves high-speed data transmission [6].

CDMA is based on spread spectrum communication; it retains the characteristics of spread spectrum communication. By using orthogonal pseudo-random noise sequence, CDMA makes all users communicate in the same channel without interfering each other, and distinguishes the information transmitted by different users using a good correlation between the spread codes, so as to realize the communication between multiple users in a limited resource environment.

The conventional CDMA is not practical when the data transmission rates are very high [13 and 14]. To combat the difficulties faced by CDMA system and to improve the BER performance in multi user environment, MC-CDMA systems are used. OFDM introduces multicarrier concept in CDMA to give rise to novel concept of MC-CDMA [11]. MC-CDMA system has advantages of OFDM and CDMA. However poor Orthogonality among the received spreading code sequence (SCS) results in introduction of the multiple access interference (MAI). MAI affects the BER performance of the MC-CDMA system. Many techniques have been proposed to improve the performance of MC-CDMA systems over fading channels, among them channel coding algorithms are the most admired technique. The maximum likelihood (ML) detector based optimal MUD is gives better BER performance in the MC-CDMA system. MUD techniques such as parallel and serial interference cancellation (PIC & SIC), minimum mean square error (MMSE) and decorrelating are considered. However the complexity of decoding is increased exponentially as the number of active user's increase [11].

For this thesis work we have chosen two classes of symbol detection techniques as it is too vast to implement all classes of detection techniques. Basically we have been chosen to implemented single user single carrier detectors (optimum detector) and Multi carrier multiuser detectors with the multiple access technique called MC-CDMA. The system model, mathematical modeling, implementation parameters and simulation results of each system will be discussed in detail in chapter 3 and 4.

Chapter Three

Implementation of Single User Single Carrier (Optimum) Symbol Detector

As we have discussed in 2.4.1.1 and 2.4.1.2 the possible detectors we have are MAP and ML. But since MAP requires knowledge of the a priori probabilities $P(\mathbf{s}_m)$ and the conditional PDFs $P(\mathbf{r}|\mathbf{s}_m)$ we will not use it for practical implementation. Instead we have chosen to implement Euclidean distance based maximum likelihood detector. For AWGN and Rayleigh channel the Euclidean distance based maximum likelihood equation is given by:

$$\hat{s}_m = \min \sum_{k=1}^N (r_k - s_{mk})^2 \quad (3.1)$$

$$\hat{s}_m = \min \sum_{k=1}^N (y_k - Hs_{mk})^2 \quad \text{Where, } y = h * s_i + n, \quad (3.2)$$

This is derived from equation 2.26 and equation 2.30 Where r_k = received observation components, s_m = possible transmitted symbols, the minimum the distance between the observation and the possible transmitted symbol gives the detected symbol \hat{s}_m .

For the implementation of this work we use Euclidean distance based maximum likelihood detector. But it is possible still to implement it with correlation based maximum likelihood detector. Typically refer to equation 2.27 of chapter two.

3.1 System Model

Figure 3.1 shows the simplified block diagram of the single user single carrier (optimum) symbol detector system. For this system, two kinds of source data are used, either the randomly produced data or an Audio file. And we consider M-ary QAM and PSK symbol mapping and a square root raised cosine filter as pulse shaping filter.

Pulse shaping plays a crucial role in spectral shaping in data transmission to reduce the spectral bandwidth. Pulse shaping is a spectral processing technique by which fractional out of band power is reduced for low cost, reliable, power and spectrally efficient communication systems. It is clear that the pulse shaping filter not only reduces inter-symbol interference (ISI), but it also reduces

adjacent channel interference. Among the different type of pulse shaping filters (rectangular pulse, raised cosine pulse, square root raised cosine pulse, Gaussian pulse, flipped exponential pulse, flipped hyperbolic, secant pulse, flipped inverse hyperbolic secant pulse) the root raised cosine filter is generally used in series pairs so that total filtering effect is that of raised cosine filter. Sometimes it is desirable to implement the raised cosine response as the product of two identical responses, one at the transmitter and the other at the receiver. In such cases, the response becomes a square-root raised cosine response since the product of the two responses yields the desired raised cosine response. Its frequency response is given by

$$H(w) = \begin{cases} \tau & 0 \leq w \leq c \\ \tau \cos^2(\tau(w - c)/4\alpha) & c \leq w \leq d \\ 0 & w > d \end{cases} \quad (3.3)$$

Where “w” is the radian frequency $2\pi f$, τ is pulse period, α is roll of factor, c is equal to $\Pi(1-\alpha)/\tau$ and d is equal to $\Pi(1+\alpha)/\tau$.

Channel Model: The transmission is corrupted by noise in reality. For this reason multipath Rayleigh fading and Additive White Gaussian Noise (AWGN) channel can be considered. As usual the fading channel introduces a multiplicative effect whereas the AWGN is additive. Rayleigh fading is a commonly used term in simulation of digital communication systems but it tends to differ in meaning in different contexts. The term Rayleigh fading as used above means a single tap channel that varies from one symbol to the next. It has an amplitude which is Rayleigh distributed and a phase which is uniformly distributed. A single tap channel means that it does not introduce any Inter Symbol Interference (ISI). Such a channel is also referred to as a flat fading Channel. The channel can also be referred to as a fast fading channel since each symbol experiences a new channel state which is independent of its previous state (also termed as uncorrelated). For a simple flat fading Rayleigh channel (modeled as a single tap filter with complex impulse response “**h**”). The channel also adds AWGN noise to the signal samples after it suffers from Rayleigh Fading. The received signal y can be represented as $y = hx + n$, where “**n**” is the noise contributed by AWGN which is Gaussian distributed with zero mean and unit variance and “**h**” is the Rayleigh fading response with zero mean and unit variance. (For a simple AWGN channel without Rayleigh fading the received signal is represented as $y = x + n$).

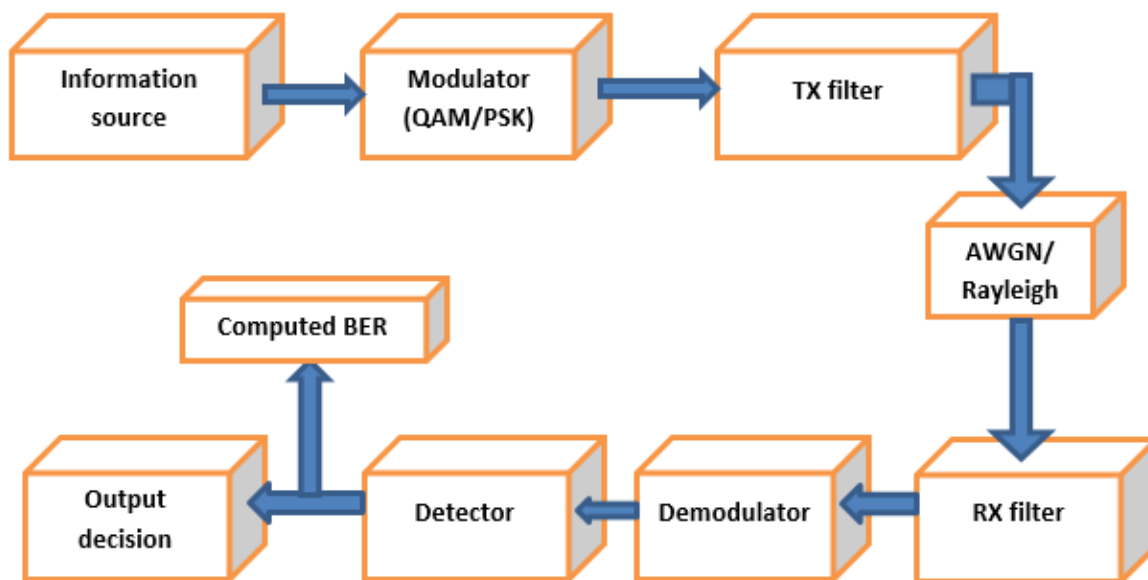


Figure 3.1 SU SC system model

The detection process is performed by finding one of the constellation symbols that has the smallest Euclidean distance with the received symbol. This simulation is based on minimum Euclidean Distance. The maximum likelihood detector computes the Euclidean distance of each received symbol against all possible ideal symbols. Then it pin points an ideal symbol which gives the minimum Euclidean Distance. Finally, the demodulated symbols are converted back to binary bits and the BER (Bit Error Rate) is calculated.

3.2 Implementation Algorithm and Parameters

The implementation algorithm and parameters are given as follows.

The implementation algorithms are:

- Step1: Generate a random binary data / Record Audio
- Step2: modulate using m-ary modulation (map in to symbols)
- Step3: pulse shaping (with or without)
- Step4: Channel (Rayleigh /AWGN)
- Step5: create scatter plot diagram before and after filtering
- Step6: matched filter (get the received signal components/constellation)

Step7: ML-detection (find the symbol with the minimum Euclidean distance to the received signal)

Step8: demodulate the detected symbols and converted back to binary bits

Step9: Compute and plot system BER performance

For the simulation of basic SC SU system, we used the following parameters as shown in Table 3.1.

Table 3.1 simulation parameters of SC SU system.

Parameters	Specification
No. of bits	10^4
Symbol Duration	1sec
Modulation type	M(4,8,16,64...)-QAM/PSK
Channel Model	AWGN, Rayleigh
EbNOdB	0:5:25dB
No of taps	1
Symbol Detection algorithm	ML
Pulse shaping filter	sqrt raised cosine filter(Number of filter order= 40;Filter Roll off factor=0.25;Filter Oversampling rate=4;
Synchronization	Perfect
Channel estimation	Perfect

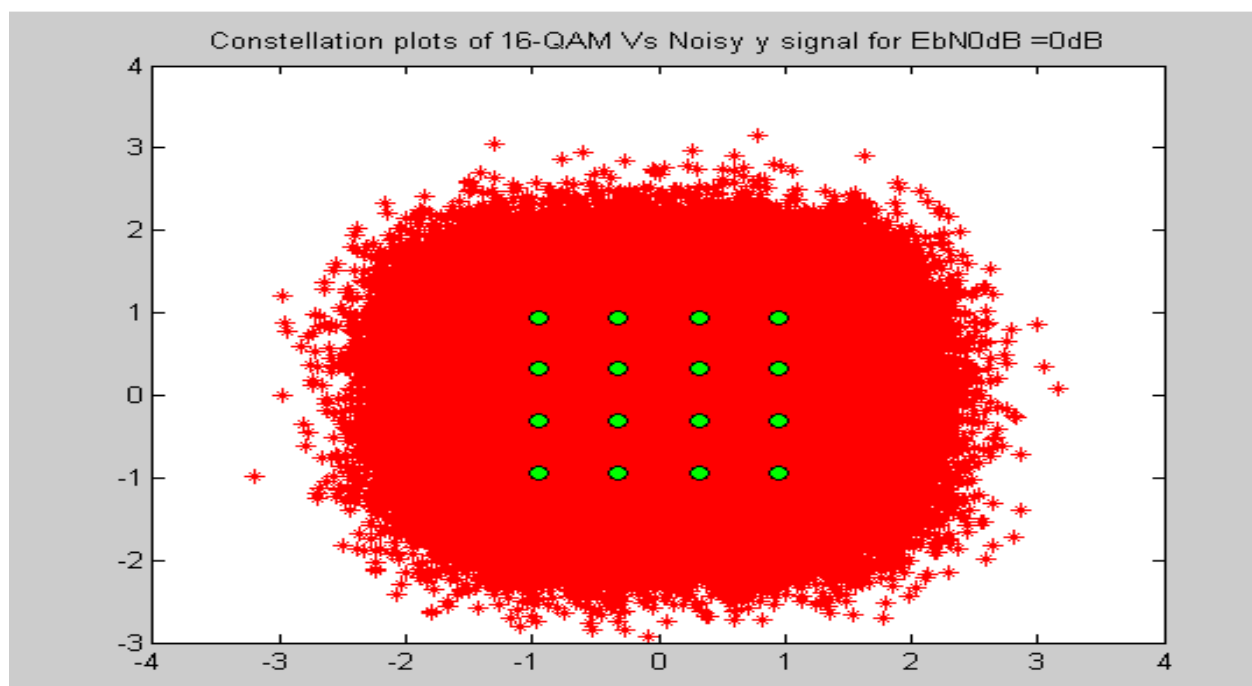
3.3 Results

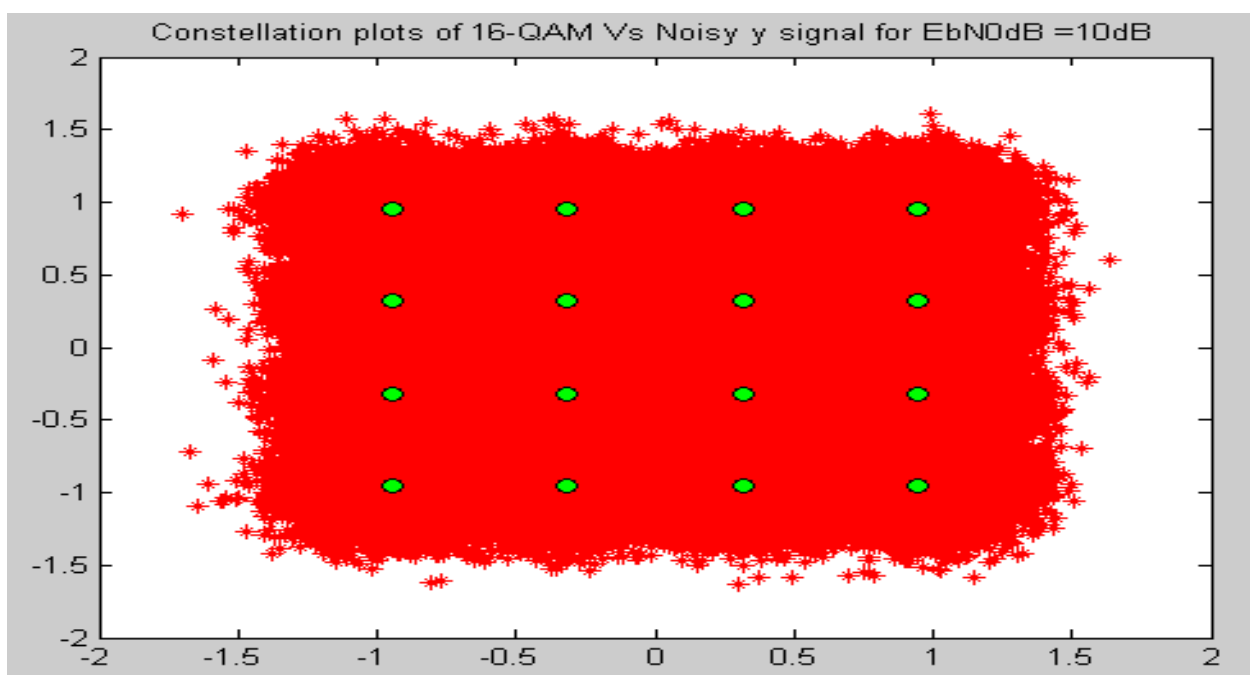
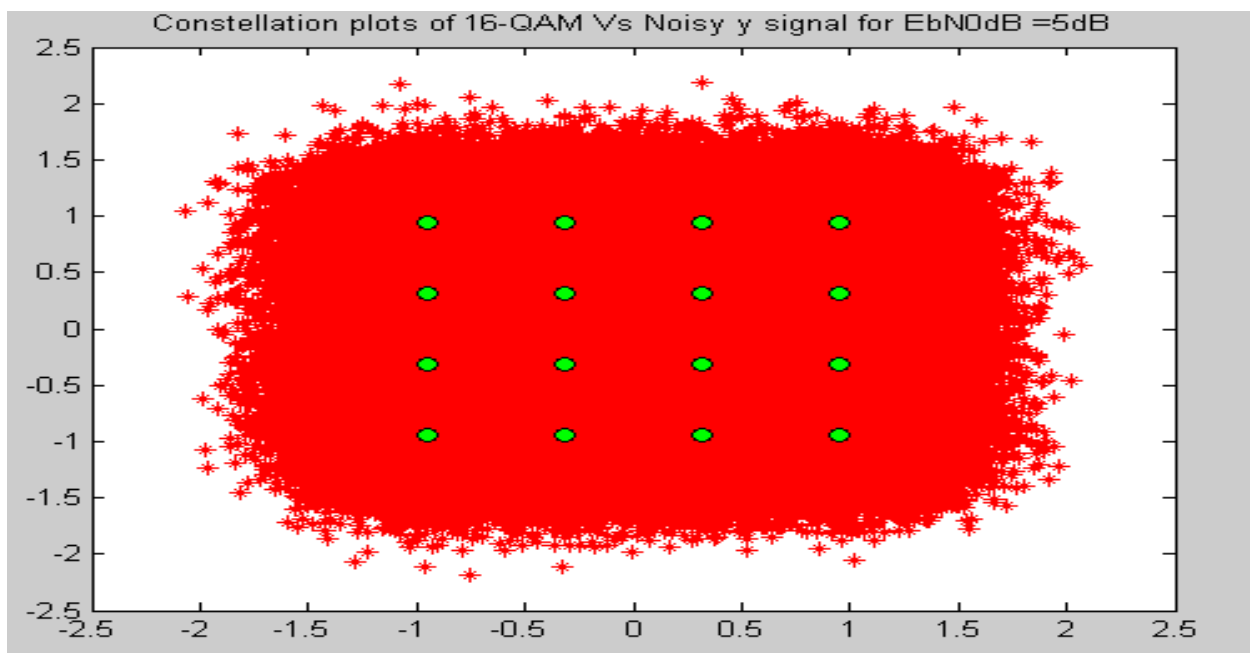
As there is always a search for digital modulation technique that is bandwidth efficient and has low bit error rate at a relatively low signal to noise power. Taking this requirement in our mind, in this paper we provide a general theoretical analysis of various M-ary modulation schemes using MATLAB taking BER as measure of performance when the system is subjected to AWGN and multipath Rayleigh fading channel followed by symbol detection algorithms. Result presented in

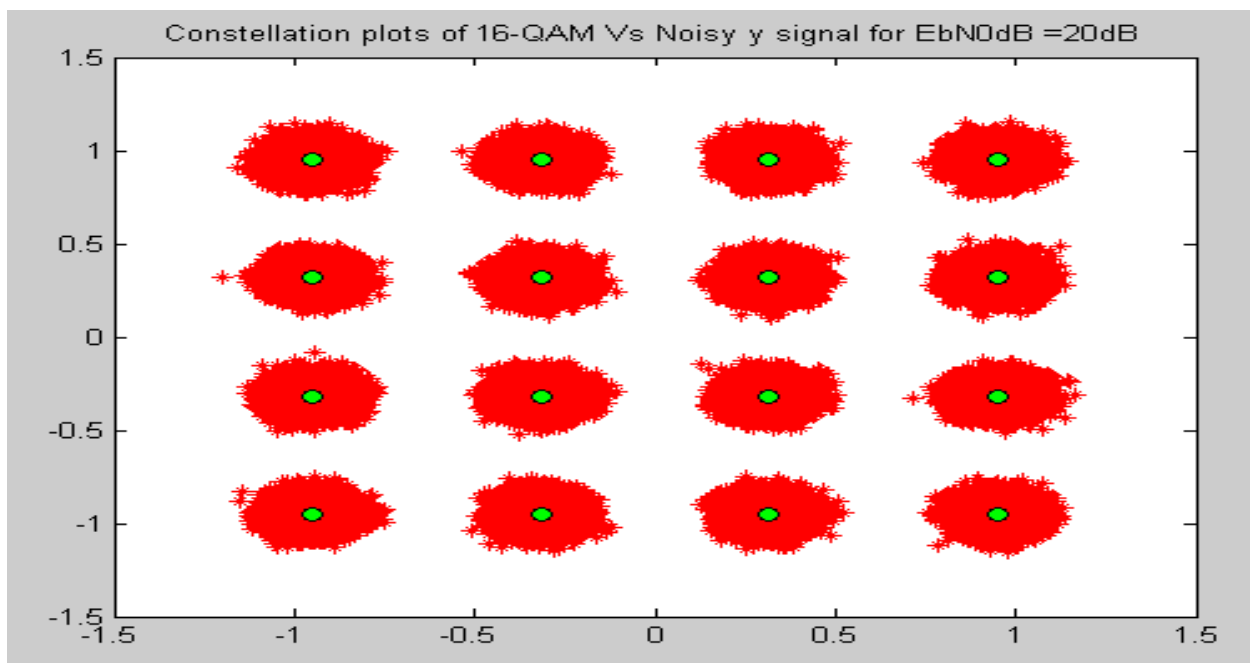
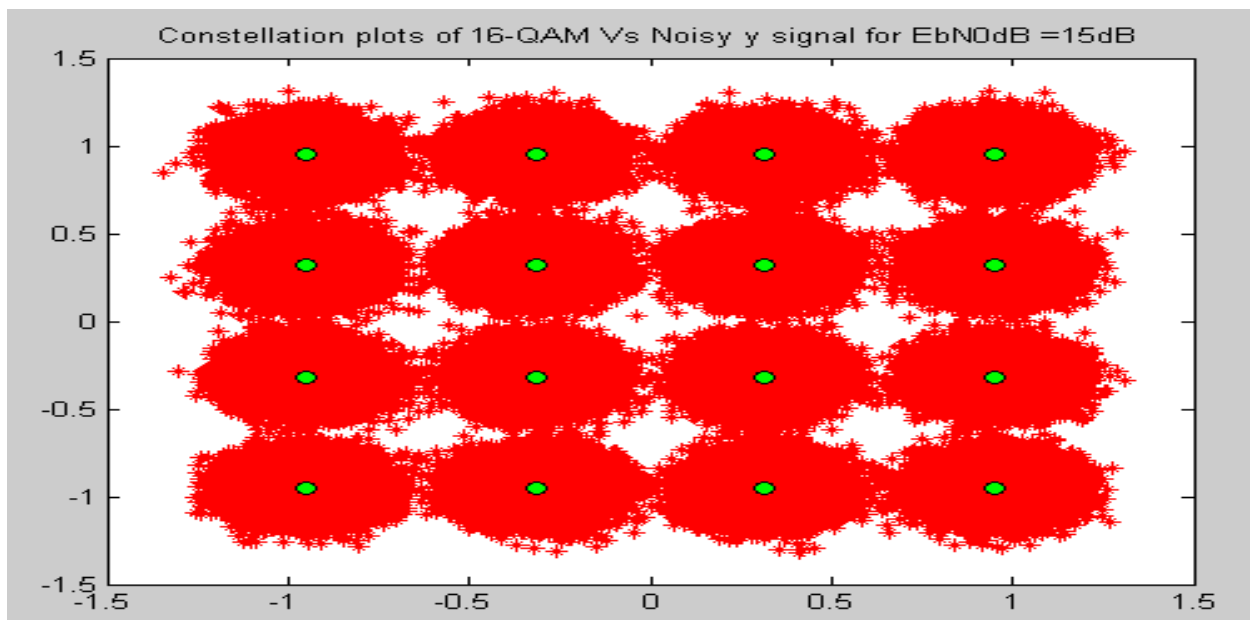
this paper proves that increasing the value of M results in increase of BER with the increase in data rate.

Because Quadrature Amplitude Modulation (QAM) makes full use of both the amplitude and phase of two orthogonal carriers, the bandwidth efficiency is increased. A QAM constellation diagram is a two-dimensional scatter plot of a digital modulated signal in the complex plane. In QAM, if a suitable constellation size is chosen, it is possible to achieve relatively high spectral efficiencies, limited only by the signal-to-noise ratio and the effects of distortion and fading in the communications channel. The constellation points are usually packed within a square or rectangular grid with equal vertical and horizontal spacing. The constellation diagram of 16-QAM, which is used in this research, the data is transmitted using 4-bit symbols. So during the transmission, the number of data bit errors is minimized when symbol detection errors occur. However, higher-order QAM constellations mean that the constellation points are more closely spaced together and are thus more susceptible to noise and other signal corruptions, possibly leading to incorrectly detected symbols and hence to bit errors.

Figure 3.2 to 3.5 shows the constellation diagram of both 16-QAM and 16-PSK at different SNR for both the AWGN and Rayleigh channels.







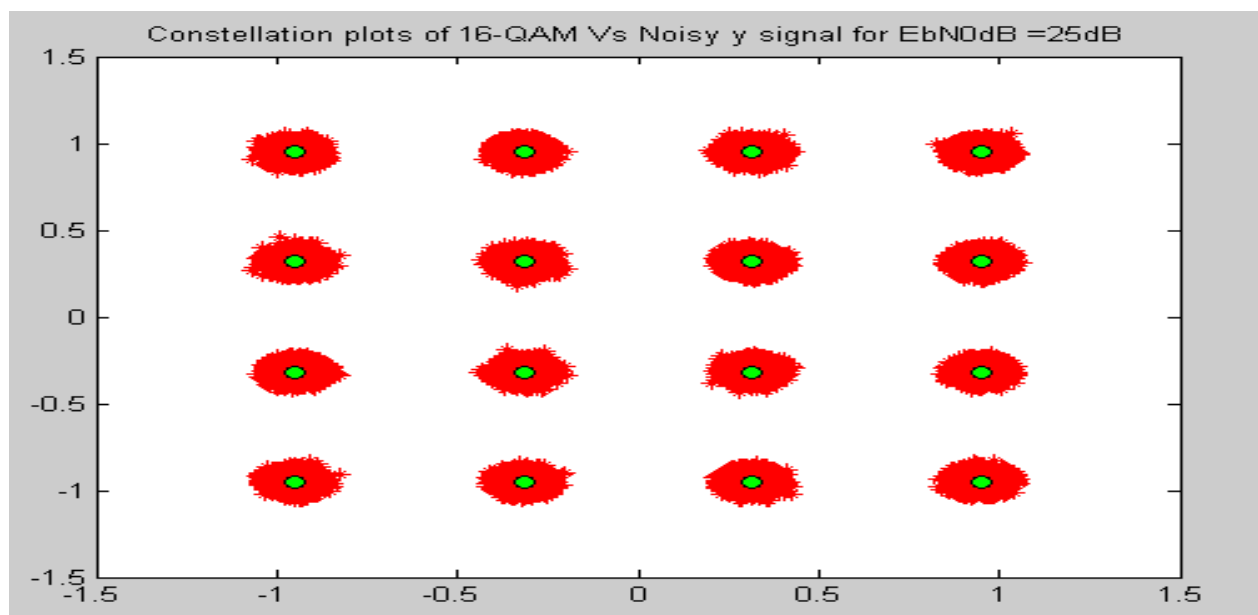
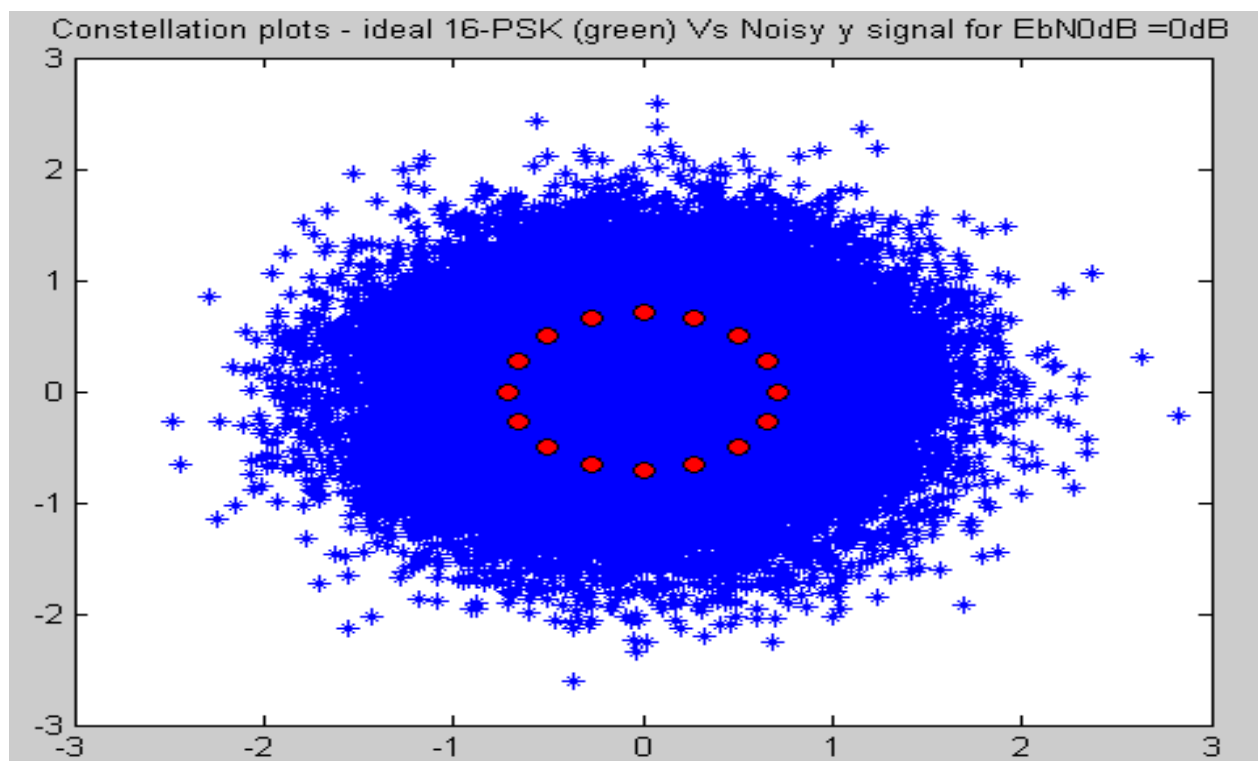
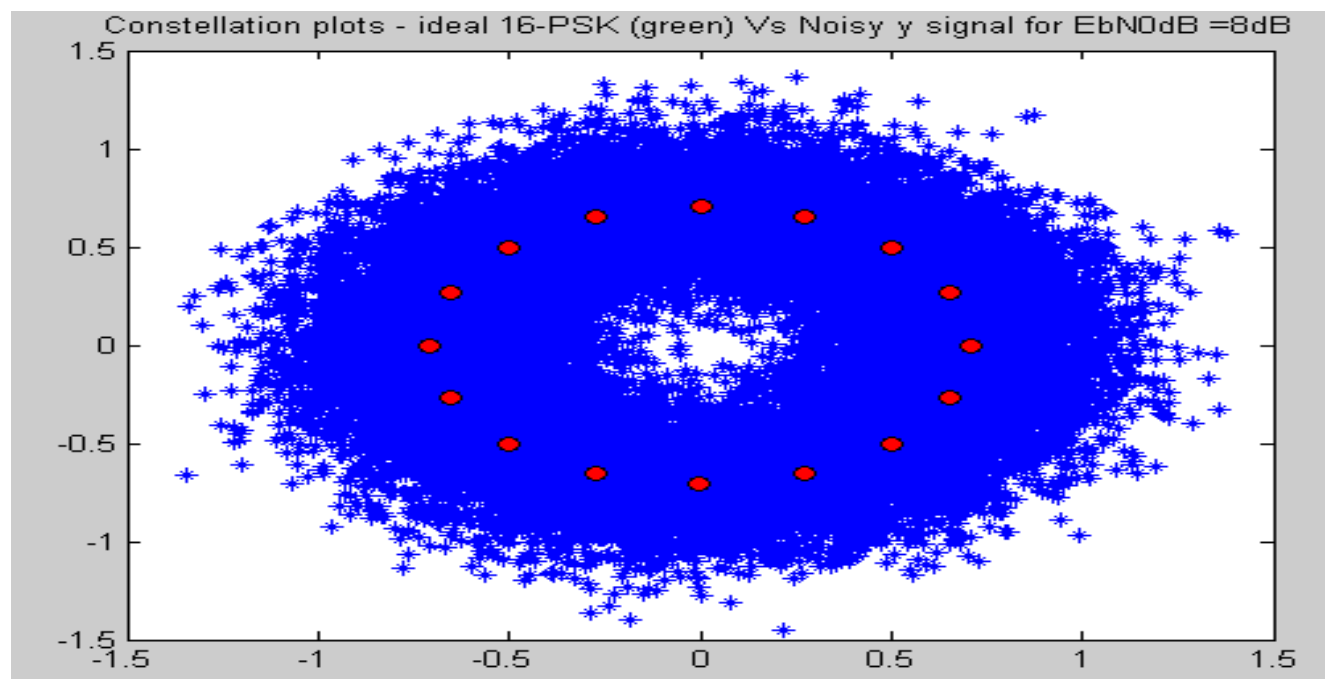
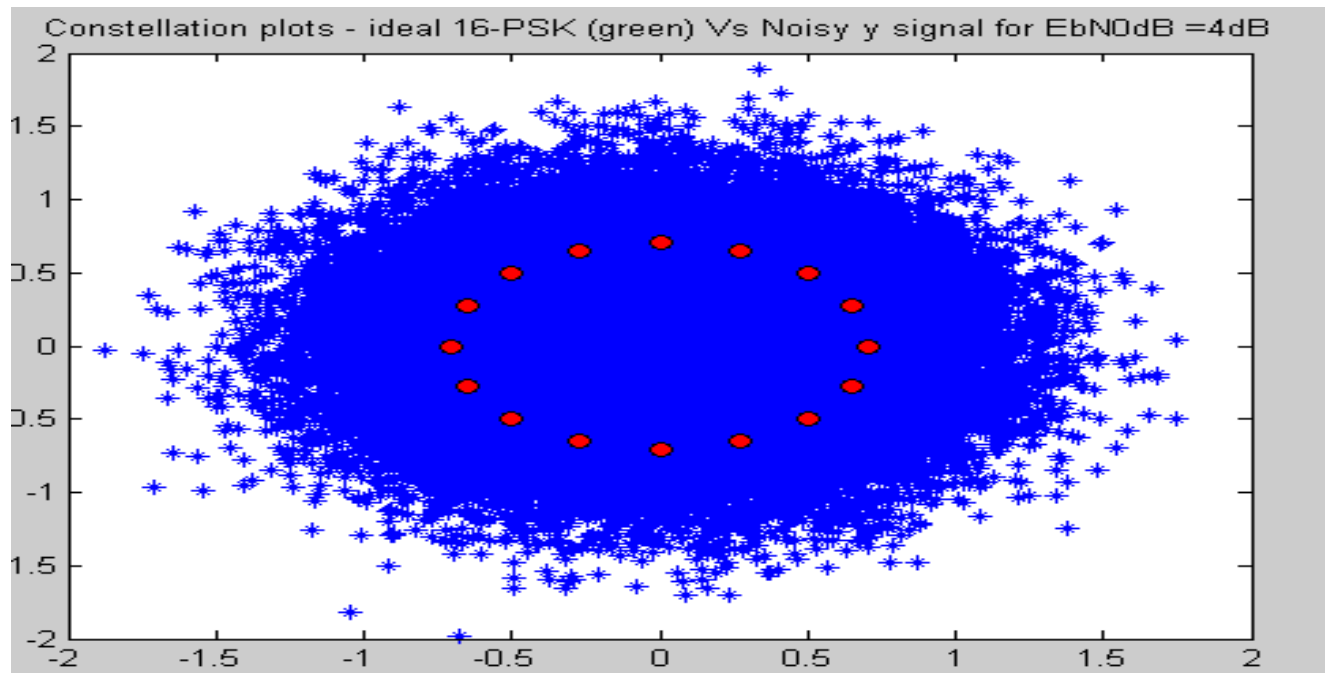
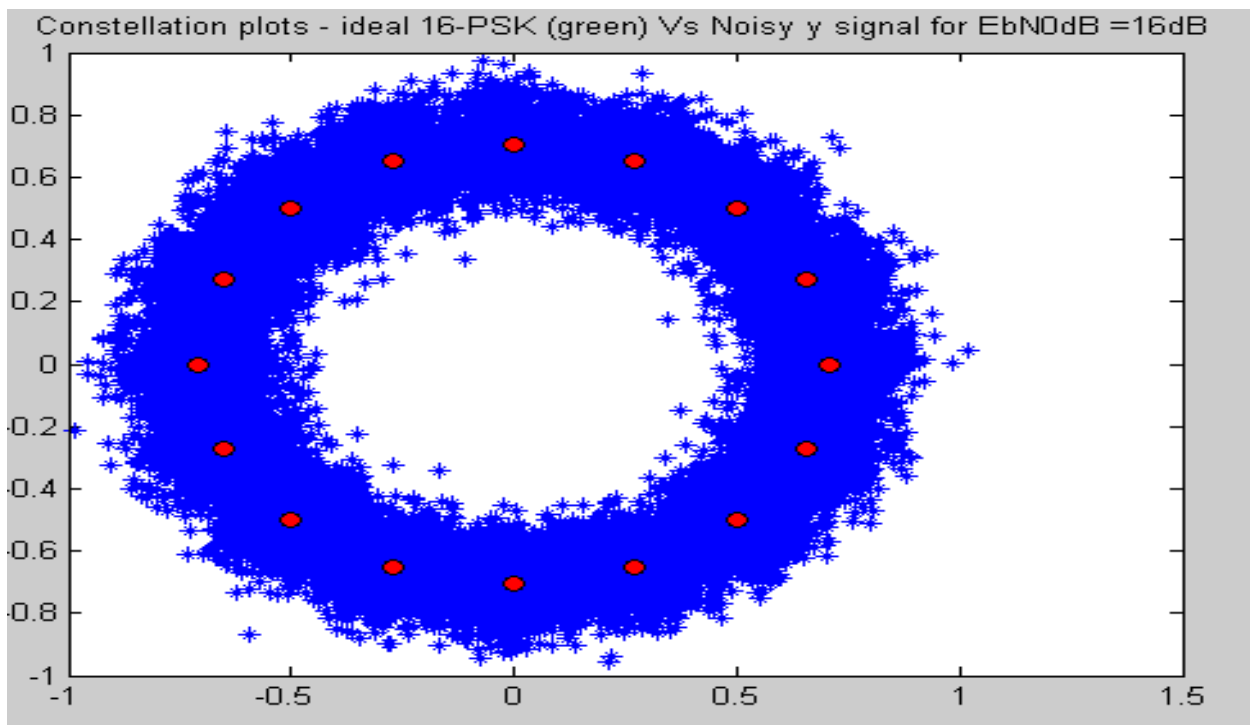
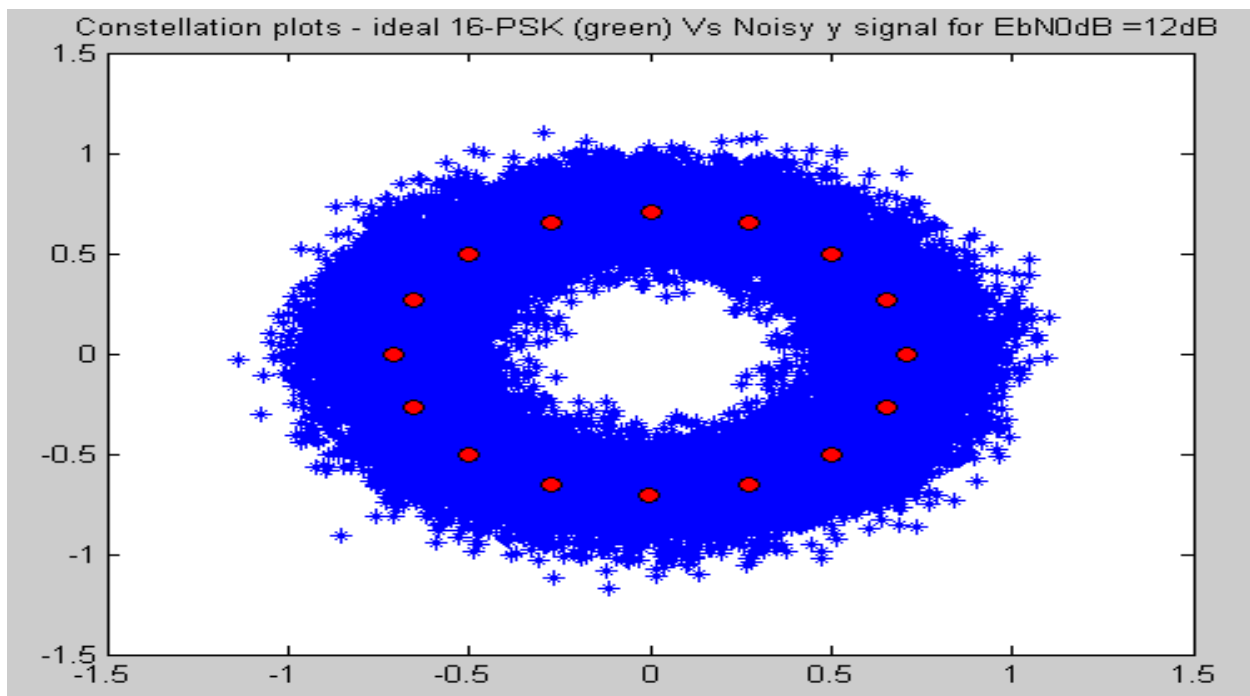


Figure 3.2 Constellation diagram of 16-QAM over AWGN channel at different E_b/N_0 dB







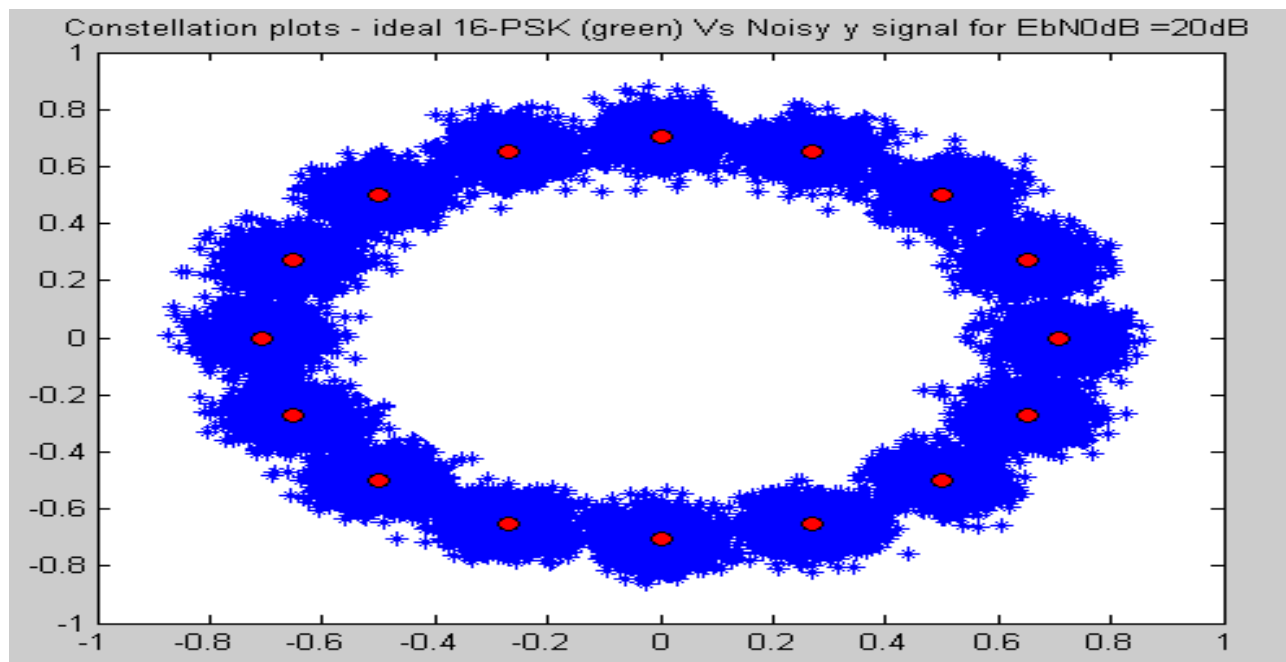
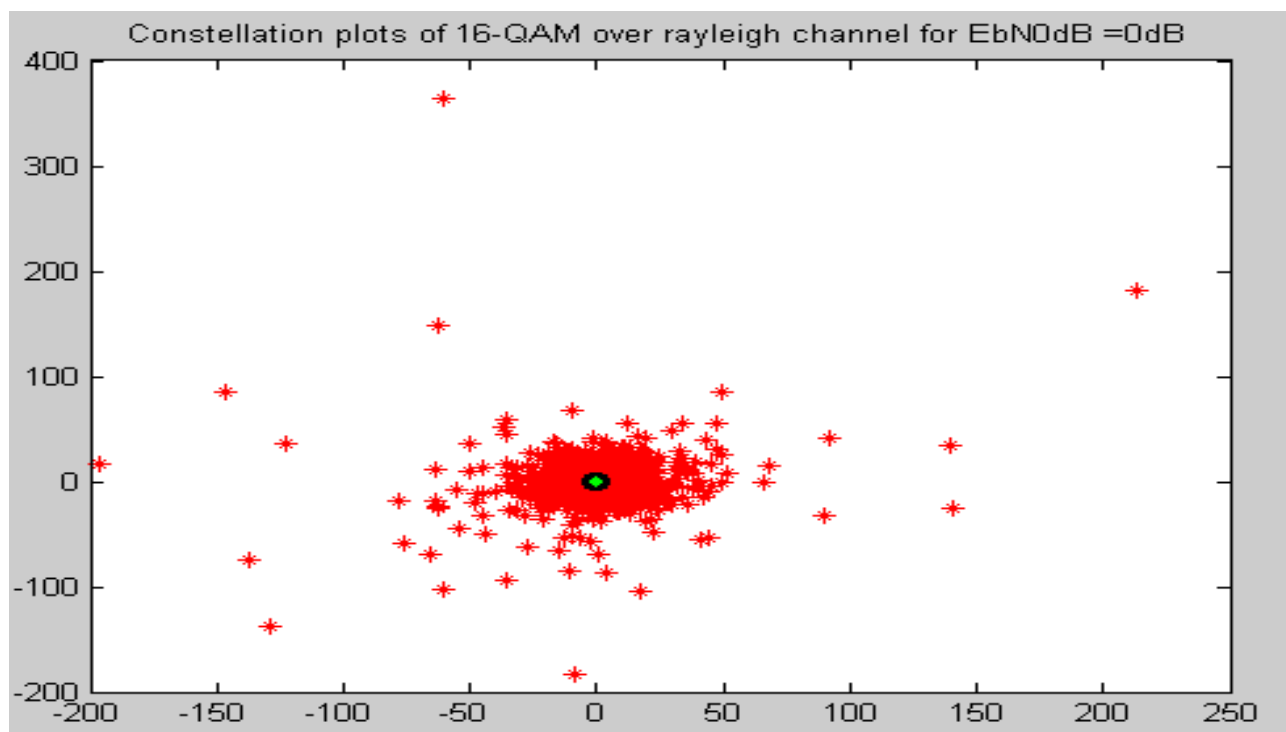
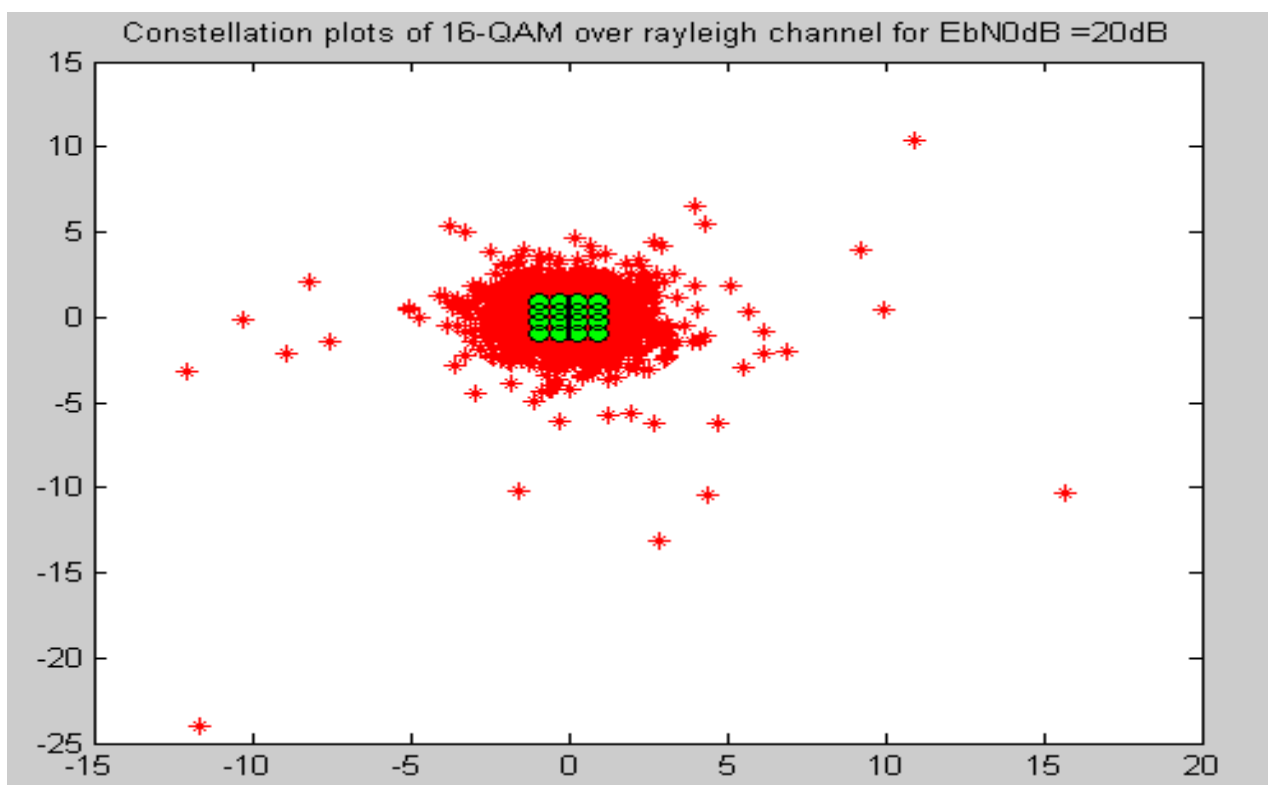
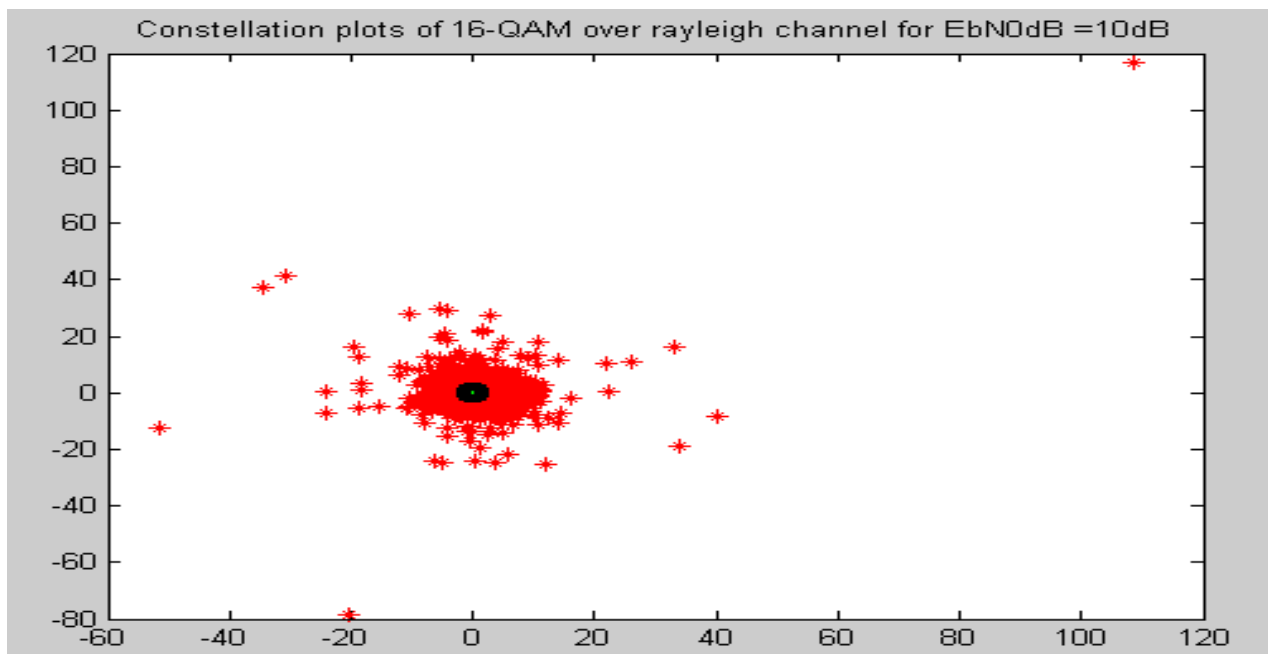
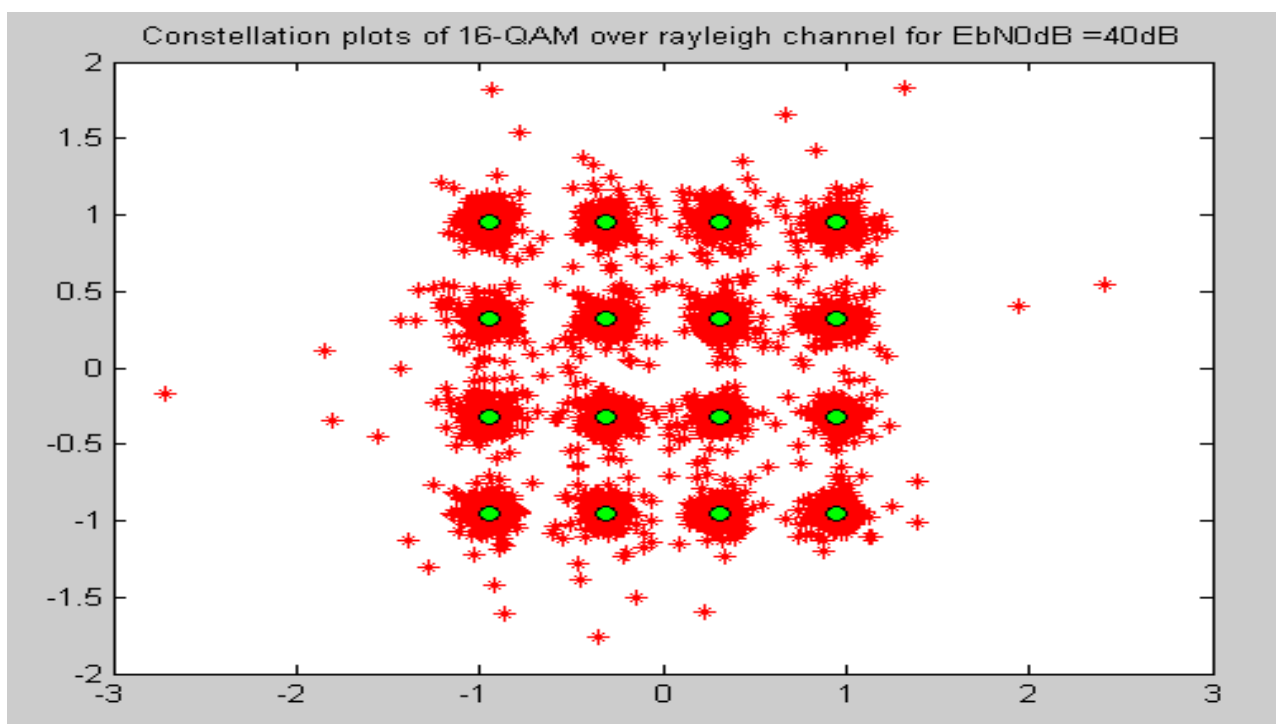
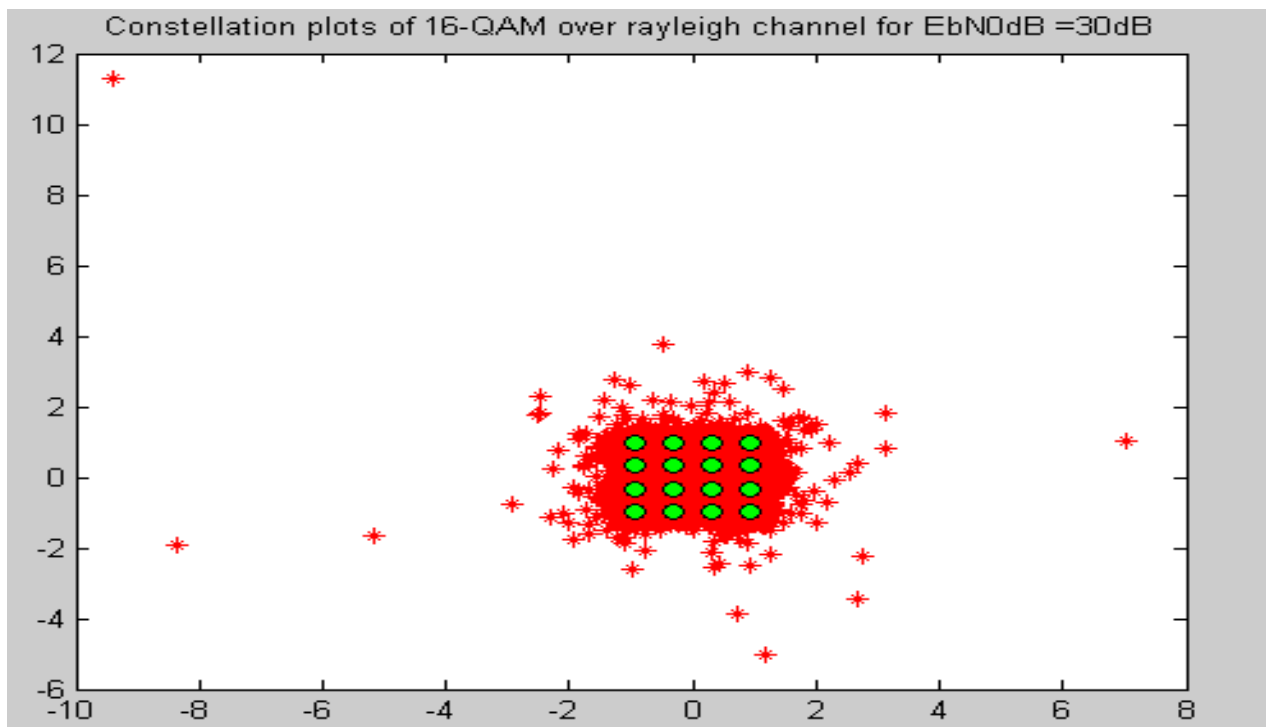


Figure 3.3 Constellation diagram of 16-PSK over AWGN channel at different Eb/N0dB







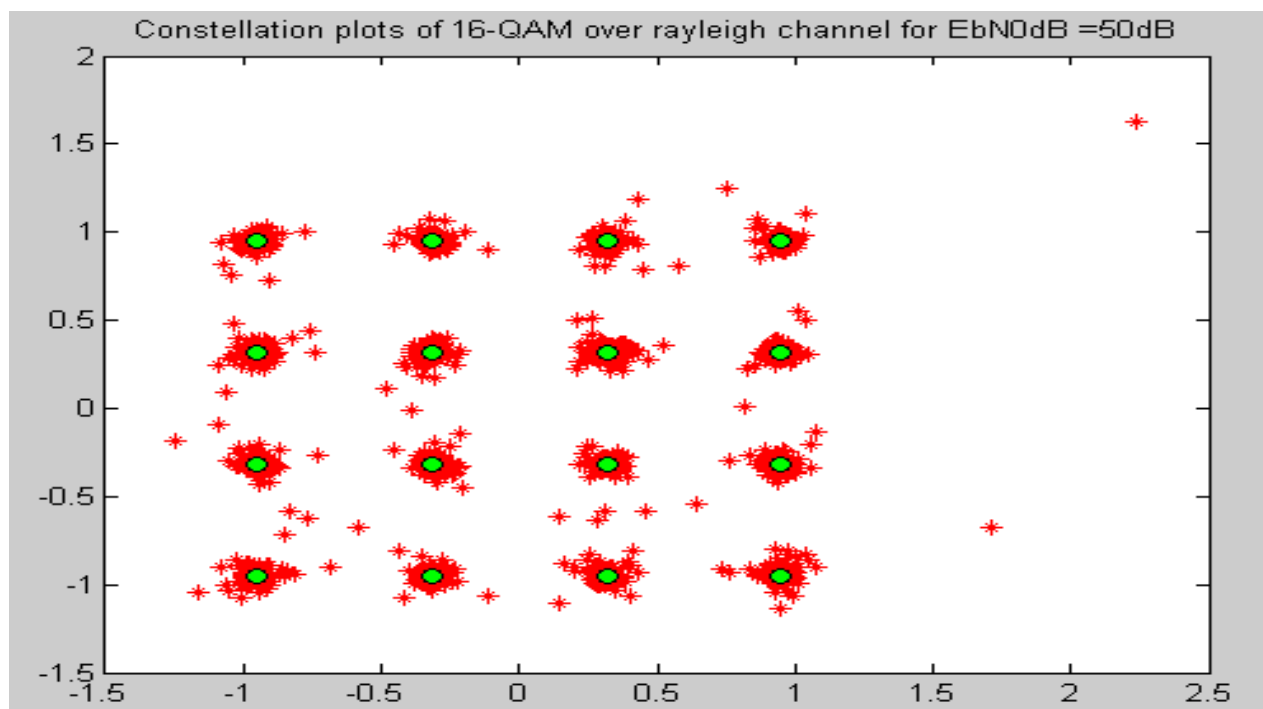
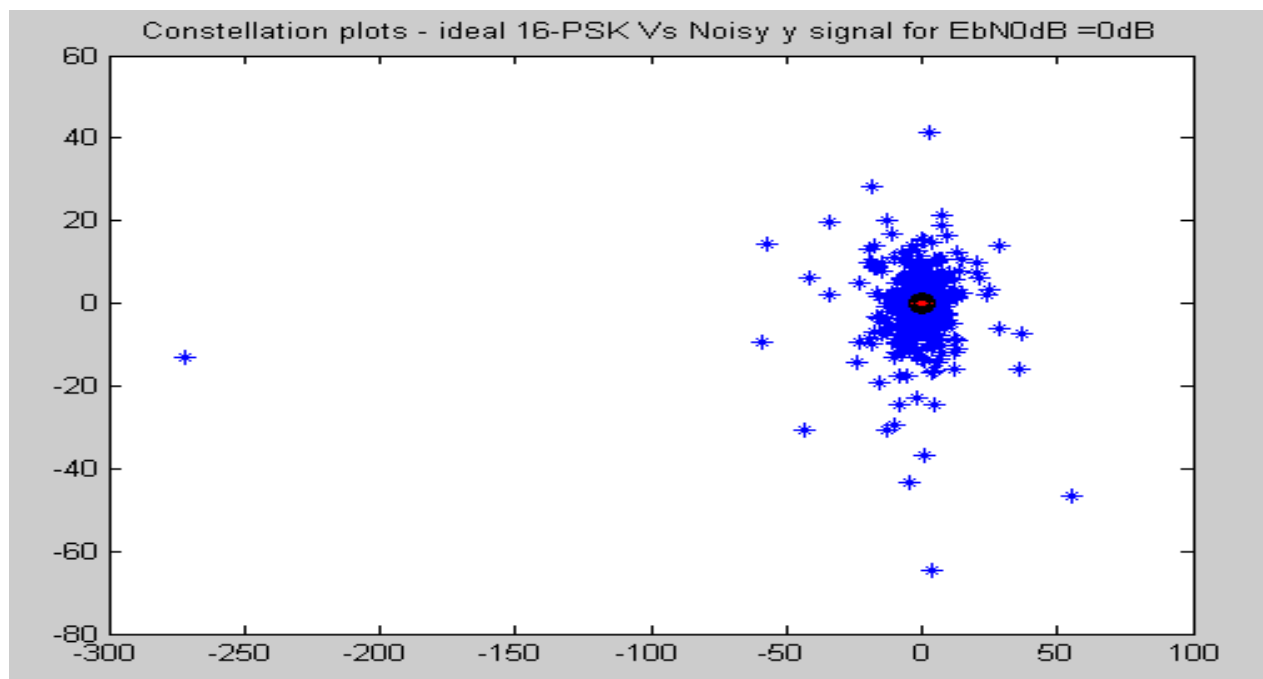
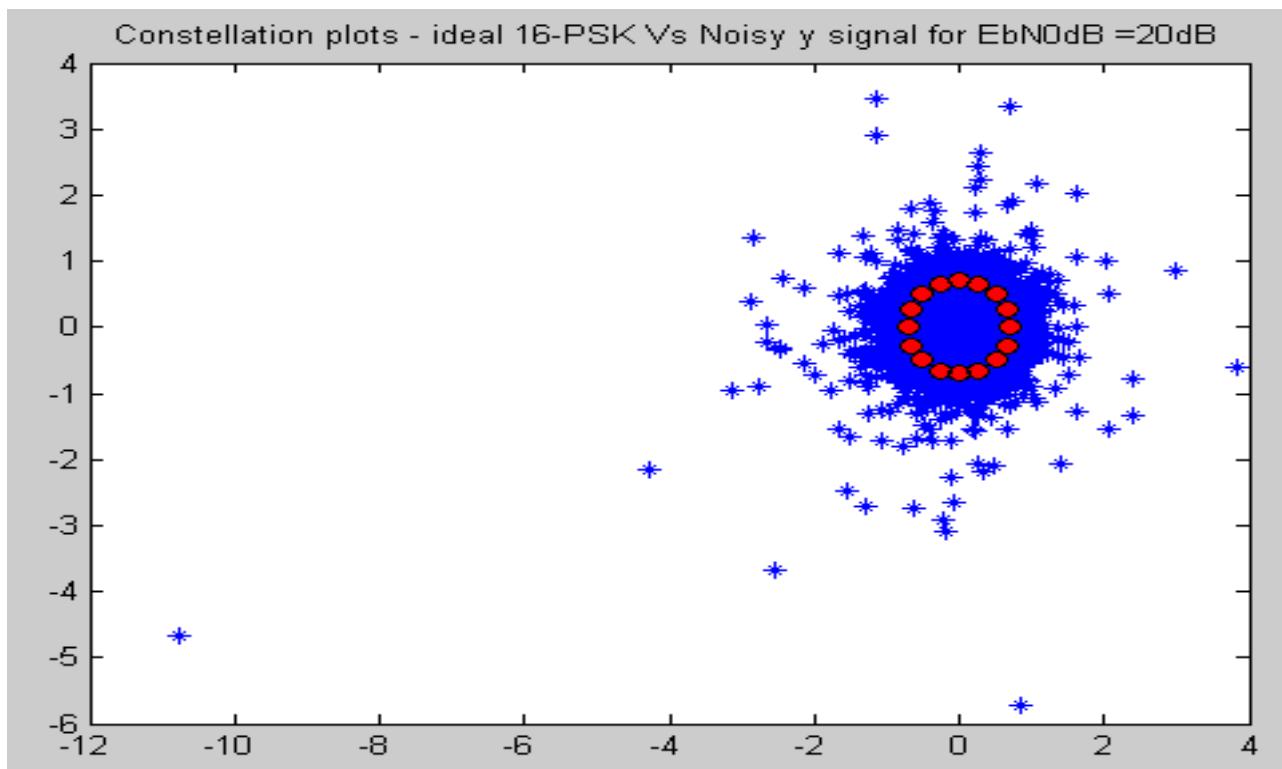
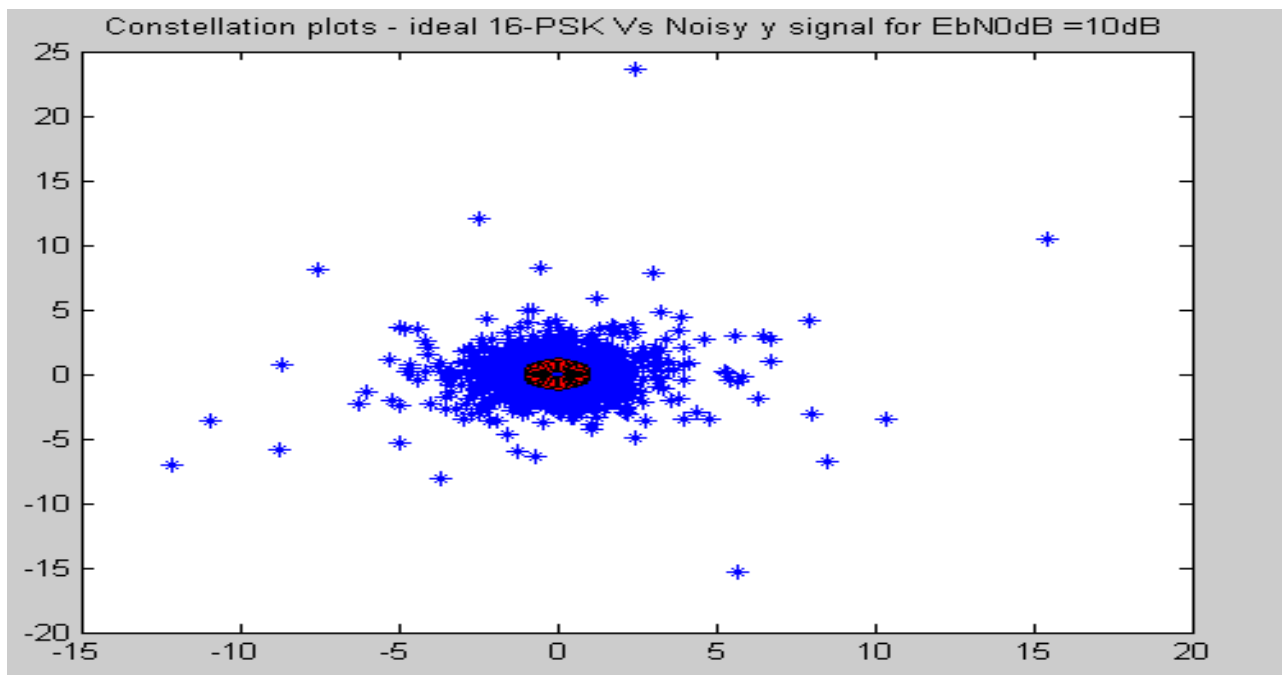
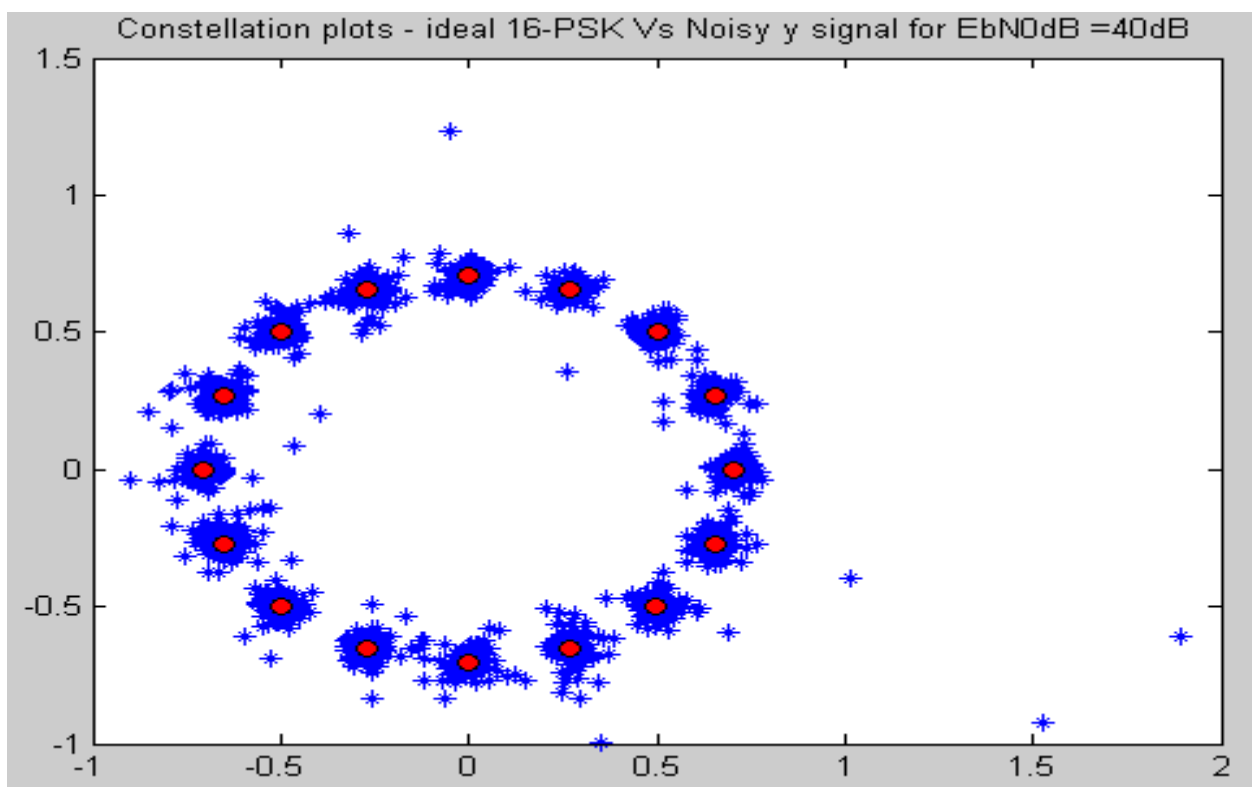
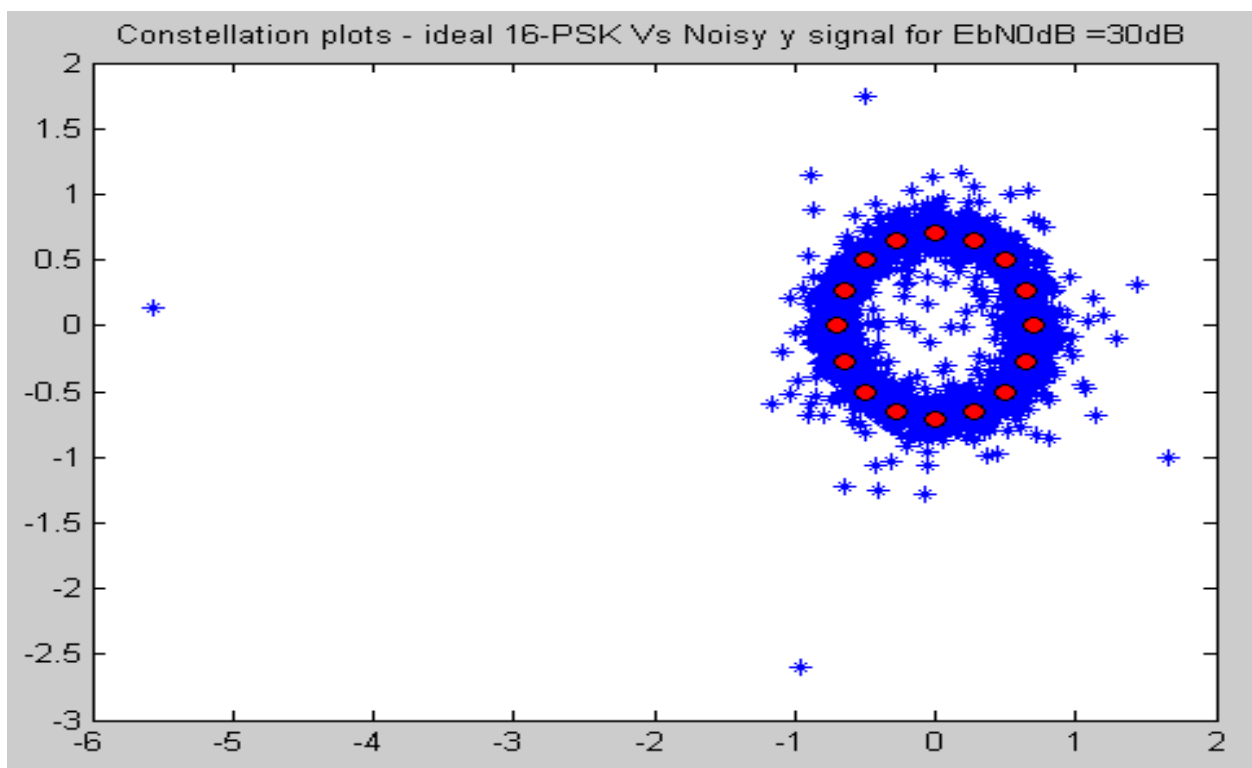


Figure 3.4 Constellation diagram of 16-QAM over Rayleigh channel at different E_b/N_0 dB







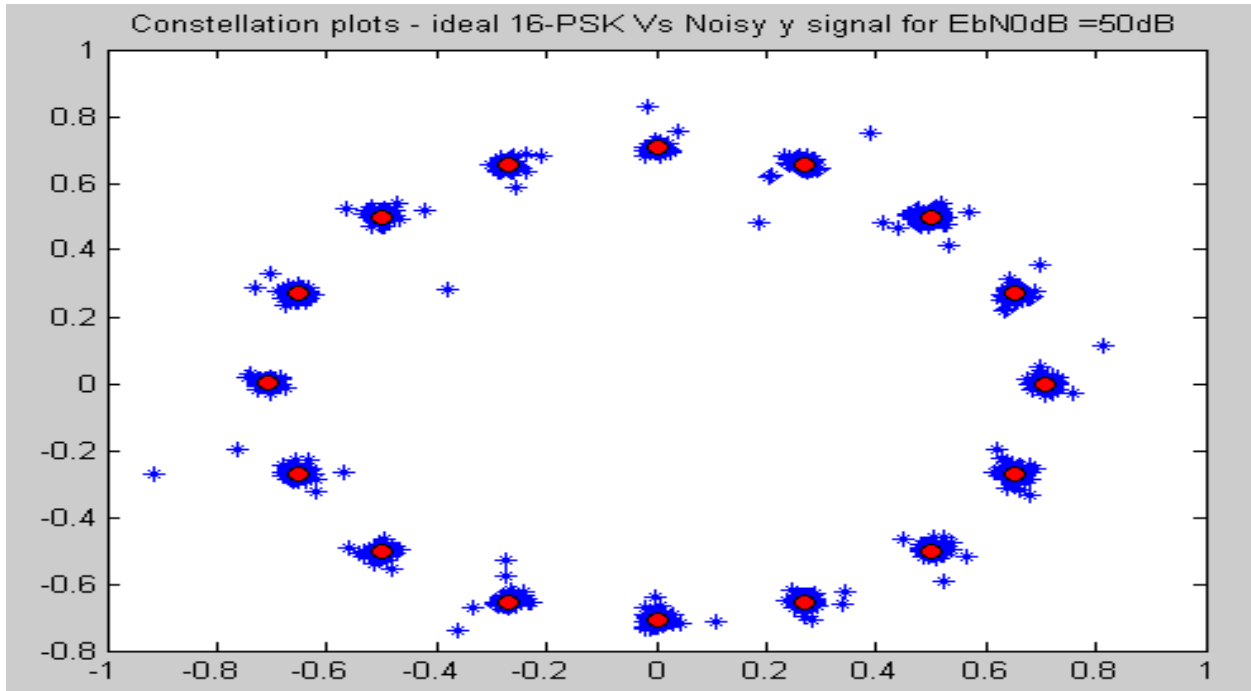
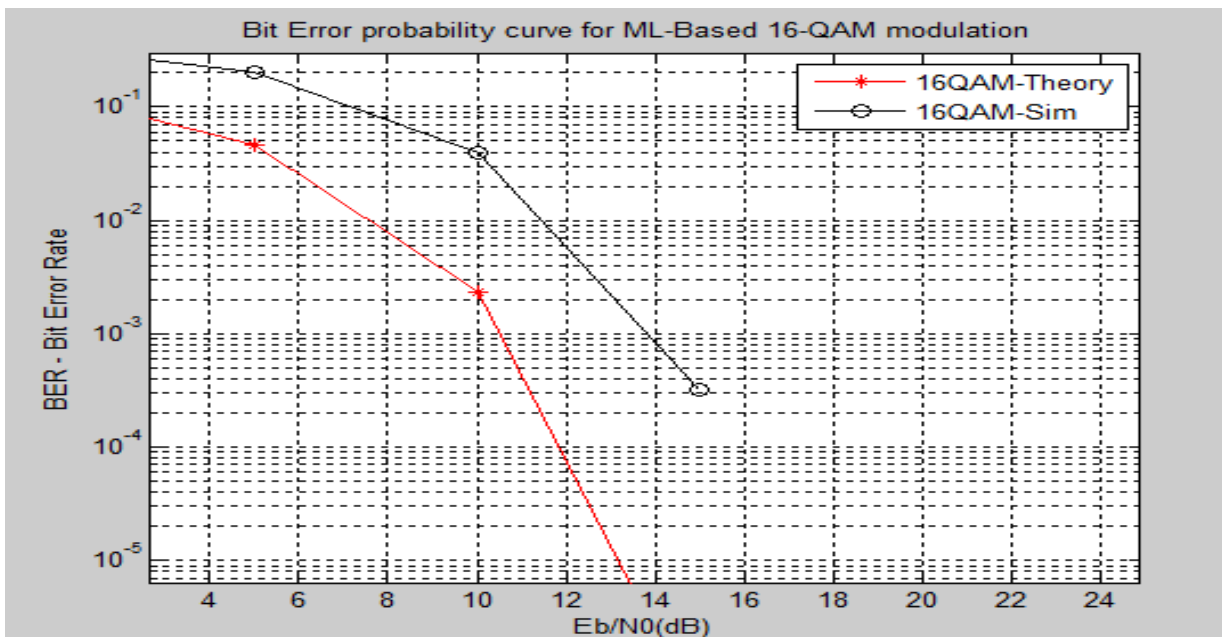


Figure 3.5 Constellation diagram of 16-PSK over Rayleigh channel at different EbN0dB

The Simulated and theoretical performance curves (Eb/N0 Vs BER) for 16-QAM and 16-PSK modulation over Rayleigh Fading channel and the AWGN is given below.



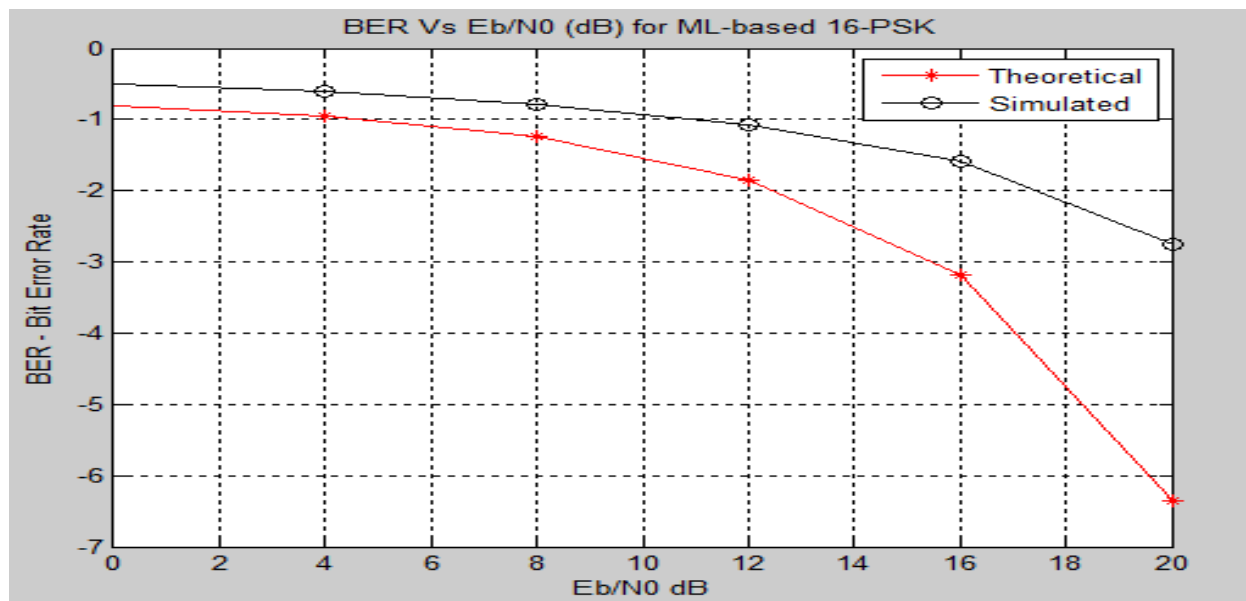
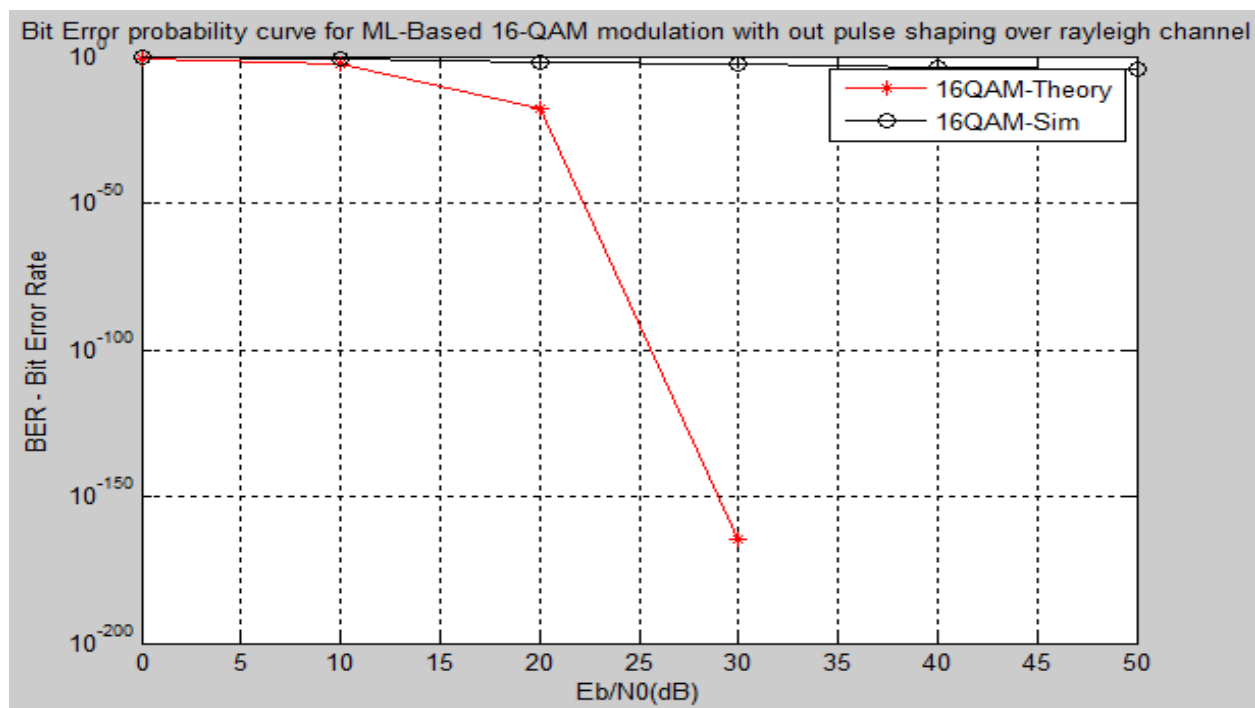


Figure 3.6 Eb/N0 Vs BER for ML based 16-QAM and 16-PSK modulation over AWGN channel



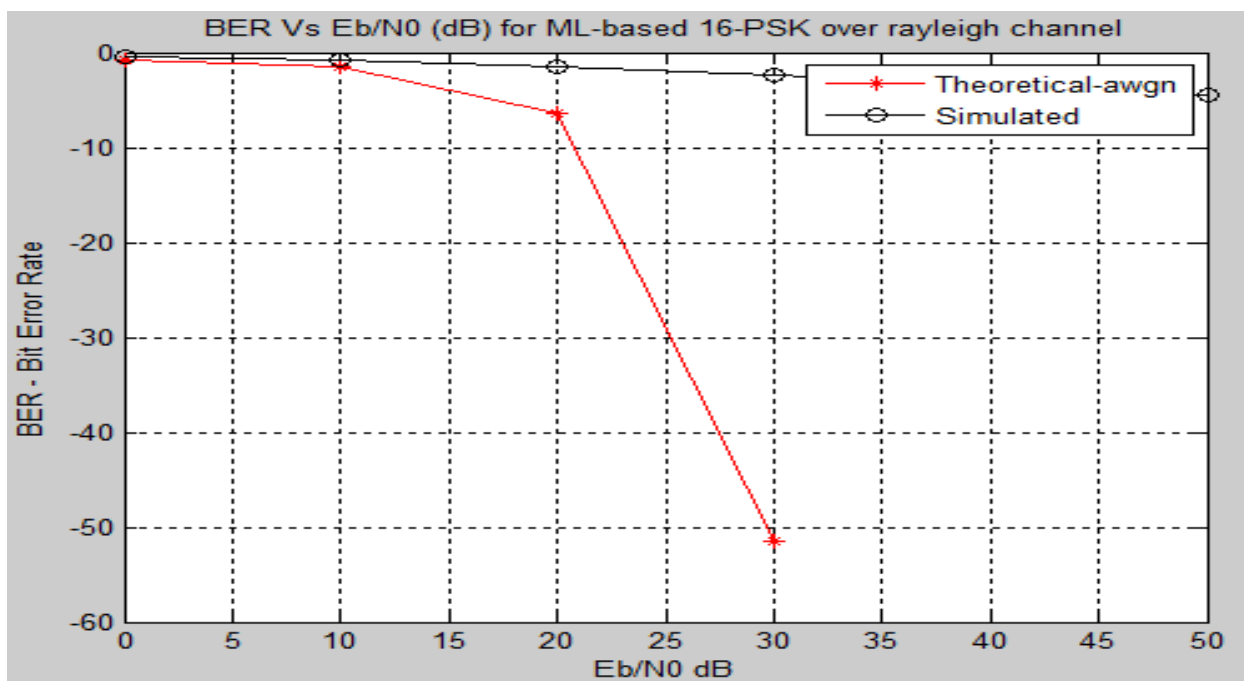


Figure 3.7 Eb/N0 Vs BER for ML based 16-QAM and 16-PSK modulation over Rayleigh Fading channel

The Simulated and theoretical performance curves (Eb/N0 Vs BER) for M-ary QAM and PSK modulation over AWGN channel is given below.

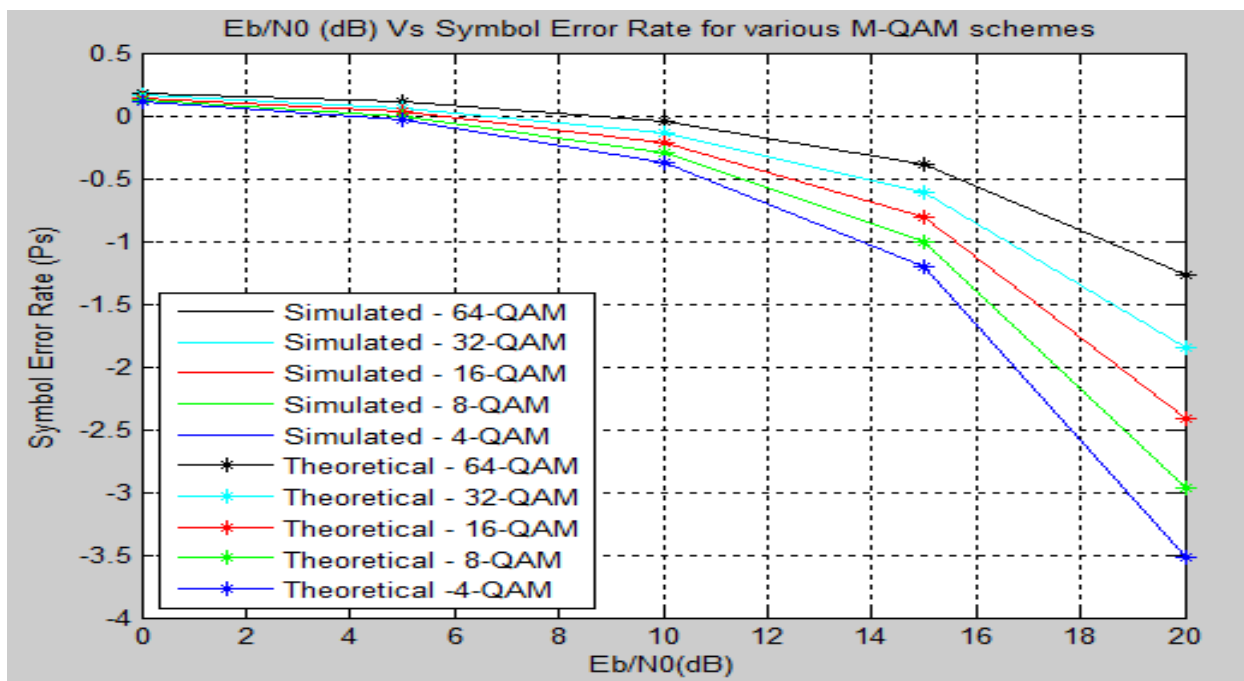


Figure 3.8 BER Performance of ML based m-ary QAM over AWGN channel

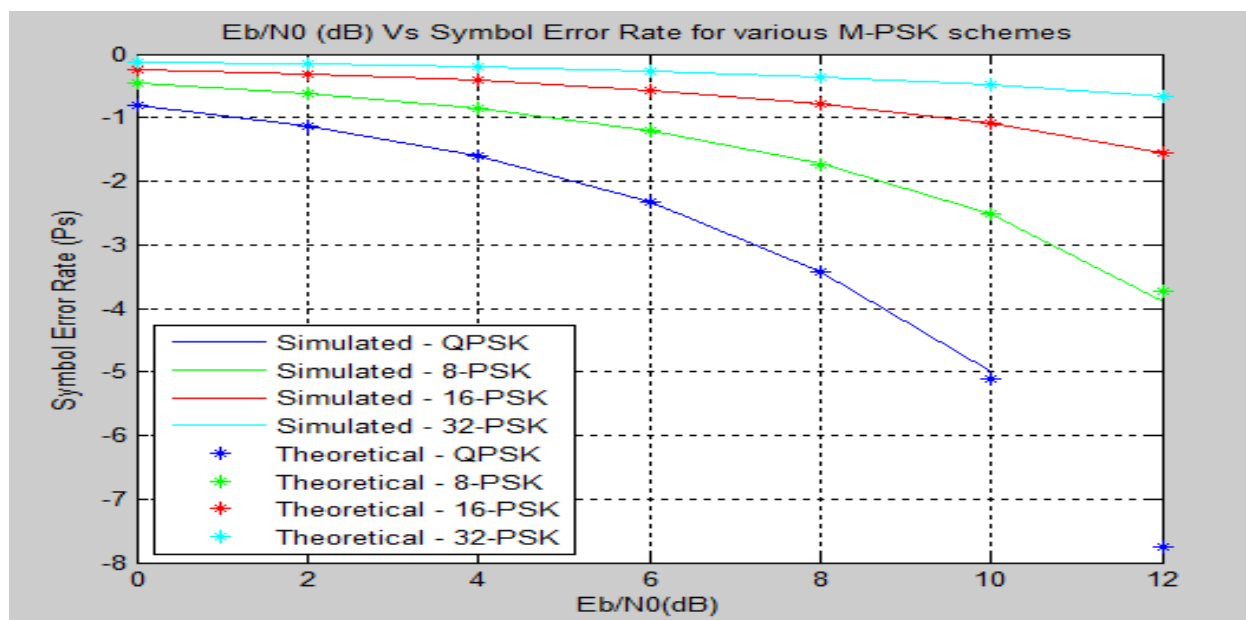


Figure 3.9 BER Performance of ML based m-ary PSK over AWGN channel

For AWGN channel the BER at 15dB is 10^{-3} , which is very acceptable. Again for the case of Rayleigh Fading channel at 35dB still we can have a BER of 10^{-3} . What we observe here is the Rayleigh channel requires additional energy to get same BER like that of AWGN.

The above system is also implemented with a recorded audio input signal, so the design is not changed except the N random input signal is replaced with a recorded wave file. The wave file have the following additional parameters sampling rate (F_s) in Hertz, number of bits and number of channels. Among the common sample rates are 8000, 11025, 22050, 44100, 48000, and 96000 Hz. The number of bits must be 8, 16, or 24. The number of channels must be 1 or 2 (mono or stereo). The audio recorder (F_s , NBITS, NCHANS) creates an audio recorder object with sample rate F_s in Hertz, number of bits NBITS, and number of channels NCHANS. So the default one is 8000 Hz, 8-bit, 1.

The time and frequency domain plot of the wave file is given by Figure 3.10 below. And the BER performance of 16-QAM modulation over the AWGN followed by ML detection is given in Figure 3.11.

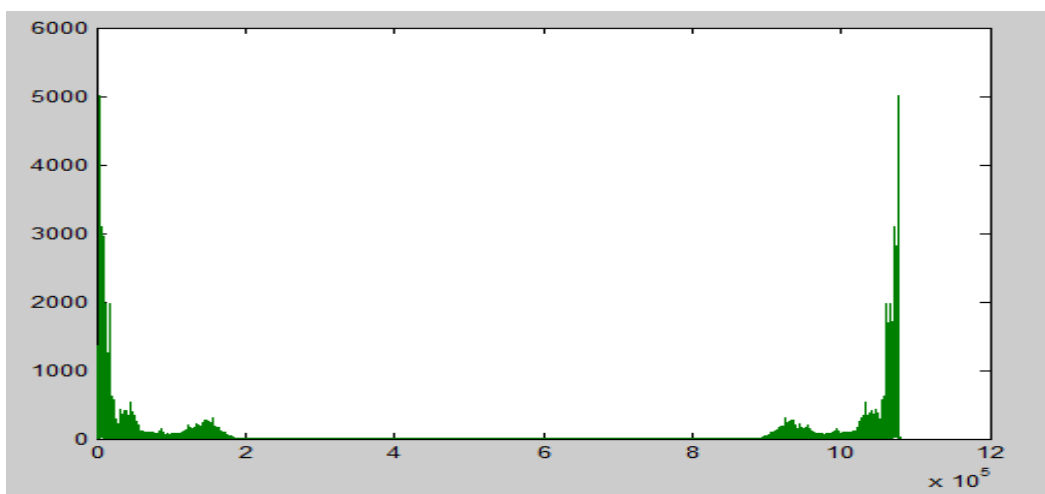
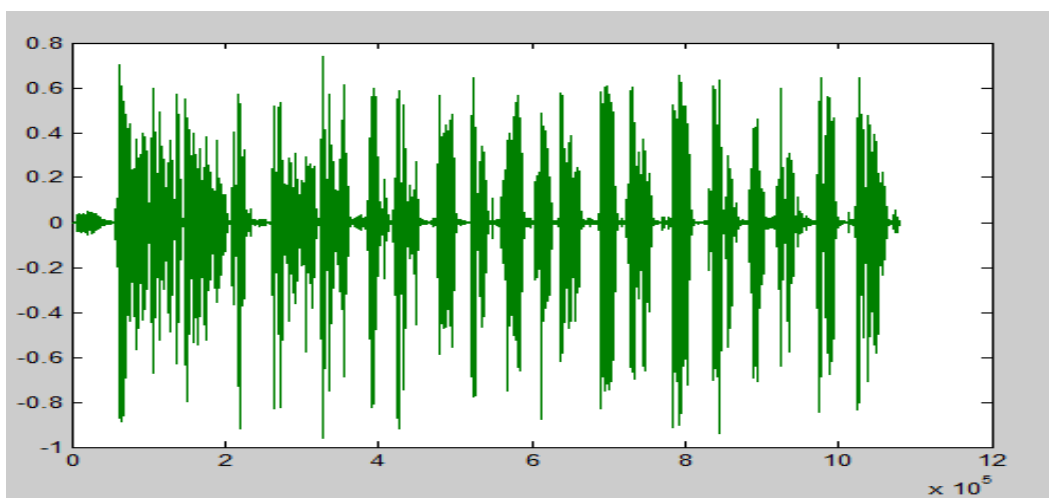


Figure 3.10 The time and frequency domain plot of the input audio file

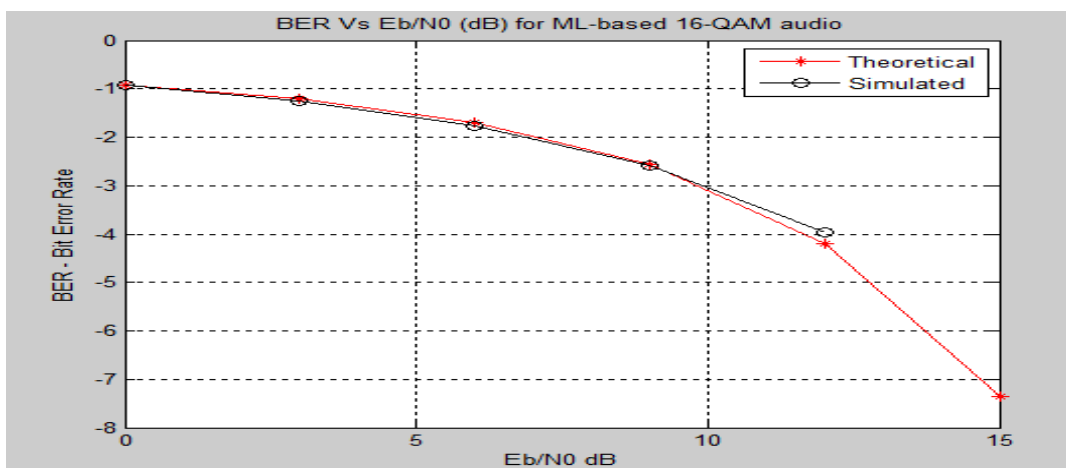


Figure 3.11 Eb/N0 Vs BER for ML based 16-QAM audio file modulation over AWGN

Here during real time implementation we can see the difference between the wave file before transmission and after detection by playing the audio.

Chapter Four

Implementation of Multi-carrier Multiuser (MC-CDMA) Symbol Detection

Now day's researchers are combining techniques to serve multiple users while keeping the Orthogonality of data symbols with the intension of obtaining advantages of both OFDM and CDMA, and the proposed new technique is generally termed as Multicarrier-Code Division Multiple Access (MC-CDMA) [21].

The basic principle of OFDM is to transmit a high-rate data stream by breaking it into several parallel low-rate data streams, and then transmitting these using multi-carrier modulations (MCM) with each subcarrier orthogonal to each other. The multiple carriers in OFDM are typically termed as "subcarriers". In practice, MCM is implemented with the Fast Fourier Transform (FFT) in most OFDM systems. A distinguishing advantage of OFDM is the ability to combat ISI, because when a larger number of subcarriers are used, the symbol period on each subcarrier increases so that it can be sufficiently larger than the channel delay spread. With the introduction of a sufficient guard interval, usually a cyclic prefix (CP), the ISI can be completely avoided in principle. Another merit that aids OFDM's wide acceptance as a good candidate technique for future communication systems is its spectrum efficiency, achieved since the spectra of adjacent subcarriers overlaps. Like any other technique, OFDM also suffers from drawbacks, such as high peak to average power ratio (PAPR), which requires amplifiers with a large dynamic (linear) range or sophisticated PAPR reduction techniques. It is also very sensitive to frequency offset, which requires accurate frequency synchronization and channel estimation [22].

CDMA, sometimes called spread spectrum multiple access (SSMA), and allows different users to transmit signals using the same frequency band at the same time. These users are distinguished with a uniquely allocated spreading code, which is used to spread the original signal to a much larger bandwidth than that of the original information.

CDMA comes from its distinctive merits. As a multiple access technique, CDMA system has a "capacity advantage," which means that it can provide more users than FDMA and TDMA at the possible cost of a slight decrease in system performance. On the other hand, there are also

disadvantages that should be noted when using CDMA systems: the transmitted signal power should be well controlled to avoid the “near-far” effect [22].

There are three types of new multiple access schemes based on a combination of CDMA and OFDM techniques. They are MC- CDMA, multicarrier DS-CDMA and multi-tone (MT) CDMA. MC-CDMA technique has been considered as an effective solution to improve bandwidth efficiency and robustness in mitigating frequency-selective fading and it has a great potential to implement future mobile communications [22].

MC-CDMA system is the strongest candidate for next generation wireless mobile communication systems due to its merits of high spectral efficiency and robustness against ISI due to the presence of CDMA and OFDM systems. The OFDM parts reduce multipath fading and inter symbol interference ISI and the CDMA part increases spectrum utilization. Advantages of this technique are its robustness in case of multipath propagation and improve security with the minimize ISI. Nevertheless, due to the loss of Orthogonality at the receiver in a mobile environment, the multiple access interference (MAI) appears. The MAI is one of the factors that degrade the BER performance of MC-CDMA system. The multiuser detection and turbo coding are the two dominant techniques for enhancing the performance of the MC-CDMA systems in terms of BER as a solution of overcome to MAI effects [23]. The multi carrier modulation (MCM) techniques, the spreading is made in frequency domain and the time synchronization requirements are much lower than conventional direct sequence CDMA schemes. The conventional CDMA is not practical when the data transmission rates are very high. To combat the difficulties faced by CDMA system and to improve the BER performance in multi user environment, MC-CDMA systems are recommended [21 and 22].

4.1 MC-CDMA System Model

In multicarrier system, the signal can be easily transmitted and received using the FFT device without increasing the transmitter and receiver complexities. Therefore, the parameters of OFDM become the basic parameters of MC-CDMA. The multicarrier CDMA scheme is categorized mainly into two groups. One spreads the original data stream using a given spreading code and then modulates a different subcarrier with each chip and other spreads the serial-to-parallel converted data streams using a given spreading code and then modulates a different subcarrier with

each of the data stream. The overall system model is given by Figure 4.1 and the OFDM transmitter and receiver is given by Figure 4.2 and 4.3 respectively.

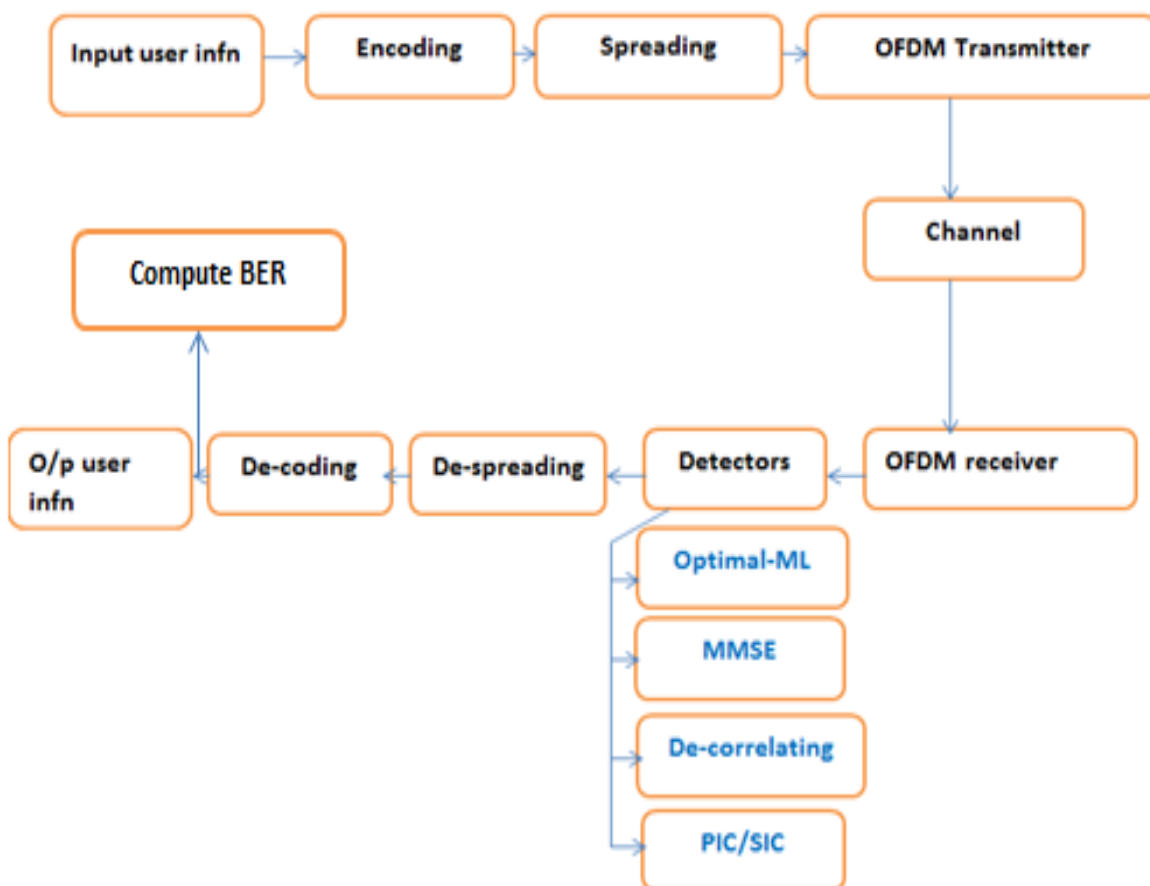


Figure 4.1 MC-CDMA system models

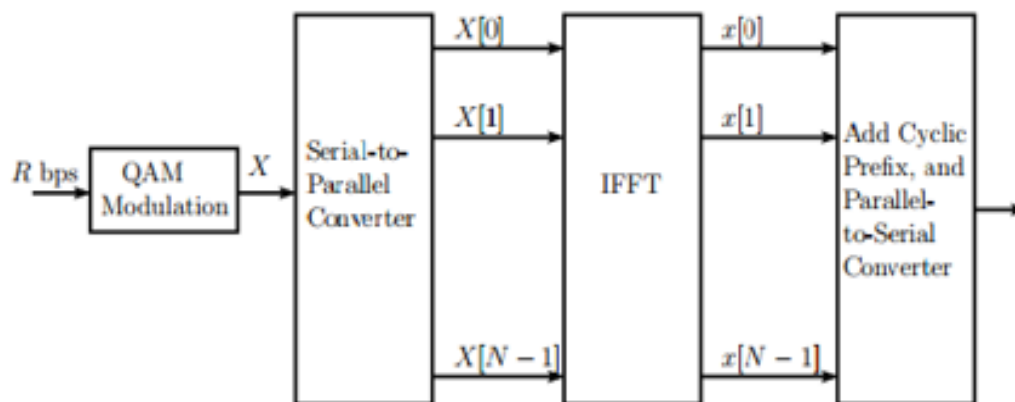


Figure 4.2 OFDM Transmitter model [24]

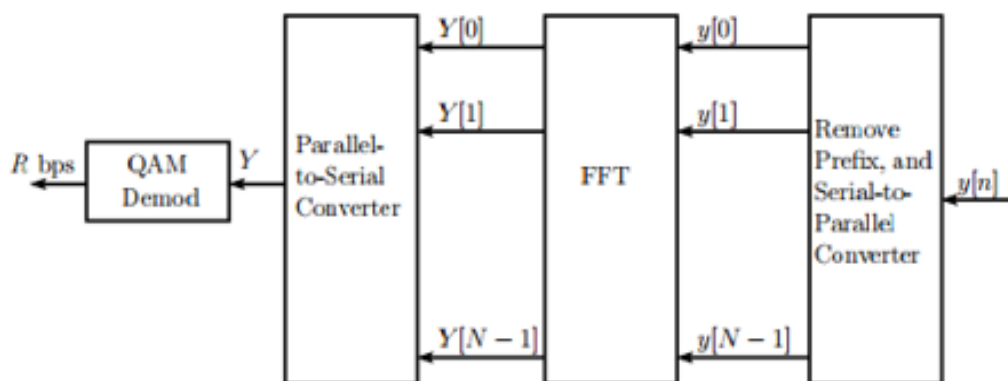


Figure 4.3 OFDM Receiver model [24]

The model shows the application of OFDM and CDMA in the MC-CDMA. In general, the spreading sequences of the spreading module can be Walsh code, which has strict Orthogonality and good cross-correlation than Gold and PN-sequences[39]. When the information is transported in MC-CDMA system, as long as the system meets the conditions that set in the channel, each individual user's orthogonal of spreading codes can be recovered. Therefore, the maximum number of users system which can accommodate is equal to the length of the spread codes. It can increase the capacity of the system by means of extending the length of the spreading code sequence, which is better than that of CDMA. The channel can be multipath Rayleigh fading and Additive White Gaussian Noise (AWGN) channel [21].

The transmission signal of the user k is:

$$S_k(t) = \sqrt{2P/N} \sum_{i=1}^N b_k(t) c_k(i) \cos(\omega_i t + \theta_k) \quad (4.1)$$

The formula represents the transmission power per bit signal. Where,

- ✓ N represents the number of sub-carriers for each information bit spreading.
- ✓ $c_k(i)$, is the spreading code for the user k.
- ✓ $b_k(t)$, represents binary data stream of user k
- ✓ θ_k , represents phase of the introduction of random, it is subject to a uniform distribution

The spreading code sequence used by the user k can be expressed as:

$$c_k = [c_{k1}, c_{k2}, \dots, c_{kN}]^T \quad (4.2)$$

$$\text{The data for the IFFT: } X_K = C_k S_k \quad (4.3)$$

Where, X_K represents the data of the k-th user transmitted on each sub-carrier and S_k represents the transmission data of users.

$$S_k = [S_{k1}, S_{k2}, \dots, S_{kN}]^T \quad (4.4)$$

On the receiver side, the signal after the FFT can be expressed as:

$$y_k = h_k * X_K + n_k = h_k * C_k S_k + n_k \quad (4.5)$$

Where n_k donates the noise, assuming the symbols on receiving end and the carrier achieve a complete synchronization, the transmission data of the kth user through the FFT operation can be expressed as:

$$y = \sum_{K=1}^K y_k = CHS_K + n \quad (4.6)$$

\mathbf{Y} , represents observation vector on the receiving end, and \mathbf{S}_k , represents all user's data vector.

4.2 MC-CDMA Symbol Detectors

Detection techniques can be classified as either single-user detection or multi-user detection. Generally, single-user detection is not preferred in MC-CDMA system since it is sub-optimal. It detects the user signal of interest by not taking into account any information about multiple access interference and therefore it is sub-optimal. This has been rectified in multi user detection by using *a priori* knowledge of the spreading codes but at the expense of receiver complexity. For multiuser Multi-carrier transmission with user information \mathbf{S}_i , where $i = 0, \dots, M-1$, the received signal \mathbf{Y} is given by,

$$Y = CH S_i + N = HX_i + N \quad (4.7)$$

“ \mathbf{Y} ” represents observation vector on the receiving end, and “ \mathbf{S} ” represents all user's data vector. Where, $S_i = [s_0, s_1, \dots, s_{M-1}]$ and $\mathbf{Y} = [y_1, y_2, \dots, y_N]$ denote the transmit symbol from the Mth subcarrier and the received signal at the Nth receiver respectively, “ \mathbf{H} ” stands for the channel transfer matrix, “ \mathbf{C} ” is the spreading code for the user k and “ \mathbf{N} ” denotes the white Gaussian noise with a variance of δ_n^2 . Then the MUD mitigates the effect of ISI and delay spread by suppressing the channel effects. Sections 4.2.1 through 4.2.3 explain methods that can be used for detection of MC-CDMA symbols.

4.2.1 Maximum likelihood (ML) Multi-User Detection

ML MUD constructs all possible combinations of the transmitted Symbols of all users and applies their estimated channel transfer functions in order to generate the expected received symbols. Explicitly, the receiver chooses the legitimate transmitted symbol, which has the smallest Euclidean distance from the received signal. Having the transmitted symbols in equation 4.4 and the possible received observation is given by equation 4.7 therefore, the symbols estimates when using ML-MUD are computed according to [11],

$$\hat{s} = \underset{s_i}{\operatorname{argmin}} \|s_i - y\|^2 \quad (4.8)$$

4.2.2 De-Correlation/zero forcing (ZF) Multi-User Detection

De-correlation (DEC) MUD can completely eliminate MAI. And de-correlation multi-user detection needs not estimate all the received signal energy at the receiving end. Let's see its mathematics

$$Z = W^H y \quad (4.9)$$

Where $(.)^H$ denotes the Hermitian transpose operation. If we substitute (4.7) in to (4.9)

$$Z = W^H C H S_i + W^H n \quad (4.10)$$

If (4.10) is satisfied

$$W^H C H = I \quad (4.11)$$

$$\text{Therefore } W = C H (H^H C^T)^{-1} \quad (4.12)$$

If (4.12) is true then $Z = S_i + C H (H^H C^T)^{-1} n = S_i + n'$, shows De-Correlation can completely eliminate MAI and background noise will be amplified.

4.2.3 Minimum Mean Square Error (MMSE) Multi-User Detection

In order to improve the negative effects of noise enhancement, MMSE multi-user detection transforms the linear detection problems to linear estimation problems. It makes a balance between interference elimination and noise enhancement, making its square error minimum between the transmission symbol vector S_i and the estimated vector z . MMSE multi-user detection is to find an optimal matrix W , and so the cost function defined by square error is minimized:

$$W_{MMSE} = \underset{W}{\operatorname{argmin}} E[\|S_i - Z\|^2] \quad (4.13)$$

$$W_{MMSE} = \operatorname{argmin}_W E[\|S_i - W^H y\|^2] \quad (4.14)$$

$$W_{MMSE} = \operatorname{argmin}_W E[\|S_i - W^H C H S_i - W^H n\|^2] \quad (4.15)$$

Let $\Delta = S_i - Z = S_i - W^H y$, the error estimates vector, its covariance matrix is:

$$R_\Delta = E[(S_i - W^H y)(S_i - W^H y)^H] \quad (4.16)$$

$$R_\Delta = I_K - R_{yS_i}^H - W^H R_{yS_i} + W^H R_y W \quad (4.17)$$

Where R_y is the autocorrelation matrix of y , i.e.

$$R_y = E[yy^H], \text{ again } R_{yS_i} = E[yS_i^H] = CH \quad (4.18)$$

$$\text{Therefore } W_{MMSE} = R_y^{-1} R_{yS_i} \quad (4.19)$$

MMSE detection is to strike a balance between noise and MAI in linear transformation, so in the same SNR, Bit Error Ratio (BER) performance using the MMSE is better than DEC. However, it requires an estimation of the amplitude of the received signal, namely, the interference of other users will affect its BER performance to a certain extent. When MAI is strong, background noise is relatively small, MMSE detection can be equivalent to the DEC multi-user detection. When MAI is much smaller than the background noise, MMSE detection can be transformed into a traditional matched filter.

4.3 MC-CDMA Parameters

For the simulation of basic MC-CDMA system, we have used the following parameters as shown in Table 4.1.

Table 4.1 simulation parameters of MC-CDMA system.

Parameters	Specification
FFT size	64
No of used Subcarriers	16
Cyclic Prefix length	4
Spreading code	Walsh hadamard code
No. of OFDM symbols	20,000
No of users	2,8...N
Modulation type	16-QAM

Channel Model	AWGN, Rayleigh multipath
SNR	0:5:30dB
No of taps	4
MUD	ZF, MMSE, ML
Synchronization	Perfect
Channel estimation	Perfect

4.4 MC-CDMA Simulation Results

Bearing the parameters in 4.3 simulations are done to simulate SNR vs. BER performance of MC-CDMA symbol detection techniques for both (AWGN and Rayleigh) channel conditions, different number of subcarriers and to analyze the effect of number of users in BER. To make the results more useful, the results are generated for different number of users and for different number of subcarriers. Figure 4.4 and 4.5 shows the simulation of BER Vs SNR of different conditions. Throughout the simulation, the information symbol is QAM modulated at the transmitters and detected by using ML, MMSE, and ZF MUD.

In case of MC-CDMA two kinds of source data are used, either the randomly produced data or an Audio file. While random data is ideal to test the channel impact to the BER performance and signal constellation, audio file give us an intuitive impression and comparison for different channels. The 16 QAM modulation schemes are used to map the bits to symbols. In the receiver, FFT is used to estimate the amplitude and phase of each subcarrier. The FFT performs the same operation as the matched receiver for the single carrier transmission, except for a bank of subcarriers. The first task performed at the receiver (in simulation) is removal of cyclic prefix. This eliminates the inter symbol interference (ISI). The data is then passed through the serial to parallel converter and then passed to the FFT for frequency domain transformation. The signal was found distorted by the channel, however, to reconstruct the original signal, the information on how these channels are acted on the transmitted signal need to be obtained to mitigate its effect.

Figure 4.4 and 4.5 provides bit error probability versus bit energy to noise density ratio (E_b/N_0), or “SNR,” simulation results for $K=2$ and 8 users MC-CDMA system with 16 subcarriers and 16-

QAM modulation. The channel fading on these subcarriers is independent and has Rayleigh fading amplitude statistics. Different symbols in time are assumed to have independent fading, and perfect channel estimation is assumed. ML, MMSE, and ZF is used at the receiver.

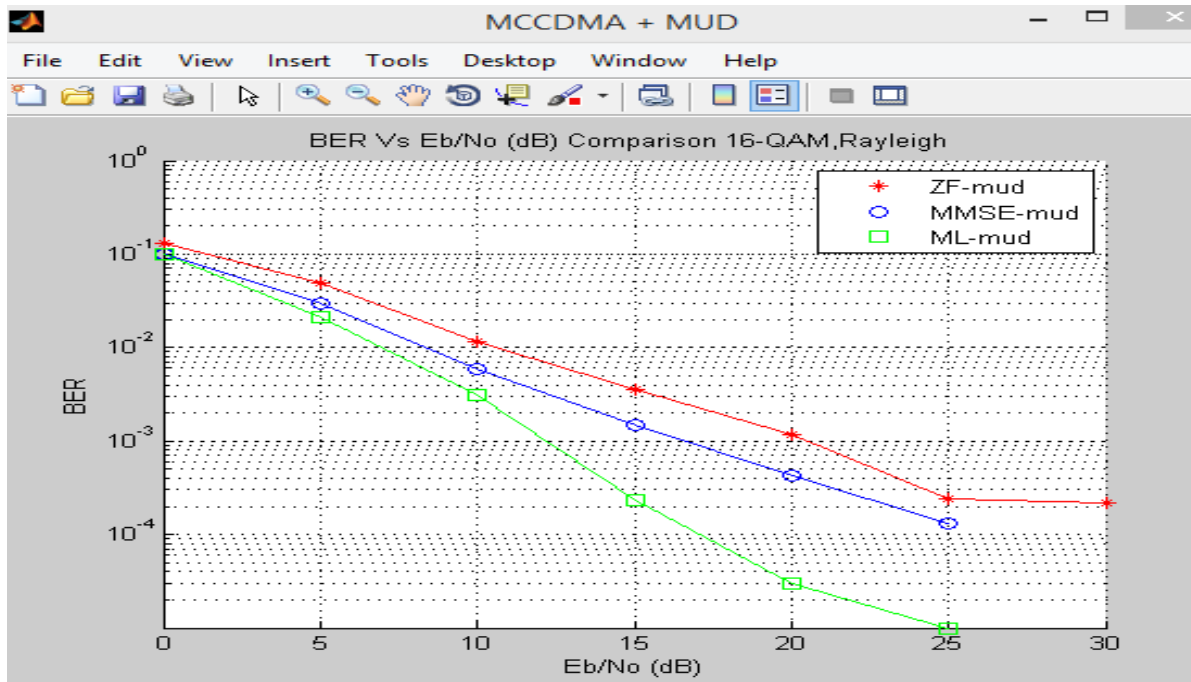


Figure 4.4 BER for 2 Users using 16-QAM Modulation over Rayleigh channel

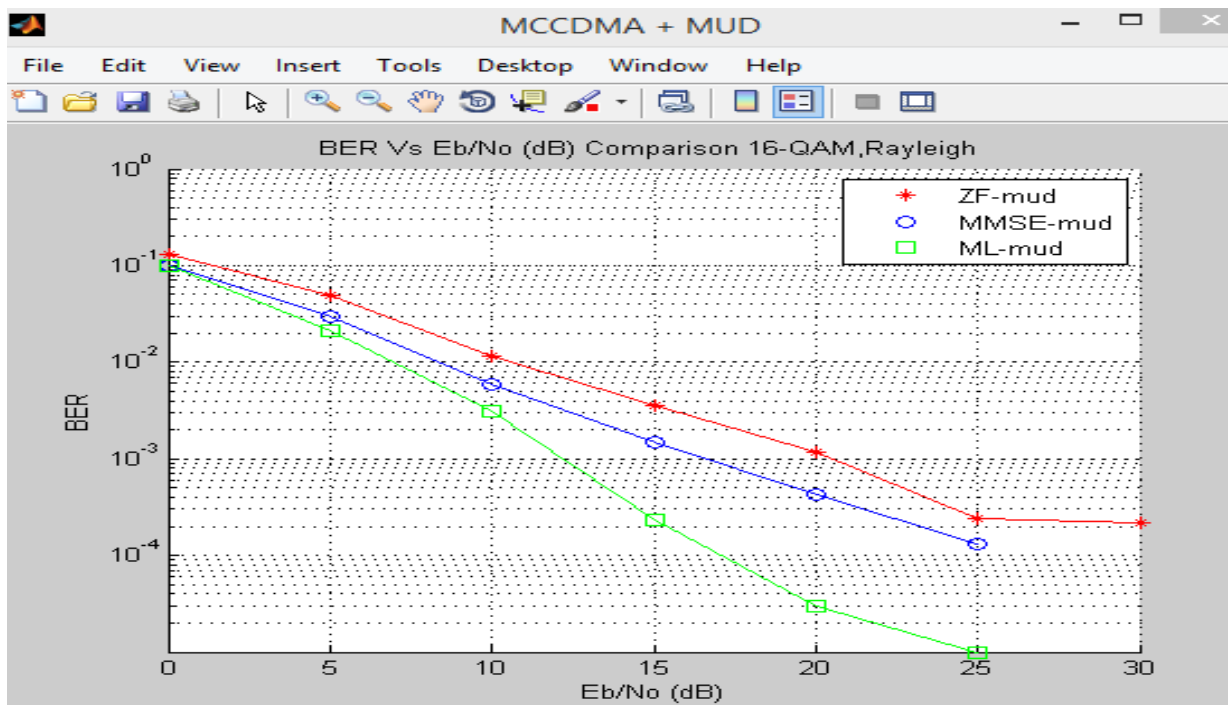


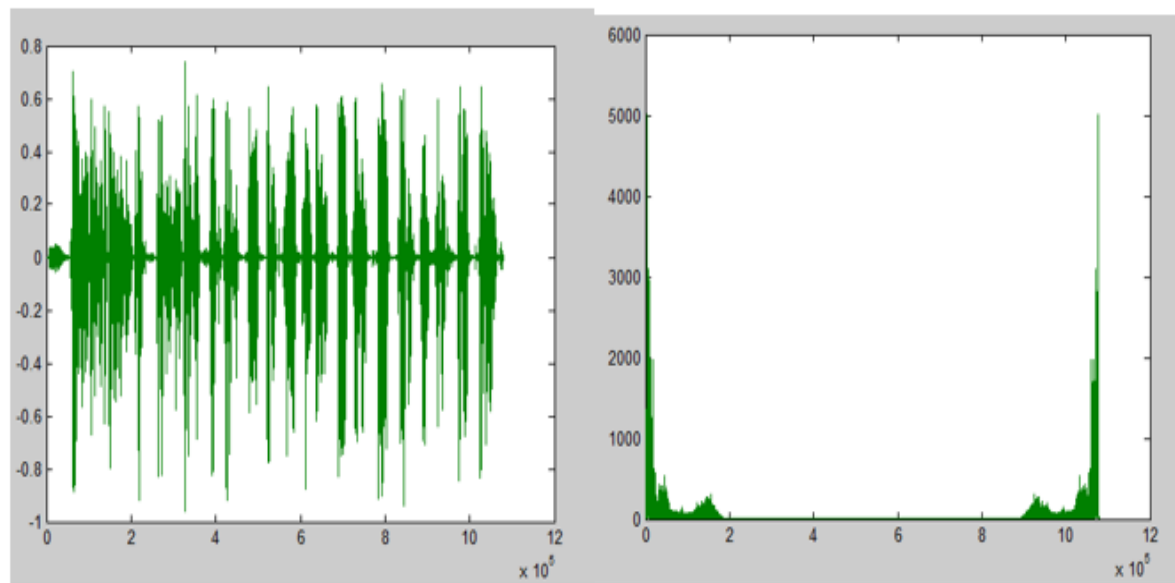
Figure 4.5 BER for 8 Users using 16-QAM Modulation over Rayleigh channel

Observations:

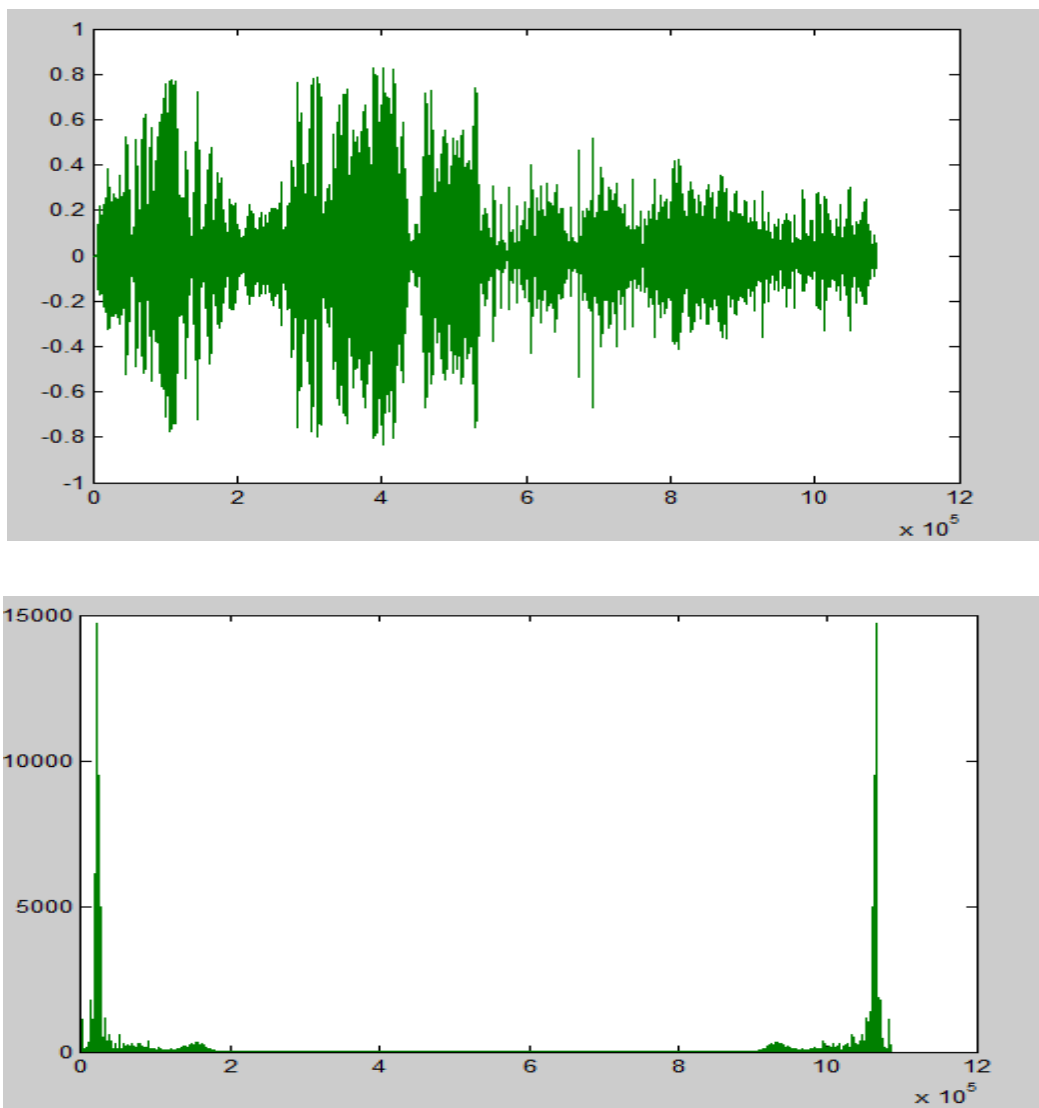
The simulation results show that ML provide much lower error probability than the linear detectors. We observe that the ML detector is the best in performance followed by the MMSE and ZF detector. In cases of $k=2$ at 15dB the BER is approximately 10^{-4} , 10^{-3} , and 10^{-2} . But when the number of users increase the performance is a little bit worst.

The MC-CDMA system is also implemented with a recorded audio input signal, so the N random input signal is replaced with a recorded wave file for two user. As ML have best performance than the linear detectors, the audio file is implemented with ML-MUD only.

The time and frequency domain plot of the wave file is given by Figure 4.6 below. And the BER performance of 16-QAM modulation over Rayleigh Fading channel followed by ML detection is given in Figure 4.7.



a) Recorded audio for user 1



b) Recorded audio for user 2

Figure 4.6 The time and frequency domain plot of each user audio file

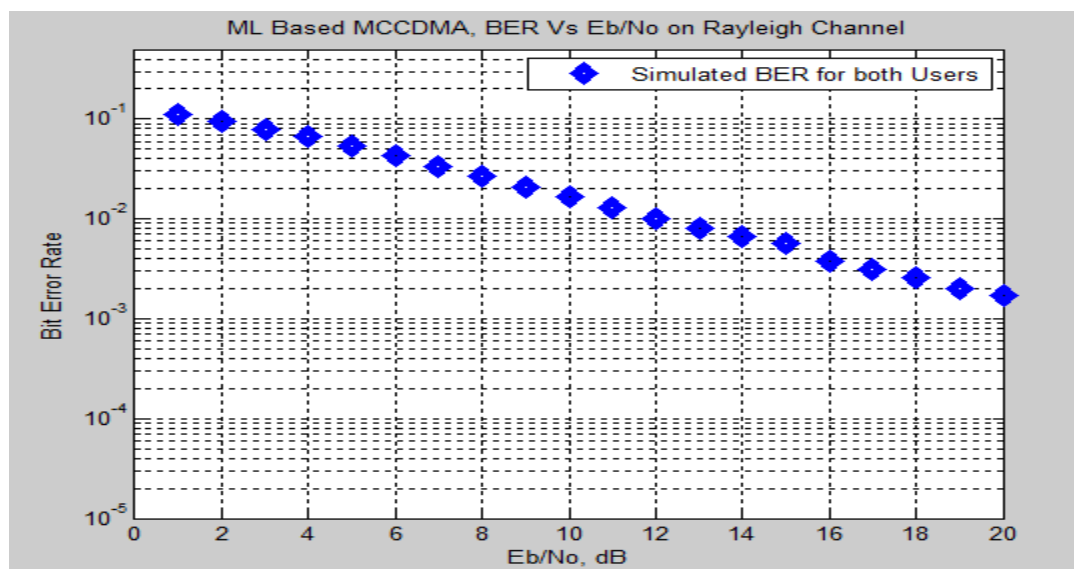


Figure 4.7 E_b/N_0 Vs BER for ML based 16-QAM MC-CDMA audio file modulation over Rayleigh Fading channel

The simulation results show that ML provide good error probability again over the audio transmission. The overall difference of the recorded wave file and the received one can be noticed by playing both audios of each users after despreading.

4.5 MC-CDMA Symbol Detectors Complexity Analysis

The computational complexity is one of the important factors of the detectors performance. In this section we evaluate all detectors' computational complexities. High performance detectors like Maximum likelihood (ML) and sphere detection, are available for MC-CDMA signal detection but their feasibility, in the presence of frequency-selective fading, is limited by high computational complexity of processing the large data input of cyclic prefixed block transmissions. There are trade-offs need to be made in terms of complexity and performance. The performance of detection is measured by numerical bit error rate, which are calculated by simulating cyclic prefixed transmission in MC-CDMA MUD. An investigation of the complexity performance trade-off of the detectors was proposed based on the following rules [25].

- ✓ **Rule 1:** suppose two matrices A and B with dimensions $C \times E$ and $D \times E$ are multiplied a total of $C(D-1)E$ additions and CDE multiplications are needed.

- ✓ **Rule 2:** The complexity of a slicer is minimal in terms of additions and/or multiplications. For an M-PSK constellation scheme, the phase range $[-\pi, \pi]$ is divided in M equal parts. In such a regular structure, a recursive search is done in which half of the (remaining) range the phase of the estimated symbol best fits. This results in a complexity equivalent to $\log_2(M)$ comparisons. For an M-QAM constellation diagram, the real and imaginary parts are split. Each of these parts is regularly divided in \sqrt{M} slicing ranges. Also in this case, a recursive search is achieved in which half of the (remaining) range the real or imaginary part of the estimated symbol best fits, and the complexity is equal to $\log_2(\sqrt{M})$ comparisons for the real and for the imaginary part, or $2\log_2(\sqrt{M})$ comparisons in total.
- ✓ **Rule 3:** determining the minimum of N values has a complexity of $N - 1$ real additions.
- ✓ **Rule 4:** direct inversion of a given square matrix A (with dimension $N \times N$) has a complexity in the order of N^3 additions and N^3 multiplications in total. This all can be summarized by the table below.

Table 4.2 shows the general overview of matrix calculation rules to determine the computational complexity. Where capital C notation represents the computational complexity and N, K, P represents the matrix size.

Table 4.2 Matrix calculation rules overview [26]

Operation	Input	Output	Algorithm	Complexity
Matrix Multiplication	Two $N \times N$ matrices	One $N \times N$ matrix	Schoolbook matrix multiplication	$C(N^3)$
Matrix Multiplication	One $N \times K$ matrix & One $K \times P$ matrix		Schoolbook matrix multiplication	$C(N \cdot K \cdot P)$
Matrix Inversion	One $N \times N$ matrix	One $N \times N$ matrix	Gauss-Jordan elimination	$C(N^3)$
Discrete Fourier Transform (DFT)	One $N \times N$ matrix	One number with at most	General DFT algorithm	$C(N \cdot \log(N))$

		C (N*log(N)) bits		
Single for loop	-	-	General for loop algorithm	C (N+1)
Minimum value	-	-	-	C(N-1)

Based on the above Matrix calculation rules overview we can analyse the complexity of the different MUD.

4.5.1 Computational Complexity for ZF Detection

The complexity of zero forcing detection is based on the calculation of pseudo-inverse of the channel transfer matrix H . For determining the complexity of the zero forcing detection, the following equation is used.

$$G_{ZF} = (H^H H)^{-1} H^H \quad (4.20)$$

Let the dimensions of G_{ZF} , H and H^H are $N_1 \times N_2$, $N_2 \times N_1$, and $N_1 \times N_2$ respectively. So possible complexity we have is:

- Complexity of the matrix product $H^H H$, is $N_1^2(N_2 - 1)$ additions and $N_1^2 N_2$ multiplications are needed (See Rule 1).
- Complexity of the inverse of $H^H H$, as size of $H^H H$ is $N_1 \times N_1$, N_1^3 additions and N_1^3 multiplications are needed (See Rule 4).
- Complexity of the inverse of $H^H H$ and H^H , is $N_1(N_1 - 1)N_2$ additions and $N_1^2 N_2$ multiplications are needed (See Rule 1).
- So the complexity of pseudo-inverse will give $C(G_{ZF}) = 7N_1^3 + 7N_1^2 N_2 - N_1$
- As $X_{ZF} = G_{ZF} Y$, $N_1(N_2 - 1)$ additions and $N_1 N_2$ multiplications are needed (See Rule 1).
- The complexity of slicing N_1 M-ary QAM constellation points is $N_2 \log 2 (\sqrt{M})$ (See Rule 2).

Therefore the total complexity of zero forcing detection is:

$$C(ZF) = 7N_1^3 + 7N_1^2 N_2 - 2N_1 + 4N_1 N_2 + \frac{1}{2} N_2 \log 2 (\sqrt{M}) \quad (4.21)$$

4.5.2 Computational Complexity for MMSE Detection

The complexity of MMSE algorithm is almost equal to the complexity of ZF method described in the previous section.

$$G_{MMSE} = (\delta I_{N_1} + H^H H)^{-1} H^H \quad (4.22)$$

The calculation of this matrix has almost the same complexity as the determination of the pseudo-inverse in case of zero forcing algorithm. Since δ is real so N_1 real additions are needed. So the complexity of pseudo-inverse will gives $C(G_{MMSE}) = 7N_1^3 + 7N_1^2 N_2$.

As $X_{MMSE} = G_{MMSE} Y$, $N_1(N_2 - 1)$ additions and $N_1 N_2$ multiplications are needed (See Rule 1).

The complexity of slicing N_1 M-ary QAM constellation points is $N_2 \log 2 (\sqrt{M})$ (See Rule 2).

Therefore the total complexity of zero forcing detection is:

$$C(\text{MMSE}) = 7N_1^3 + 7N_1^2 N_2 - N_1 + 4N_1 N_2 + \frac{1}{2} N_2 \log 2 (\sqrt{M}) \quad (4.23)$$

4.5.3 Computational Complexity for ML Detection

The complexity of the ML detection [25] per transmitted vector x in terms of real operations equals

$$C(\text{ML}) = 4N_1^2 (M + 1) + 4N_1 N_2 T(M + 1) + 6N_1 (2M + 1) \quad (4.24)$$

Where, T is processing duration.

As per the no of operations the complexity of each detector can be summarized as follows. [25]

Table 4.3 Computational complexity analysis for N=16 and 16-QAM

Detector type	Order C (...) When $N_1 \neq N_2$	Order C (...) When $N_1 = N_2 = N$	Total number of operations for N=16, M=16 and T=0.6'=36sec	Complexity
ML	$4N_1^2 (M + 1) + 4N_1 N_2 T(M + 1) + 6N_1 (2M + 1)$	$4N^2 (M + 1)(1 + T) + 6N(2M + 1)$	647264	high
MMSE	$7N_1^3 + 7N_1^2 N_2 - N_1 + 4N_1 N_2 + \frac{1}{2} N_2 \log 2 (\sqrt{M})$	$14N^3 + 4N^2 - N + \frac{1}{2} N \log 2 (\sqrt{M})$	58368	mode rate

ZF	$7N_1^3 + 7N_1^2N_2 - 2N_1 + 4N_1N_2 + \frac{1}{2}N_2 \log_2(\sqrt{M})$	$14N^3 + 4N^2 - 2N + \frac{1}{2}N \log_2(\sqrt{M})$	58352	low
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Observations:

Table 4.3 shows the complexity analysis of the three detectors. After analysis the complexity evaluation it can be concluded that the ZF detector gives the lowest computational complexity, the MMSE detector gives the moderate computational complexity and the ML detector gives the high computational complexity.

Figure 4.8 shows that the complexity versus performance of ML, MMSE and ZF detectors in terms of computing time.

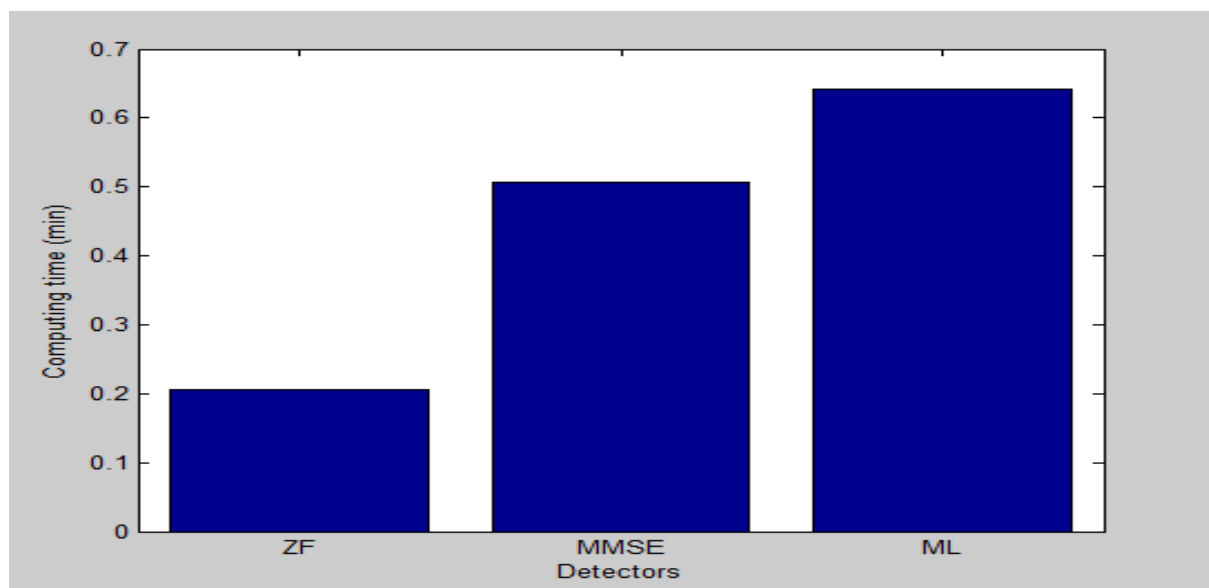


Figure 4.8 Complexity Analysis in terms of computing time

So Figure 4.6 shows that ML have high performance with high complexity and the linear detectors have good performance with acceptable complexity.

Chapter Five

Conclusion and Future work

5.1 Conclusion

The aim of this thesis study is to investigate symbol detection algorithms for single and Multicarrier systems having an acceptable bit error rate performance and feasible computational complexity. Basically we had a literature review on theoretical parts of symbol detection fundamentals which are useful to understand the thesis work, like detection theory and optimum receivers, classification of symbol detection techniques and performance of modulation schemes. Then Single carrier single user and MC-CDMA based symbol detection algorithms have been implemented with various modulation type and order. The performance of the considered detection techniques was compared in terms of BER and SNR. We had simulated M-ary PSK and M-ary QAM with the optimum and sub-optimum detectors like maximum likelihood, MMSE and ZF detectors. The system model, implementation algorithms, parameters and assumptions with the implementation of both cases was presented.

Based on the simulation results we have, for the single carrier single user case the performance of M-ary modulations schemes like M-PSK and M-QAM for transmitting random and audio signal over Additive White Gaussian Noise (AWGN) and Rayleigh Fading Channel has been done. AWGN is better than Rayleigh in terms of bit error probability as a function of SNR. The error performance of 16-PSK and 16-QAM has been studied and it has shown that error performance is improving. So the error rate depends on type of the channel, modulation type and order. Multipath fading channel provides higher error rate on the transmitted signal than normal AWGN channel. So the efficiency of symbol detection technique depends on the type of channel too.

In the case of multicarrier multi user (MC-CDMA) transmission system using Rayleigh fading channel for $K=2$ and $K=8$ users and MUD techniques has been carried out successfully. Performance versus computational complexity trade-off have been evaluated. The choice of the receiver algorithm is emphasized when the number of users increases and the channel condition. By examining the plots of the three detectors we can see that ML detector clearly outperform the

linear detectors (both MMSE and ZF), but the price is remarkably increased computational complexity in terms of number of operations and computing time. Basically it is obvious that for recorded audio transmission, the accepted BER is $\geq 10^{-3}$, at SNR of ≥ 15 dB. So in our case at 15dB for AWGN channel and 35dB for Rayleigh fading channel we have achieved same thing. What makes the detector less complex, is its computing time and the number of operations within the algorithms. Finally, from our findings, we have seen that the most complex and the best performing detector, is the Maximum Likelihood detector.

5.2 Future work

As future work, in both (Single carrier single user and MC-CDMA based symbol detection algorithms) cases we have been implementing them with the assumption that perfect synchronization and channel estimation conditions so researchers may go through taking these assumptions into account. In all simulations, we assumed that there was a perfect synchronization between the transmitter and the receiver. As a consequence, we did not take phase noise and frequency offset errors into consideration. In order to degrade the effects of lack of synchronization, frequency offset estimation and tracking must be performed. In a further study, this feature may be combined with the detection algorithms developed in this thesis.

MC-CDMA was implemented with Walsh-Hadamard spreading code. Hence other non-orthogonal codes may also provide good coding performance for MC-CDMA systems like PN-sequences, Gold sequences and Kasami codes.

The modulation and detection techniques other than the two (Single carrier single user and MC-CDMA based symbol detection algorithms) combination like single user multi-carrier and single carrier multiuser detection techniques can be further investigated.

There are trade-offs need to be made in terms of complexity and performance, and this can be solved by Group Detection algorithm like MMSE followed by sphere decoding. The grouped linear detectors can have the same performance like ML detection with acceptable complexity. So researchers can undergo further study.

Wireless systems are designed with a simple receiver in mind, but more complex receiver algorithms are still needed to achieve the high data rates in difficult environments. Furthermore, since even higher data rates are planned for the future wireless systems, the use of simple receiver algorithms may not suffice.

Wireless communications networks are expected to support various multimedia services such as voice, data and video, which require multirate transmission. Then interested researchers can go for real data and video transmission like what we had for recorded audio.

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