IMPROVED RECEIVER DESIGN FOR WBAN EMPLOYING UWB BASED MIMO SCHEME

A Thesis submitted in partial fulfillment of the Requirements for the degree of

Master of technology
In
Electrical Engineering
(Electronic Systems and Communication)

By

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May 2015

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Under the guidance of

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May 2015

Dedicated to…

My Parents and my brothers

DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ROURKELA – 769008, ODISHA, INDIA

Certificate

This is to certify that the work done in thesis "**Improved Receiver Design for WBAN employing UWB based MIMO scheme"** by **Rati Dilipkumar Jalan (213EE1286)** in partial fulfillment of the requirements for the award of the degree of Master of Technology in Electrical Engineering during session 2013-2015 in the Department of Electrical Engineering, National Institute of Technology Rourkela is an authentic work carried out by her under my supervision and guidance. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Place: NIT Rourkela

Date: 29th May2015

Prof. Susmita Das

Associate Professor

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NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ROURKELA – 769008, ODISHA, INDIA

Declaration

I, Rati Dilipkumar Jalan, declare that this thesis titled, "**Improved Receiver Design for WBAN employing UWB based MIMO scheme**" and the work presented in it are my own. I confirm that:

- I certify that the work contained in this thesis is original and has been done by me under the guidance of my supervisor.
- The work has not been submitted to any other Institute for any degree or diploma.
- I have followed the guidelines provided by the Institute in preparing the thesis.
- I have confirmed to the norms and guidelines given in the Ethical Code of Conduct of the Institute.
- Whenever I have used materials (data, theoretical analysis, figures, and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references.

Rati Dilipkumar Jalan

29th May 2015

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Abstract

Wireless sensor networks built in or around the human body are known as Wireless Body area networks (WBAN). Body area network has its own standard IEEE 802.15.6. They can be adapted for patient monitoring applications. The biological sensors are either implanted or placed on the human body. They measure vital information such as ECG, Blood pressure etc. and transmit them wirelessly to a nearby gateway.

Transmission of patient's health information is done using digital communication system. Due to time dispersive nature of communication channel, the transmitted data gets distorted and as there are multiple wireless devices on the human body, multiple access interference occurs. This leads to need for equalizers at the receiver end. Incorporating suitable equalization technique, makes the receiver design a challenge.

Ultra wideband (UWB) communication with its strong advantages has proved to be very promising for WBAN applications. It is a low power high data rate technology. They have potentially low complexity and low equipment cost. Similarly, Multiple Input Multiple Output (MIMO) systems have emerged as a promising technology to increase the data transmission rate, improving link reliability and enhancing the system coverage. Hence, in this work we have considered a WBAN system employing UWB based MIMO scheme. Another important aspect is that robustness of a particular MIMO system against multipath channel fading and division among users, depends on orthogonality of the spreading codes. Hence, Orthogonal complete complementary code has been used as the spread code.

The research aims at finding the most suitable modulation format for transmission of medical signals for the proposed system model through BER performance analysis. The prime goal is to enhance the performance UWB (Ultra Wideband) / MIMO (Multiple Input Multiple Output) (2X2) WBAN system employing Orthogonal Complete Complementary (OCC) code as the spread code. Simulation results have been obtained to validate the improvement in the performance of the system in terms of Bit Error Rate (BER).

Contents

ABBREVIATIONS

WBAN	:	Wireless Body Area Network
PDA	:	Personal Digital Assistant
UWB	:	Ultra Wide-Band
MIMO	:	Multiple Input Multiple Output
ISI	:	Inter symbol Interference
MAI	:	Multiple Access Interference
BER	:	Bit Error Rate
SNR	:	Signal to Noise Ratio
PPM	:	Pulse Position Modulation
TH	:	Time Hopping
PAM	:	Pulse Amplitude Modulation
DS	:	Direct Sequence
PN	:	Pseudo Noise
OCC	:	Orthogonal Complete Complementary
CCI	:	Co-Channel Interference
IEEE	:	Institute of Electrical and Electronics Engineers
AWGN	:	Additive White Gaussian Noise
ZF	:	Zero Forcing
MMSE	:	Minimum Mean Square Error
ML	:	Maximum Likelihood
SD	:	Sphere Decoding
CM	:	Channel Model

LOS	:	Line of Sight
NLOS	:	Non- Line of Sight
PL	:	Path Loss
PDP	:	Power Delay Profile
FIR	:	Finite Impulse Response
LMS	:	Least Mean Square
BP	:	Blood Pressure
ECG	:	Electro Cardiogram

NOMENCLATURE

$PL\ (d)$	:	Path loss at distance d
L	:	Number of arrival paths
c_n	:	OCC Sequence
d_n	:	Data Sequence
N_T	:	Number of transmitting antennas
N_R	:	Number of receiving antennas
R_{SD}	:	Radius for sphere decoding
K	:	Constellation Size

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1

Introduction

1.1 Overview

Development in the field of wireless data transmission and signal processing has led to the application of Wireless Body Area Network (WBAN) in modern healthcare system. Body Area Network consists of wearable or implanted electronic devices that transmit sensor data to gateway device or a PDA (Personal Digital Assistant). It further connects to an external access point for the medical professionals to analyse patient's condition. It enables real time collection and monitoring of physiological signals. [1]

The data collected by the body sensors are sent to the personal digital assistant (PDA). Further, this information is transmitted to the medical supervisors for constant monitoring of the patient's health information. Such systems are referred as ubiquitous healthcare (u-health) systems. As the transmission of these signals occurs in the vicinity of human body, hence it needs to be operated at low power. Ultra wideband (UWB) system is the most preferred solution for WBAN applications as it provides high data rate at low power. [2] It ensures no harmful effect on human body. UWB system with multiple input multiple output (MIMO) scheme provides with high system throughput. However, during transmission, these signals get effected by multipath fading, intersymbol interference (ISI) and multiple access interference (MAI) which results in performance degradation of the system. In order to establish a reliable communication system, it is necessary to eliminate these effects. Hence, equalizer needs to be implemented for accurate reception of the transmitted data. An equalizer works on the concept to reduce the BER (Bit Error Rate) as the SNR (Signal-to-Noise Ratio) is increased.

In this work, various equalization techniques have been investigated for the analysis of BER performance of UWB/MIMO based WBAN.

UWB system on the basis of spread spectrum technology has been used. It can be pulse position modulation (PPM) /time hopping (TH) system and pulse amplitude modulation (PAM) /direct sequence (DS) system [9]. In order to mitigate the adverse effect of MAI, spreading code can be used. Pseudo noise code is the most commonly used spreading code. But performance of the system can be improved using a spreading code with better correlation. Hence, in this work we have used orthogonal complete complementary (OCC) code as the spreading code. [8]

1.2 Literature survey

Wireless Body Area Network applications in modern healthcare system has been presented by J.Jung, K.Ha, J.Lee, Y.Kim and D.Kim," **Wireless Body Area Networks in a Ubiquitous Healthcare System for Physiological signal monitoring and Health Consulting**" [1]. This work explains the use of WBAN in for ECG, Blood Pressure etc. monitoring of a patient.

Yazdandoost and Kamran., "**Channel Model for Body Area Network (BAN)**" [2] describe the various channel models that can be considered for Body Area Networks. The propagation models, path loss models etc. for various channels of WBAN has been studied in this work.

Further, Domenico Porcino and W.Hirt, "**Ultra-wideband radio technology: potential and challenges ahead**" [3] discussed the concept of a new technology and its applications for better results. The advantages, problems faced and future scope of this particular field is studied.

J. N Bae, Y.H. Choi, J.Y.Kim, J.W.Kwon and D.I.Kim "**Efficient Interference Cancellation Scheme for Wireless Body Area Network**" [4] explain the need and result of equalization techniques in Wireless Body Area Network. In this work, MIMO based WBAN system along with the concept of UWB technology has been introduced.

This work has been extended in M. Jayasheela and A. Rajeswari, "**Improved Successive Interference Cancellation for MIMO/UWB based Wireless Body Area Network**", [5] employing different spread code. Its comparison with the previous work has also been done. In this paper better results have been obtained.

H.H.Chen, J.F Yen and N.Suihero, "**A Multicarrier CDMA Architecture Based on Orthogonal Complementary Codes for New Generations of Wideband Wireless Communications**", [6] have introduced a new spread code in multi user environment for wideband communications. This work also explains how the spread code helps to avoid multi-access interference in multi user environment.

Rohit Gupta and Amit Grover, "**BER Performance Analysis of MIMO system using Equalization Techniques**" [7] show that Maximum Likelihood and Sphere Decoding algorithm outperform the conventional equalization techniques. They have also explained that Sphere Decodinggives the same result as Maximum Likelihood, but the computational complexity is greatly reduced.

V.Kaur and J.Malhotra,"**Performance Evaluation of M-ary modulations through WBAN Channel**" [8], discusses various modulation techniques and helps decide the best possible. This work can be used in the process of selecting a modulation technique on the basis of applications.

J. Jalden and B. Ottersten,"**On the complexity of Sphere Decoding in Digital Communications**", [9] calculates the expected complexity of Sphere Decoding algorithm and the possible ways of reducing it. It has also been explained that using sphere decoding for maximum likelihood detection reduces the complexity of the system to a great extent.

H. Han, S. Oh, S. Lee, and D. Kwon,"**Computational Complexities of Sphere Decoding according to Initial Radius Selection Schemes and an Efficient Initial Radius Reduction Scheme**", [10] explains the various methods for initial radius selection scheme. In this work, the authors have also explained how the complexity of the system can be reduced by the proper choice of initial radius.

1.3 Motivation

Wireless body area networks are being widely used for patient monitoring system.Transmission of patient's health information is done using digital communication system. In digital communication system, band limited channels and multipath propagation causes interference and distortions to occur. Data rate is limited due to various types of distortions caused during transmission, These distortions occur as ISI (Intersymbol interference), CCI (Co-channel interference) in the presence of AWGN (Additive white gaussian noise).This leads to the need of channel equalizers for Body Area Networks.

1.4 Objective of the work

The prime aim of this work is to enhance the performance of UWB/MIMO based WBAN. The biological signals received must be equalized at the receiver end.

1. Study and analyse the existing Equalization techniques and various types of problems faced by them.

2. Develop a system model for UWB/MIMO based WBAN with a new spreading code.
3. Improving the performance of receiver by employing a new equalization technique that overcomes the drawbacks of the conventional methods in terms of BER.
4. Study and reduce the Computational Complexity of the technique.

1.5 Thesis Contribution

Wireless Body Area Network is being widely used for the development of a modern healthcare system that helps to monitor the patient's condition anytime and anywhere. The ultimate goal of this work is to receive the medical information transmitted in the form biological signals, accurately.
The contribution of the thesis can be described as follows:

- Orthogonal Complete Complementary code has been used as the spreading code. On the basis of which, the most suitable modulation format for transmission of medical signals through BER performance comparison can be achieved.
- Maximum Likelihood and Sphere Decoding algorithm are the equalization techniques that have been suggested and their performance has been compared with the conventional Zero Forcing and Minimum Mean Square Error techniques.

1.6 Thesis Organization

The thesis has been organized into five chapters. The ongoing chapter gives a brief introduction to the Wireless Body Area Network, Patient Monitoring System, Equalization techniques. The literature survey done, motivation, objective of work and contribution of the thesis have been briefed in the various subsections. The final subsection of this chapter explains the entire thesis organization.

Chapter 2: This chapter gives the background of Wireless Body Area Network. It includes brief introduction to the application of WBAN in modern healthcare system, overview of IEEE Standard 802.15.6, WBAN Channel Models. WBAN employing UWB based MIMO scheme and its benefits have also been presented here.

Chapter 3: In this chapter,the existing receiver design employing the conventional equalization techniques have been considered. Comparison of Zero forcing and Minimum mean square error equalizer has been done on the basis of simulation study.

Chapter 4: The fourth chapter describes the proposed receiver design incorporating two new equalization techniques. These techniques are Maximum likelihood and Sphere Decoding algorithm. Comparison between MLD and SD has been done on the basis of computational complexity. Simulation results have been obtained to validate that MLD and SD outperform the conventional techniques ZF and MMSE.

Chapter 5: This chapter presents the conclusion of the entire research work done and also discusses the future scope of the research.

2

Background Study of Wireless Body Area Network

2.1 Wireless Body Area Network

2.1.1 Introduction

With rapid growth in physiological sensors and low-power circuits, wireless communication enables a new field of wireless sensor networks. Development in the field of wireless data transmission and signal processing has led to the application of Wireless Body Area Network (WBAN) in modern healthcare system. Body Area Network consists of wearable or implanted electronic devices that transmit sensor data to gateway device or a PDA (Personal Digital Assistant). It further connects to an external access point for the medical professionals to analyse patient's condition. It enables real time collection and monitoring of physiological signals. [1]

The data collected by the body sensors are sent to the personal digital assistant (PDA). Further, this information is transmitted to the medical supervisors for constant monitoring of the patient's health information. Such systems are referred as ubiquitous healthcare (u-health) systems. This area relies on the accuracy ofthe tiny biosensors inside the human body. These implanted sensors collect various biological changes in order to monitor the health of a patient health independent of their location. In case of an emergency, the medical professionalsinform the patient through the gateway by transmitting necessary messages or alarms. [3] It is based on IEEE Standard 802.15.6-2012 published by Task Group TG15.6 which is a standard for short-range wireless communications. It is being widely used in modern healthcare system. It helps improve quality of life and for efficient healthcare management.

2.1.2 WBAN in Modern Healthcare system

Applications of BANs appear primarily in the healthcare system, for continuous monitoring of the patients suffering fromtypical diseases such as diabetes, asthma and heart attacks.[1]

- By measuring changes in patient's vital signs, a Body Area Network can inform the medical professional, even before they have a heart attack.
- It can also auto inject insulin through a pumpfor a patient suffering from diabetes when the insulin level in the body drops.

Some applications of WBAN technology includes military, sports, or security.

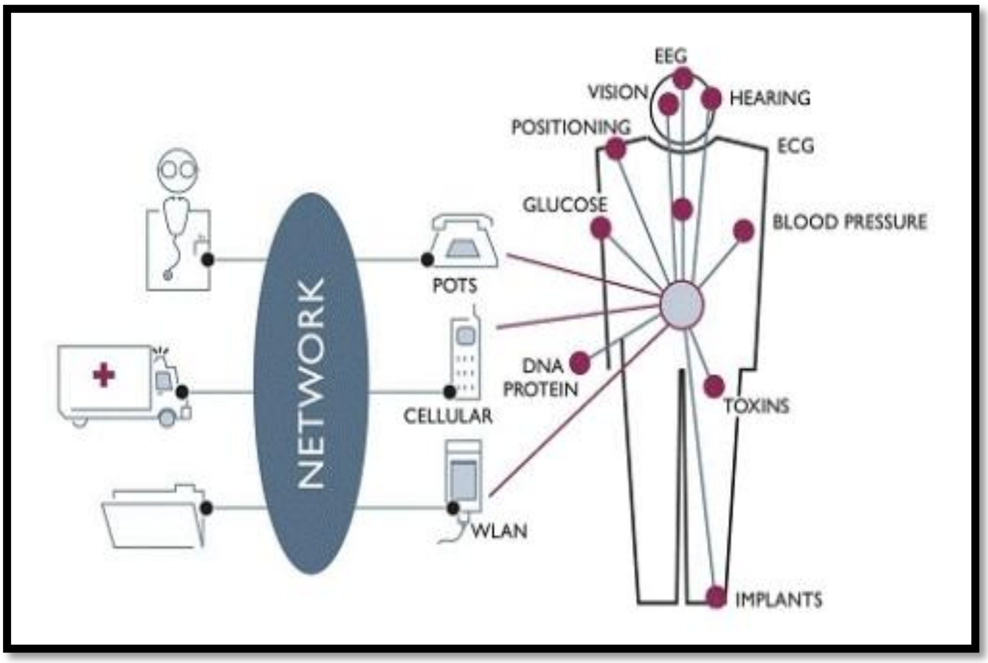

Figure 2.1 Wireless Body Area Network

2.2 Overview of IEEE Standard 802.15.6

It is an IEEE Standard designed by Task Group TG6 which has been designed so that a BAN for the purpose of medical and non-medical applications can be developed.The models described here characterize the path loss of BAN devices considering the posture of human body, shadowing effect and obstacles near human body. [3]

Table. 2.1 List of frequency band [3]

Description	Frequency Band
Implanted Sensors	402-405
On- Body Sensors	13.5 MHz
On- Body Sensors	5-50 MHz (HBC)
On- Body Sensors	400 MHz
On- Body Sensors	600 MHz
On- Body Sensors	900 MHz
On- Body Sensors	2.4 GHz
On- Body Sensors	3.1-10.6 GHz

This document describes three types of nodes, which are:

Implant node: This node is implanted either just under the skin or deep inside the body.

Body Surface node: It is mounted on the human skin or approximately 2 centimetres away.

External node: It is placed a few centimetres to approximately 5 meters away from human skin.

2.3 WBAN Channel Model

To understand the WBAN channel model it is first necessary to analyze the various propagation scenarios of Body Area Network: [4]

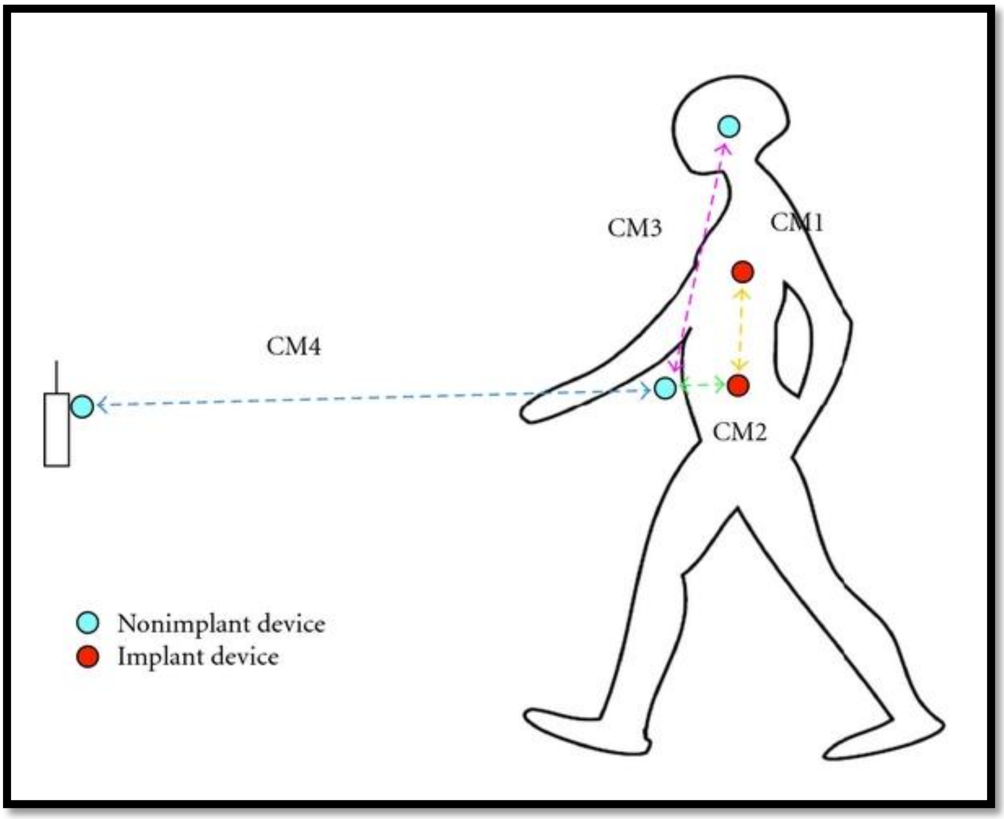

Figure2.2 WBAN Channel Models

Scenario1: It describes the propagation from implant to implant, for which channel model is CM1 and operating frequency band is 402 to 405 MHz.

Scenario2: It describes the propagation from implant to body surface, for which channel model is CM2 and operating frequency band is 402 to 405 MHz.

Scenario3: It describes the propagation from implant to external, for which channel model is CM2 and operating frequency band is 402 to 405 MHz.

Scenario4: It describes the propagation from body surface to body surface (LOS- line of sight), for which channel model is CM3 and operating frequency band is 13.5,50,400,600,900 MHz, 2.4, 3.1-10.6 GHz.

Scenario5: It describes the propagation from body surface to body surface (NLOS- non line of sight), for which channel model is CM3 and operating frequency band is 13.5,50,400,600,900 MHz, 2.4, 3.1-10.6 GHz.

Scenario6: It describes the propagation from body surface to external (LOS), for which channel model is CM4 and operating frequency band is 900 MHz, 2.4,3.1-10.6 GHz

Scenario7: It describes the propagation from body surface to external (NLOS), for which channel model is CM4 and operating frequency band is 900 MHz, 2.4,3.1-10.6 GHz

2.3.1 Channel Model (CM3)

The following pathloss model is based on the measurements that lies in the frequency range of 3.1-10.6 GHz.

Path loss model:[3]

$$PL(d)[dB] = a * log_{10}(d) + b + N \dots\dots..(1)$$

where,
a and b are the linear fitting coefficients, d is Tx-Rx distance in mm and N is normally distributed variable with zero mean and standard deviation σ_N.

The values of a, b and σ_N for hospital room and anechoic chamber can be summarized as:

Table. 2.2Parameters corresponding to the model [3]

	Hospital Room	Anechoic Chamber
A	19.2	34.1
B	3.38	-31.4
σ_N	4.40	4.85

A power delay profile model for the UWB range i.e.3.1-10.6 GHz can be given as:

The complex impulse response $h^i(t)$for the i[th] device is: [3]

$$h^i(t) = \sum_{l=0}^{L-1} a_l^i e^{j\phi_l^i} \delta(t - t_l^i) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.\dots.(2)$$

$$10log_{10}\left|a_l^i\right|^2 = 0 \ , \qquad for\ l = 0 \dots\dots..(3)$$

$$10log_{10}|a_l^i|^2 = \gamma_0 + 10\log_{10}\left(e^{\left(-\frac{t_l^i}{\Gamma}\right)}\right) + S \quad , for\ l \neq 0 \ldots..(4)$$

$$p(t_l^i|t_{l-1}^i) = \lambda \exp\left(-\lambda(t_l^i - t_{l-1}^i)\right) \ldots \ldots \ldots \ldots \ldots . \ldots \ldots \ldots \ldots ....(5)$$

$$p(L) = \frac{\bar{L}^L e^{\bar{L}}}{L!} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots ...(6)$$

where, a_l^i is the path amplitude for lth path corresponding to ith device, t_l^i is the path arrival time for lth path corresponding to ith device, Γ is an exponential decay with a Rician factor γ_0, ϕ_l^i is the phase for lth path corresponding to ith device, L is the number of the arrival paths, $\delta(t)$ is the dirac function, S is a normal distribution with zero mean and standard deviation σ_S, λ is the arrival rate for a particular path and $\bar{L}$ is the average number of L.

The table below summarizes the corresponding parameters:[3]
For a_l^i:

Table. 2.3Parameters corresponding to a_l^i [3]

γ_0	**-4.60 dB**
Γ	59.7
σ_S	5.02dB

For t_l^i:

Table. 2.4Parameter corresponding to t_l^i [3]

1/λ	**1.85ns**

and

Table. 2.5 Average number of arrival paths [3]

$\bar{L}$	**38.1**

2.3.2 Channel Model (CM4)

Considering Channel Model 4 (Body surface to external), the complex impulse response $h^i(t)$ for the i[th] device is: [3]

$$h^i(t) = \sum_{l=0}^{L-1} \alpha_l^i \delta(t - \tau_l^i) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (7)$$

where, L denotes the number of arrival paths that can be modelled as Poisson random variables whose mean value is 400 and α_l^i denotes the amplitude of l[th] path for i[th] device that can be expressed as: [3]

$$|\alpha_l^i|^2 = L_0 \exp\left(-\frac{\tau_l^i}{\Gamma} - F_k[1 - \delta(l)]\right)\beta \ldots\ldots\ldots\ldots\ldots. (8)$$

where, L_0 denotes the path loss, τ_l^i denotes the arrival time of a particular path that can be modelled as Poisson random process for which arrival rate is λ=1/ (0.50125ns), Γ denotes the exponential decay factor, β is a log-normal random variable which has mean as zero and variance as σ^2, F_k denotes the effect of factor k in particularly non-LOS environment which can be expressed as: [3]

$$F_k = \frac{\Delta k \ln 10}{10} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where, Δk calculates the difference between the magnitude of the 1[st] impulse response and the average of all the impulse responses.

Table. 2.6 Parametrs for various orientation of human body [3]

Direction of Body	σ[dB]	F_k (Δk [dB])	Γ(ns)
0	7.30	5.111(22.2)	44.6346
90	7.08	4.348(18.8)	54.2868
180	7.03	3.638(15.8)	53.4186

270	7.19	3.983(17.3)	83.9635

Table 2.6 represents the values of σ in dB, F_k and Γ in ns for various direction of human body [3].

2.4 UWB/MIMO based WBAN

2.4.1 Introduction

As a low power, high data rate technology UWB has many applications in lots of areas, such as sensor data collection, precision locating and tracking applications. Based on thesecharacteristics of UWB, one of the applications of it is the BAN. Meanwhile, due to the high center frequency of UWB, the antennas for this band are always small in size, which is adesirable property for body worn devices. Due to its large bandwidth, it is robust to jamming and has very low probability of interception. [2]

Some major advantages of UWB application in WBAN are:

1. It requires low transmission power and hence can be used in networks with low data rate and low duty cycles.
2. Due to its low transmit power characteristic, battery life of body worn sensors, increases.
3. It can be easily implemented for imaging in medical applications due to its good penetrating properties.

Some major challenges faced while designing wireless communication system are limited frequency bandwidth, constrained transmission power and complexity during implementation. Multiple Input Multiple Output (MIMO) systems is a promising technology that is used for increasing the data transmission rate, improving link reliability and enhancing the system coverage. This particular system enables a new dimension which is the spatial dimension that is used to reduce the impairments of wireless channels. MIMO has multiple transmitting and receiving antennas.[6] MIMO systems increase the link range and data throughput without increasing bandwidth and transmit power.

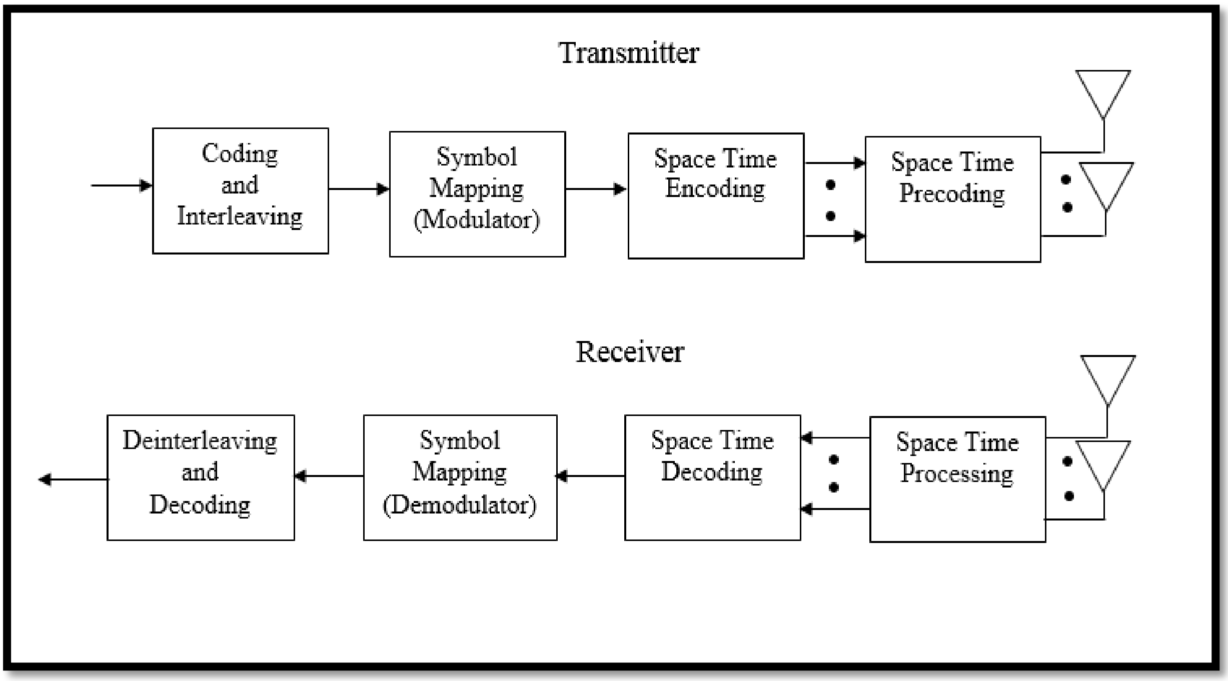

Figure 2.3 Basic building blocks of a MIMO communication system[6]

Let us assume a 2 x 2 Multiple Input Multiple Output system.

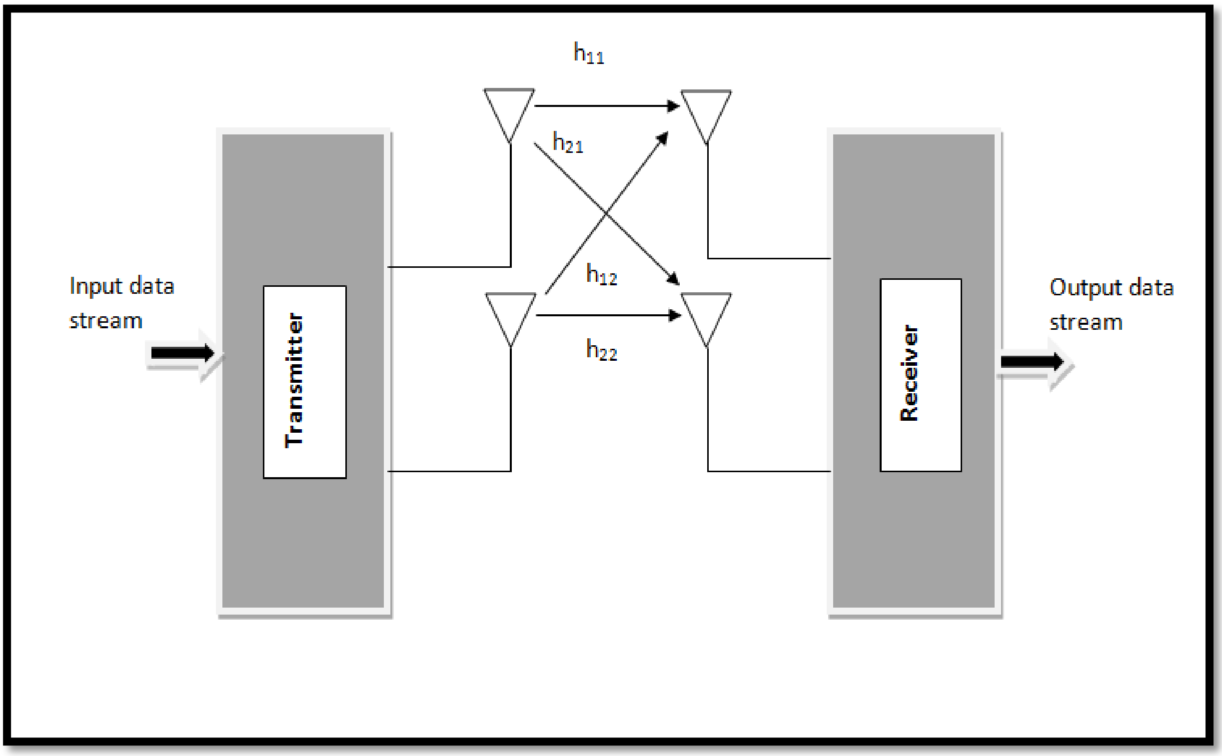

Figure2.4 2X2 MIMO System[6]

The signal received at the 1st receiving antenna is:[6]

$$y_1 = h_{11}x_1 + h_{12}x + n_1 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(10)$$

The signal received at the 2nd receiving antenna is:[6]

$$y_2 = h_{21}x_1 + h_{22}x_2 + n_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(11)$$

where y_1 *and* y_2 are the symbols received on the 1st and 2nd antenna respectively, h_{11} is the transmission channel from 1^{st} transmitting antenna to 1^{st} receiving antenna, h_{12} is the transmission channel from 2^{nd} transmitting antenna to 2^{nd} receiving antenna, h_{21} is the transmission channel from 1^{st} transmitting antenna to 2^{nd} receiving antenna, h_{22} is the transmission channel from 2^{nd} transmitting antenna to 2^{nd} receiving antenna, x_1 *and* x_2 are the symbols that are transmitted and n_1 *and* n_2 is the noise on 1^{st}*and* 2^{nd} receiving antennas respectively.
Eqn (10) and Eqn (11) can be expressed in the form of matrix as:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \dots\dots\dots\dots\dots\dots\dots\dots\dots..(12)$$

Therefore, the received signal vector can be denoted as:

$$y = Hx + n \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(13)$$

Consider a system with M_T transmitting antennas and M_R receiving antennas, the Multiple Input Multiple Output channel for a particular time instant may be represented as a M_R* M_T matrix:

$$H = \begin{bmatrix} H_{1,1} & \cdots & H_{1,M_T} \\ \vdots & \ddots & \vdots \\ H_{M_R,1} & \cdots & H_{M_R,M_T} \end{bmatrix} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(14)$$

2.4.2 System Model

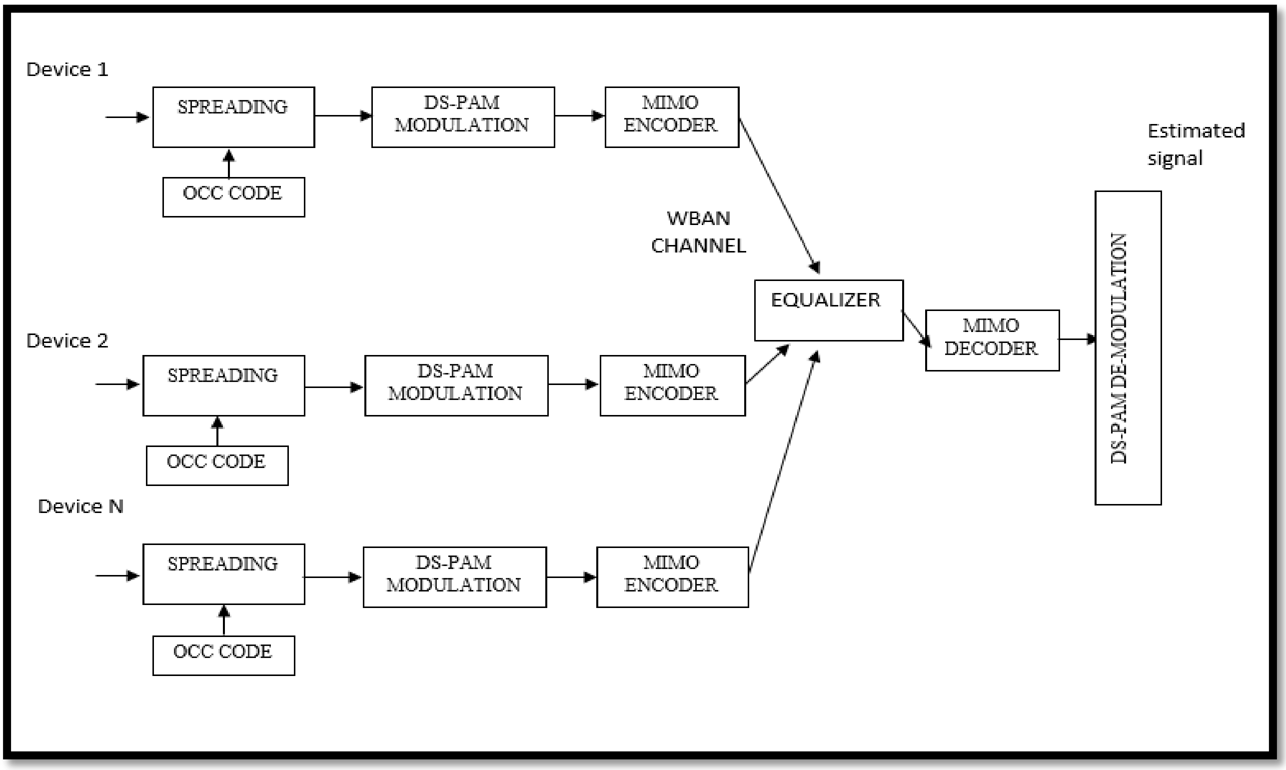

Figure 2.5 UWB/MIMO based WBAN System Model [5]

Figure 2.5 represents the UWB/MIMO based WBAN system model. The data collected by the several devices are transmitted as DS-PAM modulated signal. Orthogonal complete complementary (OCC) code has been used as the spreading code. OCC codes are ideal orthogonal codes considered with three parameters, flock size (F), set size (L) and element code length (N). The robustness of a particular MIMO system against multipath channel fading and division among users, depends on orthogonality of the spreading codes. [8]

The transmitted symbol from nth transmit antenna can be represented as: [5]

$$s_n(i) = d_n(i) * c_n \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (15)$$

where, $d_n(i)$ denotes the data sequence for nth antenna and c_n denotes the OCC sequence.

This spread signal serves as the input to UWB/MIMO encoder (2X2) which is then transmitted through WBAN channel CM3 and CM4.

The received signal at the mth receive antenna can be given as: [5]

$$y_n(t) = \sum_{n=1}^{N}\sum_{l=0}^{L} h_{m,n}(l) s_n\left(t - lT_p\right) + n_l(t) \dots \dots .(16)$$

where, $h_{m,n}(l)$ denotes the fading coefficient of lth path for signal from transmitting antenna n to receiving antenna m and $n_l(t)$ denotes the Additive white gaussian noise.

The received signal is then processed by equalizer to mitigate the interference caused.

2.4.3 Transmitter Design

2.4.3.1 Modulation Techniques

The most commonly used modulation techniques can be summarized as: [10]

<u>Pulse Amplitude Modulation:</u>

Binary pulse amplitude modulation (PAM) can be implemented using two antipodal Gaussian pulses. The transmitted PAM signal $s_{tr}(t)$can be represented as:[10]

$$s_{tr}(t) = d_k w_{tr}(t) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots ..(17)$$

where, $w_{tr}(t)$ represents the Ultra Wide Band pulse waveform, k denotes the transmitted bit which can be 0 or 1 and,

$$d_k = -1 \qquad for\ k = 0 \dots \dots \dots \dots \dots \dots . \dots (18)$$

$$d_k = 1 \qquad for\ k = 1 \dots \dots \dots \dots \dots \dots . \dots .(19)$$

denotes the antipodal representation of the k bit that has been transmitted. The pulse under transmittion is basically the 1st derivative of the Gaussian pulse defined as:[10]

$$w_{tr}(t) = -\frac{t}{\sigma^3\sqrt{2\pi}} e^{\frac{-t^2}{2\sigma^2}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(20)$$

where, σ depends on the pulse length T_p as $\sigma = T_p/2\pi$.

<u>Pulse Position Modulation (PPM):</u>

For Pulse position modulation, the data bit that has to be transmitted is encoded using the position of the impulse under transmission with regard to a reference position.[10]

In other words, if we represent bit “0” by a pulse that originates at the time instant 0 then bit “1” is represented by a pulse that is shifted in time by the amount of δ from 0.

If we assume that the informationcorresponding to each symbol is carried by a single impulse then PPM signal can be expressed as: [10]

$$s_{tr}(t) = \sum_{k=-\infty}^{k=+\infty} w_{tr}(t - kT_s - d_k\delta) \dots\dots\dots\dots\dots(21)$$

where, $w_{tr}(t)$ expresses the transmitted impulse radio and δ represents the time shift for the two states of the PPM modulation. Autocorrelation properties of the pulse help us decide the value of δ. For the implementation of a PPM with orthogonal signals, the optimum value of $\delta(\delta_{opt})$ which results in zero auto correlation $\rho(\delta_{opt})$ is such as:[10]

$$\rho(\delta_{opt}) = \int_{-\infty}^{+\infty} w_{tr}(\tau)w_{tr}(\delta_{opt} + \tau) = 0 \dots\dots(22)$$

2.4.3.2 Orthogonal Complete Complementary Code

Let us consider OCC codes with element code length N=4. There are four element codes (X_0, X_1, Y_0, Y_1) and each device uses two element codes (considering X_0, X_1 and Y_0, Y_1 together). We will now prove the zero cross correlation with zero out of phase auto correlation between these codes. Let us assume X_0 = (+ + + -), X_1 = (+ - + +) and Y_0 = (+ + -+), Y_1 = (+ - - -).

$X_0 \Theta X_0$ and $X_1 \Theta X_1$ denote the shift and-add operations to calculate autocorrelation function for X_0 and X_1, and $Y_0 \Theta Y_0$ and $Y_1 \Theta Y_1$ for Y_0 and Y_1 likewise. [8]

Then we have:

$$(X_0 \Theta X_0) + (X_1 \Theta X_1) = (0, 0, 0, 8, 0, 0, 0)$$

$$(Y_0 \Theta Y_0) + (Y_1 \Theta Y_1) = (0, 0, 0, 8, 0, 0, 0)$$

Similarly, the cross correlation function between X and Y can be represented as:

$$(X_0 \Theta Y_0) + (X_1 \Theta Y_1) = (0, 0, 0, 0, 0, 0, 0)$$

$$(Y_0 \Theta X_0) + (Y_1 \Theta X_1) = (0, 0, 0, 0, 0, 0, 0)$$

Here, ϴ symbol represents shift and add operation.

2.4.4 Simulation Study and analysis

Simulation parameters used for performance analysis of PN and OCC sequence for the system model in Figure 2.5.

Table. 2.7Simulation Parametrs

Spreading code	PN, OCC
Modulation	DS-PAM
MIMO scheme	2X2
Channel model	WBAN Channel (CM4)
Equalizer	Maximum Likelihood

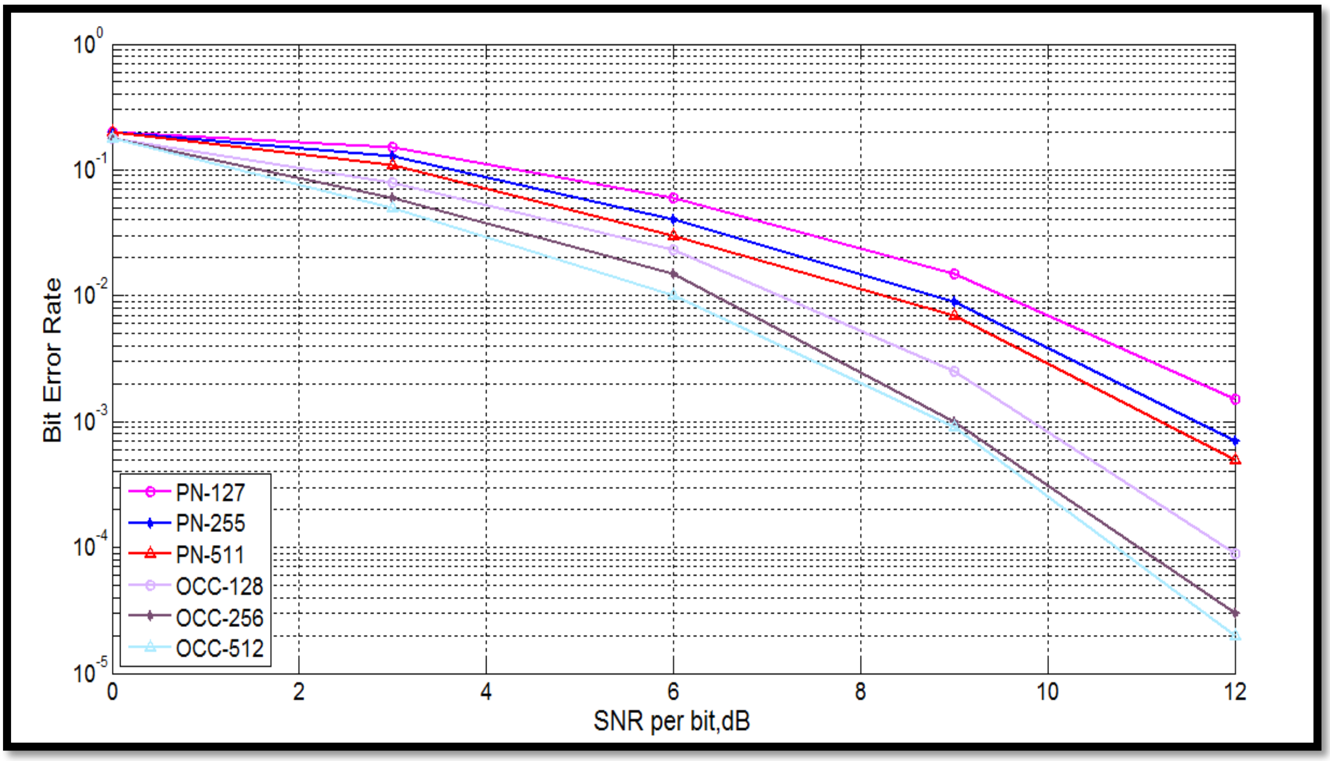

Figure 2.6 Performance of UWB/MIMO (2X2) system for different sequence length

The simulation has been performed for different values of SNR from 0 to 12dB.

At SNR = 9 dB:

Table. 2.8 BER corresponding to sequence length

Spreading Code	**Sequence Length**	**BER**
PN sequence	127	$\sim 1.5 * 10^{-2}$
PN sequence	255	$\sim 9 * 10^{-3}$
PN sequence	511	$\sim 7 * 10^{-3}$
OCC sequence	128	$\sim 2.5 * 10^{-3}$
OCC sequence	256	$\sim 10^{-3}$
OCC sequence	512	$\sim 0.95 * 10^{-3}$

From the above results, it can be observed that OCC sequence performs better than PN sequence. It is also clear that there is not much improvement in BER for OCC sequence of length 256 and 512. Hence, OCC sequence of length 256 is considered for the further simulation purpose.

At BER ~ 10^{-3}:

- SNR improvement between OCC and PN sequence of length 256 and 255 respectively is of approximately 3dB.

Hence, it can be deduced that OCC as spreading code with length 256 performs better than PN sequence as spreading code with length 255.

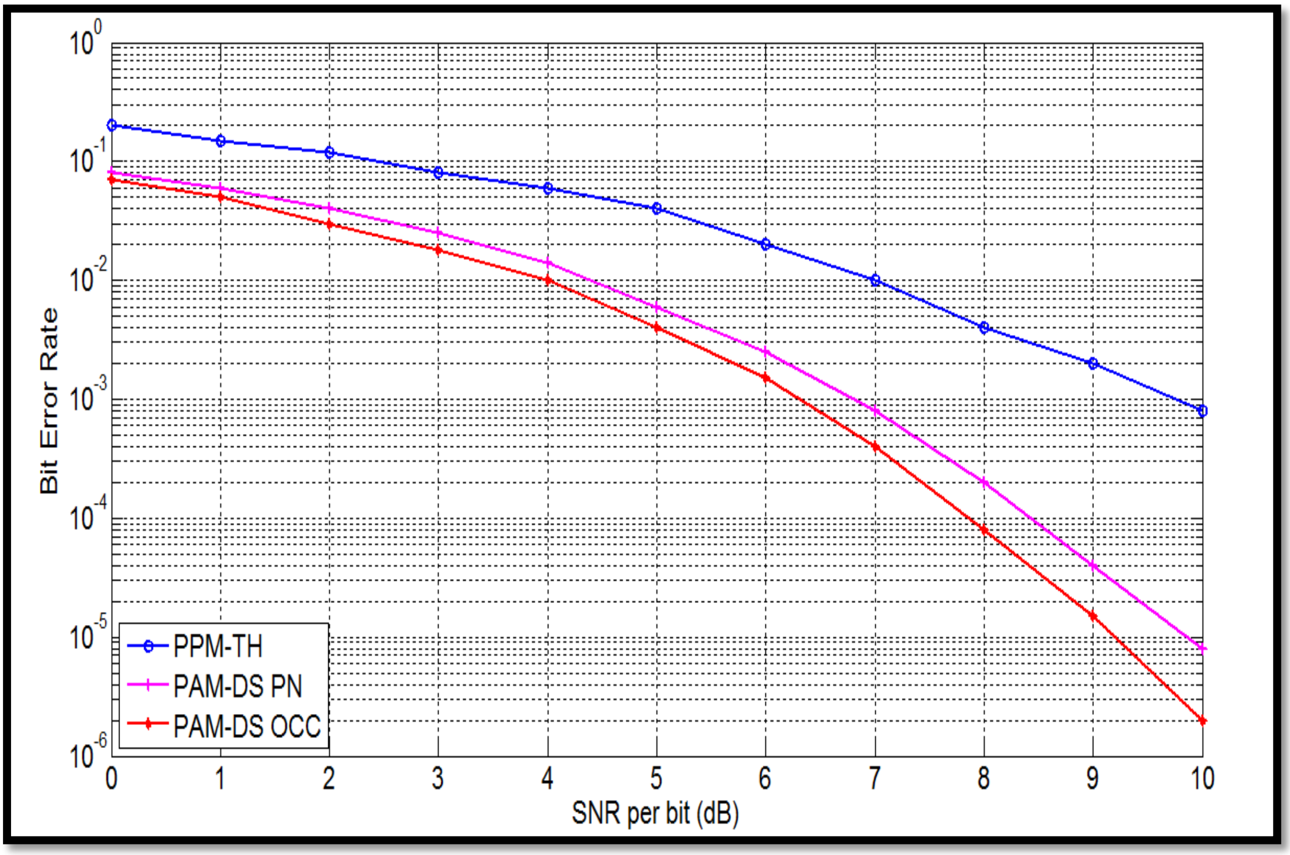

Figure 2.7 Comparison of various modulation schemes to select the best possible from them.

The simulation has been performed for different values of SNR from 0 to 10 dB.

At SNR = 8 dB:

Table. 2.9 BER corresponding to various modulation technique

Modulation technique	BER
TH-PPM	$\sim 4 * 10^{-3}$
DS-PAM with PN sequence	$\sim 2 * 10^{-4}$
DS-PAM with OCC sequence	$\sim 7 * 10^{-5}$

From Figure 2.7, we have observed that at SNR= 8 dB, BER for TH-PPM, DS-PAM using PN sequence and DS-PAM using OCC code are $\sim 4 * 10^{-3}$, $2 * 10^{-4}$ and $7 * 10^{-5}$ respectively.

At BER ~ 10^{-3}:

- SNR improvement between DS-PAM OCC and TH-PPM scheme is of approximately 2 dB.
- SNR improvement between DS-PAM OCC and DS-PAM PN scheme is of approximately 1 dB.

Hence, it can be deduced that DS-PAM modulation implemented with OCC as spreading code performs better than when it is used with PN sequence as spreading code and also when TH-PPM is used as the modulation scheme.

3

Existing Receiver Design

3.1 Introduction

In recent years, the prime focus in wireless communication system is to design low-cost wireless devices to communicate accurately at high data rates. In order to achieve this goal, we will perform channel equalization procedure. Equalization for channels which are time-varying and frequency-selective has gained a lot of importancedue to transmission at a greater speed and terminals with high mobility. An equalizer with the property to achieve high performance when it is operated at a high data rate with very less computational cost is desirable. Most of the wireless receivers are designed with the equalizer which provides good result. [6]

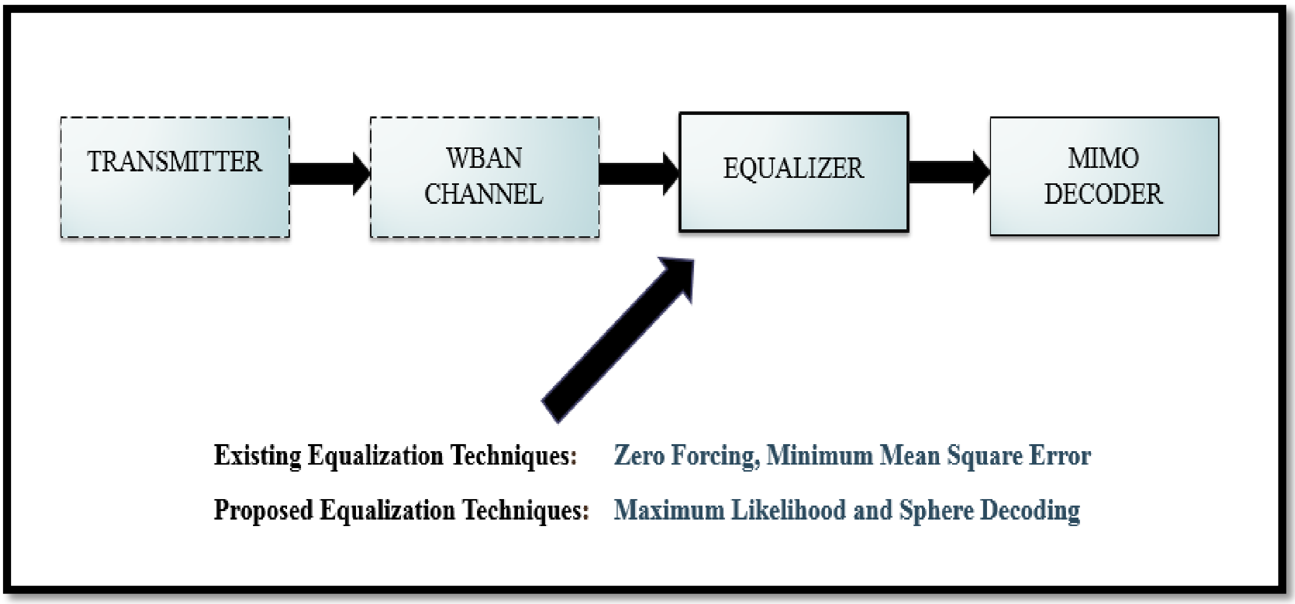

Figure 3.1. Receiver Design

For any wireless system to be efficient and utilize all the properties of its channel, it is very necessary to design an suitable equalization technique with low complexity. Various equalizers have been proposed in the past to mitigate the inter-symbol interference, signal fading etc. Its objective is minimizing the error between output received and desired output.

In the following section,we represent the work done in the past in the field of equalization technique.

3.2 Zero Forcing

A ZF equalizer compensates for the channel response by utilizing an inverse filter. At the output of the equalizer the response for the symbol detected is represented by one and zero for other symbols. This aims at the mitigation of the undesirable interference caused from the rest of the symbols but it takes place when there is no noise. ZF is an equalization technique which does not take into account the effects of noise and it may enhance the noise while trying to mitigate the interference.

Let us consider the case that number of transmitting antennas is equal to number of receiving antennas and the H is a square channel matrix. Here, the inverse of the channel matrix H exists and we have, [5]

$$yH^{-1} = x + nH^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

In order to find x, it is necessary to find a matrix W_{ZF} which follows:[5]

$$W_{ZF}H = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (24)$$

The ZF detector satisfying the above condition is given by:[5]

$$W_{ZF} = (H^H H)^{-1} H^H \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (25)$$

The covariance matrix of the noise can be represented as: [5]

$$[(nH^{-1}).nH^{-1}] = (H^{-1})^H.E[n^H.n]H^{-1} = (H.H^H)^{-1} \ldots\ldots (26)$$

The above equation explains that the noise power may increase due to the factor $(H.H^H)^{-1}$.

Hence we can also say, it inverts the channel effect as:

$$\tilde{x}_{ZF} = W_{ZF}y \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$$

$$= x + (H^H H)^{-1} n$$

The error performance is dependent on the power of $(H^H H)^{-1} n$that is$\|(H^H H)^{-1} n\|_2^2$.[6]

Using this technique may enhance the noise in the process of eliminating the interference as it does not take into consideration, the effects of noise.

3.3 Minimun Mean Square Error

MMSE is a detection technique which considers both, mitigation of interference and reducing the effect of noise and anything that tries to enhance it. It aims at minimizing the mean square error between the symbols that were transmitted and the symbols that have been detected.

Minimum Mean Square Error detector can be expressed as W_{MMSE} and detection operation by:[5]

$$x\hat{}_k = sgn[W_{MMSE}\, y] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

The W_{MMSE} that aims at maximizing the Signal to Noise Ratio and minimizing the mean square error is represented as:[5]

$$E[(x\hat{}_k - W_{MMSE}\, y)^T (x\hat{}_k - W_{MMSE}\, y)] \ldots\ldots\ldots\ldots\ldots (29)$$

To solve for x , it is necessary to find a matrix W_{MMSE} . The detector to meet this constraint is represented as:[5]

$$W_{MMSE} = (H^H H + \sigma_n^2 I)^{-1} H^H \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

Therefore,

$$W_{MMSE} = \left(H^{*}H + \frac{1}{SNR}I\right)^{-1} H^{*} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (31)$$

where,

• ( )* represents the complex conjugate of channel H.

• It is considered that the number of transmitting antennas is more than the number of receiving antennas.

• SNR denotes the Signal to Noise Ratio.

MMSE at a high SNR:[5]

$$W_{MMSE} = \left(H^{*}H + \frac{1}{SNR}I\right)^{-1} H^{*} \approx (H^{H}H)^{-1}H^{H} \ldots\ldots\ldots (32)$$

MMSE detector is an optimal equalization method that considers both the objective, interference mitigation and reduction of noise increment. [5]

3.4 Simulation Study and Analysis

Simulation parameters used for performance analysis of ZF and MMSE equalization technique for the system model for Channel Model CM3 and CM4 in Figure 2.5.

Table. 3.1 Simulation Parametrs

Spreading code	OCC
Modulation	DS-PAM
MIMO scheme	2X2
Channel model	WBAN Channel CM3 & CM4

Equalizer	ZF, MMSE

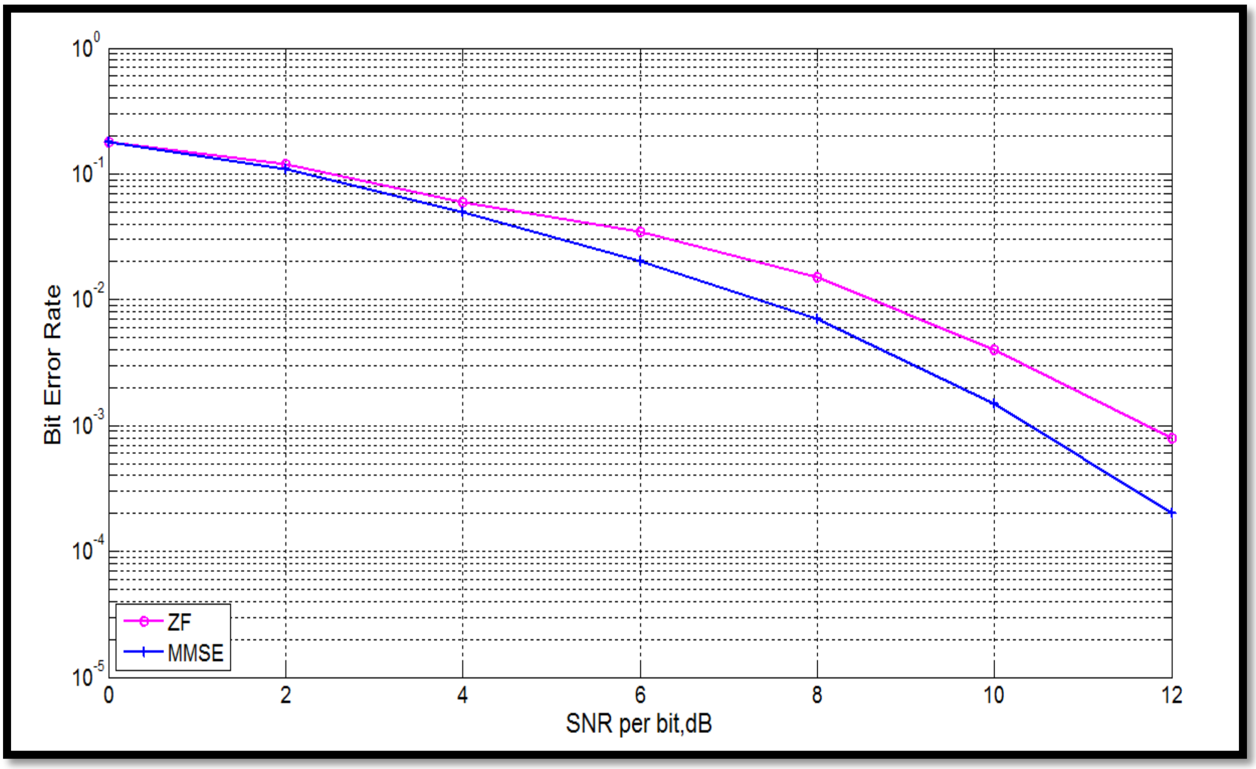

Figure 3.2. Comparison of various Equalization techniques (ZF, MMSE) for Channel model CM3

At SNR = 12 dB:

Table 3.2 BERcorresponding to ZF and MMSE for CM3

Equalization Technique	**BER**
Zero Forcing	$\sim 8 * 10^{-4}$
Minimum mean square error	$\sim 2 * 10^{-4}$

At BER ~ 10^{-3}:

SNR improvement between MMSE and ZF technique is of approximately 1dB.

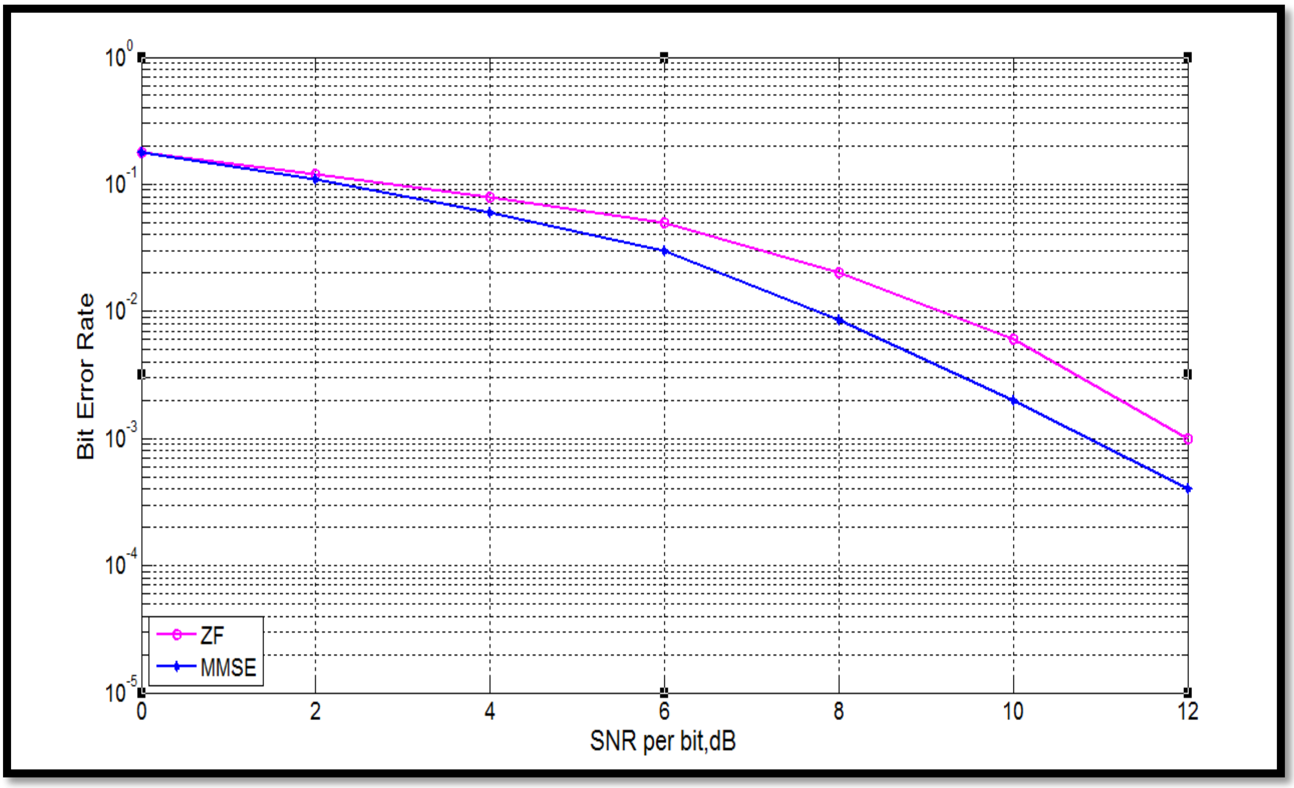

Figure 3.3 Comparison of various Equalization techniques (ZF, MMSE) for Channel model CM4

At SNR = 12 dB:

Table 3.3 BER corresponding to ZF and MMSE for CM4

Equalization Technique	**BER**
Zero Forcing	$\sim 10^{-3}$
Minimum mean square error	$\sim 4 * 10^{-4}$

At BER ~ 10^{-3}:

SNR improvement between MMSE and ZF technique is of approximately 1dB.

3.5 Summary

Equalization techniques are of enormous importance in the design of high data rate wireless systems. They can mitigate the effect of inter symbol interference for mobile fading channel with a lot of efficiency. ZF equalizer provides high performance only for theoretical assumptions that are when noise is zero. Its performance degrades in mobile fading environment. It is quite simple with ease of implementation but its disadvantage is that it happens to amplify the noise. MMSE equalizer uses Least Mean Squaremethod to mitigate the effect of ISI. The MMSE equalizer results in around 1dB gain of SNR with respect to ZF equalizer.

But the performance of MMSE receiver is significantly inferior to that of optimal Maximum Likelihood detection.

4

Proposed Receiver Design

4.1 Introduction

Implementation of equalizers at the receiver are of great significance in the design of wireless systems of high data rate. They are used to mitigate the effect of ISI even in mobile fading channel with a lot of efficiency.

Zero Forcing equalizer is the most basic form of equalizer and performs well when noise is zero. It is quite simple with ease of implementation but its disadvantage is that it happens to amplify the noise. MMSE equalizer uses LMS (Least Mean Square) method for the removal of ISI. The MMSE equalizer results in around 1dB of SNR gainwith respect to ZF.

But the performance of MMSE receiver is significantly inferior to that of optimal Maximum Likelihood detection.[6] Hence for enhancing the performance of the system, Maximum Likelihood technique can be used. But it suffers from complexity issues. This has lead to implementation of Sphere Decoding algorithm at the receiver side whose performance is almost same as ML but the complexity is significantly reduced.

4.2 Maximun Likelihood

The Linear detection method have very less complexity when compared to that of the optimal Maximum Likelihood technique. But it should also be noted that they provide inferior performance is when compared to ML technique.

ML detection measures the Euclidean distance between arrived signal vector and the product of the given channel H with all the transmitted signal vectors, and selects the minimum vector metric.

If C denotes the constellation points and N_T denotes the number of transmitting antennas. Then, ML calculates the estimated transmitted signal vector x as:[6]

$$\hat{x}_{ML} = arg \min_{x \in C^{N_T}} \|y - Hx\|^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33)$$

where, $\|y - Hx\|^2$ signifies the ML solution metric.

The Maximum Likelihood technique gains the optimal performance when the vectors that have been transmitted are most likely. But, its computational complexity grows exponentially with increase in number of transmitting antennas and constellation points. The required number of ML metric calculation is $|C|^{N_T}$.[6]

This receiver uses optimum decoding technique tominimize the error probability. It performs the comparison of the received signals with all possible modified transmitted signal vectors and calculates the symbol vector transmitted in accordance with the Maximum Likelihood principle, which can be written as:[6]

$$\hat{C} = \min_{C} arg\|y - C'H\|_F^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (34)$$

where F denotes the Frobenius norm. Cost function can be calculated using Frobenius norm given by:[6]

$$\hat{C} = \min_{\hat{C}} arg\left[Tr[(y - C'H)^H.(y - C'H)]\right] \ldots\ldots\ldots\ldots (35)$$

Considering $r^H.r$ doesnot depend on the transmitted codeword, hence it can be expressed as:[6]

$$\hat{C} = \min_{\hat{C}} arg[Tr[H^H.C'^H.C'.H] - 2.Real(Tr[H^H.C'^H N.y])] \ldots\ldots (36)$$

ML detection scheme offers better performance as compared to previously discussed methods.

4.2.1 Simulation Study and analysis

Simulation parameters used for performance analysis of ZF, MMSE and ML equalization technique for the system model for Channel Model CM3 and CM4 in Figure 2.5.

Table. 4.1 Simulation Parametrs

Spreading code	OCC
Modulation	DS-PAM
MIMO scheme	2X2
Channel model	WBAN Channel CM3 & CM4
Equalizer	ZF, MMSE,ML

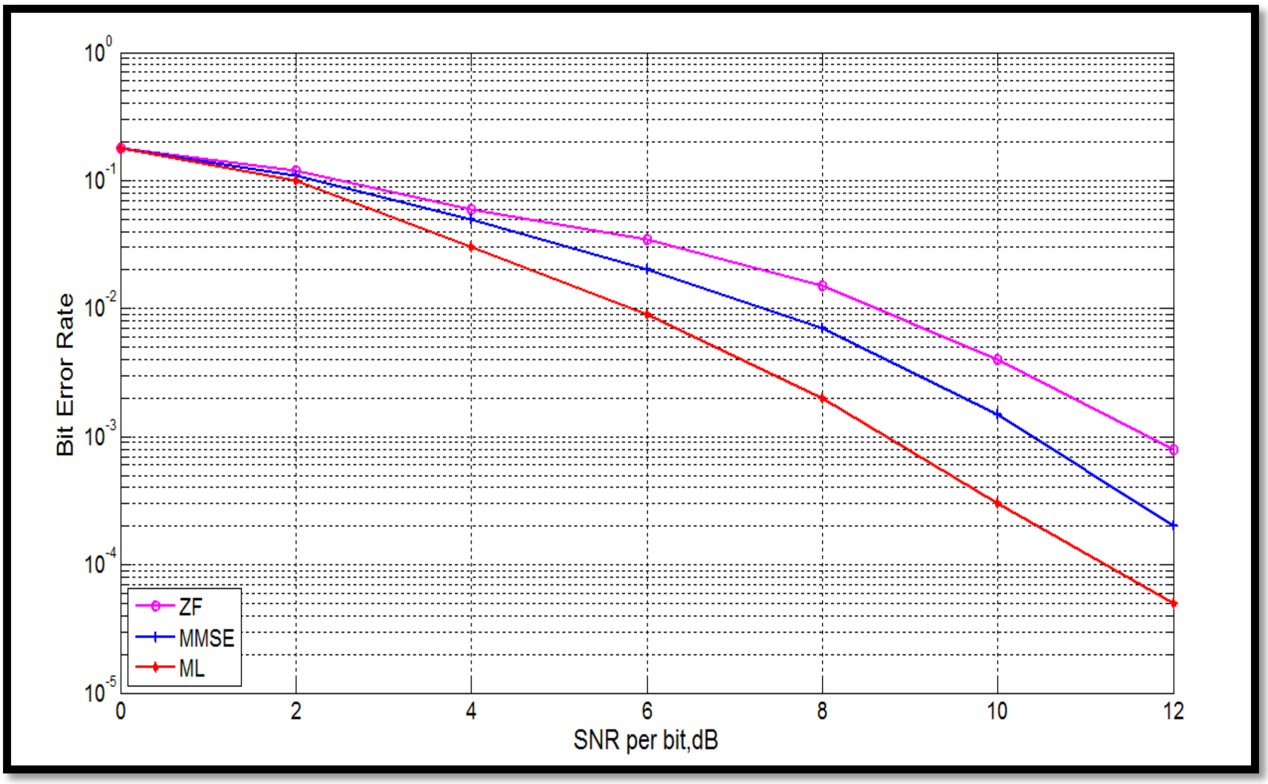

Figure 4.1 Comparison of various Equalization techniques (ZF, MMSE,ML) for Channel model CM3

The simulation has been performed for different values of SNR from 0 to 12 dB.

At SNR = 12 dB:

Table 4.2 BER corresponding to ZF, MMSE and ML for CM3

Equalization Technique	BER
Zero Forcing	$\sim 7 * 10^{-4}$
Minimum mean square error	$\sim 2 * 10^{-4}$
Maximum Likelihood	$\sim 6 * 10^{-5}$

From Figure 4.1, we have observed that at SNR= 12 dB, BER for ZF, MMSE, and ML equalization techniques are $\sim 7 * 10^{-4}$, $2 * 10^{-4}$ and $6 * 10^{-5}$ respectively.

At BER ~ 10^{-3}:

- SNR improvement between ML and ZF technique is of approximately 2 dB.
- SNR improvement between ML and MMSE technique is of approximately 1 dB.

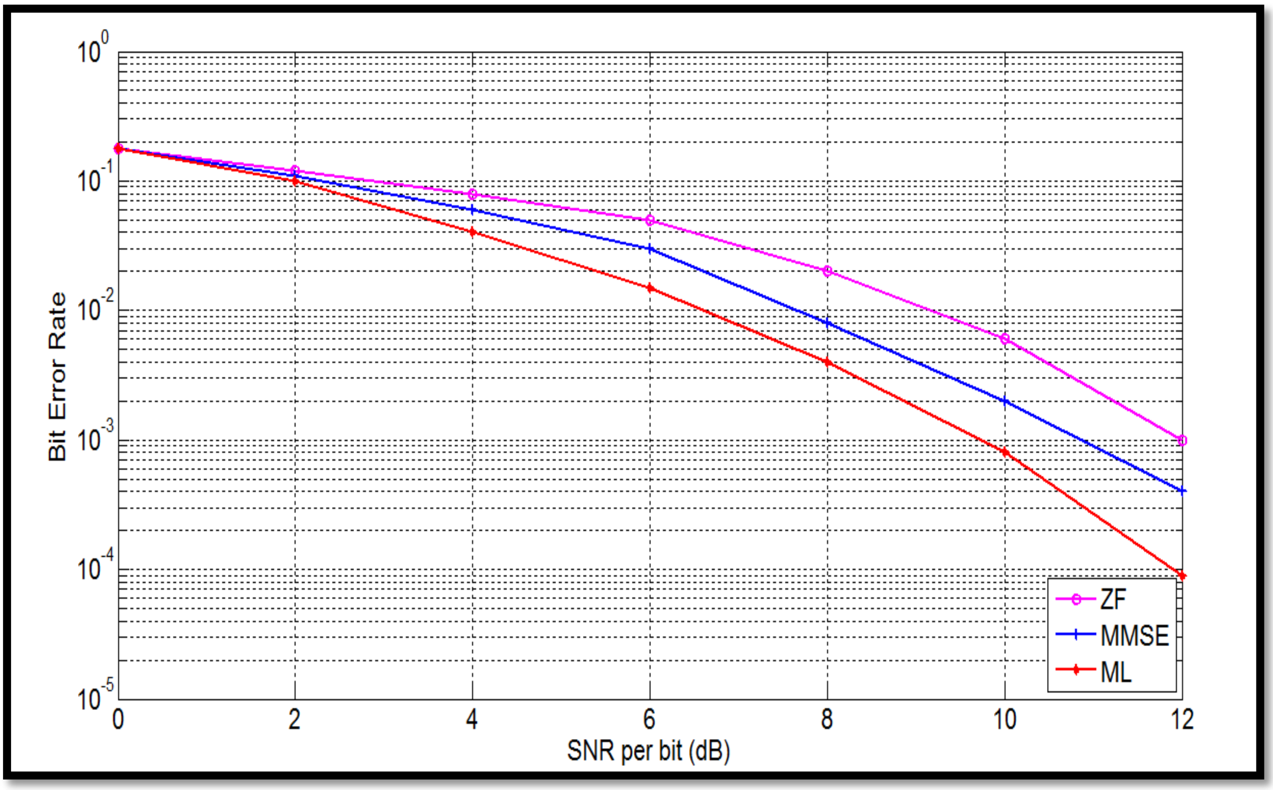

Figure 4.2 Comparison of various Equalization techniques (ZF, MMSE,ML) for Channel model CM4

The simulation has been performed for different values of SNR from 0 to 12 dB.

At SNR = 12 dB:

Table 4.3 BER corresponding to ZF, MMSE and ML for CM4

Equalization Technique	**BER**
Zero Forcing	$\sim 10^{-3}$
Minimum mean square error	$\sim 4 * 10^{-4}$
Maximum Likelihood	$\sim 10^{-4}$

From Figure 4.2, we have observed that at SNR= 12 dB, BER for ZF, MMSE, and ML equalization techniques are $\sim 10^{-3}$, $4 * 10^{-4}$ and 10^{-4} respectively.

At BER ~ 10^{-3}:

- SNR improvement between ML and ZF technique is of approximately 2 dB.
- SNR improvement between ML and MMSE technique is of approximately 1 dB.

From the result, it can be inferred that ML outperforms the ZF and MMSE techniques.

Maximum Likelihood Decoding is the optimum decoding method used in MIMO systems. But the computational complexity of Maximum Likelihood increases exponentially with the increase in number of transmitting antennas and the constellation order.
Hence, Sphere Decoder (SD) has been introduced as an alternative approach to provide MLD performance with least possible complexity.

4.3 Sphere Decoding Algorithm

Sphere decoding (SD) technique aims at finding the signal vector that has been transmitted with minimum metric vector according to maximum likelihood principle. However, instead of searching for all transmitted signal vectors, only a small set of vectors enclosed in the sphere is considered. Then we adjust the radius of the sphere so that there exists only 1 ML solution metric vector in it. If there is no vector that lies in the sphere, it increases its radius and the radius is decreased if there are many vectors within the sphere.[13]

Consider a 2X2 complex Multiple Input Multiple Output channel. The considered complex system can be represented into its respective real system. Let the real part and imaginary part of the signal received at the jth receive antenna be represented as y_{jR} denote and y_{jI} respectively. In other words, $y_{jR} = Re\{y_j\}$ and $y_{jI} = Im\{y_j\}$.[13]
In the similar way, the transmitted signal from the ith antenna can be denoted as $x_{iR} = Re\{x_i\}$ and $x_{iI} = Im\{x_i\}$.

For the 2X2 MIMO channel, the signal that is received at the receiver is as follows:[13]

$$\begin{bmatrix} y_{1R} + jy_{1I} \\ y_{2R} + jy_{2I} \end{bmatrix} = \begin{bmatrix} h_{11R} + jh_{11I} & h_{12R} + jh_{12I} \\ h_{21R} + jh_{21I} & h_{22R} + jh_{22I} \end{bmatrix} \begin{bmatrix} x_{1R} + jx_{1I} \\ x_{2R} + jx_{2I} \end{bmatrix} + \begin{bmatrix} z_{1R} + jz_{1I} \\ z_{2R} + jz_{2I} \end{bmatrix} \ldots\ldots (37)$$

where, h_{ijR}=Re{h_{ij}} and h_{ijI}=Im{h_{ij}}, z_{iR}=Re{z_i} and z_{iI}=Im{z_i}.

The real part of the above equation can be expressed as:[13]

$$\begin{bmatrix} y_{1R} \\ y_{2R} \end{bmatrix} = \begin{bmatrix} h_{11R} & h_{12R} \\ h_{21R} & h_{22R} \end{bmatrix} \begin{bmatrix} x_{1R} \\ x_{2R} \end{bmatrix} - \begin{bmatrix} h_{11I} & h_{12I} \\ h_{21I} & h_{22I} \end{bmatrix} \begin{bmatrix} x_{1I} \\ x_{2I} \end{bmatrix} + \begin{bmatrix} z_{1R} \\ z_{2R} \end{bmatrix}$$

$$= \begin{bmatrix} h_{11R} & h_{12R} - h_{11I} & -h_{12I} \\ h_{21R} & h_{22R} - h_{21I} & -h_{22I} \end{bmatrix} \begin{bmatrix} x_{1R} \\ x_{2R} \\ x_{1I} \\ x_{2I} \end{bmatrix} + \begin{bmatrix} z_{1R} \\ z_{2R} \end{bmatrix}$$

And the imaginary part as:

$$\begin{bmatrix} y_{1I} \\ y_{2I} \end{bmatrix} = \begin{bmatrix} h_{11I} & h_{12I} h_{11R} & h_{12R} \\ h_{21I} & h_{22I} h_{21R} & h_{22R} \end{bmatrix} \begin{bmatrix} x_{1R} \\ x_{2R} \\ x_{1I} \\ x_{2I} \end{bmatrix} + \begin{bmatrix} z_{1I} \\ z_{2I} \end{bmatrix}$$

If we combine the above two equations:

$$\begin{bmatrix} y_{1R} \\ y_{2R} \\ y_{1I} \\ y_{2I} \end{bmatrix} = \begin{bmatrix} h_{11R} & h_{12R} & -h_{11I} & -h_{12I} \\ h_{21R} & h_{22R} & -h_{21I} & -h_{22I} \\ h_{11I} & h_{12I} & h_{11R} & h_{12R} \\ h_{21I} & h_{22I} & h_{21R} & h_{22R} \end{bmatrix} \begin{bmatrix} x_{1R} \\ x_{2R} \\ x_{1I} \\ x_{2I} \end{bmatrix} + \begin{bmatrix} z_{1R} \\ z_{2R} \\ z_{1I} \\ z_{2I} \end{bmatrix}$$

The LHS represents $\bar{y}$, 1st part of RHS represents $\bar{H}$, 2nd part explains $\bar{x}$ and the last part is $\bar{z}$.

Sphere decoding algorithm follows the following relation:[13]

$$arg\min_{\bar{x}} \|\bar{y} - \overline{H\bar{x}}\|^2 = arg\min_{\bar{x}} (\bar{x} - \bar{x}^{\hat{}})^{\mathrm{T}} \bar{H}^T \bar{H} \, (\bar{x} - \bar{x}^{\hat{}}) \dots \dots \dots \dots (38)$$

where, $\bar{x}^{\hat{}} = (\bar{H}^H \bar{H})^{-1} \bar{H}^H \bar{y}$ which is the constrained solution of the real system.

It is observed that ML solution can be obtained by the different metric:[13]

$$(\bar{x} - \bar{x}^{\hat{}})^{\mathrm{T}} \bar{H}^T \bar{H} (\bar{x} - \bar{x}^{\hat{}}) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (39)$$

Let us consider sphere with radius R_{SD} as:[13]

$$(\bar{x} - \bar{x}^{\hat{}})^{\mathrm{T}} \bar{H}^T \bar{H} (\bar{x} - \bar{x}^{\hat{}}) \leq R_{SD}^2 \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (40)$$

This particular technique considers the vectors that lie inside a sphere defined by above equation and the vectors can be ignored.

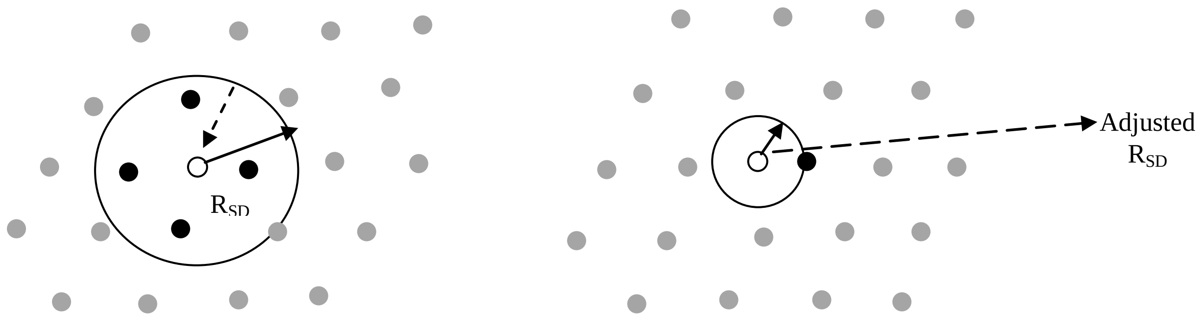

Figure 4.3Illustration of Sphere in Sphere Decoding [13]

The above figure illustrates a sphere of radius $R_{SD}$with center at $\bar{x}\hat{} = (\bar{H}^H\bar{H})^{-1}\bar{H}^H\bar{y}$.
Here, the sphere contains 4 vectors. From these four vectors, one is the ML solution vector. It is to be remembered that the vectors that lie out of the sphere cannot be the solution vector because their metric values corresponding to the maximum likelihood principle are greater than the ones that lie in the sphere. Our aim is to choose the closest from these four vectors. If we are able to do that, we can reduce the radius so thatthere exists a single vector in the sphere. Now, the solution vector lies in this sphere with new radius, as seen in the figure.[13]

The new metric in is also expressed as:[13]

$$(\bar{x} - \bar{x}\hat{})^{\mathrm{T}}\bar{H}^T\bar{H}(\bar{x} - \bar{x}\hat{}) = (\bar{x} - \bar{x}\hat{})^{\mathrm{T}}R^TR(\bar{x} - \bar{x}\hat{}) = \|R(\bar{x} - \bar{x}\hat{})\|^2 \ldots\ldots(41)$$

where, R can be derived from QR decomposition of the channel matrix which can be expressed as $\bar{H} = QR$. If N_T=N_R=2, the metric is given as:[13]

$$\|R(\bar{x} - \bar{x}\hat{})\|^2 = \left\| \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ 0 & r_{22} & r_{23} & r_{24} \\ 0 & 0 & r_{33} & r_{34} \\ 0 & 0 & 0 & r_{44} \end{bmatrix} \begin{bmatrix} \bar{x}_1 - \bar{x}_1\hat{} \\ \bar{x}_2 - \bar{x}_2\hat{} \\ \bar{x}_3 - \bar{x}_3\hat{} \\ \bar{x}_4 - \bar{x}_4\hat{} \end{bmatrix} \right\|^2$$

$$= |r_{44}(\bar{x}_4 - \bar{x}_4\hat{})|^2 + |r_{33}(\bar{x}_3 - \bar{x}_3\hat{}) + r_{34}(\bar{x}_4 - \bar{x}_4\hat{})|^2 + |r_{22}(\bar{x}_2 - \bar{x}_2\hat{}) + r_{23}(\bar{x}_3 - \bar{x}_3\hat{}) + r_{24}(\bar{x}_4 - \bar{x}_4\hat{})|^2 + |r_{11}(\bar{x}_1 - \bar{x}_1\hat{}) + r_{12}(\bar{x}_2 - \bar{x}_2\hat{}) + r_{13}(\bar{x}_3 - \bar{x}_3\hat{}) + r_{14}(\bar{x}_4 - \bar{x}_4\hat{})|^2$$

This can be expressed as:

$$|r_{44}(\bar{x}_4 - \bar{x}_4\hat{\ })|^2 + |r_{33}(\bar{x}_3 - \bar{x}_3\hat{\ }) + r_{34}(\bar{x}_4 - \bar{x}_4\hat{\ })|^2 + |r_{22}(\bar{x}_2 - \bar{x}_2\hat{\ }) + r_{23}(\bar{x}_3 - \bar{x}_3\hat{\ }) + r_{24}(\bar{x}_4 - \bar{x}_4\hat{\ })|^2 + |r_{11}(\bar{x}_1 - \bar{x}_1\hat{\ }) + r_{12}(\bar{x}_2 - \bar{x}_2\hat{\ }) + r_{13}(\bar{x}_3 - \bar{x}_3\hat{\ }) + r_{14}(\bar{x}_4 - \bar{x}_4\hat{\ })|^2 \leq R_{SD}^2$$

Using the above equation, we will follow few steps:

Step1: $\bar{x}_4$is chosen from the following inequality and is represented as $\tilde{\bar{x}}_4$: [13]

$$\bar{x}_4\hat{\ } - \frac{R_{SD}}{r_{44}} \leq \bar{x}_4 \leq \bar{x}_4\hat{\ } + \frac{R_{SD}}{r_{44}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (42)$$

If no candidate exists, then radius needs to be increased.

Step 2: A value is chosen for $\bar{x}_3$ from the points in the following expression:[13]

$$|r_{44}(\bar{x}_4 - \bar{x}_4\hat{\ })|^2 + |r_{33}(\bar{x}_3 - \bar{x}_3\hat{\ }) + r_{34}(\bar{x}_4 - \bar{x}_4\hat{\ })|^2 \leq R_{SD}^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (43)$$

which is equivalent to,

$$\bar{x}_3\hat{\ }\hat{\ } - \frac{\left(\sqrt{R_{SD}^2 - |r_{44}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{\ })|^2}\right) - r_{34}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{\ })}{r_{33}} \leq \bar{x}_3 \leq \bar{x}_3\hat{\ }\hat{\ } + \frac{\left(\sqrt{R_{SD}^2 - |r_{44}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{\ })|^2}\right) - r_{34}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{\ })}{r_{33}}$$

If there exixts no value for $\bar{x}_3$, return to Step 1 and select a different value for $\tilde{\bar{x}}_4$. Then search for $\bar{x}_3$ satisfying the above equation for the selected $\tilde{\bar{x}}_4$. If there exixts no value for $\bar{x}_3$ after considering all possible calculated values of $\tilde{\bar{x}}_4$, increase the radius R_{SD} of sphere and Step 1 is repeated.

Step 3: A candidate value for $\bar{x}_2$ is chose from:[13]

$$|r_{44}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{\ })|^2 + |r_{33}(\tilde{\bar{x}}_3 - \bar{x}_3\hat{\ }) + r_{34}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{\ })|^2 + |r_{22}(\bar{x}_2 - \bar{x}_2\hat{\ }) + r_{23}(\tilde{\bar{x}}_3 - \bar{x}_3\hat{\ }) + r_{24}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{\ })|^2 \leq R_{SD}^2 \ldots\ldots (44)$$

If no value for $\bar{x}_2$ satisfies the above condition, return to Step 2 and find out another expected value of $\tilde{\bar{x}}_3$. If there exists no candidate value for $\bar{x}_2$corresponding to all the expected candidate values for $\tilde{\bar{x}}_3$, return to Step 1 and select other candidate value for $\tilde{\bar{x}}_4$.

Step 4: A value for $\bar{x}_1$ is chose from:[13]

$$|r_{44}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{})|^2 + |r_{33}(\tilde{\bar{x}}_3 - \bar{x}_3\hat{}) + r_{34}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{})|^2 + |r_{22}(\tilde{\bar{x}}_2 - \bar{x}_2\hat{}) + r_{23}(\tilde{\bar{x}}_3 - \bar{x}_3\hat{}) + r_{24}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{})|^2 + |r_{11}(\bar{x}_1 - \bar{x}_1\hat{}) + r_{12}(\tilde{\bar{x}}_2 - \bar{x}_2\hat{}) + r_{13}(\tilde{\bar{x}}_3 - \bar{x}_3\hat{}) + r_{14}(\tilde{\bar{x}}_4 - \bar{x}_4\hat{})|^2 \leq R_{SD}^2 \ldots\ldots(45)$$

If there is no candidate value for $\bar{x}_1$ after solving the above equation with the various possible values for $\tilde{\bar{x}}_2$, we return to Step 2 to select a different value for $\tilde{\bar{x}}_3$. Let us consider that $\tilde{\bar{x}}_1$denotes the candidate vector value for $\bar{x}_1$. After finding all the values, then the radius corresponding to these values is calculated by using above equation. Using this new radius, return to Step 1 and follow the same process.

If $[\tilde{\bar{x}}_1\tilde{\bar{x}}_2\tilde{\bar{x}}_3\tilde{\bar{x}}_4]$ returns as a single point that lies in the sphere with that particular radius, it is the required metric solution vector and the procedure is terminated.

4.2.1 Simulation Study and analysis

Simulation parameters used for performance analysis of ZF, MMSE, ML and SD equalization technique for the system model for Channel Model CM3 and CM4 in Figure 2.5

Table. 4.4 SimulationParametrs

Spreading code	OCC
Modulation	DS-PAM
MIMO scheme	2X2
Channel model	WBAN Channel CM3 & CM4
Equalizer	ZF, MMSE, ML, SD

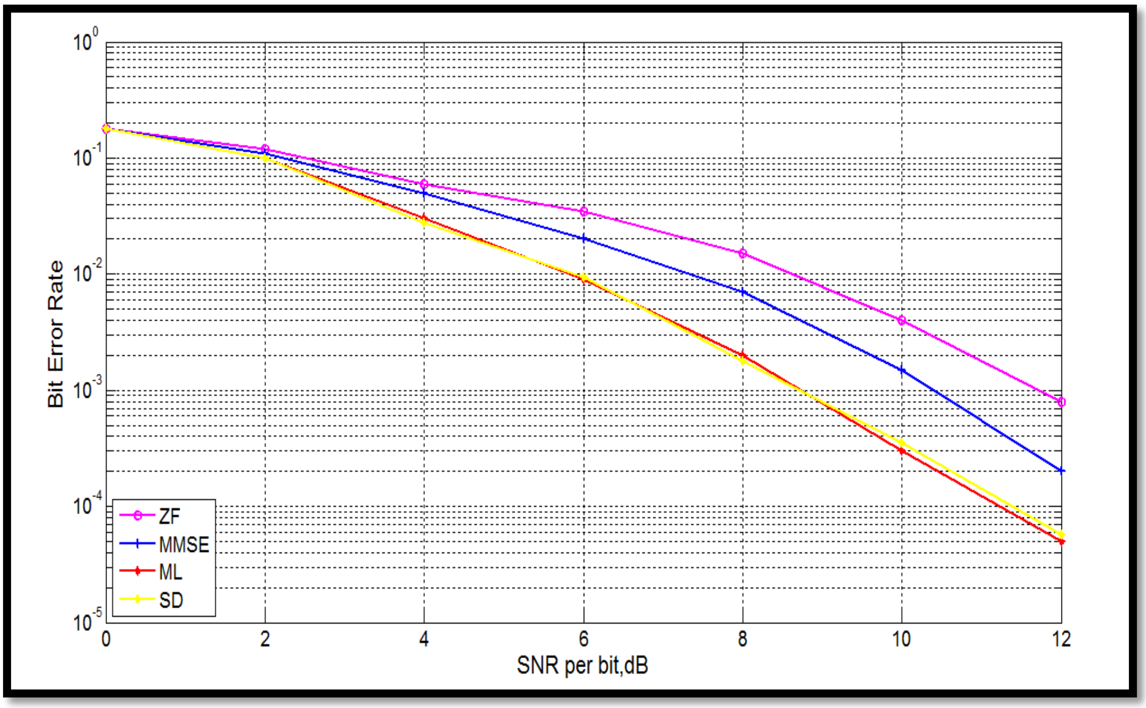

Figure 4.4 Comparison of various Equalization techniques (ZF, MMSE,ML,SD) for Channel model CM3

At SNR = 12 dB:

Table 4.5 BER corresponding to ZF, MMSE, ML and SD for CM3

Equalization Technique	BER
Zero Forcing	$\sim 8 * 10^{-4}$
Minimum mean square error	$\sim 2 * 10^{-4}$
Maximum Likelihood	$\sim 6 * 10^{-5}$
Sphere Decoding	$\sim 6 * 10^{-5}$

At BER ~ 10^{-3}:

- SNR improvement between SD and ZF technique is of approximately 2 dB.
- SNR improvement between SD and MMSE technique is of approximately 1 dB.

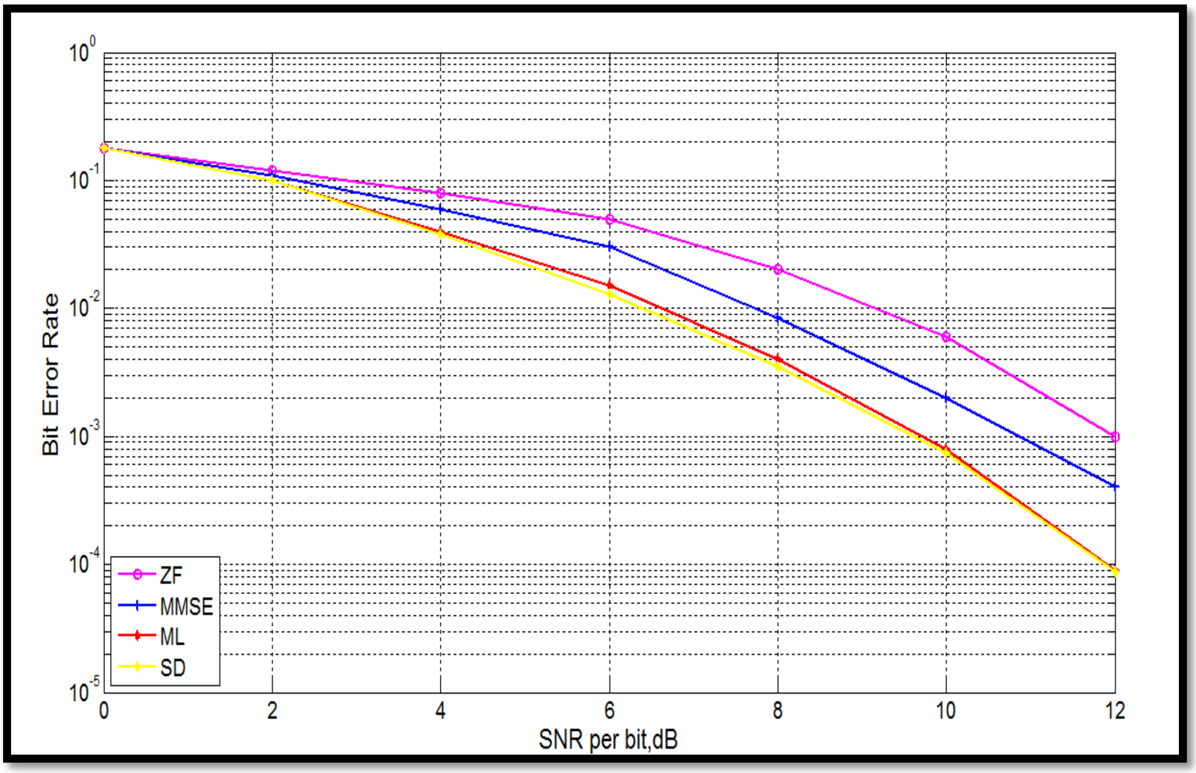

Figure 4.5 Comparison of various Equalization techniques (ZF, MMSE,ML,SD) for Channel model CM4

At SNR = 12 dB:

Table 4.6 BER corresponding to ZF, MMSE, ML and SD for CM4

Equalization Technique	BER
Zero Forcing	$\sim 10^{-3}$
Minimum mean square error	$\sim 4 * 10^{-4}$
Maximum Likelihood	$\sim 10^{-4}$
Sphere Decoding	$\sim 10^{-4}$

At BER ~ 10^{-3}:

- SNR improvement between SD and ZF technique is of approximately 2 dB.
- SNR improvement between SD and MMSE technique is of approximately 1 dB.

4.4 Comparison of ML and SD

The disadvantage of ML technique for MIMO systems is that its complexity grows exponentially with the increase in the number of transmitting antennas. Several algorithms have been developed that are less complex in comparison to ML technique but are suboptimal.

Sphere decoder (SD) is basically a set of extremely efficient and accurate algorithms that provide nearly-optimal solutions withlesser average computational complexity with respect to the standard ML decoding.[12]

4.4.1 Computational Complexity

There are several ways to study the computational complexity of an algorithm. One of the way is to study through the number of mathematical operations, it needs to perform i.e in terms of number of real multiplications etc.

For Maximum Likelihood detection algorithm, computational complexity is proportional to K^{Nt} where K is the size of constellation symbols and N_t represents the number of transmit antennas.

Number of real multiplications required by MLD can be expressed as:[12]

$$4N_r N_t K + 2N_r K^{N_t} \dots\dots\dots\dots\dots (46)$$

where, N_t represents the number of transmitting antennas, N_r represents the number of receiving antennas, K is the size of constellation points.

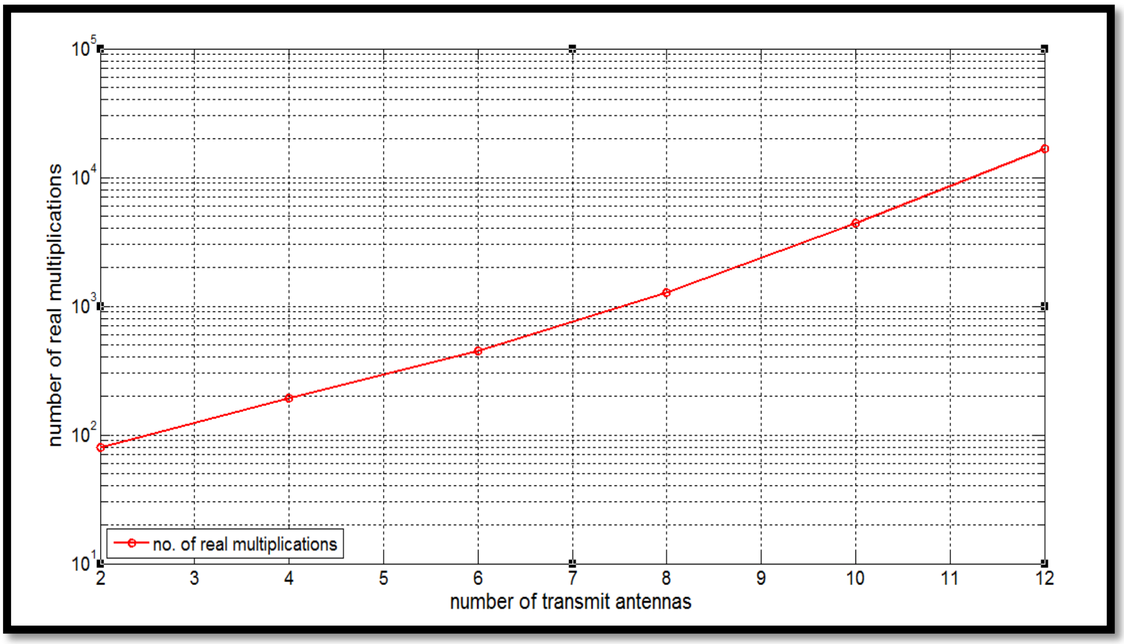

Figure 4.6Complexity of ML against number of transmit antennas

Hence, the complexity of Maximum Likelihood grows exponentially with the increase in number of transmiting antennas N_t and number of bits per symbol ($\log_2 K$).

Considering 2X2 MIMO sytem for 4-PAM modulation:

Number of real multiplications for MLD=

$$4X2X2X4+2X2X4^2$$

$$=128.$$

Let us find out the computational complexity of SD by considering 2X2 MIMO system. The complexity of this algorithm depends on the selection of the initial radius.

There are several ways to determine the initial radius but let us consider that the initial radius is determined as:[13]

$$R_{SD}^2 = \sum_{i=1}^{4} \left| \sum_{k=i}^{4} r_{ik} (\bar{\bar{x}}_k - \bar{x}_k\hat{}) \right|^2 \dots\dots (47)$$

where, $\bar{x}\hat{} = [\bar{x}_1\hat{}\bar{x}_2\hat{}\bar{x}_3\hat{}\bar{x}_4\hat{}]^T$ is considered to be the unconstrained solution and $\bar{\bar{x}}_i = Q(\bar{x}_i\hat{})$, i=1,2,3,4.

For the computation of this initial radius mentioned above, we require 14 real multiplications.

From this calculated radius, the expressions for parameter selection for $\bar{x}_i$, i=4-s+1 in Step s where s represents 1,2,3,4 can be represented in a general form as: [13]

$$\hat{x}_{i,LS} + \frac{-\alpha_i - \beta_i}{r_{ii}} \leq x_i \leq \hat{x}_{i,LS} + \frac{\alpha_i - \beta_i}{r_{ii}} \ldots \ldots (48)$$

where, $\alpha_i = \sqrt{R_{SD}^2 - \sum_{k=i+1}^{4} \left| \sum_{p=k}^{4} r_{kp} \left(\bar{\bar{x}}_p \hat{\bar{x}}_{p,LS} \right) \right|^2}$ and $\beta_i = \sum_{k=i+1}^{4} r_{ik} \left(\bar{\bar{x}}_k - \bar{x}_k\hat{} \right)$

For calculating the above equation, number of multiplication, divisions and square root operations required are 1, 2 and 1 respectively. In Step 1, (s=1), β_4=0, hence the number of square root operation and division required is one each. For finding out the new radius of the sphere, a new vector of length 2X(N_R)=4 is necessary. The number of multiplication required is only one, since the results from the previous steps can be considered.

The Complexity of SD in terms of mathematica computations required for each step:[13]

Table 4.7 Number of Computations required by SD for each step

	Multiplications	Divisions	Square roots
$\hat{\bar{x}} = (\bar{H})^{-1}\bar{y}$	16	0	0
R_{SD}^2	14	0	0
Step 1	0	1	1
Step 2-4 each	1	2	1
R_{SD}^2 ***update***	1	0	0

where as the complexity for MLD as expressed earlier is 128.

Hence, it can be inferred that the complexity reduces to a great extent by the application of Sphere Decoding algorithm in place of Maximum Likelihood detection without compromising the performance of the system.

The system model in Figure 2.5 with the proposed receiver design has been tested for biological signals i.e. ECG signal and Blood Pressure signal. [7] Here, we have considered two device system. Device 1 transmits the Blood pressure signal and ECG signal is transmitted by Device 2. The sample biological signals have been collected from the MIT-BIH database.

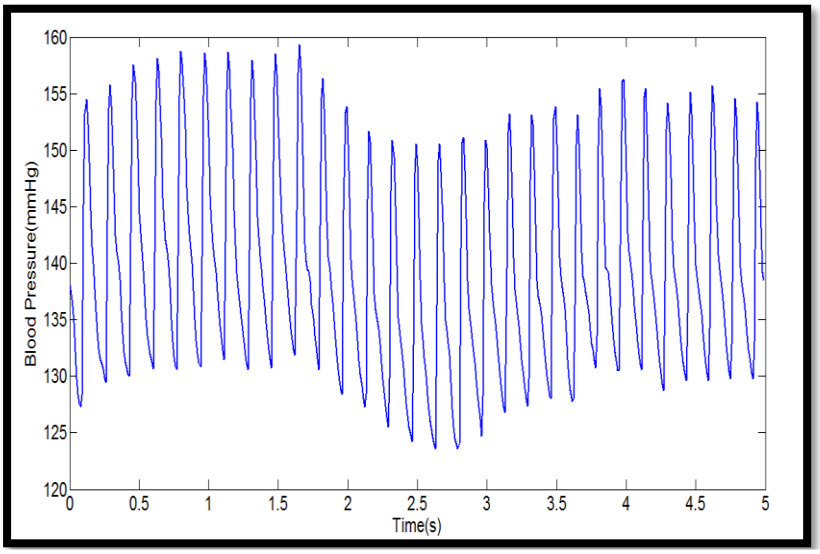

Figure 4.7Original Blood Pressure Signal

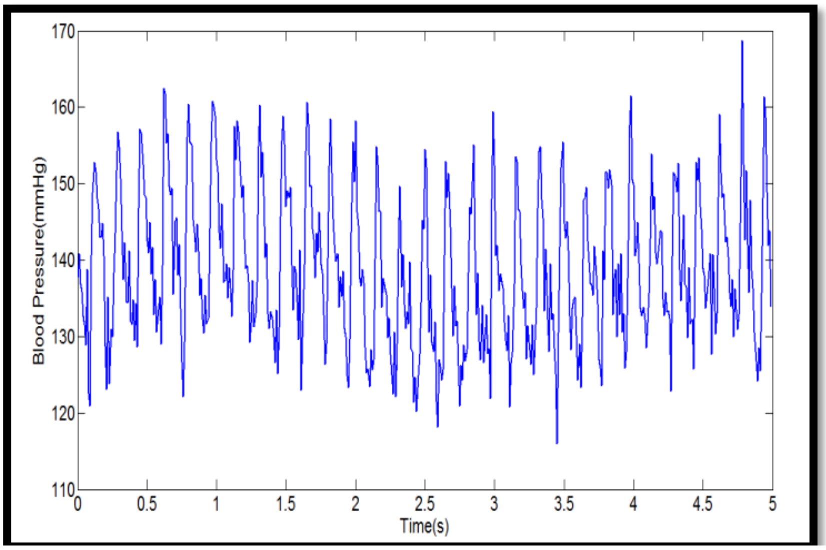

Figure 4.8Blood Pressure Signal after passing through WBAN channel

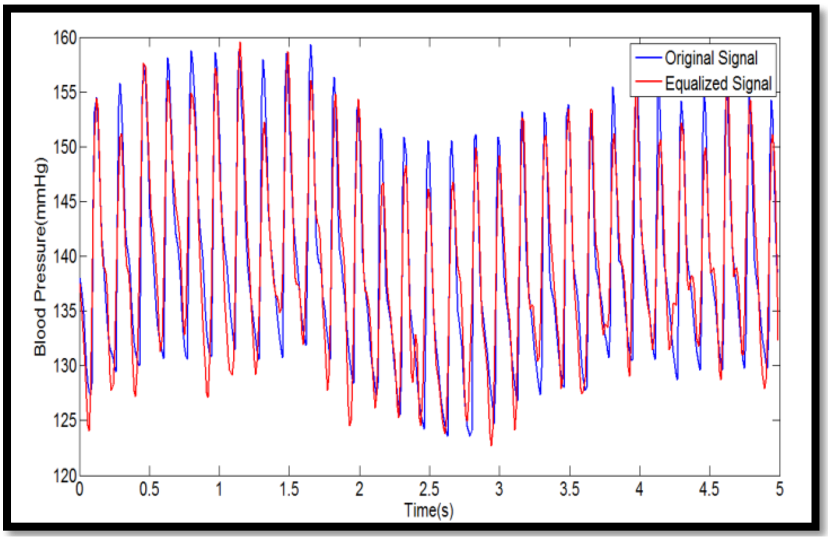

Figure 4.9Equalized Blood Pressure Signal

Figure 4.7 represents the original Blood Pressure signal for five seconds collected from MIT-BIH database. Here, Blood pressure represents the systolic pressure.

If we need to find out the blood pressure at a particular time instant, let us consider at t=2.5 s.
Blood pressure at t=2.5 s is ~150mmHg.When the blood pressure signal is transmitted through WBAN channel, it undergoes fading and interference leading to a distorted form of the signal.

Figure 4.8 represents the distorted Blood Pressure signal after the original signal has been passed through WBAN channel (CM4). At t=2.5s, there are two peaks that can be observed. This is due to the WBAN channel effect which makes it difficult to analyze the signal and measure blood pressure at t=2.5s.

Figure 4.9 represents the equalized Blood Pressure signal using SD technique with BER~ 10^{-4} for SNR=12 dB. After equalization, we have analyzed that:
Blood pressure measured from equalized signal at t=2.5s is ~148mmHg.

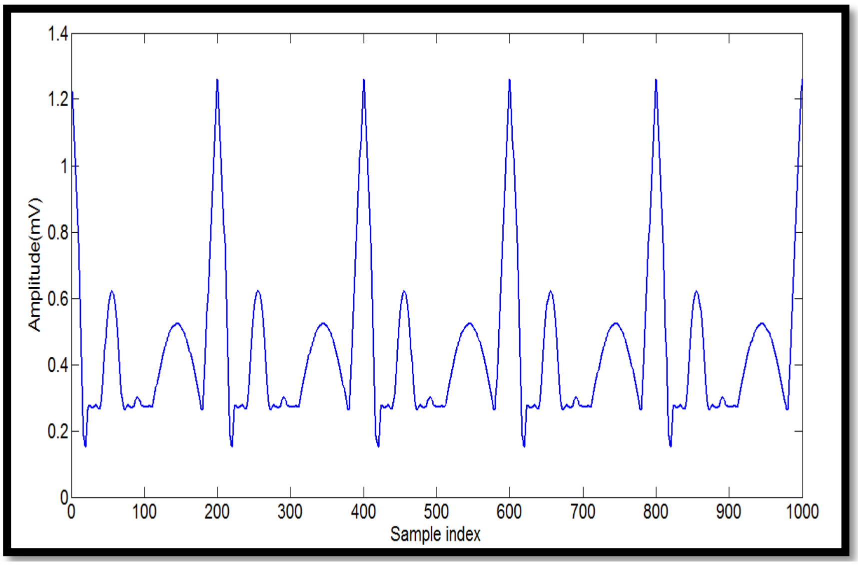

Figure 4.10Original ECG Signal

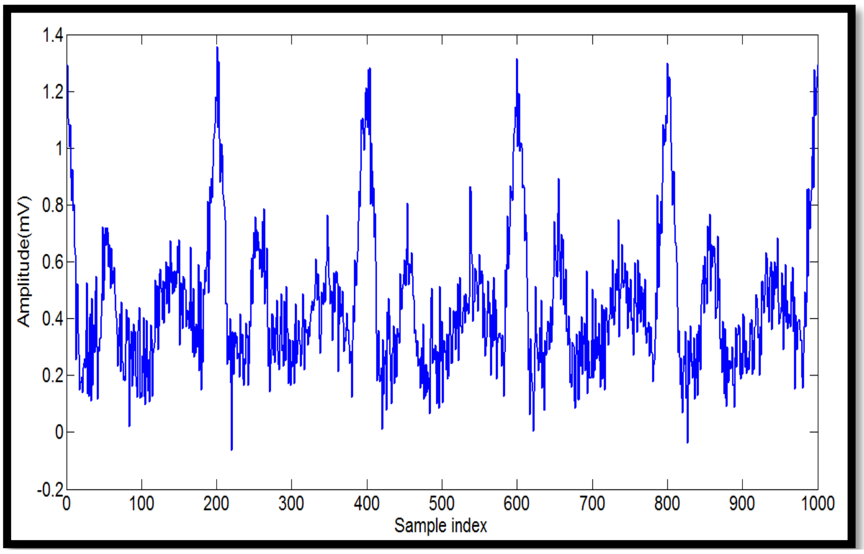

Figure 4.11 ECG signal after passing through WBAN channel

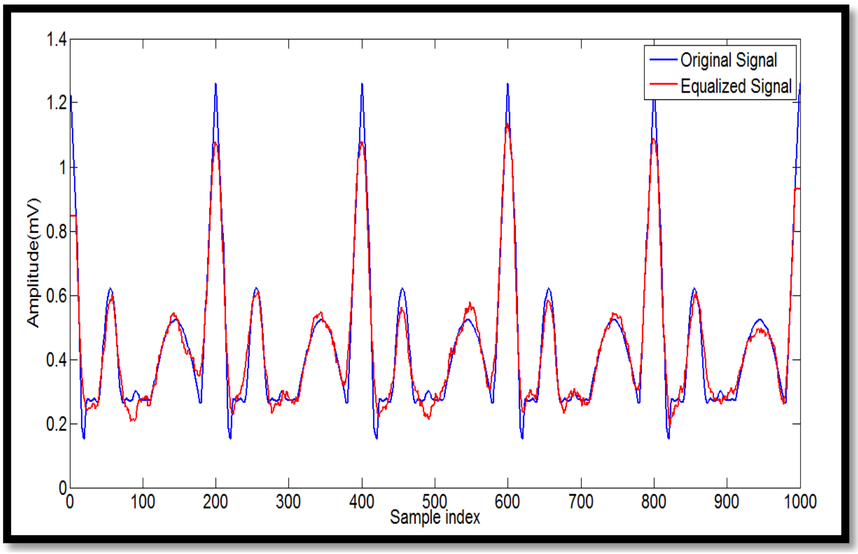

Figure 4.12 Equalized ECG signal

Figure 4.10 represents the original ECG signal for 1000 samples collected from MIT-BIH database.

Figure 4.11 represents the distorted ECG signal after the original signal has been passed through WBAN channel (CM4). ECG parameters such as P wave, QRS complex etc. cannot be extracted due to channel effect.

In ECG, the frequency of the P waves is used to indicate the atrial rate by and the frequency of the QRS complexes helps to calculate the ventricular rate.

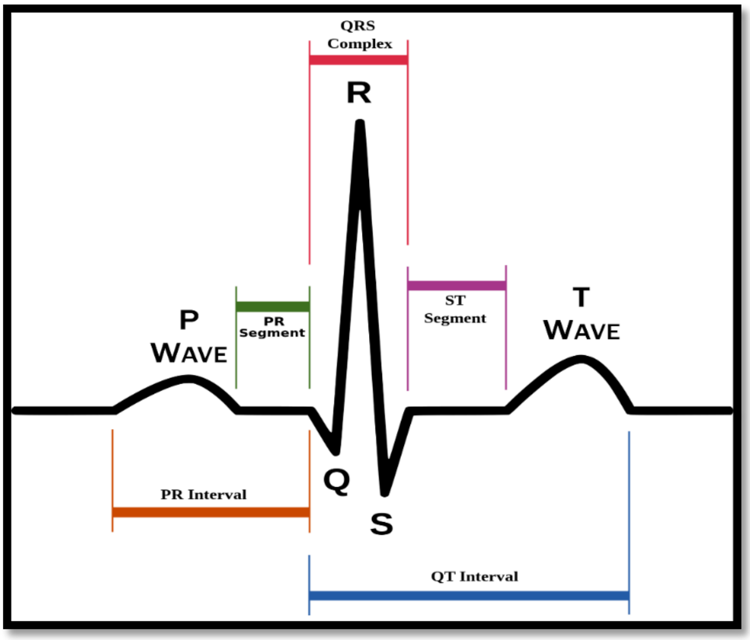

Figure 4.13 ECG signal

Figure 4.12 represents the equalized ECG signal using SD technique with BER~ 10^{-4} for SNR=12 dB. From equalized ECG signal, major parameters related to ECG (P wave, QRS complex etc.) can be easily extracted.

5

Conclusion and Future Scope of Research

5.1 Conclusion

WBAN is widely used in the patient monitoring system and hence proper reception of the transmitted signal is very necessary.Buttransmission of patient's health information is done using digital communication system and due to time dispersive nature of communication channel, the transmitted data gets distorted. There are multiple wireless devices on the human body, hence multiple access interference also occurs.

So, equalization of the distorted signal at the receiver of a communication system is crucial. In this work, we have implemented an efficient method to mitigate interference for UWB/MIMO WBAN system using theorthogonal complete complementary (OCC) code as the spreading code at the transmitter end and various equalization techniques at the receiver end. OCC code helps in reducing the effect of multiple access interference in multi device environment. Equalization techniques are used to compensate the effect of multipath fading, ISI and channel interference.

From the results obtained after simulation, it can be inferred that the system performance can be improved using OCC code as the spreading code and ML (Maximum Likelihood) as the equalization technique. But the complexity of the system increases.

To reduce the computational complexity of the WBAN system, Sphere Decoding (SD) Algorithm can be implemented at the receiver end. Sphere Decodingperforms the same as that of Maximum Likelihood method, but the complexity is greatly reduced. With proper choice of initial radius in the process of SD algorithm, the system performance has been enhanced.

The performance of the proposed receiver design has been validated using biological signals i.e. ECG signal and Blood Pressure signals.

5.2 Future Scope of Research

The work done in this thesis can be extended further for various other equalization techniques. Performance can be enhanced using other spreading codes for the UWB system. The system model can be further extended for a greater number of transmitting and receiving antennas. The number of devices in multi device environment also can be increased.

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Online Resources

1. www.wikipedia.org
2. www.google.com- Search Engine for data and images.

Dissemination

Rati Dilipkumar Jalan, Deepak Kumar Rout and Susmita Das, **"Performance Enhancement of MIMO/UWB based Wireless Body Area Network,"** *IEEE Global Conference on Communication Technologies (GCCT'15),* Kanyakumari 23rd - 24th April 2015.