SIMULATION STUDY OF MMSE AND ZF RECEIVER TECHNIQUES IN MIMO SYSTEM

Submitted in partial fulfilment of the

requirements for award of the degree of

Master of Technology

In

Communication System Engineering

Submitted by

DEEPAK KUMAR (19092031)

Under the guidance of

DR. MANOJ KUMAR SINGH

Department of Electronics Engineering

INDIAN INSTITUTE OF TECHNOLOGY (BHU)

Varanasi, Uttar Pradesh, India -221005

Certificate

This is certify that this project title **"SIMULATION STUDY OF MMSE AND ZF RECIEVER TECHNIQUES IN MIMO SYSTEM"** submitted by Deepak Kumar (Roll number:- 19092031), to the Department of Electronics and Telecommunication Department, Indian Institute of Technology (Bharat Hindu University), Varanasi, in partial fulfillment of the requirements for the reward of the degree **"Master of Technology"** in Electronics Engineering (**Communication System Engineering**) is an authentic work carried out at the Department Of Electronics Engineering, Indian Institute of Technology (Bharat Hindu University), Varanasi, by him under my supervision and guidance on the concept vide project grant as acknowledged.

Supervisor Name   Head of Department

(M.K. Singh)

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis : SIMULATION STUDY OF MMSE AND ZF RECIEVER TECHNIQUES IN MIMO SYSTEM

Name of the Student: Deepak Kumar

Copyright Transfer

This under designed hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exists in and for above thesis submitted for the award of the "Master of Technology".

Place: ________________ Signature of Student: __________________

DECLARATION

I hereby declare that the work presented in this thesis titled **"SIMULATION STUDY OF MMSE AND ZF RECIEVER TECHNIQUES IN MIMO SYSTEM"** is an authentic record of my own work carried out at the Department of Electronics and Telecommunication Department, Indian Institute of Technology (Bharat Hindu University), Varanasi, as the requirements for the reward of the degree of Master of Technology in in Electronics Engineering (Communication System Engineering) submitted in the Indian Institute of Technology (Bharat Hindu University), Varanasi, under the supervision of M.K.Singh, Department of Electronics and Telecommunication Department, Indian Institute of Technology (Bharat Hindu University), Varanasi. It does not contain any part of work, which has been submitted for the award of any degree without proper citation.

Deepak Kumar (19092031)
M.Tech (Communication System Engineering)
IIT BHU (Varanasi)

Dedicated

To

My Parents, Teachers

and Friends

Acknowledgments

First and foremost, I wish to express my deep sense of gratitude of my supervisor Prof. M.K Singh, Department of Electronics Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi for his guidance, advice and encouragement. The kind of confidence and firm belief that he had bestowed upon me and the amount of patience and the endurance he had, cannot be adequately expressed. The various values that I have tried to learn from him shall remain a source of inspiration for forever.

I am also indebted to all the faculty members of Department of Electronics Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi for the deep insights and discernment given through the various courses they had taught.

Above all, it was my family and friends who gave me endless support and provided me with opportunity to reach this far with my studies. Their constant encouragement has always help me to walk over all the hurdles. It is just not possible to express my gratitude and indebtedness towards them in words.

Finally I thank everyone who made this work possible and my experience enjoyable and delightful.

Abstract

After a few decades of evolution of wireless communication systems, engineers are still facing the challenge of ensuring reliable high-speed communication over unreliable wireless channels. The multiple antennas at transmitter side and receiver side, known as multiple-input-multiple-output (MIMO) communications, is a very good technology delivering better wireless service. In wireless communications, the presence of multiple antennas for both way transmission is the performance gain of fundamental nature. One such gain system from the special-multiplexing capabilities of wireless MIMO systems.

The main goal of this thesis to study the performance of different receiver techniques in between for wireless MIMO communication systems. The Optimal maximum likelihood (ML) receiver result in optimal performance but has a prohibitively high computational complexity, its complexity increases exponentially with the number of transmitting antennas. We considered zero-forcing (ZF), minimum mean square error (MMSE), and successive interference cancellation (SIC) receiver, which is sub-optimal in error rate performance but has a linear computational complexity that is affordable in practice. Along with this linear-complexity sub-optimal receiver, we study the performance of a recently proposed liner-regression of minimum mean square error (MMSE) residual (LRR) receiver through Monte Carlo simulation. Further this in receiver technique is extended to Z-F, MMSC, ZF-SIC, and MMSE-SIC receivers.

In this project, we consider RF jamming of a MIMO system and evaluate the performance of multi-antenna receiver technique for minimizing the effect of jamming.

We have study the usefulness of ZF-LRR receiver to cancel the jamming signal and evaluates the performance of this receiver under jamming.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

In past, basic method of communication is sign and sound through moving hands and voice. Later for slightly more distance communication people start using drums, smoke signal, and flags. But later the technologies advance and people start using electromagnetic spectrum and antennas for communication.

1.1 Background

1.1.1 The wireless communication system

High data rate in wireless communication is interest in emerging wireless (LAN) Local area networks and next-generation wireless systems. Designing high-speed communication systems so that they can support reliable transmission over wireless channels constitutes a significant research and engineering challenge. The use of multiple is transmitter and receiver commonly referred to as multiple-input-multiple-output (MIMO) communications, is one promising technology delivering high data rate wireless service with higher reliability [1].

Wireless communication is the transmission of information from one place to another place without using any wires or cables. In a wireless system, the signal can reach direct, reflected, and scattered paths as shown in figure 1. So at the wireless receiver, there is the interference of signal received over these multiple propagation paths, which is termed as multiple interferences, due to which the received signal strength fluctuates at the receiver. This variation in received signal power is called fading. So, compared with wireline communication, one major impairment for wireless communication systems is a time-varying channel with possible multipath fading, shadowing path loss, interference, and so on. This may lead to severe performance degradation. One effective way to combat fading channels is to use the so-called diversity techniques, in which multiple replicas of the transmitted signals are sent to the receiver. The commons commonly used diversity techniques include temporal diversity, frequency diversity, and spatial diversity.

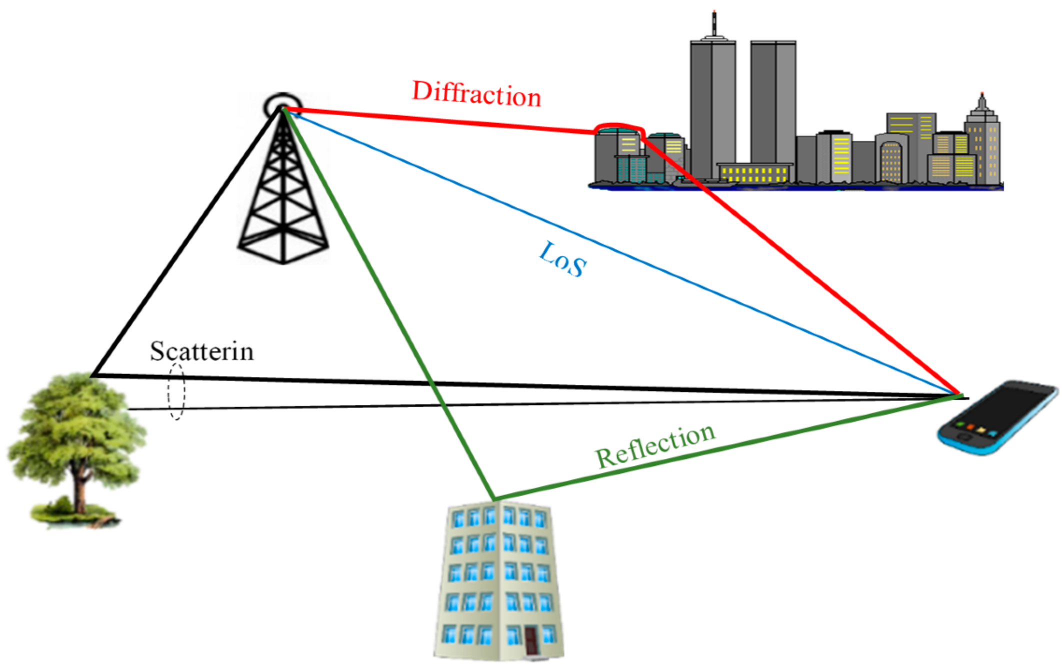

Figure 1.1 The wireless propagation environment

MIMO communication system can be defined as MIMO system when there is multiple antennas are used at both the source end as well as at the destination end. For example, considering the transmission of the signal through a MIMO system having N transmit antenna, and M receive antennas. Since the signal goes through the M x N independent path, it is possible to achieve the diversity of N x M by appropriately combining this signal. The fading channels may be made advantages for a wireless communication system. By increasing the independent fading path between the transmitter and receiver, the degree of freedom of the whole system is increased as well. If a different degree of freedom is used to transmit different signals, the total data rate can be increased significantly. This is why the MIMO- system can provide much higher spectral efficiency than single-antenna systems.

1.1.2 Basic Model for wireless communication system

Here we would introduce analytical models to analyze the performance of wireless communication systems. For simplicity, we assume that the channel is time invariant channel. We consider a channel with (L) multi-path components. Each path of wireless channel basically has two properties. It delays the signal because of there is an attenuation of the signal due to scattering effects and propagation distance.

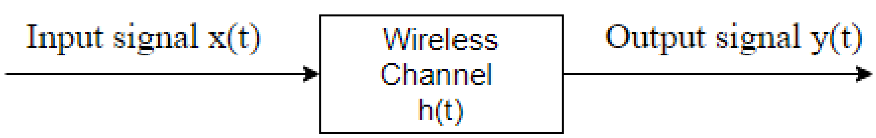

Fig 1.2 Basic Model for Wireless communication system

Figure 1.2 shows the basic model for wireless channel where x(t) is input signal, y(t) is output signal and h(t) is impulse response of wireless channel. Let the a_i and τ_i denotes the signal attenuation and delay of the i^{th} path respectively. We know that the impulse response of a linear time invariant system which delays it by τ_i and attenuates signal by a_i is given as

$$h_i(\tau) = \alpha_i\delta(\tau-\tau_i) \tag{1.1}$$

The above equation (1.1) explain the impulse response of a wireless channel with single path. The wireless channel represent a linear input-output system, since the signal received at the receiver is sum of the different multipath signal copies impinging on the receive antenna. Therefore, a typical channel impulse response (CIR) of a multipath-scattering based wireless channel is given by the sum of the impulse response corresponding to the individual paths[1],

$$h(\tau) = \sum_{i=0}^{L-1} a_i\, \delta(\tau - \tau_i) \tag{1.2}$$

This channel model is called the taped delay-line model because of the nature of the arrival of several progressively delayed components of the signal [1]. We can observe that the above wireless channel model consists of L propagation paths arising from the several reflection and scattering multipath non-line-of-sight (NLOS) components. One of the multipath components an also be a direct line-of-sight (LOS) components [1]. Each such i_{th} path is characterized by three parameters:

1. The attenuation factor- a_i

2. The path delay-τ_i

The above wireless system is a linear time-invarient (LTI) system, so the received signal y(t) can be expressed ass convolution of transmitted signal x(t) with the CIR h(t).

$$y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} h(\tau)x(t-\tau)d\tau \tag{1.3}$$

1.2 MIMO Systems

1.2.1 MIMO (Multiple Input Multiple Output)

MIMO (Multiple Input Multiple Output), also known as space-time communication, system which refers to communication system which consists of multiple antennas at the transmitter and also at the receiver end. MIMO communication systems can be defined by considering that multiple antennas are used at both the source end (Transmitter) as well as at the destination end (Receiver). The antennas at both end of the communication link minimize the probability of bit errors and optimize the data speed. MIMO gives us reliable high speed and data rate communication over different types of wireless channels.

A transmitter antenna transduces electrical signals into electromagnetic waves that propagate in air (space). The receiver antenna transduces that electromagnetic waves into an electrical signal. Antennas that are insensitive to the arrival/departure direction of the waves are called Omni-directional or isotropic antenna and which are sensitive to the arrival/departure direction of the wave are called directional antenna.

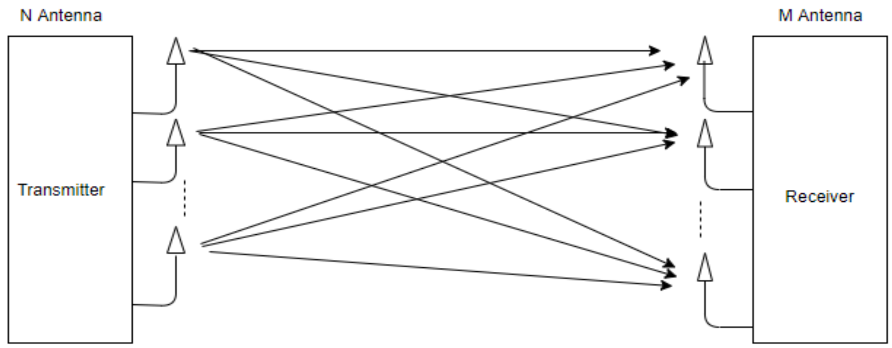

Figure 1.3 MIMO communication system

MIMO makes antenna work smarter enabling them to merge data streams arriving from a different path and at a different time so that the performance of the receiver gets increased. A typical MIMO model having an N transmitting antenna and M receiving antenna is shown in figure 1.

The capacity of an M x N MIMO system, at high SNRs, can be expressed as [4]:

$$C = Blog_2(1 + \min\{M, N\}SNR)\frac{bit}{sec}/Hz \tag{1.13}$$

Where C is capacity of the system and B is bandwidth of the system.

1.2.2 Performance gains of MIMO systems

There are 2 fundamental performance gains of using multiple antennas for communication over fading channels:

- Diversity gain:- It is defined as amount of the transmission power can be reduced ,after introducing a diversity scheme ,without loss in performance. In simple words “It is the increase in signal-to-interference ratio”.

- Multiplexing gain:- when antenna transmitting different streams (data) from the same source end in different spatial dimensions then this multiplexing gain is achieved. It is also called “degree of freedom gain”.

1.3 Thesis objective

Here we focus on the simulation study the performance of different receiver techniques in between for wireless MIMO communication systems. The Optimal maximum likelihood (ML) receiver result in optimal performance but has a prohibitively high computational complexity, its complexity increases exponentially with the number of transmitting antennas. We considered zero-forcing (ZF), minimum mean square error (MMSE), and successive interference cancellation (SIC) receiver, which is sub-optimal in error rate performance but has a linear computational complexity that is affordable in practice. Along with this linear-complexity sub-optimal receiver, we study the performance of a recently proposed liner-regression of minimum mean square error (MMSE) residual (LRR) receiver through Monte Carlo simulation. Further this in receiver technique is extended to Z-F, MMSC, ZF-SIC, and MMSE-SIC receivers.

In this project, we consider RF jamming of a MIMO system and evaluate the performance of multi-antenna receiver technique for minimizing the effect of jamming.

1.4 Thesis Outline

The remaining thesis is structured in the following manner. Chapter 2 introtroduces to the channel and the receiver techniques we are using for simulation study. Chapter 3 contains the Linear regression (LRR) approach for the following receiver introduces in chapter 2. Chapter 4 contains the jamming scenario and ways to reduces its affect in wireless MIMO transmission.

1.5 Notation

In this thesis we have used various notation:-

Boldface uppercase letters denotes matrices and boldface lowercase denotes vector, a is a scaler. The superscripts $(.)^*$,$(.)^T$ and $(.)^H$ denotes conjugate, transpose and conjugate transpose respectively. $(.)^{-1}$ is the inverse operation. **I** is the Identity matrix. E(.), O(.) and Q(.) denote the expectation operator, order of ,and nearest neighbor quantizer respectively. |**A**| is the determinant of **A** and ||a|| is 2-norm of a vector **a.** $CN(\mu, \sigma^2)$ is the complex Gaussian distribution with μ as its mean and σ^2 as its variance.

CHAPTER 2

MIMO RECEIVERS (SIMULATION PROCESS)

Here, we first explain the maximum-likelihood (ML) detector, which minimizes the probability of vector detection error and can be considered optimal. The rest of the detectors presented in this chapter are designed to offer an approximate solution to ML detection with lower complexity. All the detectors share the idea that the effect of **H** should be explicitly cancelled or undone.

Before reviewing these classical detectors, we establish a way by which we can compare the detector performance. Let each components of x contains independent data and is equi-probably chosen from a finite set X, and so $x \epsilon X^N$. The BER (bit error rate) is the number of bit errors divided by the total number of transferred bits.

2.1 Additive White Gaussian Noise Channel

AWGN is an effective model for the noise generated at the receiver in a communication link. It denotes some specific characteristics:

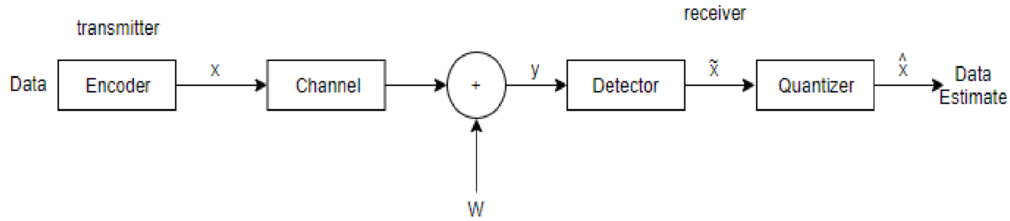

Figure 2.1 An AWGN communication channel

- ***Additive*** :- it means it can added to any noise that may be intrinsic to the information system.
- ***White*** :- It means that it has uniform power across the frequency band for the information system. It is an analogy to the color white which has uniform emissions at all frequencies in the visible spectrum.
- ***Gaussian*** :- It means it has a normal distribution in the time domain with an average time domain value of zero

The received signal in AWGN channel can be expressed as,

$$y = x + w \tag{2.1}$$

where x is transmitted symbol, y denotes the received symbol and w denotes the added AWGN noise.

2.2 ML Detection

With all vector **x** equally likely, the detector which minimizes the probability of detection error vector, i.e., maximizing the probability of correctly estimating **x** is the ML detector[5].

$$\hat{x} = \arg \max_{x \epsilon X^N} f(y|x) \tag{2.2}$$

As the noise is independent of x, uncorrelated and Gaussian, (2) simplifies to the minimum-distance rule, given by

$$\hat{x} = \arg \min_{x \epsilon X^N} ||\boldsymbol{y} - \boldsymbol{Hx}|| \,, \tag{2.3}$$

Thus, The ML detector chooses the message **x** which yields the smallest distance between the received vector **y**, and Hypothesized message **Hx**.

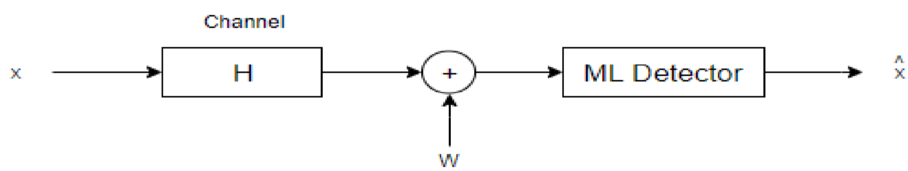

Figure 2.2 Maximum-Likelihood (ML) Detection

2.3 Linear Detection

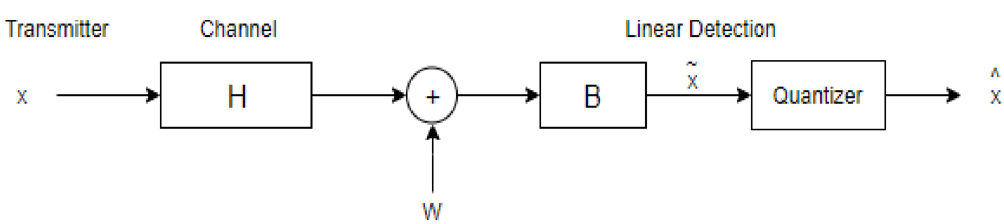

Figure.2.3 Linear Detection

As shown in figure 4 linear detection take the received vector **y** and pre-multiply it by a matrix **B** and the resultant product is, $\tilde{\boldsymbol{x}}$, is passed to a minimum distance symbol-by-symbol detection device to produce $\hat{\boldsymbol{x}}$, an estimate of the transmit vector. The matrix **B** can be optimized by different algorithms. Two of the most popular algorithm are zero-forcing (ZF) and the minimum mean square error (MMSE).

2.3.1 ZF Detector

The ZF algorithm, also known as the interference-nulling algorithm, chooses B to completely eliminate interference in $\tilde{\boldsymbol{x}}$, and invert the frequency response of the channel. The name "Zero forcing "corresponds to bringing down the inter symbol interference (ISI) to zero when there is no noise[6]. This will be useful in ISI is both predominant than noise.

For illustrating the function of ZF receiver, we consider a 2 x 2 MIMO system with uncorrelated Rayleigh fading channels between any pair of transmitting receive antennas,

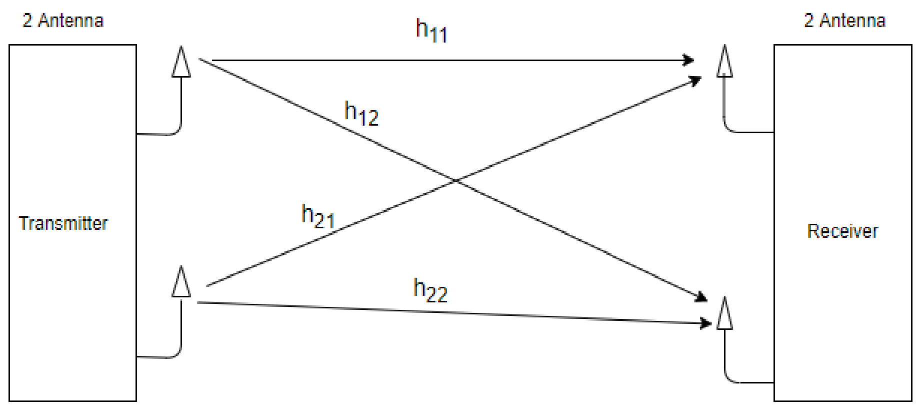

Figure 2.4 2 x 2 MIMO system

The received signal on the first receiving antenna is:

$$y_1 = h_{11}x_1 + h_{12}x_2 + w_1 \tag{2.4}$$

The received signal on the second receiving antenna is:

$$y_2 = h_{21}x_1 + h_{22}x_2 + w_2 \tag{2.5}$$

Where, y_1 and y_2 are the received symbols on the first and second antenna respectively, x_1 and x_2 are the transmitted symbols and w_1 and w_2 denote the noise on the first and second receiver antenna respectively.

h_{ij} , $1 \leq i, j \leq 2$, is the channel from i^th^ transmit antenna to j^th^ receive antenna as shown in Figure . In matrix form received symbol y_1 and y_2 are:

$$\begin{bmatrix} y1 \\ y2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}$$

Therefore, the received vector can be expressed as:

$$\boldsymbol{y} = \boldsymbol{Hx} + \boldsymbol{w} \tag{2.6}$$

Where **y** is received symbol in vector form of order 2 x1, **H** is channel matrix of order 2 x 2, **x** is transmitted symbol vector of order 2 x 1 and **w** is noise vector of order 2 x1. To produce $\tilde{\boldsymbol{x}}$**,** we need to find the equalization matrix **B = $\mathbf{G_{ZF}}$** which satisfy

$\boldsymbol{G_{ZF}H} = \boldsymbol{I}$. The Zero forcing (ZF) detector for meeting this constraint is given by,

$$\boldsymbol{G}_{ZF} = (\boldsymbol{H}^H \boldsymbol{H})^{-1} \boldsymbol{H}^H \tag{2.7}$$

When **H** is not a square matrix, the ZF equalization matrix $\mathbf{G}_{ZF}$ is the Pseudo inverse of **H**. Using $\mathbf{G}_{ZF}$, $\tilde{x}$**,** can be calculated as

$$\tilde{x} = \boldsymbol{G}_{ZF}\boldsymbol{y} \tag{2.8}$$

Now $\tilde{x}$ is quantized to get $\hat{x}$ and we will compare x and $\hat{x}$ to find out the errors.

2.3.2 MMSE Detector

A **minimum mean square error** (**MMSE**) estimator is an estimation method which minimizes the mean square error (MSE), which is a common measure of estimator quality, of the fitted values of a dependent variable. In the Bayesian setting, the term MMSE more specifically refers to estimation with quadratic loss function. In such case, the MMSE estimator is given by the posterior mean of the parameter to be estimated. Since the posterior mean is cumbersome to calculate, the form of the MMSE estimator is usually constrained to be within a certain class of functions. Linear MMSE estimators are a popular choice since they are easy to use, easy to calculate, and very versatile.

MMSE criterion to choose B to minimize the variance of $\tilde{x} - x$ [6].

$$E\{[Gy - x][Gy - x]^H\}$$

So, MMSE receiver is given by

$$G_{mmse} = \arg\min_{G} E[||x - Gy||^2] \tag{2.9}$$

Where we assume that the entries of x are choosen i.i.d uniform over the input constellation. On solving Eq.(2.11) we get following equation [7].

$$G_{mmse} = (H^H H + \frac{\sigma^2}{E_s} I)^{-1} H^H \tag{2.10}$$

Where σ^2 is the variance of the additive Gaussian noise and E_s is the average symbol energy. Comaprison Eq. (2.9) and Eq. (2.12) we can see that, when there is no noise, i.e., when $\sigma^2 = 0$, the MMSE receiver gets reduced to ZF receiver.

2.3.3 Flowchart of MMSE, ZF Simulation

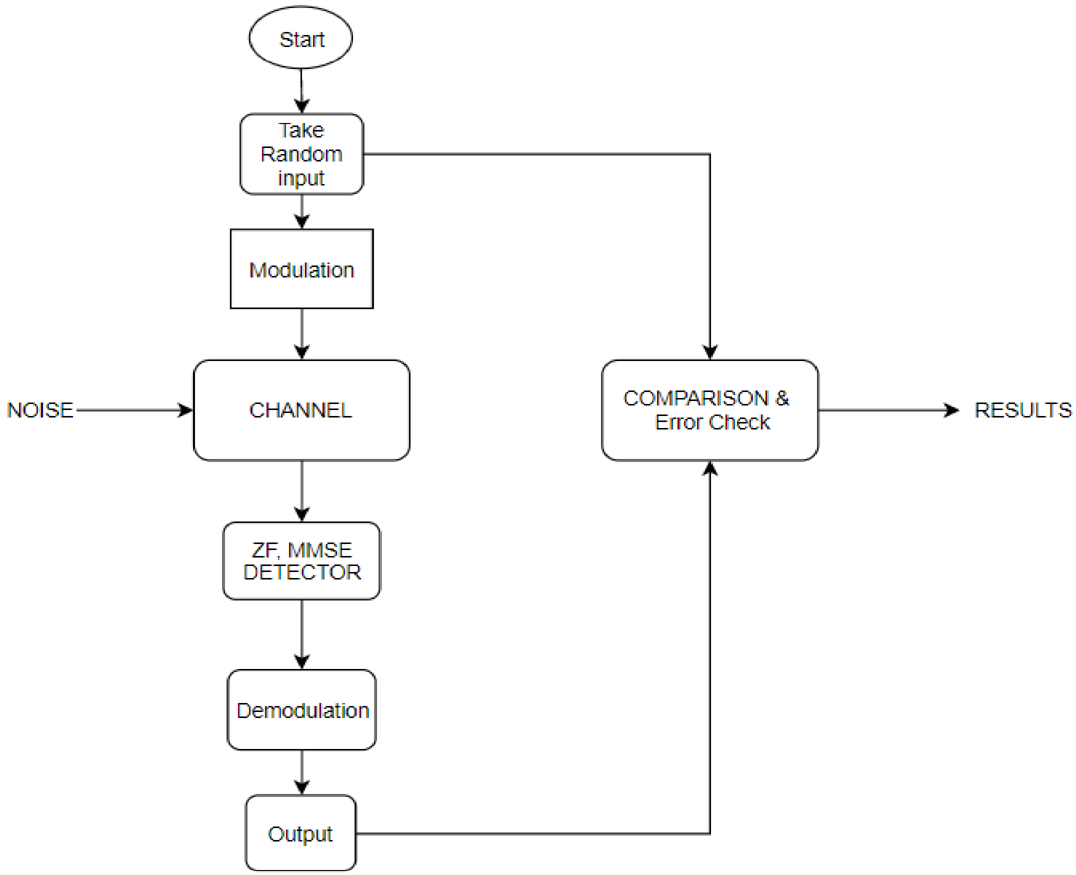

Figure 2.5 Flowchart of ZF, MMSE receiver simulation

Here in Flowchart we see the Simulation process of using ZF, MMSE receiver as describe as follows:-

i) First, we take random generated inputs (actual data) and then we modulate actual data via QPSK or 4-QAM modulation technique.

ii) After modulation it can be send to the channel via multiple antenna at different places.

iii) In Channel, Noise is added and then that signal is received by the receiving antenna.

iv) After receiving the signal at receiver the following Detector uses following step:-

For ZF Detector:-Using equation 2.6, 2.7, 2.8 we detect the incoming signal.

For MMSE Detector:-Using equation 2.9, 2.10 we detect the incoming signal.

v) After detection of signal, we demodulate the signal and the compare with the actual data.

vi) After Comparison we plot the Bit Error Rate of the output signal.

2.4 SIC Detector

Successive interference cancellation (SIC) is a promising detection technique for improving the performance at the receiving end with relatively small additional complexity [8].The Idea of SIC is to detect different messages sequencially, i.e., the interference due to a message is subtracted before detecting other users messages.

2.4.1 ZF with Successive Interference Cancellation (ZF-SIC)

Using the ZF approach discussed in 2.3.1 , for 2 x 2 MIMO system .there we obtain the two transmitted symbol x_1 and x_2 by quantizing $\tilde{x}_1$ and $\tilde{x}_2$. $\tilde{x}_1$ and $\tilde{x}_2$ are given as follows:-

$$\begin{bmatrix}\tilde{x}_1\\ \tilde{x}_2\end{bmatrix} = (H^H H)^{-1} H^H \begin{bmatrix}y_1\\ y_2\end{bmatrix} \tag{2.11}$$

Now after quantizing $\tilde{\boldsymbol{x}}$ we will find $\hat{\boldsymbol{x}}$**.** Now take one of the following estimated symbols (For example $\hat{\boldsymbol{x}}_2$) and subtract its effect from the received vector y having symbols y_1 and y_2 and i.e.,

$$\begin{bmatrix}r_1\\ r_2\end{bmatrix} = \begin{bmatrix}y_1 - h_{12}\hat{x}_1\\ y_2 - h_{22}\hat{x}_2\end{bmatrix} = \begin{bmatrix}h_{11}x_1 + w_1\\ h_{11}x_2 + w_2\end{bmatrix} \tag{2.12}$$

In matrix notation ,

$$\boldsymbol{r} = \mathbf{h}x_1 + \boldsymbol{w} \tag{2.13}$$

The equalized symbol is obtained as $\tilde{x}_1 = (\boldsymbol{h}^H\boldsymbol{h})^{-1}\boldsymbol{h}^H\boldsymbol{r}$ .Now after quantizing $\tilde{x}_1$ we will get $\hat{x}_1$. This is method to find the ZF-SIC Receiver.

2.4.2 MMSE with Successive Interference Cancellation (MMSE-SIC)

Using the MMSE approach discussed in 2.3.2 , for 2 x 2 MIMO system .there we obtain the two transmitted symbol x_1 and x_2 by quantizing $\tilde{x}_1$ and $\tilde{x}_2$. $\tilde{x}_1$ and $\tilde{x}_2$ are given as follows:-

$$\begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} = (H^H H \ + \ \frac{\sigma^2}{E_s} I)^{-1} H^H \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \tag{2.14}$$

Now after quantizing $\tilde{\boldsymbol{x}}$ we will find $\hat{\boldsymbol{x}}$**.** Now take one of the following estimated symbols (For example $\hat{\boldsymbol{x}}_2$) and subtract its effect from the received vector y having symbols y_1 and y_2 and i.e.,

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} y_1 - h_{12}\hat{x}_1 \\ y_2 - h_{22}\hat{x}_2 \end{bmatrix} = \begin{bmatrix} h_{11}x_1 + w_1 \\ h_{11}x_2 + w_2 \end{bmatrix} \tag{2.14}$$

In matrix notation ,

$$\boldsymbol{r} = \mathbf{h}x_1 + \boldsymbol{w} \tag{2.15}$$

The equalized symbol is obtained as $\tilde{x}_1 = (\boldsymbol{h}^H \boldsymbol{h} + \frac{\sigma^2}{E_s} I)^{-1} \boldsymbol{h}^H \boldsymbol{r}$ .Now after quantizing $\tilde{x}_1$ we will get $\hat{x}_1$. This is method to find the MMSE-SIC Receiver.

2.4.3 Flowchart of MMSE-SIC, ZF-SIC Simulation

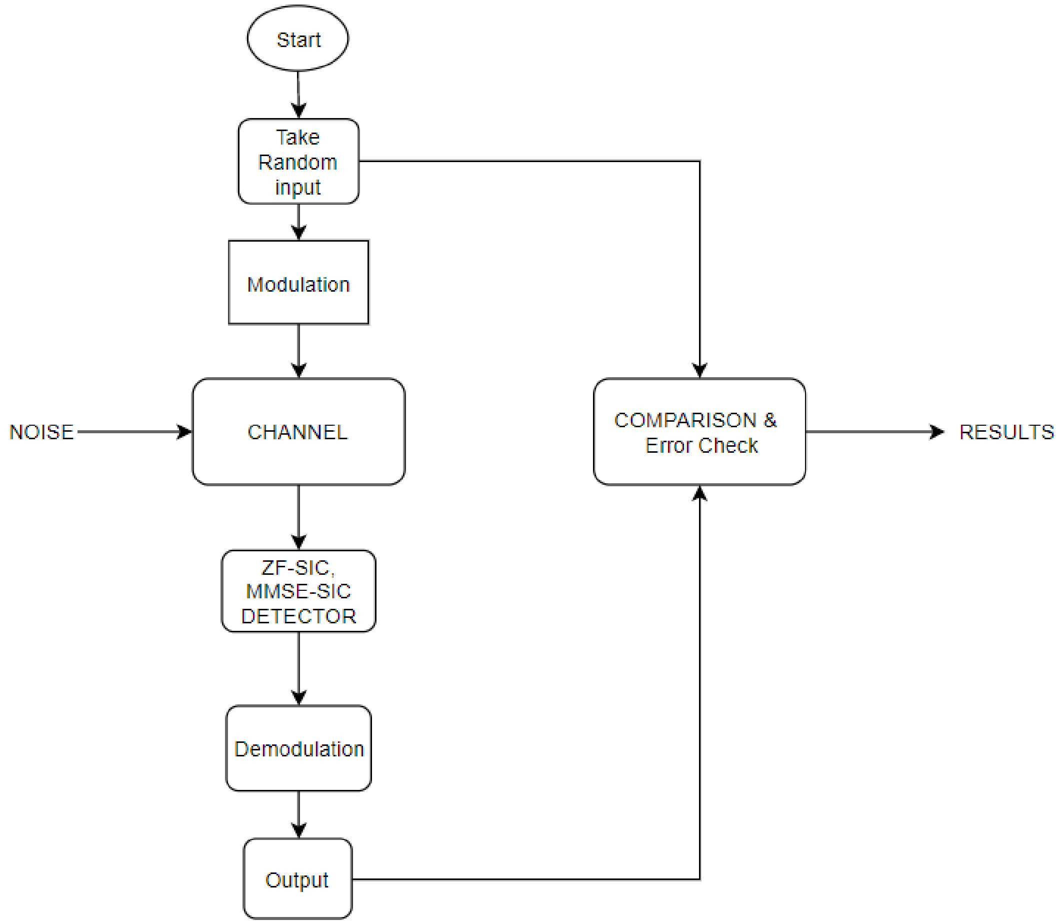

Figure 2.6 Flowchart of ZF-SIC, MMSE-SIC receiver simulation

Here in Flowchart we see the Simulation process of using ZF-SIC, MMSE-SIC receiver as describe as follows:-

i) First, we take random generated inputs (actual data) and then we modulate actual data via QPSK or 4-QAM modulation technique.

ii) After modulation it can be send to the channel via multiple antenna at different places.

iii) In Channel, Noise is added and then that signal is received by the receiving antenna.

iv) After receiving the signal at receiver the following Detector uses following step:-

For ZF-SIC Detector:-Using equation 2.11, 2.12, 2.13 we detect the incoming signal.

For MMSE-SIC Detector:-Using equation 2.14, 2.15 we detect the incoming signal.

v) After detection of signal, we demodulate the signal and the compare with the actual data.

vi) After Comparison we plot the Bit Error Rate of the output signal.

CHAPTER 3

SIMULATION WITH LRR APPROACH

In the implementation of MIMO system receiver we need to detect the transmitted data with low probability of error. For this her we introduces a new receiver called LRR (Linear Regression) model, which improve the detector by learning a linear regression model for the error of the receiver. The LRR receiver uses pilot data to estimate the channel, and then uses locally generated training data (which is not transmitted over the channel), to find the linear regression parameters. The proposed receiver is suitable for applications where the channel remains constant for long period and performs quite a well city. The complexity of the LRR receiver consists of two parts: The complexity of the training phase and the actual phase. We do not consider the complexity of the channel estimation since it is the same for all the receivers. The complexity of the training is incurred only once in every coherence interval, so if the length of the coherence period is large, the effective complexity of the LRR receiver scales similar to that of the MMSE receiver. Hence for large coherence time, the complexity order of the LRR receiver is the same as of the ZF/MMSE receiver.

3.1 MMSE-LRR Detector

The structure of linear regression of MMSE residual is very simple and it consists of two linear filters. The first filter is the conventional MMSE receiver which is used to get the MMSE estimate of transmitted data vector and the second filter then acts on the residual of the MMSE estimate - to obtain a correction vector. The final estimate is just the sum of the MMSE estimate and the correction vector which is the MMSE-LRR receiver. In the receiver, no additional bandwidth is required over the traditional MMSE receiver.

The block diagram of the MMSE-LRR receiver is shown in Figure3.1. Let $x\epsilon\ X^N$.be the vector to be transmitted, where X is the modulation alphabet and N is the number of transmit antenna. For simplicity, we have taken the number of transmit antennas is

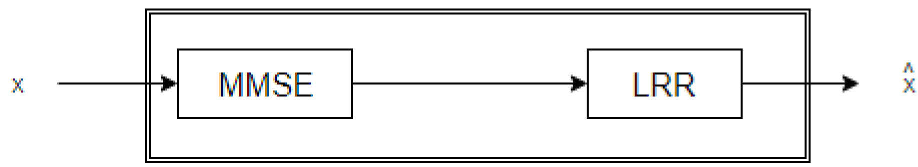

Figure 3.1 MMSE-LRR receiver

the same as the number of receiving antennas, so the received vector is $y\epsilon\ C^N$.The relation between x and y is given by the linear vector channel model as

$$y = Hx + w \tag{3.1}$$

Where the entries of the N x N channel matrix H are modelled as i.i.d with distribution *CN(0 , 1).* The entries of the noise vector w are assumed to be i.i.d . $CN(0, \sigma^2)$. An N x N orthonormal pilot matrix X_{pilot} is sent over the channel with power P and the corresponding output Y_{pilot} is observed. The corresponding MMSE channel estimate is

$$\widehat{H} = \frac{P}{P+\sigma^2} Y_{pilot} X_{pilot}^H \tag{3.2}$$

While the MMSE receiver yields decent performance, it is not optimal, and the error vector $x_e = x - \hat{x}$ is dependent on y. So, further processing of y can lead to an improvement over the MMSE estimate $\hat{x}$ can be found using G_{mmse} as explained in section 2.3.2 and given as

$$\hat{x} = Q(G_{mmse} y) \tag{3.3}$$

If the channel matrix H is known at the receiver, then we can form the residual

$y_e = y - H\hat{x}$, which satisfies

$$y_e = Hx_e + w, \tag{3.4}$$

This relationship between the residual y_e, x_e suggest that we could use linear filter regression again: we can form an estimate $\hat{x}_e = G_{res}y_e$, where G_{res} could again be chosen as per the MMSE criterion. The pseudo-code for LRR (Linear Regression of MMSE residual) receiver is given in the following Algorithm [7]:

Training Phase:

$$\mathbf{X}_T \leftarrow [\boldsymbol{x}_1\boldsymbol{x}_2\cdots\boldsymbol{x}_t\cdots\boldsymbol{x}_T]$$
$$\mathbf{W}_T \leftarrow [\boldsymbol{w}_1\boldsymbol{w}_2\cdots\boldsymbol{w}_t\cdots\boldsymbol{w}_T]$$
$$\mathbf{Y}_T \leftarrow \hat{\mathbf{H}}\mathbf{X}_T + \mathbf{W}_T$$

Find $\mathbf{G}_{mmse}$:

$$\mathbf{G}_{mmse} \leftarrow \left(\hat{\mathbf{H}}^H\hat{\mathbf{H}} + \frac{\sigma^2}{E_s}\mathbf{I}\right)^{-1}\hat{\mathbf{H}}^H$$

$$\widehat{\mathbf{X}}_T \leftarrow \mathcal{Q}(\mathbf{G}_{mmse}\mathbf{Y}_T)$$
$$\widetilde{\mathbf{Y}}_T \leftarrow \mathbf{Y}_T - \hat{\mathbf{H}}\widehat{\mathbf{X}}_T \qquad \widetilde{\mathbf{X}}_T \leftarrow \mathbf{X}_T - \widehat{\mathbf{X}}_T$$

Find $\mathbf{G}_{res}$:

$$\mathbf{G}_{res} \leftarrow \widetilde{\mathbf{X}}_T\widetilde{\mathbf{Y}}_T^H\left(\widetilde{\mathbf{Y}}_T\widetilde{\mathbf{Y}}_T^H\right)^{-1}$$

Detection Phase:

$$\widehat{\boldsymbol{x}}_{mmse} \leftarrow \mathcal{Q}(\mathbf{G}_{mmse}\boldsymbol{y})$$

$$\widetilde{\boldsymbol{y}} \leftarrow \boldsymbol{y} - \widehat{\mathbf{H}}\widehat{\boldsymbol{x}}_{mmse}$$
$$\widehat{\boldsymbol{x}} \leftarrow \mathcal{Q}(\widehat{\boldsymbol{x}}_{mmse} + \mathbf{G}_{res}\widetilde{\boldsymbol{y}})$$

The Training Data $\{X_T, Y_T\} \epsilon \{X^{N\times T} \times C^{N\times T}\}$ are generated at the receiver using the relation :

$$Y_T = \widehat{H} X_T + W_T \tag{3.5}$$

Where T is the length of the Training data, $\widehat{H}$ is the estimate of the channel matrix and W_T , whose entries are i.i.d with zero mean and variance σ^2, is the noise matrix artificially generated at the receiver.

3.2 ZF-LRR Detector

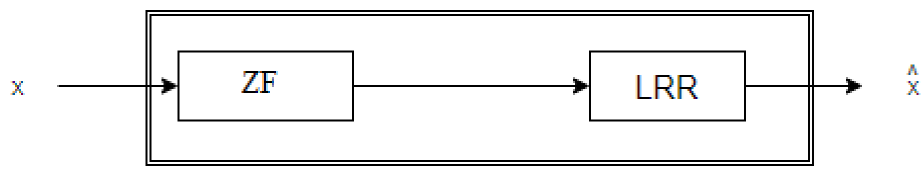

Figure 3.2 ZF-LRR Receiver

The structure of linear regression of ZF residual is very simple and it consists of two linear filters. The first filter is the conventional ZF receiver which is used to get the ZF estimate of transmitted data vector and the second filter then acts on the residual of the ZF estimate - to obtain a correction vector. The final estimate is just the sum of the ZF estimate and the correction vector which is the ZF -LRR receiver. In the receiver, no additional bandwidth is required over the traditional ZF receiver.

This work same as the MMSE-LRR .The difference is that we will use

$$G_{ZF} = (H^H H\,)^{-1} H^H \tag{3.6}$$

Instead of

$$G_{ZF} = (H^H H + \frac{\sigma^2}{E_s} I\ )^{-1} H^H \tag{3.7}$$

3.3 Flowchart of LRR Simulation

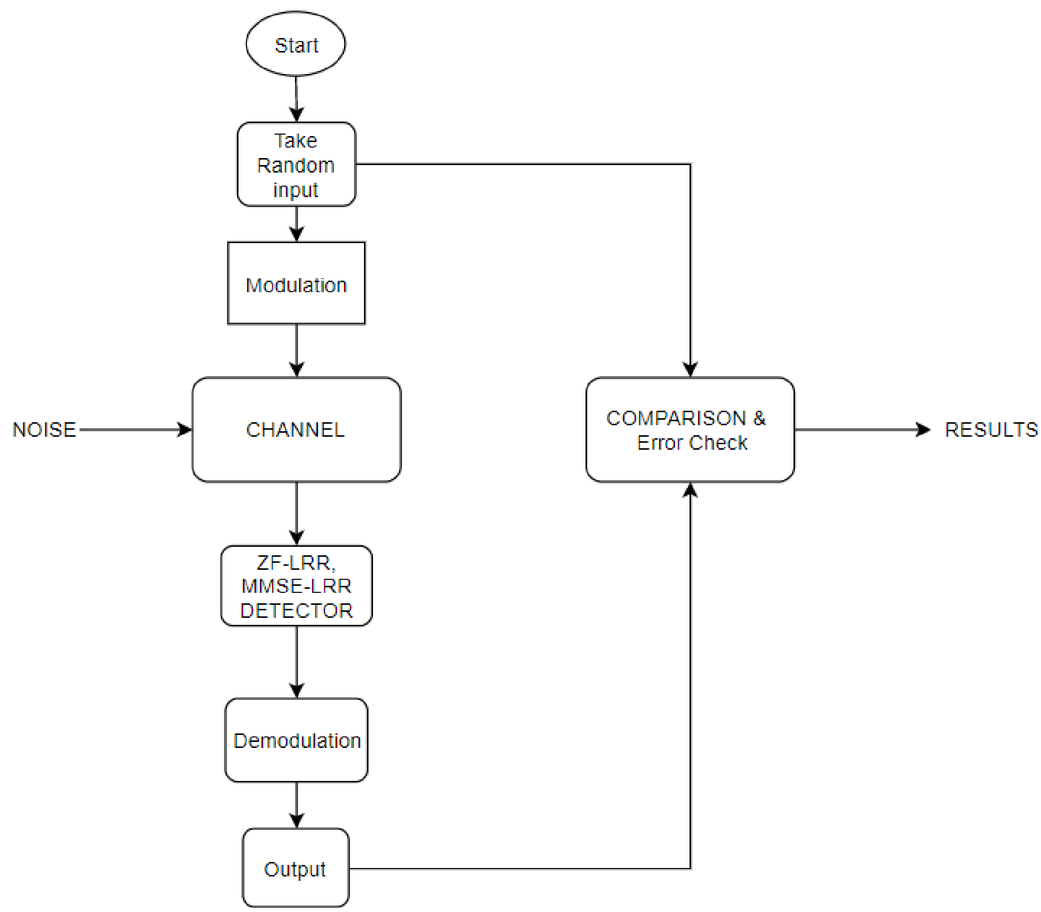

Figure 3.3 Flowchart of ZF-LRR, MMSE-LRR receiver simulation

Here in Flowchart we see the Simulation process of using ZF-LRR, MMSE-LRR receiver as describe as follows:-

i) First, we take random generated inputs (actual data) and then we modulate actual data via QPSK or 4-QAM modulation technique.

ii) After modulation it can be send to the channel via multiple antenna at different places.

iii) In Channel, Noise is added and then that signal is received by the receiving antenna.

iv) After receiving the signal at receiver the following Detector uses following step:-

For ZF-LRR Detector:-Using equation 3.6, 3.7 we detect the incoming signal.

For MMSE-LRR Detector:-Using equation 3.3, 3.4 we detect the incoming signal.

v) After detection of signal, we demodulate the signal and the compare with the actual data.

vi) After comparison we plot the Bit Error Rate of the output signal.

CHAPTER 4

JAMMING

4.1 Introduction

Jamming in wireless networks is defined as the disruption of existing wireless communications by decreasing the signal-to-noise ratio at receiver sides through the transmission of interfering wireless signals[9]. Jamming is different from regular network interferences because it describes the deliberate use of wireless signals in an attempt to disrupt communications whereas interference refer to unintentional forms of disruptions[9]. Unintentional interference may be caused by the wireless communications among nodes within the same networks or other devices (e.g. microwave and remote controller) [9]. On the other hand, intentional interference is usually conducted by an attacker who intends to interrupt or prevent communications in networks[9]. Jamming can be done at different levels, from hindering transmission to distorting packets in legitimate communications[9].

To understand how a jammer attacks wireless networks and how to avoid jamming to achieve efficient communication, we investigate three different aspects of wireless network jamming[9]:

1) Types of existing jammers,

2) Protocols for localizing jammers and

3) Jamming detection and countermeasure.

First, a network can be jammed in various ways using different types of jammers. To avoid jamming in networks, it is important to know how a jammer works. So we discuss in detail different types of jammers, e.g. proactive, reactive, function-specific and hybrid-smart jammers, and the optimal placements of jammers in order to achieve the best jamming affects[9]. Then, we investigate existing technologies for localizing jammers in networks. Finally, we look into how to deal with the jamming problem. This is the most challenging issue where much research has been conducted. For instance, one simple solution is to apply high transmission power on jammed channels rendering this jamming to be less of a threat. Another countermeasure of jamming is to use directional antennas instead of omnidirectional antennas. However, none of existing detection or countermeasure methods can address all types of jammers without giving false alarms[9]. Therefore, more research is required for detecting and avoiding different types of wireless network jamming.

4.2 Cancelling Jamming Signal Through ZF

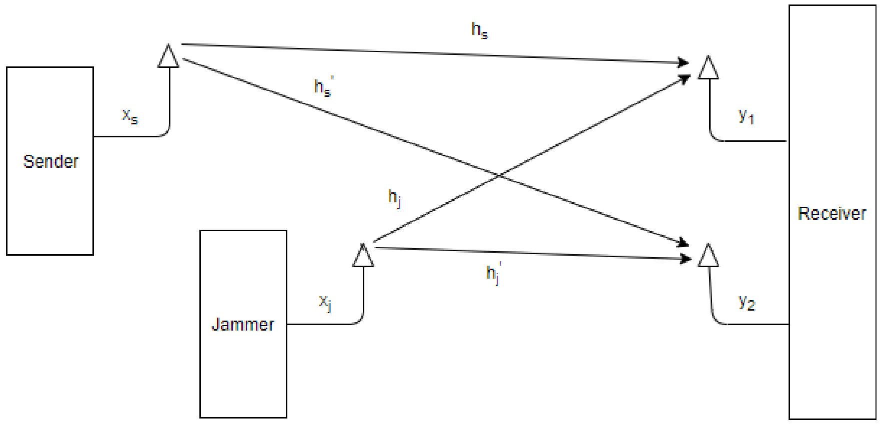

Figure 4.1 1 X 2 MIMO System with Jammer

We consider that sender is transmitted signal antenna and receiver is receiving with two receive antenna. Assuming that the jammer is operating with a single transmitting antenna, we can implement the following scheme for cancelling the jamming signal at the receiver end.

Refer to Figure 4.1 At the receiver, we receive y_1 and y_2, where y_1 is the signal received at the ith receive antenna.

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_s & h_j \\ h_s' & h_j' \end{bmatrix} \begin{bmatrix} x_s \\ x_j \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \tag{4.1}$$

Here x_s is the symbol sent by the sender and x_j is the symbol sent by the jammer, n_i is the additive Gaussian noise at the ith receive antenna of the receiver. $E[|x_s|^2]$ is the average power spent by the sender for the receiver and $E[|x_j|^2]$ is the power transmitted by the jammer. The Eq. (3.1) can be re-written as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_s \\ h_s' \end{bmatrix} x_s + [\begin{matrix} h_j \\ h_j' \end{matrix}] x_j + \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \tag{4.2}$$

After receiving the signal at the receiver, we can cancel the jamming signal by projecting $[y_1 \;\; y_2]^T$ onto the subspace orthogonal to the direction in which the jamming signal x_j has arrived, i.e., $[h_j \;\; h_j']^T$. This is exactly equivalent to what a ZF receiver does. In other words, by implementing the zero-forcing receiver, we can cancel the jamming signal completely. Howevet, the critical point here is that, we need to know the channel matrix at the receiver to implement ZF receiver. Through training symbols, we can estimate channel vector $[h_s \;\; h_s']^T$, but we also need to know the direction of the jammer's channel $[1 \; j\frac{h_j'}{h_j}]^T$, a scaled version of the jammer's channel vector as described below.

4.2.1 Estimating the Direction of Jammer signal

1. We made sender to mute its transmission to the receiver for some time, say(1ms).
2. During the period in which sender is not transmitting, receiver receives only the jamming signal at both antennas, along with the noise n_1 and n_2.
3. As $y_1 = h_j x_j + n_1$ and $y_2 = h_j' x_j + n_2$, $\frac{y_1}{y_2} \approx \frac{h_j}{h_j'}$. Since the noise power would be much lower than the jamming power, so we can neglect the noise in comparison of jamming signal. Thus, we can obtain the vector $[\frac{h_j'}{h_j} \quad 1]^T$,having the same direction as the vector $[h_j \;\; h_j']^T$.
4. If the jammer knows when the sender is going to mute. Then he may also muted during same time, making it impossible to estimate $[h_j \;\; h_j']^T$. So, the sender should randomly mute its transmission for making it difficult for the jammer to know when the sender mutes its transmission. At the same time, the receiver should know when the sender is going to mute so that it can estimate the direction of the jammer's channel.

CHAPTER 5

SIMULATION RESULTS

Different receiver techniques discussed in previous chapters and receiver for anti-jamming discussed in chapter 4. In our simulation, we have chosen length of training sequence, denoted by T, as $T = N^2$.

5.1 MMSE and MMSE-LRR using QPSK

Here we have study about the performance of MMSE and MMSE-LRR receivers with QPSK modulation schemes. The default parameters are as follows:-

Description	Values
Number of Transmit antennas	16
Number of Receive antennas	16
Digital modulation Scheme	QPSK
Number of Training Sequence	256

Table 5.1 Parameters used in simulation of MMSE Vs MMSE-LRR receiver in 16 x 16 MIMO.

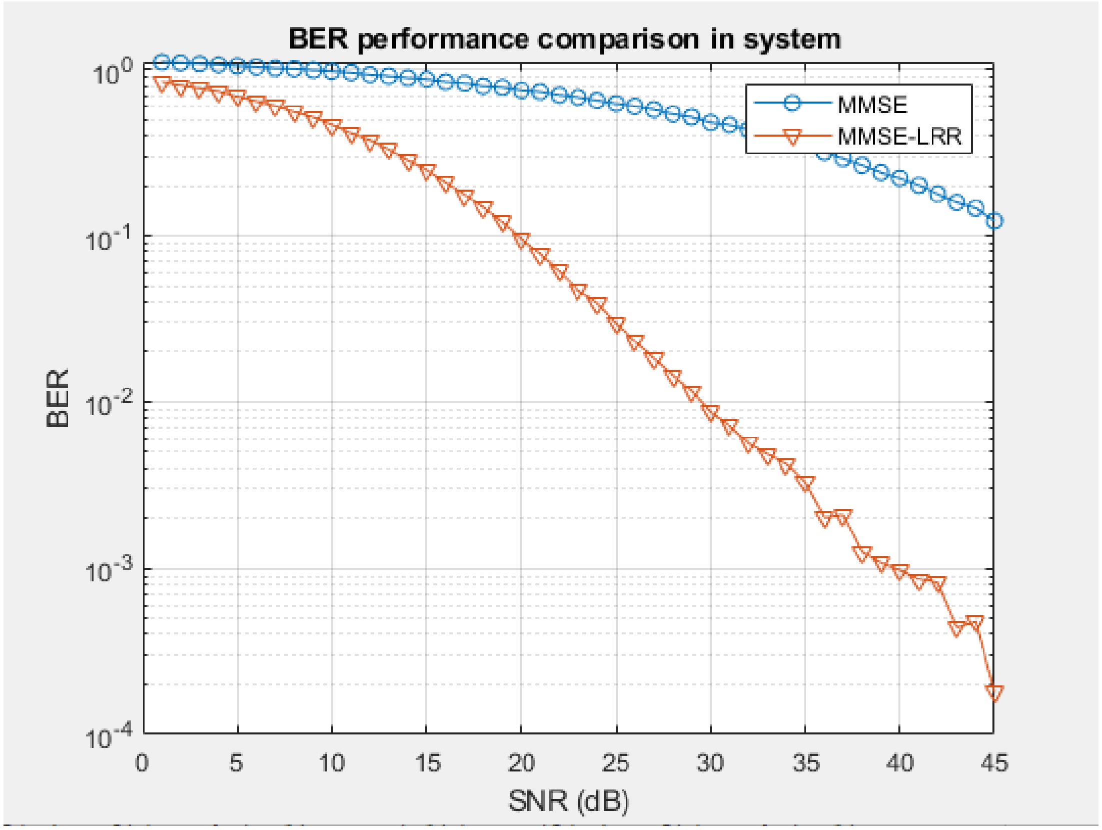

Figure 5.1 BER Performance of MMSE and MMSE-LRR receiver in 16 X 16 with QPSK modulation.

5.2 ZF and ZF-LRR using QPSK

In previous we study about the MMSE vs MMSE-LRR in QPSK modulation scheme. Here we study the comparison of ZF vs ZF-LRR in same Modulation scheme for the given default parameters as follows:-

Description	Values
Number of Transmit antennas	16
Number of Receive antennas	16
Digital modulation Scheme	QPSK
Number of Training Sequence	256

Table 5.2 Parameters used in simulation of ZF Vs ZF-LRR receiver in 16 x 16 MIMO.

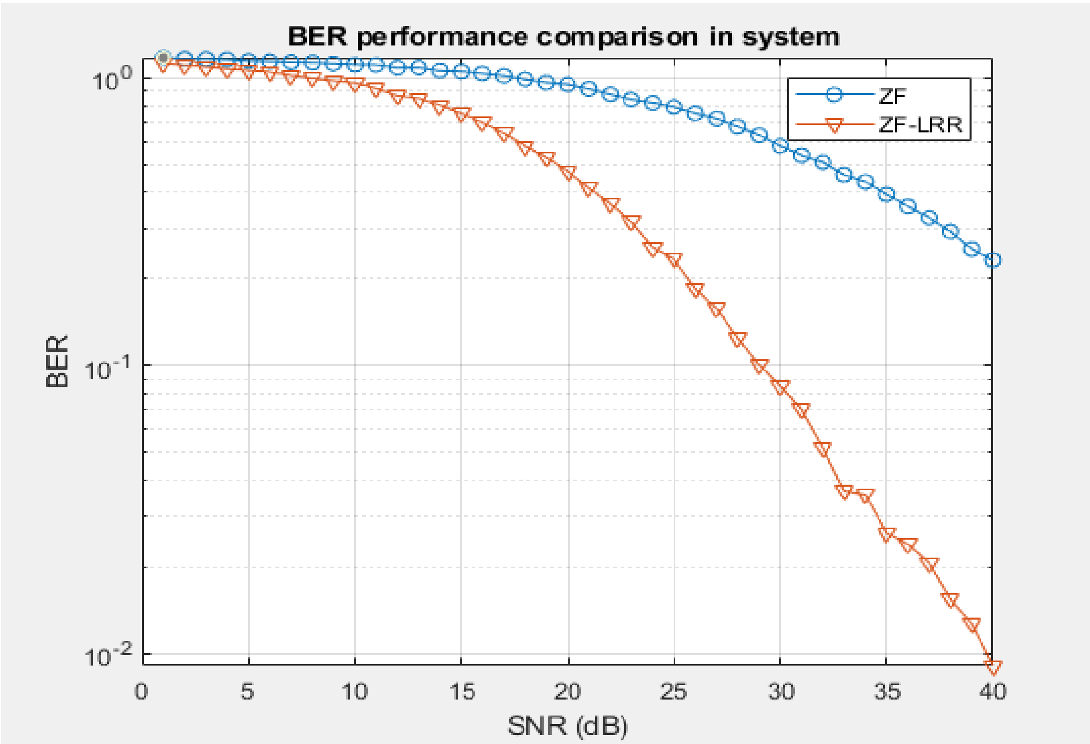

Figure 5.2 BER Performance of ZF and ZF-LRR receiver in 16 X 16 with QPSK modulation.

5.3 MMSE and MMSE-LRR using 16-QAM

Here we have study about the performance of MMSE and MMSE-LRR receivers with QPSK modulation schemes. The default parameters are as follows:-

Description	Values
Number of Transmit antennas	16
Number of Receive antennas	16
Digital modulation Scheme	16-QAM
Number of Training Sequence	256

Table 5.3 Parameters used in simulation of MMSE Vs MMSE-LRR receiver in 16 x 16 MIMO.

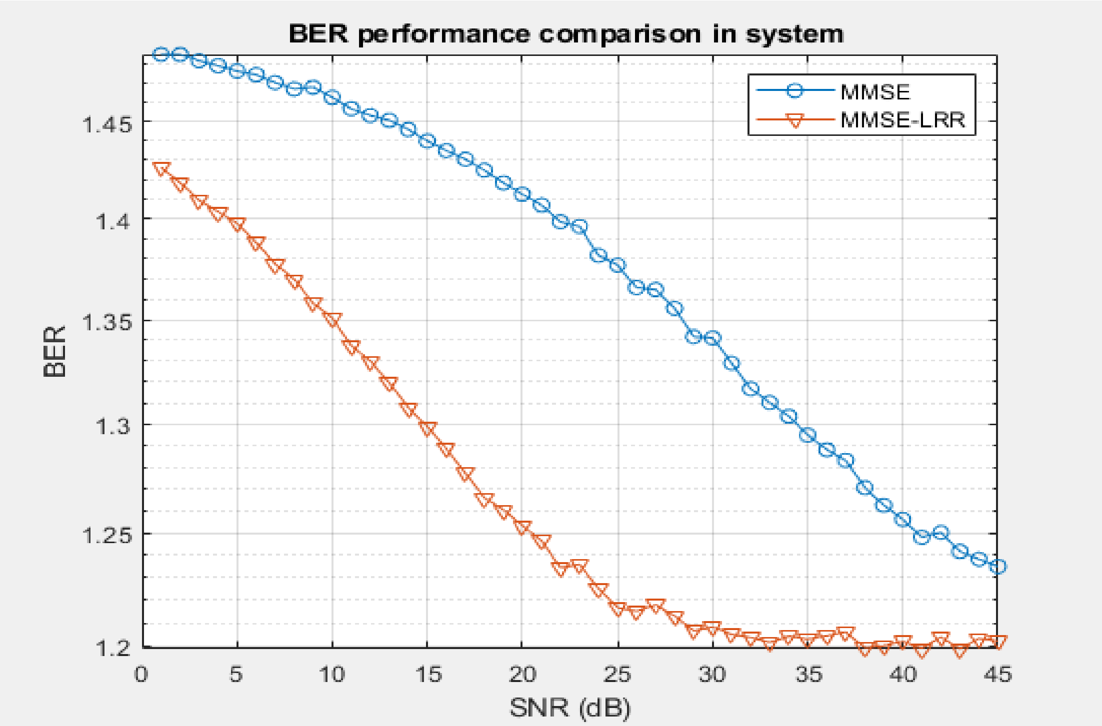

Figure 5.3 BER Performance of MMSE and MMSE-LRR receiver in 16 X 16 with 16-QAM modulation.

5.4 ZF and ZF-LRR using 16-QAM

In previous we study about the MMSE vs MMSE-LRR in QPSK modulation scheme. Here we study the comparison of ZF vs ZF-LRR in same Modulation scheme for the given default parameters as follows:-

Description	Values
Number of Transmit antennas	16
Number of Receive antennas	16
Digital modulation Scheme	16-QAM
Number of Training Sequence	256

Table 5.4 Parameters used in simulation of ZF Vs ZF-LRR receiver in 16 x 16 MIMO.

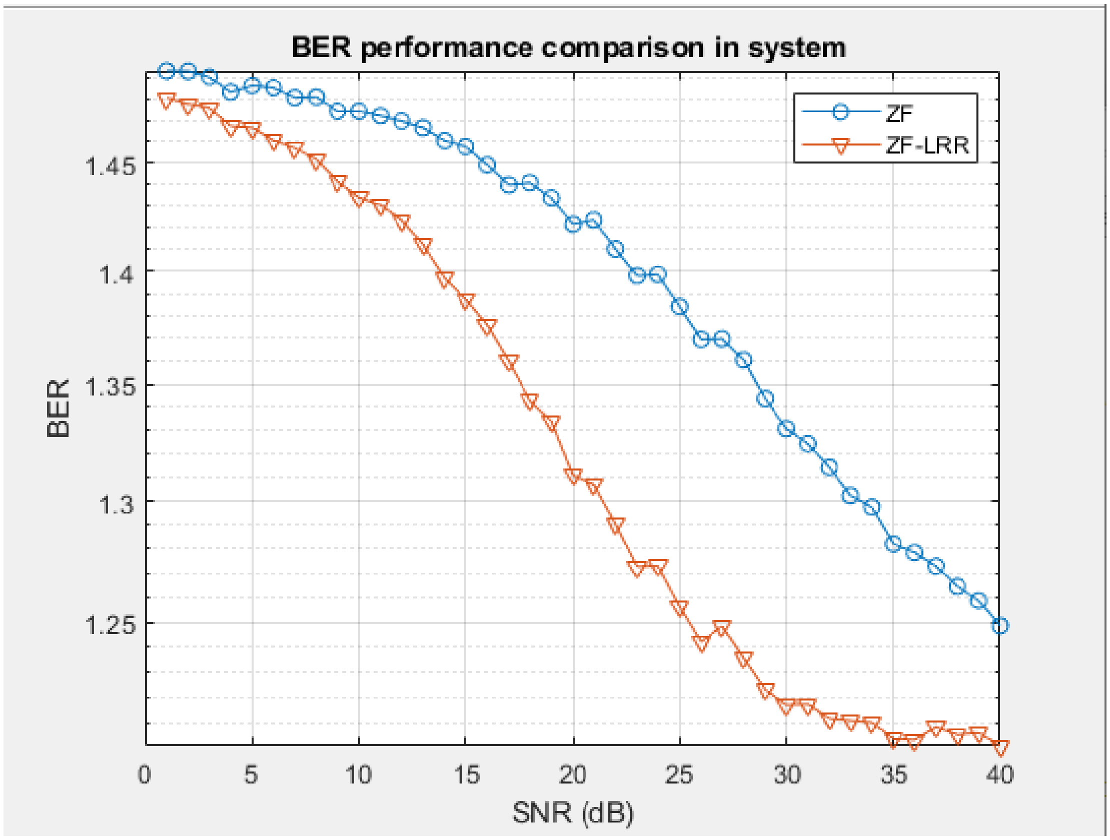

Figure 5.4 BER Performance of ZF and ZF-LRR receiver in 16 X 16 with 16-QAM modulation.

5.5 MMSE, ZF, MMSE-LRR and ZF-LRR

Here we compare all types of receiver at one place with same configuration and see the error rate performance:-

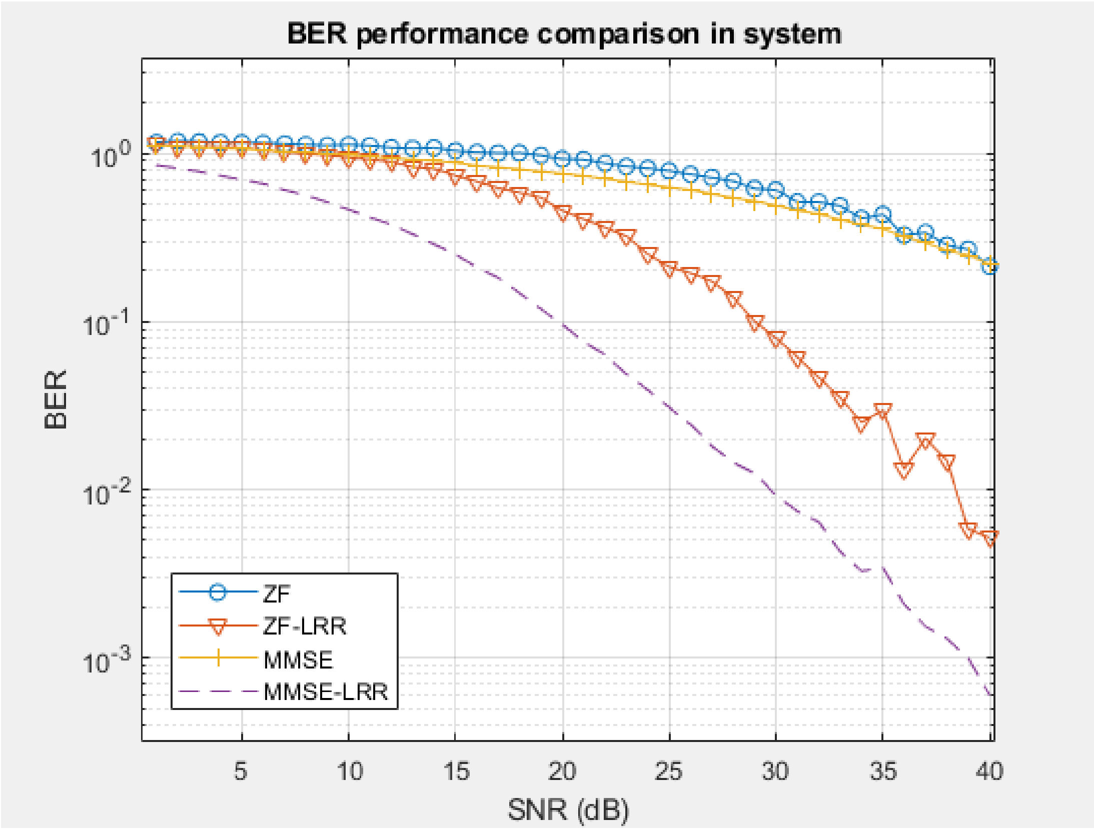

Figure 5.5 BER Performance of ZF, MMSE, MMSE-LRR and ZF-LRR receiver in 16 X 16 with QPSK modulation.

5.6 ML, MMSE-SIC, ZF-SIC

We have studied the performance of ML, MMSE-SIC and ZF-SIC Detection in previous chapters, and here we are comparing the all these detectors with following parameters as follows:-

Description	Values
Number of Transmit antennas	2
Number of Receive antennas	2
Digital modulation Scheme	QPSK

Table 5.5 Parameters used in simulation of MMSE-SIC, ZF-SIC and ML receiver in 16 x 16 MIMO.

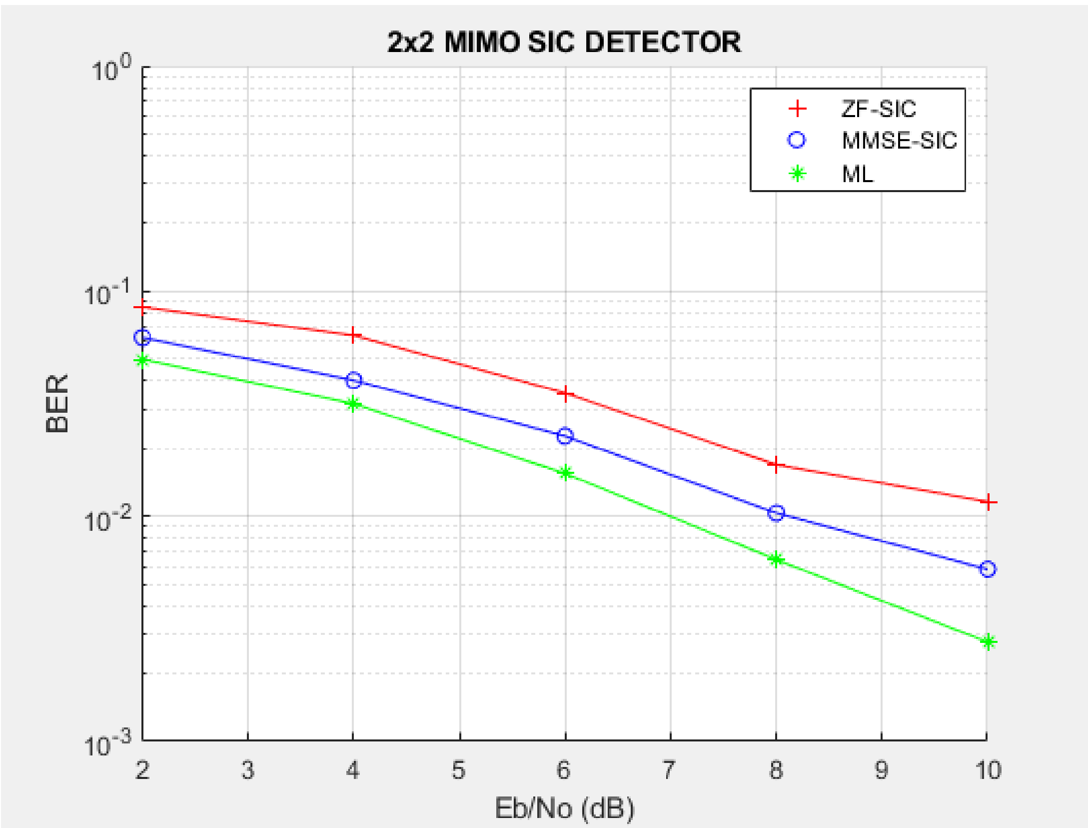

Figure 5.6 BER Performance of ML, MMSE-SIC and ZF-SIC receiver in 2 X 2 with QPSK modulation.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

.

6.1 Conclusion

Here in simulation results, we see that the performance and reliability of LRR receivers increases. Here we see that MMSE receiver perform better than ZF receivers. Among MMSE, ZF MMSE-LRR and ZF-LRR, best performance and reliability is achieved from MMSE-LRR receiver followed by ZF-LRR then MMSE and in last ZF. Here we also see that ZF-LRR performs better than the MMSE.

Even in SIC we see that ML performs better than anyone and the MMSE-SIC performs better than the ZF-SIC. MMSE-SIC bit error performance is better than the ZF-SIC.

6.2 Future Scope

In this project, we have used QPSK and 16-QAM modulation schemes, we can extend this to various modulation schemes like 32-QAM etc. Also we can apply LRR to this modulation schemes and used in various other application.

In jamming scenario, we can are using here only two receive antenna. The described algorithm can be used to receive signal with high reliability if we use more than two antenna.

REFERANCES

[1] Aditya K.Jagannathan,"*Principle of Modern Wireless Communication System* ", McGraw Hill Education (India) Private Limited,2016.

[2] i) https://en.wikipedia.org/wiki/Rayleigh_fading

ii) https://en.wikipedia.org/wiki/Rician_fading

[3] M.Kumar, A. Singh*," Channel capacity comparison of MIMO System with Rician Distribution, Rayliegh Distribution and Nakagami-m*", International Journal Of Engineering Research & Technology (IJRET), vol.2,june 2013.

[4] K.sengar, N.Rani,"*Study of Capacity Evaluation of SISO,MISO and MIMO RF Wireless Communication Systems*", International Journal Of Engineering Trends & Technology (IJETT),vol-9,march 2015.

[5] Upamanyu Madhow University of California, Santa Babara," *Intrduction to Communication System*", January17,2014.

[6] Abhishek Rawat," *A Comparative study of Equalization Techniques for MIMO Systems*", International Journal Of Digital Application & Contemporary research, vol-1, October 2012.

[7] Srinidhi Nagraja, Onkar Dabeer," *Large-MIMO Receiver based on Linear Regression of MMSE Residual*", Department of ECE, Indian Institute of Science,Banglore,India.

[8] X.Zhang and M.Haenggi,” *The Performance of Successive Interferance Cancellation in Random Wireless Networks*”, IEEE Transaction on Information Theeory, vol.60, 2018.

[9] Int. J. Ad Hoc and Ubiquitous Computing,” *Jamming and Anti-jamming Techniques inWireless Networks: A Survey”*.

Appendix A

Matlab Codes

1. Matlab code for ZF and ZF-LRR With QPSK Modulation.

```
clc;clear; close all;
n=16;% number of transmitters
m=16;% number of receivers


Xt=(2*randi([0,1],n,1)-ones(n,1))+sqrt(-1)*(2*randi([0,1],n,1)-ones(n,1)); % Training sequence
SNRrange=1:40;
count=0;
for s=SNRrange
SNRdb=s;
    for monte=1:2000
    x=(2*randi([0,1],n,1)-ones(n,1))+sqrt(-1)*(2*randi([0,1],n,1)-ones(n,1)); % QPSK Modulated input

    sigmas2=2;%signal variance in QPSK
    H=1/sqrt(2*m)*randn(m,n)+sqrt(-1)/sqrt(2*m)*randn(m,n);%Channel matrix
    sigma2=2*n/m*10^(-SNRdb/10); %noise variance in control by SNR in DB
    w=sqrt(2*sigma2)*randn(m,1)+sqrt(-1)*sqrt(2*sigma2)*randn(m,1);% Noise of AWGN Channne
    y=H*x+w; %channel model

     x_zf=(H'*H)^(-1)*H'*y;% simple ZF Detection
     % LRR Approach
     Yt=H*Xt+w;
     X_t=(H'*H)^(-1)*H'*Yt;
     Ye=Yt-H*X_t;
      Xe=Xt-X_t;
      Gr= Xe.*Ye'.*(Ye.*Ye').^(-1);
      y_e= y-H*x_zf;
      x_resd=x_zf+(Gr*y_e);

      x_zf=sign(real(x_zf))+sqrt(-1)*sign(imag(x_zf));
      x_resd=sign(real(x_resd))+sqrt(-1)*sign(imag(x_resd));

     errorLRR(monte)=sum(x~=x_zf);% Checking error
     errorZF(monte)=sum(x~=x_resd);% Checking error
     end
     count=count+1;
berZF(count)=0.1*mean(errorZF);% Checking mean error
berLRR(count)=0.1*mean(errorLRR);% Checking mean error
end
% Plot the BER
figure(2)
semilogy(SNRrange, berZF,'-o',SNRrange, berLRR,'-v');
grid on;
legend( 'ZF','ZF-LRR');
xlabel('SNR (dB)'); ylabel('BER');
title('BER performance comparison in system ');
title('BER performance comparison in system ');
```

2. Matlab code for MMSE and MMSE-LRR With QPSK Modulation

```
clc;clear; close all;
n=16;% # number of transmitters
m=16;% # number of receivers

Xt=(2*randi([0,1],n,1)-ones(n,1))+sqrt(-1)*(2*randi([0,1],n,1)-ones(n,1)); % Training sequence
SNRrange=1:45;
count=0;
for s=SNRrange
SNRdb=s;
    for monte=1:5000
    x=(2*randi([0,1],n,1)-ones(n,1))+sqrt(-1)*(2*randi([0,1],n,1)-ones(n,1)); % QPSK Modulated input

    sigmas2=2;%signal variance in QPSK
    H=1/sqrt(2*m)*randn(m,n)+sqrt(-1)/sqrt(2*m)*randn(m,n); %Channel matrix
    sigma2=2*n/m*10^(-SNRdb/10); % Noise variance in control by SNR in DB
    w=sqrt(2*sigma2)*randn(m,1)+sqrt(-1)*sqrt(2*sigma2)*randn(m,1);% Noise of AWGN Channne
    y=H*x+w; %channel model     1

     x_mmse=(sigma2/sigmas2*eye(n)+H'*H)^(-1)*H'*y;% simple MMSE Detection
     % LRR Approach
     Yt=H*Xt+w;
     X_t=(sigma2/sigmas2*eye(n)+H'*H)^(-1)*H'*Yt;
     Ye=Yt-H*X_t;
     Xe=Xt-X_t;
      Gr= Xe.*Ye'.*(Ye.*Ye').^(-1);
      y_e= y-H*x_mmse;
      x_resd=x_mmse+(Gr*y_e);

      x_mmse=sign(real(x_mmse))+sqrt(-1)*sign(imag(x_mmse));
      x_resd=sign(real(x_resd))+sqrt(-1)*sign(imag(x_resd));

     errorLRR(monte)=sum(x~=x_mmse);% Checking error
     errorMMSE(monte)=sum(x~=x_resd);% Checking error
     end
     count=count+1;

berMMSE(count)=0.1*mean(errorMMSE);% Checking mean error
berLRR(count)=0.1*mean(errorLRR);% Checking mean error
end
% Plot the BER
figure(1)
semilogy(SNRrange, berMMSE,'-o',SNRrange, berLRR,'-v');
grid on;
legend( 'MMSE','MMSE-LRR');
xlabel('SNR (dB)'); ylabel('BER');
title('BER performance comparison in system ');
```

3. Matlab code for ML, ZF-SIC and MMSE-SIC With QPSK Modulation

```
N = 2;                      % Number of transmit antennas
M = 2;                      % Number of receive antennas
EbNoVec = 2:2:10;            % Eb/No in dB
modOrd = 2;                 % constellation size = 2^modOrd

% Create a local random stream to be used by random number generators for
% repeatability.
stream = RandStream('mt19937ar');

% Create PSK modulator and demodulator System objects
pskModulator   = comm.PSKModulator(...
            'ModulationOrder',  2^modOrd, ...
            'PhaseOffset',      0, ...
            'BitInput',         true);
pskDemodulator = comm.PSKDemodulator( ...
            'ModulationOrder',  2^modOrd, ...
            'PhaseOffset',      0, ...
            'BitOutput',        true);

% Create error rate calculation System objects for 3 different receivers
zfBERCalc = comm.ErrorRate;
mmseBERCalc = comm.ErrorRate;
```

```
mmseBERCalc = comm.ErrorRate;
mlBERCalc = comm.ErrorRate;

% Get all bit and symbol combinations for ML receiver
allBits = de2bi(0:2^(modOrd*N)-1, 'left-msb')';
allTxSig = reshape(pskModulator(allBits(:)), N, 2^(modOrd*N));

% Pre-allocate variables to store BER results for speed
[BER_ZF, BER_MMSE, BER_ML] = deal(zeros(length(EbNoVec), 3));
% Set up a figure for visualizing BER results
fig = figure;
grid on;
hold on;
ax = fig.CurrentAxes;
ax.YScale = 'log';
xlim([EbNoVec(1)-0.01 EbNoVec(end)]);
ylim([1e-3 1]);
xlabel('Eb/No (dB)');
ylabel('BER');
fig.NumberTitle = 'off';
fig.Renderer = 'zbuffer';
fig.Name = 'Comparison of SIC Detector ';
```

```matlab
title('2x2 MIMO SIC DETECTOR');
set(fig,'DefaultLegendAutoUpdate','off');

% Loop over selected EbNo points
for idx = 1:length(EbNoVec)
    % Reset error rate calculation System objects
    reset(zfBERCalc);
    reset(mmseBERCalc);
    reset(mlBERCalc);

    % Calculate SNR from EbNo for each independent transmission link
    snrIndB = EbNoVec(idx) + 10*log10(modOrd);
    snrLinear = 10^(0.1*snrIndB);

    while (BER_ZF(idx, 3) < 1e5) && ((BER_MMSE(idx, 2) < 100) || ...
            (BER_ZF(idx, 2) < 100) ||  (BER_ML(idx, 2)   < 100))
        % Create random bit vector to modulate
        msg = randi(stream, [0 1], [N*modOrd, 1]);

        % Modulate data
        txSig = pskModulator(msg);

        % Flat Rayleigh fading channel with independent links
        rayleighChan = (randn(stream, M, N) +  1i*randn(stream, M, N))/sqrt(2);

        % Add noise to faded data
        rxSig = awgn(rayleighChan*txSig, snrIndB, 0, stream);

        % ZF-SIC receiver
        r = rxSig;
        H = rayleighChan; % Assume perfect channel estimation
        % Initialization
        estZF = zeros(N*modOrd, 1);
        orderVec = 1:N;
        k = N+1;
        % Start ZF nulling loop
        for n = 1:N
            % Shrink H to remove the effect of the last decoded symbol
            H = H(:, [1:k-1,k+1:end]);
            % Shrink order vector correspondingly
            orderVec = orderVec(1, [1:k-1,k+1:end]);
            % Select the next symbol to be decoded
            G = (H'*H) \ eye(N-n+1); % Same as inv(H'*H), but faster
            [~, k] = min(diag(G));
            symNum = orderVec(k);

            % Hard decode the selected symbol
            decBits = pskDemodulator(G(k,:) * H' * r);
            estZF(modOrd * (symNum-1) + (1:modOrd)) = decBits;

            % Subtract the effect of the last decoded symbol from r
            if n < N
                r = r - H(:, k) * pskModulator(decBits);
            end
        end

        % MMSE-SIC receiver
        r = rxSig;
        H = rayleighChan;
        % Initialization
        estMMSE = zeros(N*modOrd, 1);
        orderVec = 1:N;
        k = N+1;
        % Start MMSE nulling loop
```

```
        for n = 1:N
            H = H(:, [1:k-1,k+1:end]);
            orderVec = orderVec(1, [1:k-1,k+1:end]);
            % Order algorithm (matrix G calculation) is the only difference
            % with the ZF-SIC receiver
            G = (H'*H + ((N-n+1)/snrLinear)*eye(N-n+1)) \ eye(N-n+1);
            [~, k] = min(diag(G));
            symNum = orderVec(k);

            decBits = pskDemodulator(G(k,:) * H' * r);
            estMMSE(modOrd * (symNum-1) + (1:modOrd)) = decBits;

            if n < N
                r = r - H(:, k) * pskModulator(decBits);
            end
        end

        % ML receiver
        r = rxSig;
        H = rayleighChan;
        [~, k] = min(sum(abs(repmat(r,[1,2^(modOrd*N)]) - H*allTxSig).^2));
        estML = allBits(:,k);

        % Update BER
        BER_ZF(  idx, :) = zfBERCalc(msg, estZF);
        BER_MMSE(idx, :) = mmseBERCalc(msg, estMMSE);
        BER_ML(  idx, :) = mlBERCalc(msg, estML);
    end

    % Plot results
    semilogy(EbNoVec(1:idx), BER_ZF(  1:idx, 1), 'r+', ...
             EbNoVec(1:idx), BER_MMSE(1:idx, 1), 'bo', ...
             EbNoVec(1:idx), BER_ML(  1:idx, 1), 'g*');
    legend('ZF-SIC', 'MMSE-SIC', 'ML');

end

% Draw the lines
semilogy(EbNoVec, BER_ZF(  :, 1), 'r-', ...
         EbNoVec, BER_MMSE(:, 1), 'b-', ...
         EbNoVec, BER_ML(  :, 1), 'g-');

hold off;
```