RV College of Engineering®

Autonomous institution affiliated to Visvesvaraya Technological University, Belagavi)

Approved by AICTE, New Delhi, Accredited by NAAC, Bengaluru.

*Go, change the world*

# Development of MCM-MIMO Processing for Urban Cellular Link

*A Project Report*

**Submitted by,**


**Nagendra Kumar Jamadagni** **1RV17EC083**

**Nischith T.R** **1RV17EC093**


**Under the guidance of**


**Dr. S Ravi Shankar**

Professor

Dept. of ECE

RV College of Engineering


**In partial fulfillment of the requirements for the degree of**

**Bachelor of Engineering in**

**Electronics and Communication Engineering**

**2020-2021**

# RV College of Engineering®, Bengaluru

*(Autonomous institution affiliated to VTU, Belagavi)*

**Department of Electronics and Communication Engineering**

.

## CERTIFICATE

Certified that the minor project work titled ***Development of MCM-MIMO Processing for Urban Cellular Link*** is carried out by **Nagendra Kumar Jamadagni** (**1RV17EC083**) and **Nischith T.R** (**1RV17EC093**) who are bonafide students of RV College of Engineering, Bengaluru, in partial fulfillment of the requirements for the degree of **Bachelor of Engineering** in **Electronics and Communication Engineering** of the Visvesvaraya Technological University, Belagavi during the year 2020-2021. It is certified that all corrections/suggestions indicated for the Internal Assessment have been incorporated in the minor project report deposited in the departmental library. The minor project report has been approved as it satisfies the academic requirements in respect of minor project work prescribed by the institution for the said degree.

| Signature of Guide | Signature of Head of the Department | Signature of Principal |
|---|---|---|
| Dr. S Ravi Shankar | Dr. K S Geetha | Dr. K. N. Subramanya |

# DECLARATION

We, **Nagendra Kumar Jamadagni** , **Nischith T.R** students of seventh semester B.E., Department of Electronics and Communication Engineering, RV College of Engineering, Bengaluru, hereby declare that the minor project titled '**Development of MCM-MIMO Processing for Urban Cellular Link** ' has been carried out by us and submitted in partial fulfilment for the award of degree of **Bachelor of Engineering** in **Electronics and Communication Engineering** during the year 2020-2021.

Further we declare that the content of the dissertation has not been submitted previously by anybody for the award of any degree or diploma to any other university.

We also declare that any Intellectual Property Rights generated out of this project carried out at RVCE will be the property of RV College of Engineering, Bengaluru and we will be one of the authors of the same.

Place: Bengaluru

Date:

| | Name | Signature |
|---|---|---|
| 1. | Nagendra Kumar Jamadagni(1RV17EC083) | |
| 2. | Nischith T.R(1RV17EC093) | |

# ACKNOWLEDGEMENT

We are indebted to our guide, **Dr. S Ravi Shankar**, Professor, RV College of Engineering . for the wholehearted support, suggestions and invaluable advice throughout our project work and also helped in the preparation of this thesis.

We also express our gratitude to our panel members **Dr. S Ravi Shankar**, Professor and **Dr. Shushrutha K.S.**, Associate Professor, Department of Electronics and Communication Engineering for their valuable comments and suggestions during the phase evaluations.

Our sincere thanks to **Dr. K S Geetha**, Professor and Head, Department of Electronics and Communication Engineering, RVCE for the support and encouragement.

We express sincere gratitude to our beloved Principal, **Dr. K. N. Subramanya** for the appreciation towards this project work.

We thank all the teaching staff and technical staff of Electronics and Communication Engineering department, RVCE for their help.

Lastly, we take this opportunity to thank our family members and friends who provided all the backup support throughout the project work.

ABSTRACT

Modern day mobile communication systems rely heavily on Multi Carrier Modulation (MCM) and Multiple Input Multiple Output(MIMO) technologies. The challenges predominantly faced are of maximizing data rates and capacity. We will examine in this report how to overcome these challenges through MCM and MIMO. MIMO however is too broad a term as it consists of various configurations and setups. In this report we examine $2 \times 1$ MISO in diversity mode and $1 \times 2$ SIMO and $2 \times 2$ MIMO in both diversity and multiplexing modes.

In this report, we develop the methodology to use current 4G and future 5G systems in both diversity and multiplexing modes to improve on both data rates and capacities. Theoretically, it is possible to use Single Input Single Output(SISO) systems to achieve the same capacities and data rates. However, the complexities involved in designing modems that are capable of achieving these rates are too cost prohibitive and thus it becomes necessary for us to address this problem through MCM and MIMO.

We design a system which can be operated in two modes, namely diversity and multiplexing. Diversity is suitable for low SNR regimes where Bit Error Rate(BER) could be high, so multiple copies of the same data needs to be sent to maintain a feasible Quality of Service(QoS). Multiplexing is the scheme of choice in high SNR regimes where we have the option of maximizing data rates and capacity by transmitting multiple copies over good channels that are already providing low BER.

We show the simulations of our work with the help of MATLAB. In our results, we show that through an optimal tone loading algorithm we are able to achieve a BER close to zero. As expected we observe that data rates in multiplexing modes are higher (almost doubled) than that of in diversity mode. We also show that by using sufficient precoding methods like Alamouti, Inverse Channel Decomposition and SVD we improve the speed with which our modem is able to transmit and receive data. Through these results, it becomes clear to us that our system could be easily used to improve upon existing 4G and 5G systems to improvise on capacity and data rates.

# CONTENTS

# LIST OF FIGURES

# LIST OF ALGORITHMS

# ABBREVIATIONS

$B_c$ Coherence Bandwidth

$G_r$ Receive Antenna Gain

$G_t$ Transmit Antenna Gain

$T_d$ Delay Spread

$T_g$ Guard Time

**4G** 4th Generation Mobile Systems

**5G** 5th Generation Mobile Systems

**AWGN** Additive White Gaussian Noise

**BER** Bit Error Rate

**BS** Base Station

**DAC** Digital to Analog Converter

**FDM** Frequency Division Multiplexing

**FFT** Fast Fourier Transform

**IFFT** Inverse Fast Fourier Transform

**ISI** Inter Symbol Interference

**ITU** International Telecommunication Union

**LFSR** Linear Feedback Shift Register

**LOS** Line Of Sight

**LTI** Linear Time Invariant

**MCM** Multi Carrier Modulation

**MIMO** Multiple Input Multiple Output

**MISO** Multple Input Single Output

**MLI** Maximum Likelihood Estimator

**NSC** Number of Subchannels

**OFDM** Orthogonal Frequency Division Multiplexing

**OSTBC** Orthogonal Space Time Block Coding

**PAPR** Peak to Average Power Ratio

**PRBS** Pseudo Random Binary Sequence

**QAM** Quadrature Amplitude Modulation

**QoS** Quality of Service

**RF** Radio Frequency

**SIMO** Single Input Multiple Output

**SISO** Single Input Single Output

**SNR** Signal to Noise Ratio

**SVD** Singular Value Decomposition

**UE** User Equipment

# LIST OF TERMS

**cyclic prefix** The redundant bits added to the beginning of an OFDM symbol so that the linear convolution of the symbol can be converted to circular convolution

**MATLAB** A programming language developed by MathWorks that allows for simulations of various algorithms.

**modems** Short for modulator and demodulator

**pilot signal** The signal known both to the transmitter and receiver that is transmitted initially before actual data transmission begins so that the receiver and transmitter can be aware of channel characteristics and also to establish clock synchronization

**Rayleigh fading** A statistical model that is used to measure the loss in power of the transmitted signal over the distance of separation between the transmitter and receiver.

**spatial diversity** The system of sending copies of the same data across multiple spatial paths so as to increase the reliability of receiving the data without errors.

**spatial multiplexing** The system of sending blocks of different data bits across multiple spatial paths so as to increase the capacity of the system or the rate of data transfer.

# Chapter 1

# Introduction to Wireless Communication Systems

# CHAPTER 1

# INTRODUCTION TO WIRELESS COMMUNICATION SYSTEMS

We begin this report by providing an introduction to wireless communication systems in general and how the growth of wireless communication has lead to a new information revolution. We look at the motivation behind choosing this topic for our project and the objectives we wish to complete in our chosen field of study. A survey of the literature in this field is provided for the benefit of the reader, so that he/she may be acquainted with the current happenings in the field of mobile communication. Following this, a glimpse into the design methodology is given and the constraints set on the project which define the scope within which our research is applicable.

## 1.1 Introduction

Guglielmo Marconi invented the wireless radio system in 1895, and since then wireless communication has grown to become ubiquitous. As of 2018, there are 5.1 billion unique mobile phone users with this number expected to touch 5.8 billion between 2018-2025. [1]. In all this time, the basic components of a wireless communication systems have remained the same as shown in Figure. 1.1

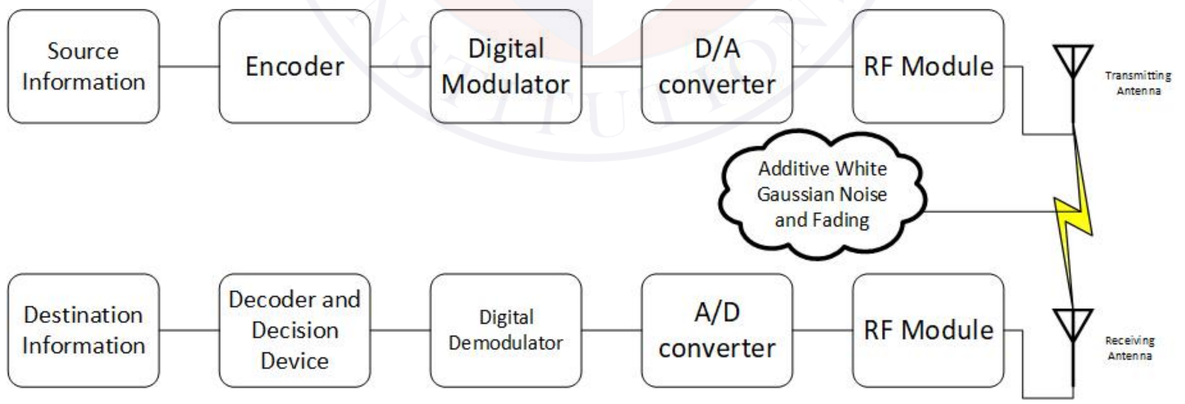



Figure 1.1: Wireless Digital Communication System

In further chapters we discuss the various components of this system and the different techniques we used in implementing them in MATLAB. In this report we are only concerned with the digital aspects of the system and we do not pay much attention to the antenna parameters which can have a significant role to play in wireless systems.

## 1.2 Motivation

There is an exponential increase in the number of new mobile users being added every year. Also, there are a host of services available for mobile users which demand high data rates. Video Teleconferencing, Real Time Video Streaming and other such services are some examples. These services coupled with the large number of people subscribing to such services means that there is a requirement for high capacity and high data rate systems.

At present the state of the art MIMO system is only being used in spatial diversity mode which limits the capacity of the mobile system. Hence, it becomes attractive for telecom service providers to use the existing MIMO systems in spatial multiplexing mode as well so that capacity is increased and at the same time maximum possible data rates are achieved for existing channel SNR conditions.

## 1.3 Problem statement

The problem statement which we try to address in this report is the implementation of suitable MIMO models for urban cellular links that can help to increase the capacity of the system.

## 1.4 Objectives

The objectives of the project are

1. To develop an effective channel model for $2 \times 2$ MIMO links
2. To develop an efficient transmitter and receiver supporting MCM and MIMO processing.

## 1.5 Literature Review

### 1.5.1 Multicarrier Systems

The backbone of modern day 4G and 5G systems is the paradigm shift from single-channel systems to multi-carrier systems. We build upon the work of Weinstein and Ebert [2] where they offer a low cost and easy to implement solution with the help of an IFFT and FFT blocks which allows the system designer to use a single modulator rather than a block of modulators for each subchannel. This coupled with multiplexing capabilities of OFDM as discussed by Yiyan Wu and Zou [3] form the foundation upon which our project is based.

### 1.5.2 Modulation and Precoding Schemes

#### Modulation Schemes

Coming to digital modulation schemes available at our disposal, we have decided to use QAM as it is best suited for our purposes. However, to achieve effective higher order QAM constellations we follow in the work of Bellili, Methenni, and Affes [4] to use a recursive algorithm that effectively maps symbols to higher order constellations in a computationally inexpensive manner. This method starts with the basic 4QAM and 8QAM constellations and dynamically creates higher order constellations without the need to save the points in memory.

#### Precoding Schemes

In certain cases, like $2 \times 1$ MISO systems where we choose to go for spatial diversity scheme, we include some precoding measures as suggested by Alamouti [5] so that we can ease the burden on our system and improve overall system performance. Apart from this we also use precoding schemes like inverse channel coders and singular value decomposers as suggested by Klema and Laub [6] as we notice huge improvements in speed by using these methods.

### 1.5.3 Channel Modeling

In terms of modeling the real world channel, we must consider various random processes to accurately define the channel. However, for the sake of simplicity we find it easier to model multipath systems as previously shown by Hanlen and Fu [7] where we place more importance on Rayleigh fading and ignore other effects like those of shadowing. Although, Rayleigh fading is a statistically simple model, it serves us well in showing the effects of fading on data signals while at the same time keeping complexity low. Channel estimation becomes an integral part of wireless systems as it directly correlates with the accuracy of our receiver and thereby our system performance.

Along with modeling fading, we also take into consideration the aspects of noise that the channel adds to our data signal. Similarly as before, we have chosen AWGN type of noise to represent an accurate but simplistic model. In our survey we have noticed that most research scholars stick to a similar approach and we have decided to follow in their footsteps.

### 1.5.4 Transceiver Architecture and Channel Loading Methods

**Transceiver Architecture**

In the design of our transmitter and receiver systems, we have relied upon standards set by the ITU as per their technical document ITU [8]. We build upon the pilot signal generation scheme provided here and suggest an alternative scheme with two $M \times N$ LFSR banks to increase the dynamic range of the PRBS generator by observing the results of Peinado and Fúster-Sabater [9]. We also follow the same ITU [8] standard in designing our transmitter and receiver systems to remain compliant with existing market service providers. The improvisation for the receiver comes in the form of Singular Value Decomposition method as described by Klema and Laub [6]. It is our claim that this method enhances the system performance while reducing complexity making it commercially viable and attractive.

**Channel Loading Methods**

Effective channel loading not only helps users with improving data rates but is also required for service providers to improve spectral efficiency. In our study of the existing literature we found that the method followed by Chow, Cioffi, and Bingham [10] to be effective but unsuitable as it is rate adaptive in nature. Therefore, we drew inspiration from this tone loading algorithm to define our own fine gains algorithm to achieve an effective bit loading scheme. This loading scheme uses directly builds on the seminal work of Shannon [11] and satisfies our requirements well while also being highly optimal.

## 1.6 Brief Methodology of the project

We first begin by developing a Pseudo Random Binary Sequence generator (PRBS) generator to generate pilot signals for the purposes of channel estimation. Then, load these bits onto the channel with the help of an adaptive tone loading algorithm. We then develop a QAM constellation mapper and QAM. modulator to map the bits to QAM symbols. Along with this, suitable encoders like Alamouti encoders, Inverse Channel Coders, and Singular Value Decomposition Coders are added to form the transmitter end of the system.

By transmitting the pilot signals we determine the channel characteristics and model it to our satisfaction and use this information at the receiver to decode the bits correctly.

Similar to the transmitter, the receiver contains precoding decoder, and QAM demodulator to obtain the transmitted signal. Finally we measure the system performance by looking at the BER and measure the effectiveness of our system.

## 1.7 Assumptions made / Constraints of the project

Some of the constraints we have set for our project are as follows.

1. We only introduce Rayleigh fading in our channel and focus on LOS paths. We do not focus on other delayed paths in the channel.

2. All the channel parameters including SNR tables and channel coefficients have been provided to us by our guide.

3. The distance of separation between the transmitter and receiver is taken to be $1Km$.

4. The transmitter is assumed to be operating on a power budget of $1mW$.

5. The antenna design parameters are not focused upon but are approximated to the values of $G_r$ and $G_t$.

6. The system is taken to be operating in the frequency range of $1MHz$.

7. We are limiting the number of bits transmitted to around $10^7$ to measure our BER.

## 1.8 Organization of the report

This report is organized as follows.

- Chapter 2 discusses the fundamentals of MCM and MIMO systems. We discuss the key technologies in MCM and MIMO that enable it to be an effective solution for modern cellular systems. Along with this we also discuss some of the challenges faced in their implementation.

- Chapter 3 informs the reader about the steps we have taken to design our communication system delving into the details of the design parameters and algorithms used.

- Chapter 4 shows the results we have obtained by performing simulations of our system on MATLAB. We show the comparison of performance between existing systems and our system and highlight the effectiveness of our system.

- Chapter 5 is the final chapter where we conclude our report and mention the scope for future research and list some additional features that can be added to our system to improve it.

# Chapter 2

# Theory and Fundamentals of MIMO and MCM

# CHAPTER 2

# THEORY AND FUNDAMENTALS OF MIMO AND MCM

This chapter focuses on the fundamental principles of MIMO and MCM. We firmly establish some of the prerequisite learning required before we can discuss the actual design of our system in the next chapter. We begin by looking at the shortcomings of single channel systems and how they can be overcome with the help of MCM. We also highlight how some of the shortcomings of single channel systems can be used to our advantage in MCM-MIMO systems. We also spend some time looking into concepts such as Rayleigh fading and different precoding schemes to gain a thorough understanding on mobile communication systems.

## 2.1 The Need for MIMO

In a typical mobile communication system, the User Equipment (UE) and Base Station (BS) are quite far apart. Typical distances are in the kilometer range. As a result, the signal undergoes attenuation as it travels and signal quality degrades to levels that make retrieval of information impossible. A typical example of the variation of received power with distance is given in the figure 2.1.
Various statistical models have been developed to model path loss and fading. In our report, we use a simple Line Of Sight path loss function abbreviated as LOS. This coupled with Rayleigh fading and AWGN noise forms the channel component of our report. The exact implementation details of each of these terms is discussed in Chapter 3.

Apart from this, there are also considerations for the service provider with regards to maximizing user capacity and spectral efficiency. Along with this, it becomes necessary to provide high data rates to subscribers for various applications. Meeting all these requirements in single channel systems leads to the design of extremely cost prohibitive modems and in some cases is almost impossible. Hence, we must come up with large scale and complex systems of transmitters and receivers to meet the demand. In this report, we show the implementation of various versions of MIMO upto $2 \times 2$. MIMO itself can be used in various ways namely multiplexing and diversity. In the following sections we take a closer look at these configurations.

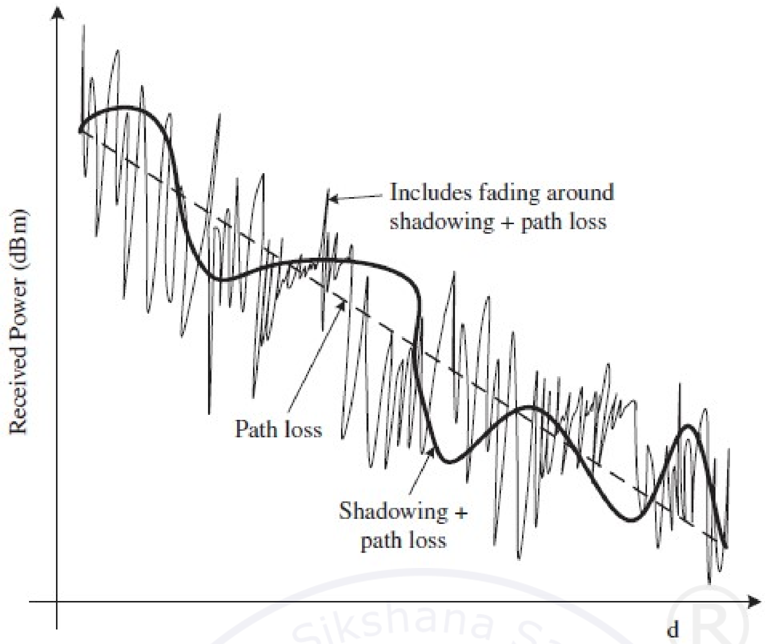



Figure 2.1: Variation of Received Signal Power with Distance of separation (d) between transmitter and receiver

## 2.2 Diversity

Mitigation of fading and overcoming low SNR regimes to maintain a suitable QoS requires techniques such as diversity, wherein copies of the same data are sent from the transmitter to the receiver so that reliability of accurately decoding the transmitted symbols is increased.

Diversity can be achieved primarily in three ways, they are

1. **Frequency Diversity**: Where multiple copies of the same data are sent on different frequency channels
2. **Time Diversity**: Where multiple copies of the same data are sent at different instances of time
3. **Spatial Diversity**: Where multiple copies of the same data are sent along different antenna paths.

Among the three possible methods, spatial diversity is attractive to us because, the multiple reflections that a signal undergoes in a typical urban setup already provides us with the required diversity without the loss of bandwidth efficiency. Hence, when we refer to diversity, unless otherwise mentioned, it is assumed to refer to spatial diversity. A simplified illustration of multipath propagation in urban setting is shown in the figure 2.2

However, in a single channel system, the multiple copies arriving at different time in-

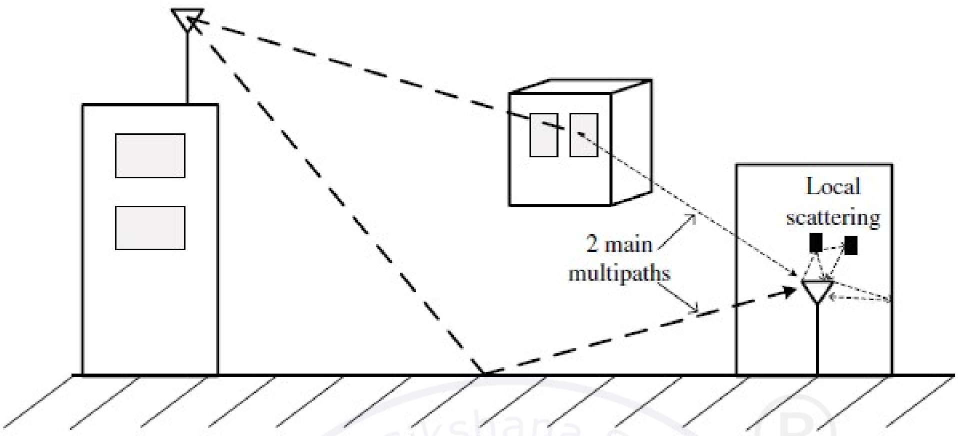



Figure 2.2: Multipath Propagation in a typical urban setting

stances leads to interference of the signal. This interference may be constructive or destructive in nature as shown in the figure 2.3. This can lead to difficulties in decoding as it would mean the requirement of expensive equalizers or reduction in the symbol rate. Neither option is feasible for us, and hence, it becomes apparent to us how having multiple transmit and receive antennas can easily overcome this issue. With the help of multiple antennas, the same situation which was causing Inter Symbol Interference (ISI) becomes a boon to us by allowing multiple antenna paths between the transmitter and receiver allowing for easy implementation of spatial diversity. This situation is shown in the figure 2.4

## 2.3 Multiplexing

Supposing the channel conditions are suitable and the SNR is sufficiently high, meaning we are in a high SNR regime, instead of sending multiple copies of the same data, we can send different data blocks on different antenna paths increasing the overall data rate per user and the user capacity of the system. This concept is known as spatial multiplexing demonstrated in the figure 2.5.

Apart from spatial multiplexing we can also implement time multiplexing and frequency multiplexing wherein different data symbols are sent in different time slots or frequency blocks respectively. Modern day 4G and 5G uses all three forms of multiplexing to increase data rates and capacity.

When we are given the various options for multiplexing, we can either

1. Assign multiple resource blocks (either in time, frequency or antenna paths) to a single user to significantly improve his data rate and QoS.

2. The alternative is to accommodate more users by assigning each one or more resource blocks to each and improving the capacity.

This option is left to the service providers to implement resource allocation as per the market requirements. Hence, we see the significant advantages MIMO has enabled for us by opening the doors to MIMO and MCM.

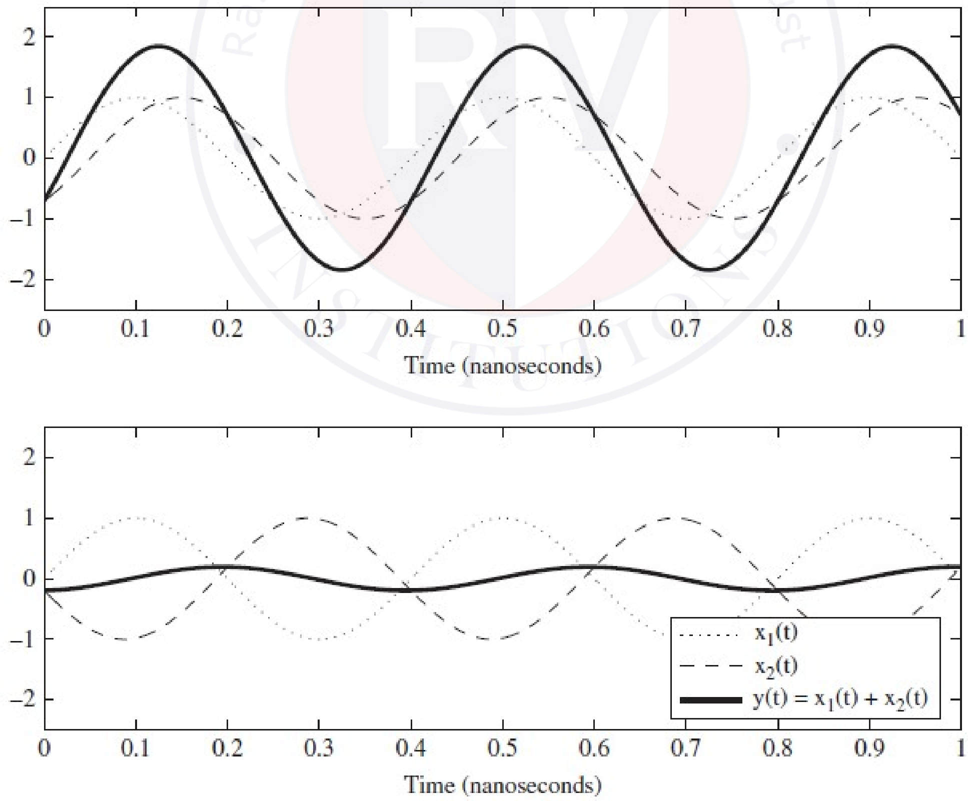



Figure 2.3: Constructive and Destructive Interference leading to large variation in received signal power.

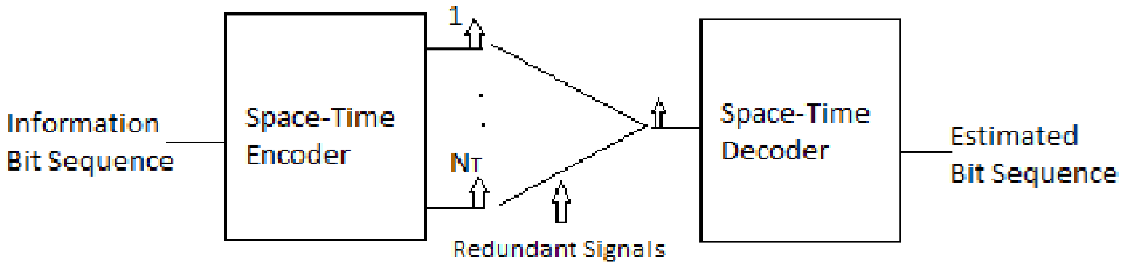



Figure 2.4: Spatial Diversity

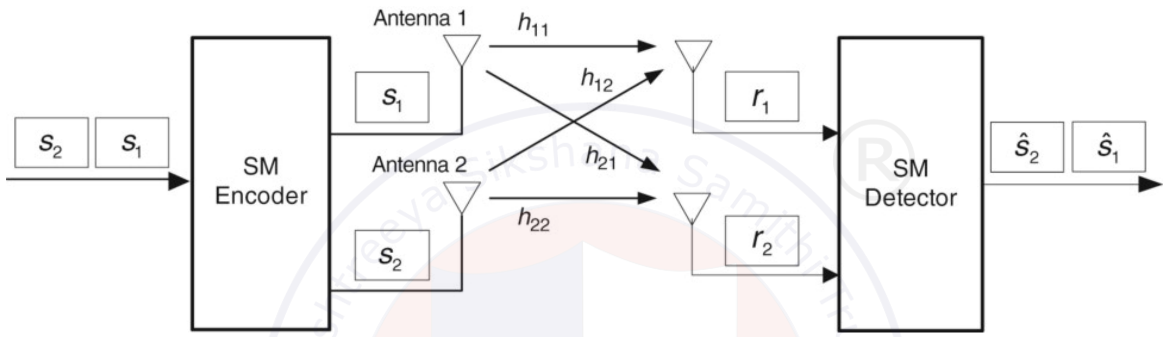



Figure 2.5: Spatial Multiplexing

## 2.4 Intersymbol Interference, Frequency Selective Fading and the need for MCM

In the previous section we saw sufficient motivation to move in the direction of multiple antenna system. However, the issue of ISI needs to be tackled sufficiently to provide significantly high data rates. Added to the menace of ISI the channel can also degrade the message in a frequency selective manner leading to added difficulties in information recovery at the receiver as shown in the figure 2.6. Frequency selective fading occurs because the channel conditions are in constant flux and the message time period is not the same as the time period for which the channel conditions are relatively constant

An effective way to combat frequency selective fading is to breakup the entire bandwidth into smaller subchannels where the bandwidth of each subchannel is smaller than the Coherence Bandwidth ($B_c$), thus ensuring that the message time period is smaller than the Delay Spread ($T_d$). This approach to communication is called as Multi Carrier Modulation(MCM) technique. The implementation of MCM is simple if we realize that we can split the given bandwidth into different subchannels by simply introducing an IFFT block at the transmitter and to achieve the opposite effect introduce an FFT block at the receiver. With the help of this, we are able to significantly reduce the problems of frequency selective fading and ISI. The basic structure of a MCM transmitter and receiver is given in the figures 2.8 and 2.9.

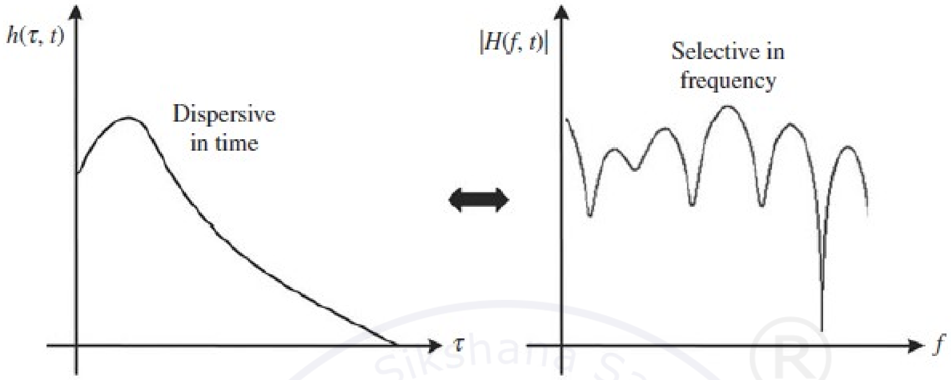



Figure 2.6: Frequency Selective Fading which occurs because the message is longer than the delay spread of the channel.

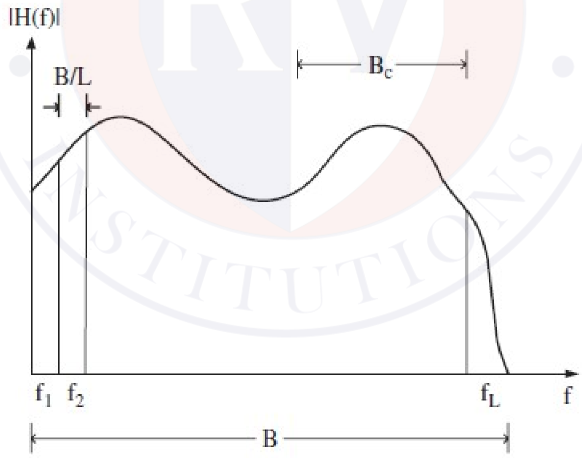



Figure 2.7: By breaking the large bandwidth into smaller subchannels, we can achieve an almost flat fading subchannel which is desirable.

## 2.5 Shortcomings of simple MCM and the need for OFDM

Having shown the implementation of a simple MCM system, we address some of the shortcomings of this. Primarily,

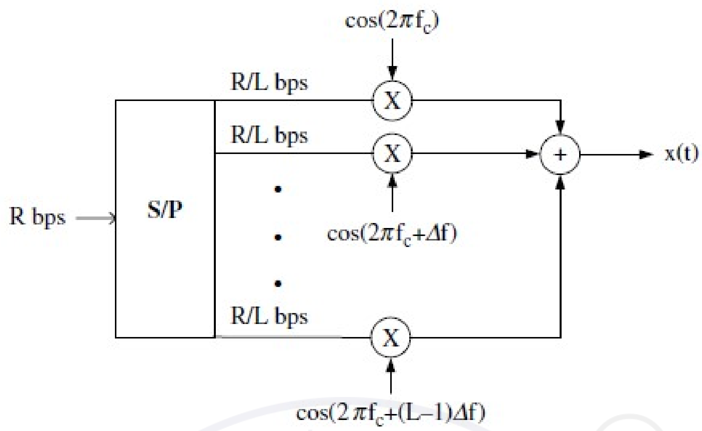



Figure 2.8: An MCM transmitter with an IFFT block to split the given bandwidth into smaller $L$ subchannels.

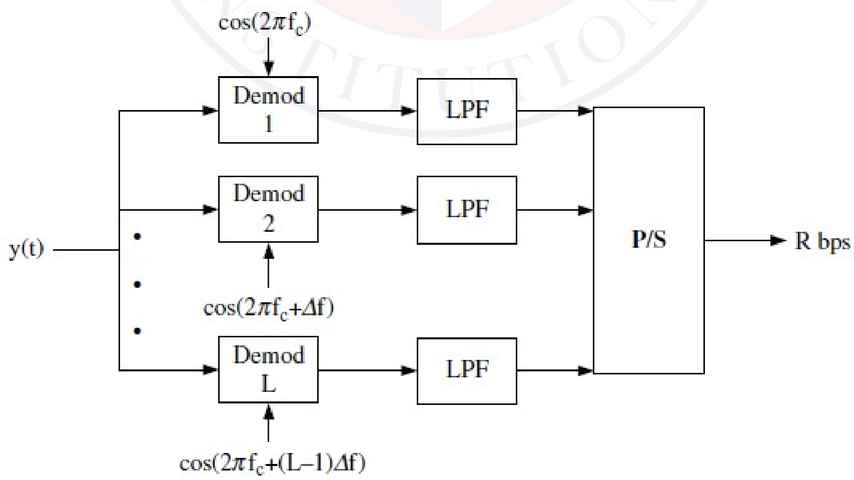



Figure 2.9: An MCM transmitter with an FFT block to reverse the effects of IFFT block at the transmitter.

- It is impossible to realistically have sharply defined bandwidths, as there exists no way to define a pulse which is strictly rectangular in the frequency domain.
- Expensive low pass filters will be necessary to maintain orthogonality of the sub-channels.
- Importantly, multiple RF units are required at both ends for the system to work. This setup, as a result becomes unfeasible and thus, in the next section we look into the OFDM scheme as an alternative to simple MCM.

## 2.6 OFDM

### 2.6.1 Concept of OFDM

Orthogonal Frequency Division Multiplexing is a multiplexing scheme where different data symbols are modulated to different frequencies. These frequencies are chosen such that they are all orthogonal. Hence a given instance, only one wave is at it's peak while the rest are at zero allowing us to read the data bits without any Inter Symbol Interference. This situation is shown in the figure 2.10.

Therefore, we club the different data bits into one block called an OFDM symbol. To avoid ISI between the OFDM symbols themselves, there is a small time delay introduced between the OFDM symbols called as Guard Time which is abbreviated to $T_g$. It is important that this delay, is atleast as large as the Delay Spread.
We know that the wireless channel behaves as a Linear Time Invariant system and hence, the channel coefficient and data bits are linearly convolved together whenever a message is passed through it. However, we know that, circular convolution in the time domain yields simple multiplication in the frequency domain. This multiplication is desirable as it leads to simplified computation at the transmitter and receiver. A simple way to covert this linear convolution to circular convolution is to add redundant bits known as cyclic prefix. This cyclic prefix is just copying the last $L$ bits of the OFDM symbol and adding it to the beginning of the symbol. These $L$ bits are transmitted during the time $T_g$ and hence will be lost due to interference between the OFDM symbols.

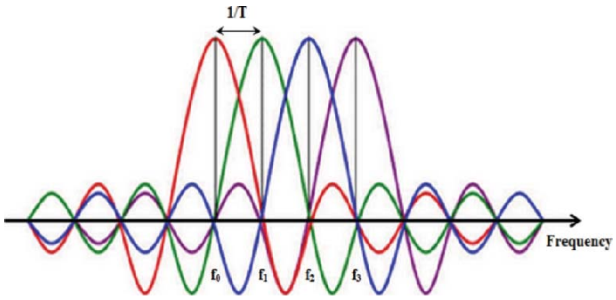



Figure 2.10: An OFDM symbol where different coloured waves correspond to different bits. Notice how when one wave peaks, all the other waves are at their null points.

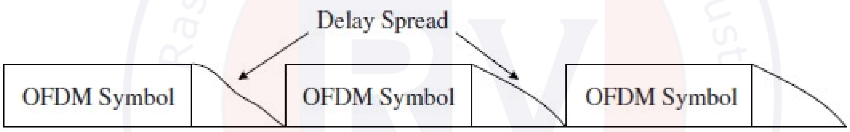



Figure 2.11: A delay of $T_g$ is introduced between the symbols to avoid interference between the OFDM symbols. Notice that this does not do anything to combat ISI within the OFDM symbol itself.

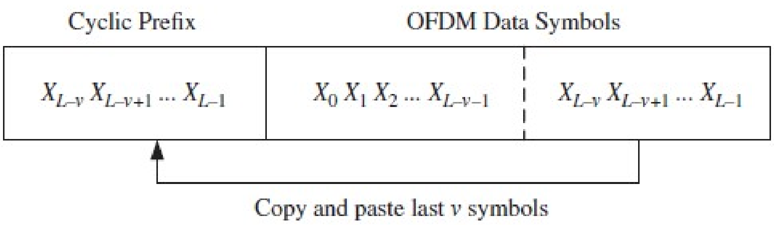



Figure 2.12: The cyclic prefix in an OFDM symbol.

### 2.6.2 Advantages of OFDM

Some of the advantages of OFDM compared to traditional FDM are as follows.

- There is no need for any guard bands between carriers leading to higher spectral efficiency.
- Higher data rates can be achieved as symbol rate need not be lowered for the sake of ISI.
- System is more robust to multipath effects.

### 2.6.3 Disadvantages of OFDM

OFDM also comes with a few disadvantages chief among them is the issue of high PAPR. Discussing the ways to mitigate this issue is outside the scope of this report and the reader is encouraged to refer to literature such as Ghosh, Zhang, G, *et al.* [12] to gain a better understanding.

## 2.7 OFDM Transceiver System

After having seen the motivation for the development of MCM, MIMO and OFDM schemes and also having seen a basic MCM transceiver system, we will combine all the concepts to create an OFDM transceiver which is capable of sending and receiving data bits packaged in OFDM symbols.
In figure 2.13 we see how normal QAM modulated symbols are passed through an IFFT block to assign them to different frequency subchannels. Additional cyclic prefix is added before converting the parallel streams to a serial stream and transmitting it.
The OFDM receiver in figure 2.14 on the other hand does the exact opposite process, where the received symbols are demodulated according to their respective frequencies and passed through an FFT block to undo the IFFT process. Then, it the demodulated symbols are passed through a Maximum Likelihood Estimator detector to get back the information bits.

## 2.8 Alamouti Coding Scheme

Alamouti coding scheme is a simple coding scheme designed for the purpose of achieving spatial diversity in MISO systems. The advantage of this coding scheme is that the

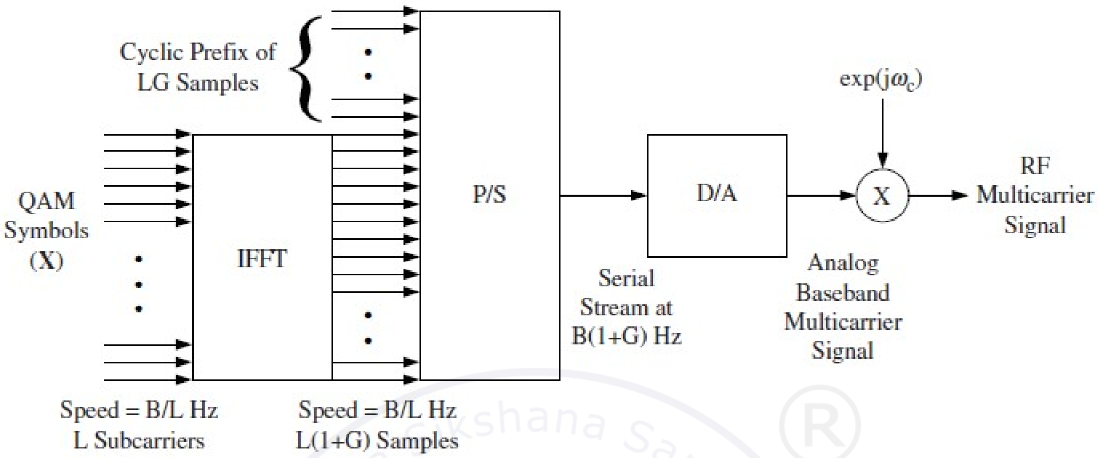



Figure 2.13: OFDM Transmitter

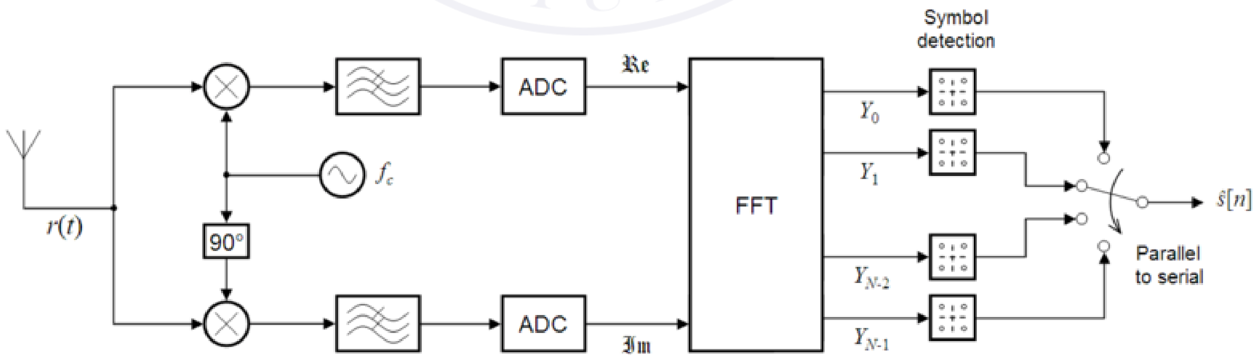



Figure 2.14: OFDM Receiver

transmitter need not know the channel information before sending the data. We describe the coding scheme in this section.

Consider two transmitting antennas $T_1$ and $T_2$ and one receiving antenna $R$.

Let $h_1$ be the channel coefficient of the first antenna path and $h_2$ be the channel coefficient of the second antenna path.

Let $x_1$ and $x_2$ be transmitted by antennas $T_1$ and $T_2$ respectively at a given time instance, and $-x_2{}^*$, $-x_1{}^*$ be the data transmitted in the next time instance by the antennas respectivey.

We know that the wireless channel behaves as an LTI system which performs convolution of the data bits and the channel coefficient. Also, let $w_1$ and $w_2$ be the noise vectors added at the two time instances respectively.

This situation can be represented mathematically as follows.

$$y_1 = \begin{bmatrix} h_1 & h_2 \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + w_1$$

$$y_2 = \begin{bmatrix} h_1 & h_2 \end{bmatrix} \times \begin{bmatrix} -x_2{}^* \\ x_1^* \end{bmatrix} + w_2$$

This can be further simplified as,

$$y = \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = c_1 x_1 + c_2 x_2 + w$$

Where,

$$c_1 = \begin{bmatrix} h_1 \\ h_2^* \end{bmatrix}$$

$$c_2 = \begin{bmatrix} h_2 \\ -h_1^* \end{bmatrix}$$

Here $c_1$ and $c_2$ can be shown as orthogonal in nature and so, this coding scheme is also known as Orthogonal Space Time Block Coding scheme.

At the receiver, once we have matrix $y$, $x_1$ and $x_2$ can be recovered as follows,

$$\frac{c_1^H}{||c_1||} \cdot y = ||c_1||x_1 + \overline{w_1}$$
$$\frac{c_2^H}{||c_2||} \cdot y = ||c_2||x_2 + \overline{w_2}$$

Here, $c_1^H$ and $c_2^H$ are the result obtained after performing the Hermitian operator on the $c$ matrices. We notice that $x_1$ and $x_2$ are scaled by a factor and mixed with AWGN noise. With a suitable decision criteria, both $x_1$ and $x_2$ can be decoded correctly in two time slots. This shows how Alamouti coding scheme is effective when used in the spatial diversity mode of a $2 \times 1$ MISO system. However, in higher order schemes, Alamouti coding loses it's efficiency and is not feasible.

## 2.9 Inverse Channel Estimation

The received symbol vector $y$ is related to the transmitted vector $x$ and channel coefficient matrix $h$ as

$$\begin{bmatrix} y \end{bmatrix} = \begin{bmatrix} x \end{bmatrix} \times \begin{bmatrix} h \end{bmatrix} + \begin{bmatrix} n \end{bmatrix}$$

where $\begin{bmatrix} n \end{bmatrix}$ is the AWGN noise vector.
From this, we can extract the sent symbols by multiplying $\begin{bmatrix} y \end{bmatrix}$ with the inverse of the channel coefficient matrix which yields the following expression.

$$\begin{bmatrix} y \end{bmatrix} \times \begin{bmatrix} h \end{bmatrix}^{-1} = \begin{bmatrix} x \end{bmatrix} + \begin{bmatrix} w_1 \end{bmatrix}$$

where $\begin{bmatrix} w_1 \end{bmatrix}$ is the result obtained after multiplying $\begin{bmatrix} n \end{bmatrix}$ with $\begin{bmatrix} h \end{bmatrix}^{-1}$.

Further processing is necessary to remove the noise vector $\begin{bmatrix} w_1 \end{bmatrix}$. However, one of the issues we face is that $\begin{bmatrix} w_1 \end{bmatrix}$ is no longer AWGN but becomes colored noise. Therefore, to overcome this hindrance, we precode the transmitted symbols vector $\begin{bmatrix} x \end{bmatrix}$ by multiplying it with $\begin{bmatrix} h \end{bmatrix}^{-1}$. The received vector $\begin{bmatrix} y \end{bmatrix}$ then becomes

$$\begin{bmatrix} y \end{bmatrix} = \begin{bmatrix} x \end{bmatrix} \times \begin{bmatrix} h \end{bmatrix}^{-1} + \begin{bmatrix} n \end{bmatrix}$$

Finally, when we try and extract the transmitted symbols at the receiver by multiplying with $\begin{bmatrix} h \end{bmatrix}$ we get

$$\begin{bmatrix} y \end{bmatrix} \times \begin{bmatrix} h \end{bmatrix} = \times \begin{bmatrix} x \end{bmatrix} + \begin{bmatrix} w_2 \end{bmatrix}$$

where $\begin{bmatrix} w_2 \end{bmatrix}$ is the result obtained after multiplying $\begin{bmatrix} n \end{bmatrix}$ with $\begin{bmatrix} h \end{bmatrix}$.

Now, $\begin{bmatrix} w_2 \end{bmatrix}$ remains to be Gaussian and hence further noise processing becomes simpler with normal demodulators and MLI estimators.

## 2.10 Singular Value Decomposition

In the previous section we saw the advantage of using Inverse Channel Estimation precoding. However, in massive MIMO systems where the number of antenna paths are plenty and the order of the channel coefficient matrix is large, inversion of matrices becomes a computationally intensive task. Since we are required to have high speed modems which do not take more than a few microseconds to make the necessary computations, we must look to faster ways of inverting the channel coefficient matrix.
In this effort we use the singular value decomposition technique where we decompose the channel coefficient matrix $\begin{bmatrix} h \end{bmatrix}$ into three orthogonal matrices $\begin{bmatrix} U \end{bmatrix}$ , $\begin{bmatrix} \Sigma \end{bmatrix}$ and, $\begin{bmatrix} V \end{bmatrix}$.

At the transmitter we multiply the transmitted symbol vector $\begin{bmatrix} x \end{bmatrix}$ with $\begin{bmatrix} V \end{bmatrix}$ and similarly at the receiver we multiply the received vector $\begin{bmatrix} y \end{bmatrix}$ with $\begin{bmatrix} U \end{bmatrix}$ to achieve the same effect as inversion.
Singular value decomposition is faster than regular inversion for large matrices and hence proves faster in massive MIMO systems.

## Summary

In this section we have elaborated on the motivations behind MCM and MIMO. We have also clearly elaborated on the key technologies that enable them. In the next chapter, we will discuss the implementation details of our MCM-MIMO system and explain the different algorithms we have used. Finally, in Chapter 4 we will discuss the results obtained after simulations and draw conclusions as to the overall system performance.

# Chapter 3

# Design of MCM and MIMO Processing Systems for Urban Communication

# CHAPTER 3

# DESIGN OF MCM AND MIMO PROCESSING SYSTEMS FOR URBAN COMMUNICATION

This chapter focuses on the algorithms implemented as part of the MCM-MIMO system. We look into the different aspects of transmitter block, channel parameters and receiver block of our system. We look into the simulation of SISO, SIMO ( transmit spatial diversity), MISO (OSTBC) and MIMO ( both spatial diversity and multiplexing(inverse channel decoding and SVD)).

## 3.1 Basic Overview of our System

Figure 3.1 shows the general block diagram of a communication system, similar to the one mentioned in Chapter 1. In the following sections we discuss the role of each block in detail by building on the foundation we have laid in the previous chapter.

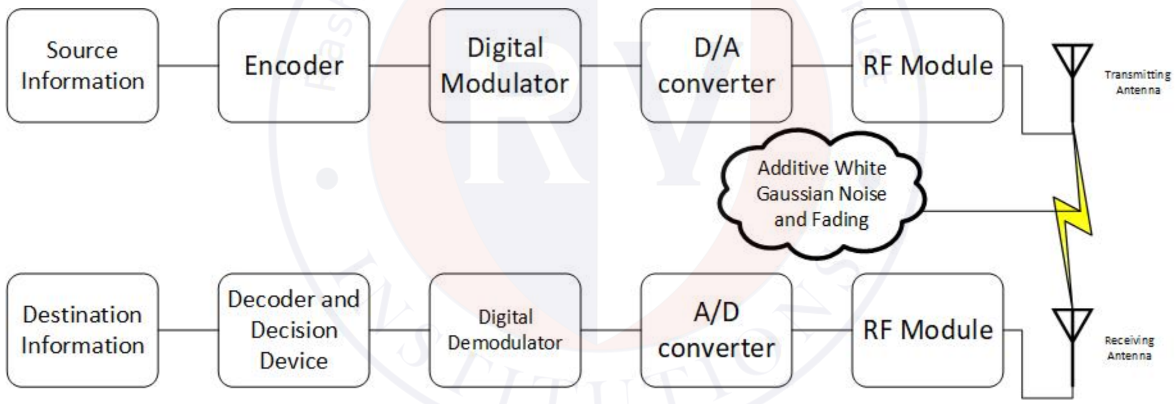



Figure 3.1: General Wireless Communication System Block Diagram

## 3.2 Transmitter

We begin by exploring the various sections of the transmitter block. We do not concern ourselves with the source information as they are just randomized binary digits generated by the MATLAB rand function. Neither do we concern ourselves with the Digital to Analog Converter(DAC) as it is beyond the scope of this report.

Instead, in this section we focus on the QAM modulator and various precoders which work on the principles explained in Chapter 2. We also look into the Pseudo Random Binary Sequence(PRBS) generator which is used for channel estimation and the tone loading algorithm which we employ in the cases of SISO, SIMO and MIMO both in diversity and multiplexing cases.

### 3.2.1 PRBS Generator

A good Pseudo Random Binary Sequence generator is key for generating the pilot signals which is needed for the modem training phase and channel characteristic estimation. For our purposes we use the PRBS generator algorithm presented in ITU [8] which is defined below.

The $n^{th}$ pseudo random binary digit $d_n$ is given by

$$
\begin{aligned}
d_n &= 1 && \text{for n = 1 to 9} \\
d_n &= d_{n-4} \oplus d_{n-9} && \text{for n = 10 to } 2 \times \text{NSC} \\
d_n &= d_{n-2\times NSC} && \text{for n = } 2 \times \text{NSC} + 1 \text{ to } 2 \times \text{NSC} + 2 \\
d_n &= d_{4\times NSC+2-n} && \text{for n = } 2 \times \text{NSC} + 3 \text{ to } 4 \times \text{NSC (n odd)} \\
d_n &= 1 \oplus d_{4\times NSC+4-n} && \text{for n = } 2 \times \text{NSC} + 3 \text{ to } 4 \times \text{NSC (n even)}
\end{aligned}
$$

Here NSC is the total number of subcarriers, taken to be 256 in our case. Hence, we can generate upto 1024 PRBS digits. However, we limit ourselves to the first 512 digits only.

### 3.2.2 Tone Loading Algorithm for the transmitter

Once we have determined the channel conditions by transmitting the pilot signals and measured the SNR of each subchannel to create a channel profile, it becomes necessary to load the data bits onto these subchannels in an efficient manner. Common sense tells us that the subchannels with higher SNR should carry more bits than those with lower SNR. We show through our algorithm that this is indeed the case.

The basis for our tone loading algorithm is the capacity law given by Shannon in **Shannnon1948**. Using this formula, we determine the number of bits that a given subchannel can support for it's given SNR. Then, we round the number of bits and calculate the power deviation thus obtained by applying the inverse of the capacity law. As long as this deviation is within the agreed upon threshold, we add and remove bits between the subchannels until a stable tone loading situation arises.

The limit we have set for our purposes is ±2 dB and we have added the additional constraint of setting the maximum number of bits for any channel to be 20. The exact details of the algorithm is given in Algorithm 1.

**Algorithm 1** Fine Gains Tone Loading Algorithm

$b_i \leftarrow log_2(1 + SNR_i)$
$\hat{b}_i \leftarrow \lfloor b_i \rceil$
$\delta_i \leftarrow b_i - \hat{b}_i$
$P_{\delta_i} \leftarrow 3 \times \delta_i$
$P_{\delta_{total}} \leftarrow \sum_{i=1}^{NSC} P_{\delta_i}$
**while** $P_{\delta_{total}} > P_{threshold}$**or**$P_{\delta_{total}} < -P_{threshold}$ **do**
  **if** $P_{\delta_{total}} > P_{threshold}$ **then**
    $position = \texttt{POS}(\texttt{MAX}(\delta_i))$
    $\hat{b}_{position} \leftarrow \hat{b}_{position} - 1$
    $\delta_{position} \leftarrow b_{position} - \hat{b}_{position}$
    $P_{\delta_{position}} \leftarrow 3 \times \delta_{position}$
    $P_{\delta_{total}} \leftarrow \sum_{i=1}^{NSC} P_{\delta_i}$
  **else if** $P_{\delta_{total}} < -P_{threshold}$ **then**
    $position = \texttt{POS}(\texttt{MIN}(\delta_i))$
    $\hat{b}_{position} \leftarrow \hat{b}_{position} + 1$
    $\delta_{position} \leftarrow b_{position} - \hat{b}_{position}$
    $P_{\delta_{position}} \leftarrow 3 \times \delta_{position}$
    $P_{\delta_{total}} \leftarrow \sum_{i=1}^{NSC} P_{\delta_i}$
  **end if**
**end while**
$SNR_i \leftarrow 2^{\hat{b}_i} - 1$

### 3.2.3 QAM Modulator

Among the various modulation schemes available for us, we chose the QAM modulation technique because it is extremely power efficient and also maintains a good degree of spectral efficiency.

One of the problems we run into with QAM modulation is the fact that we need to maintain large symbol constellations, especially when we are dealing with higher order QAM modulation schemes. Therefore, in this section we describe a fast recursive algorithm that can generate large symbol constellations by keeping only a few small constellations in memory. This approach reduces the cost of hardware required by reducing the memory elements required but still maintains a high degree of speed. The details of this are given in 2

## 3.3 Channel Parameters

In the previous section, we discussed the transmitter portion of our system, now we look into the channel parameters which are mostly randomized in nature. The vari-

**Algorithm 2** Bits to Constellation Mapping Algorithm

```
LUT ← {QAM_1, QAM_2, QAM_3, QAM_5}
matrix_transform ← {0, -2i, 2, 2+2i}
i ← 1
while i < NSC do
    flag_recursion ← false
    if b_i == 1 then
        symbol_i ← QAM_1(bits_i)
    else if b_i%2 == 0   and   b_i   not = 0 then
        bits_extracted ← extract bits into groups of 2
        bits_decimal ← DEC(bits_extracted)
        symbol_i ← QAM_2(bits_decimal)
        flag_recursion ← true
    else if b_i%2 == 1 then
        symbol_i ← QAM_3(bits_i)
        if b_i > 3 then
            bits_extracted ← Extract bits into groups of 2
            bits_decimal ← DEC(bits_extracted)
            if bits_decimal < 4 then
                symbol_i ← QAM_3(bits_decimal)
            else
                symbol_i ← QAM_5(bits_decimal)
            end if
            flag_recursion ← true
        end if
    end if
    if flag_recursion then
        count = 2
        while count < SIZE(bits_decimal) do
            bits_decimal_extracted ← Extract the bits individually
            point_quadrant ← GET BASIC QUADRANT POINT
            offset ← FIND OFFSET(point_quadrant, bits_decimal_extracted)
            symbol_i ← 2 × symbol_i − QAM_2(bits_decimal_extracted) + point_quadrant + offset
            count ← count + 1
        end while
    end if
    i ← i + 1
end while
```

ous channel parameters like noise, fading and path loss are discussed in the following paragraphs.

### 3.3.1 AWGN Noise

All communication is affected by noise, we have assumed Additive White Gaussian Noise noise as the noise function of choice. To generate this, we have used the MATLAB function *randn* which generates a Gaussian function with mean as 0 and variance as 1. Then we multiply this function with the noise variance of our choice to get the noise signal. Mathematically, AWGN function is given by

$$noise = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{x^2}{2\sigma^2}}$$

Where $\sigma$ is the noise variance or power. In MATLAB, this is given by the statement

```
noise = sqrt(noise_power_abs/2) .* ((randn(Nsc,1)) + 1i*randn(Nsc,1));
```

Here, NSC is the Number of Subchannels. Since we are trying to add noise to all the subchannels, the vector is of the size $NSC \times 1$.

### 3.3.2 Rayleigh Fading

In the previous chapter we mentioned fading in wireless channels. We also mentioned that Rayleigh fading was the model of choice for our report. Rayleigh fading is viewed as a reasonable model for tropospheric and ionospheric propagation as well as for heavy urban settings for wireless signals. Rayleigh fading is most applicable when there is no dominant propagation along a line of sight between the transmitter and receiver. Rayleigh fading is any function that varies as per the Rayleigh distribution which is the radial component of the sum of two uncorrelated Gaussian random variables. In MATLAB this is generated through,

```
rayleigh_channel = sqrt(1/2) .* (randn(1) + 1i*randn(1))
```

where the two *randn* functions produce the two uncorrelated Gaussian functions.

### 3.3.3 Path Loss Function

Path loss function determine the way in which the transmitted signal degrades with distance before the signal reaches the receiver. Since we are focused on Line Of Sight path propagation we consider LOS path loss formulation as given by Friis Transmission formula.

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2}$$

where:

$P_r$ = Received Signal Power

$P_t$ = Transmitted Signal Power, in our simulations it is 1 mW

$G_t$ = Transmitter Antenna Gain, in our simulations it is 8

$G_r$ = Receiver Antenna Gain, in our simulation it is 1

$r$ = Distance of separation between the two antennas, in our simulations it is 1 Km

$\lambda$ = Wavelength of the signal wave.

## 3.4 Receiver

The receiver we have employed in our system consists of an estimator, decoder and demodulator. The estimator uses the principle of maximum likelihood estimation. In MLI at the receiver we take the received symbol and plot it as a point on the symbol constellation. Then, we calculate the Euclidian distance of this point from all the constellation points and select the constellation point whose Euclidian distance is closest to our received symbol point. This technique is optimal and gives us the least amount of error thereby improving our system performance.

The decoders like Alamouti decoder and SVD decoder have already been discussed in the previous chapter.

Our estimator system also works on a similar principle but makes use of the unique constellation mapping algorithm to greatly simplify the decision making process by following Algorithm 3.

Once the estimator has estimated a constellation point for us, the demodulator converts this constellation point into the binary digits representing the constellation point.

Similar to the case of modulation, we do not have all the constellations stored in memory but generate them dynamically using a recursive algorithm. This process is shown in Algorithm 4

**Algorithm 3** Estimation Algorithm

```
LUT ← {QAM_1, QAM_2, QAM_3}
i ← 1
while i < NSC do
  if b_i == 0 then
    estimate_i ← 0
  else if b_i == 1 then
    estimate_i ← CLOSEST(QAM1, received_i)
  else if b_i == 3 then
    estimate_i ← CLOSEST(QAM_3, received_i)
  else if b_i ≥ 2 then
    real_i ← ⌊REAL(received_i)⌋
    imag_i ← ⌊IMAG(received_i)⌋
    if real_i%2 == 0 then
      real_i = real_i + 1
    end if
    if imag_i%2 == 0 then
      imag_i = imag_i + 1
    end if
    estimate_i ← real_i + imag_i
    estimate_i ← BOUND TO MAX(estimate_i)
  end if
  i ← i + 1
end while
```

## 3.5 Operation of the System in Different Modes

In this section we demonstrate the various modes in which our system can be operated. The algorithm that the system follows in each mode is described in detail in this section. In some cases like MIMO it is possible to operate the system with various precoders and hence we discuss in detail these algorithms as well.

### 3.5.1 SISO Mode

In the Single Input Single Output mode, only one antenna each is present at both the transmitter and receiver. The steps involved in sending the data from transmitter to the receiver in the SISO is given in Algorithm 5.

**Algorithm 4** Constellation to Bits Mapping Algorithm

$LUT \leftarrow$ `{QAM_1, QAM_2, QAM_3, QAM_5}`
$matrix_{transform} \leftarrow$ `{0, -2i, 2, 2+2i}`
$i \leftarrow 1$
**while** $i < NSC$ **do**
  **if** $b_i == 1$ **then**
    $symbol_i \leftarrow$ `BIN(FIND(`$estimate_i$, `QAM_1))`
  **else if** $b_i == 3$ **then**
    $symbol_i \leftarrow$ `BIN(FIND(`$estimate_i$, `QAM_3))`
  **else if** $b_i \geq 2$ **then**
    $symbol_i \leftarrow$ `NULL`
    **if** $b_i \% 2 == 0$ **then**
      $limit \leftarrow \frac{b_i}{2} - 1$
    **else**
      $limit \leftarrow \frac{b_i - 3}{2} - 1$
    **end if**
    $point_{quadrant} \leftarrow$ `GET BASIC QUADRANT POINT`
    $count \leftarrow 1$
    **while** $count < limit$ **do**
      $offset \leftarrow$ `FIND OFFSET(`$point_{quadrant}, estimate_i$`)`
      $value_{binary} \leftarrow$ `BIN(FIND(`$offset, matrix_{transform}$`))`
      $symbol_i \leftarrow symbol_i + value_{binary}$
      $estimate_i \leftarrow \frac{estimate_i}{2}$
      $count \leftarrow count + 1$
    **end while**
  **end if**
  $i \leftarrow i + 1$
**end while**

**Algorithm 5** Operation in SISO Mode

1. Get pilot signals through the PRBS Generator
2. Get QAM symbols by modulating the pilot bits with the modulator
3. Obtain the Rayleigh channel coefficient
4. Obtain the received power with the help of LOS function
5. Generate the noise signal
6. Determine the channel coefficient as $h \leftarrow \sqrt{\frac{P_r}{P_t}} \times rayleigh$
7. Send the pilot signals from transmitter to the receiver
8. Get the received pilot symbols by doing $symbol_{received} \leftarrow symbol_{sent} \times h$
9. Estimate the SNR of the subchannels with the help received power
10. Estimate the value of channel coefficients at the receiver with the help of received pilot signals
11. Get the data bits and modulate them into QAM symbols
12. Perform tone loading with the help of fine gains algorithm
13. Send the data QAM symbols as per the tone loading profile
14. Add noise signal and multiply data signal with channel coefficients to simulate path loss and fading
15. Demodulate the received data symbols with the help of estimated channel coefficients at the receiver
16. Use a Maximum Likelihood Estimator to determine the sent bits
17. Calculate the BER for the system

### 3.5.2 SIMO System

In the Single Input Multiple Output mode, only one antenna is present at the transmitter but there are 2 antennas at the receiver leading to 2 possible antenna paths. The steps involved in sending the data from transmitter to the receiver in the SIMO is given in Algorithm 6.

**Algorithm 6** Operation in SIMO Mode

1. Get pilot signals through the PRBS Generator
2. Get QAM symbols by modulating the pilot bits with the modulator
3. Obtain both the Rayleigh channel coefficient
4. Obtain the received power with the help of LOS function for both paths
5. Generate the noise signal
6. Determine both the channel coefficients as $h_i \leftarrow \sqrt{\frac{P_{r_i}}{P_{t_i}}} \times rayleigh_i$
7. Send the pilot signals from transmitter to the receiver in both paths
8. Get the received pilot symbols for both paths by doing $symbol_{received} \leftarrow symbol_{sent} \times h_i$
9. Estimate the SNR of the subchannels for both paths with the help received power
10. Estimate the value of channel coefficients for both paths at the receiver with the help of received pilot signals
11. For each subchannel choose the optimal antenna path between the two possibilities
12. Get the data bits and modulate them into QAM symbols
13. Perform tone loading with the help of fine gains algorithm for the optimal data paths
14. Send the data QAM symbols as per the tone loading profile in the optimal data paths
15. Add noise signal and multiply data signal with respective channel coefficient to simulate path loss and fading
16. Demodulate the received data symbols with the help of estimated channel coefficient of the path in which data was received at the receiver
17. Use a Maximum Likelihood Estimator to determine the sent bits
18. Calculate the BER for the system

### 3.5.3 MISO System

In the Multple Input Single Output mode, only one antenna is present at the receiver but there are 2 antennas at the transmitter leading to 2 possible antenna paths. The steps involved in sending the data from transmitter to the receiver in the MISO is given in Algorithm 7.

**Algorithm 7** Operation in MISO Mode

1. Get pilot signals through the PRBS Generator
2. Get QAM symbols by modulating the pilot bits with the modulator
3. Obtain both the Rayleigh channel coefficient
4. Obtain the received power with the help of LOS function for both paths
5. Generate the noise signal
6. Determine both the channel coefficients as $h_i \leftarrow \sqrt{\frac{P_{r_i}}{P_{t_i}}} \times rayleigh_i$
7. Send the pilot signals from transmitter to the receiver in both paths
8. Get the received pilot symbols for both paths by doing $symbol_{received} \leftarrow symbol_{sent} \times h_i$
9. Estimate the value of channel coefficients for both paths at the receiver with the help of received pilot signals
10. Get the data bits and modulate them into QAM symbols
11. Perform Alamouti Coding and send the data symbol and the conjugate data symbol in alternate cycles and alternate paths as described in Alamouti Coding Scheme
12. Add noise signal and multiply data signal with respective channel coefficient to simulate path loss and fading
13. Demodulate the received data symbols with the help of estimated channel coefficient of the path in which data was received at the receiver
14. Perform Alamouti decoding as previously described to get 2 data symbols in 2 consecutive cycles
15. Use a Maximum Likelihood Estimator to determine the sent bits
16. Calculate the BER for the system

### 3.5.4 MIMO System

In the Multiple Input Multiple Output mode, 2 antennas are present at both the receiver and the transmitter leading to 4 possible antenna paths. This also affords us the option of whether we want to use the system in diversity mode or multiplexing mode depending on the channel conditions.
If the channel we are operating in has low SNR characteristics, we go ahead and operate in the diversity mode. The steps involved in sending the data from transmitter to the receiver in the MIMO diversity mode is given in Algorithm 8.
However, supposing we have a sufficiently high SNR, we can then operate in the multiplexing mode. The steps involved in operating the system in MIMO multiplexing mode are given in Algorithm 9.

For the multiplexing mode again, we have different precoding options like Inverse Channel Estimation Precoding and Singular Value Decomposition precoding. These techniques have already been discussed in the previous chapter and we provide the algorithm for implementation here. Algorithm 10 provides the details of operating the system with an Inverse Channel Estimator and Algorithm 11 provides the details for operating the system with a SVD precoder.

## Summary

In this chapter we saw the details of the implementation of the entire system. We also studied some of the algorithms we developed to help us achieve optimal system performance like the fine gains algorithm and the dynamic constellation mapping algorithm. In the next section we will see the system performance for the different modes and compare the performance across various modes.

**Algorithm 8** Operation in MIMO Diversity Mode

1. Get pilot signals through the PRBS Generator
2. Get QAM symbols by modulating the pilot bits with the modulator
3. Obtain all the Rayleigh channel coefficients
4. Obtain the received power with the help of LOS function for all paths
5. Generate the noise signal
6. Determine all the channel coefficients as $h_i \leftarrow \sqrt{\frac{P_{r_i}}{P_{t_i}}} \times rayleigh_i$
7. Send the pilot signals from transmitter to the receiver in all paths
8. Get the received pilot symbols for all paths by doing $symbol_{received} \leftarrow symbol_{sent} \times h_i$
9. Estimate the SNR of the subchannels with the help received power
10. Estimate the value of channel coefficients for all paths at the receiver with the help of received pilot signals
11. For each subchannel choose the optimal antenna path between the four possibilities
12. Get the data bits and modulate them into QAM symbols
13. Perform tone loading with the help of fine gains algorithm for the optimal data paths
14. Add noise signal and multiply data signal with respective channel coefficient to simulate path loss and fading
15. Demodulate the received data symbols with the help of estimated channel coefficient of the path in which data was received at the receiver
16. Use a Maximum Likelihood Estimator to determine the sent bits
17. Calculate the BER for the system

**Algorithm 9** Operation in MIMO Multiplexing Mode

1. Get pilot signals through the PRBS Generator
2. Get QAM symbols by modulating the pilot bits with the modulator
3. Obtain all the Rayleigh channel coefficients
4. Obtain the received power with the help of LOS function for all paths
5. Generate the noise signal
6. Determine all the channel coefficients as $h_i \leftarrow \sqrt{\frac{P_{r_i}}{P_{t_i}}} \times rayleigh_i$
7. Send the pilot signals from transmitter to the receiver in all paths
8. Get the received pilot symbols for all paths by doing $symbol_{received} \leftarrow symbol_{sent} \times h_i$
9. Estimate the SNR of the subchannels with the help received power
10. Estimate the value of channel coefficients for all paths at the receiver with the help of received pilot signals
11. For transmitting antenna $T_1$ choose the optimal channel path from the two available paths. Similarly, for $T_2$ choose an optimal path from the two available paths.
12. Get the data bits and modulate them into QAM symbols
13. Perform tone loading for $T_1$ and $T_2$ onto their respective optimal channels with the help of fine gains algorithm
14. Add noise signal and multiply data signal with respective channel coefficient to simulate path loss and fading
15. Demodulate the received data symbols with the help of estimated channel coefficient of the path in which data was received at the receiver
16. Use a Maximum Likelihood Estimator to determine the sent bits
17. Calculate the BER for the system

**Algorithm 10** Operation in MIMO Multiplexing Mode with Inverse Channel Estimation Precoding

1. Get pilot signals through the PRBS Generator
2. Get QAM symbols by modulating the pilot bits with the modulator
3. Obtain all the Rayleigh channel coefficients
4. Obtain the received power with the help of LOS function for all paths
5. Generate the noise signal
6. Determine all the channel coefficients as $h_i \leftarrow \sqrt{\frac{P_{r_i}}{P_{t_i}}} \times rayleigh_i$
7. Send the pilot signals from transmitter to the receiver in all paths
8. Get the received pilot symbols for all paths by doing $symbol_{received} \leftarrow symbol_{sent} \times h_i$
9. Estimate the value of channel coefficients for all paths at the receiver with the help of received pilot signals
10. Obtain the inverse of the channel coefficient matrix
11. Get the data bits and modulate them into QAM symbols
12. Precode the data bits being sent with the inverse of the channel coefficient matrix
13. Add noise signal and multiply data signal with respective channel coefficient to simulate path loss and fading
14. Demodulate the received data symbols with the help of estimated channel coefficient of the path in which data was received at the receiver. Since we are precoding with the inverse channel matrix, the channel effects nullify the precoding and there is no need for a decoder.
15. Use a Maximum Likelihood Estimator to determine the sent bits
16. Calculate the BER for the system

**Algorithm 11** Operation in MIMO Multiplexing Mode with SVD Precoding

1. Get pilot signals through the PRBS Generator
2. Get QAM symbols by modulating the pilot bits with the modulator
3. Obtain all the Rayleigh channel coefficients
4. Obtain the received power with the help of LOS function for all paths
5. Generate the noise signal
6. Determine all the channel coefficients as $h_i \leftarrow \sqrt{\frac{P_{r_i}}{P_{t_i}}} \times rayleigh_i$
7. Send the pilot signals from transmitter to the receiver in all paths
8. Get the received pilot symbols for all paths by doing $symbol_{received} \leftarrow symbol_{sent} \times h_i$
9. Estimate the value of channel coefficients for all paths at the receiver with the help of received pilot signals
10. Obtain the Singular Value Decomposition of the channel coefficient matrix by doing $[U \Sigma V] \leftarrow \texttt{SVD}(\big[h\big]$
11. Get the data bits and modulate them into QAM symbols
12. Precode the data bits being sent by doing $symbols_{precoded} \leftarrow symbols_{sent} \times \big[V\big]$
13. Add noise signal and multiply data signal with respective channel coefficient to simulate path loss and fading
14. Demodulate the received data symbols with the help of estimated channel coefficient of the path in which data was received at the receiver.
15. Decode the data bits received by doing $symbols_{decoded} \leftarrow symbols_{received} \times \big[U\big]$
16. Use a Maximum Likelihood Estimator to determine the sent bits
17. Calculate the BER for the system

# Chapter 4

# Results and Inferences

# CHAPTER 4

# RESULTS AND INFERENCES

In this chapter we look at the various results of the simulations our models have gone through. We begin by showing that the system parameter, BER is within the required limits (less than $10^{-5}$) and also discuss the time taken to transmit $10^6$ bits in the various schemes. We also compare and contrast the results obtained across different schemes and draw conclusions.

## 4.1 Parameters for Simulations

The common channel parameters for all simulations is as follows

- In all simulations the noise power spectral density is -80 dBm/Hz
- The distance between the transmitting and receiving antenna is 1km
- The gain of the BS antenna is 8 and UE antenna is taken as 1
- A total of $10^6$ bits are transmitted in all cases
- The maximum number of bits that can be loaded on a subchannel in case of tone loading operation being performed at the transmitter is 20 bits.
- The number of subchannels is taken to be 256.
- The power input to the transmitter is 1 mW.

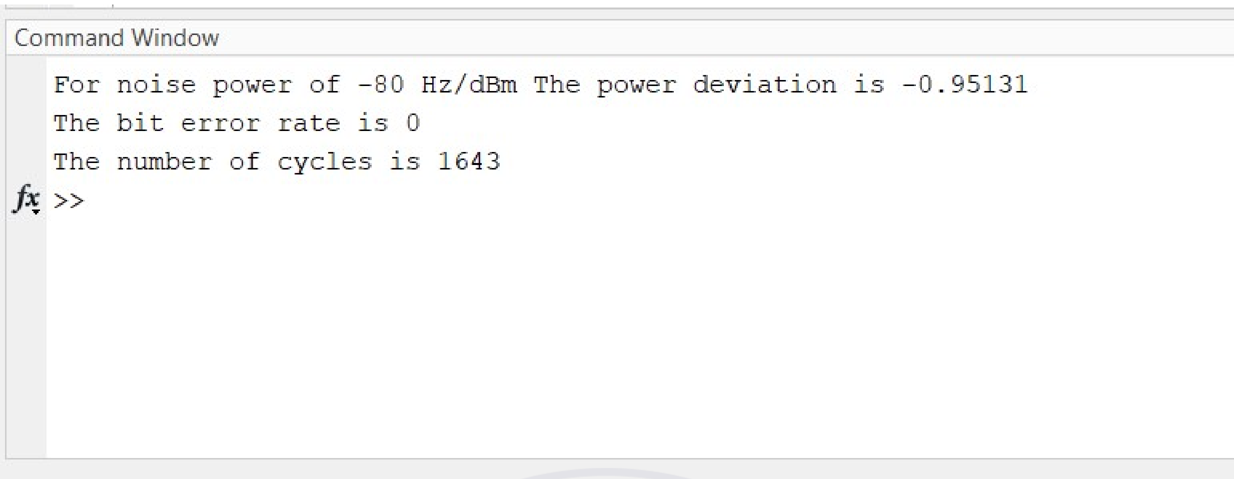
Apart from these there are certain randomized parameters such as the Rayleigh fading coefficient and the noise signal which is additive white Gaussian in nature.

## 4.2 SISO System Results

The result for the SISO simulation is shown in figure 4.1. The BER is observed to be 0, which is within the expected range. Also, the total power deviation due to rounding of the number of bits per tone is $-0.95131$ dB which is less than our threshold value of $\pm 2$ dB.

We observe in figure 4.2 that the subchannels with higher SNR have more bits loaded onto them which is the expected behavior of our tone loading algorithm.

Since we have only one antenna path to transmit $10^6$ bits, we need a total of 1643 cycles of transmitting bits as per the tone loading profile in 4.2. We shall see how using MIMO systems improve this rate.



```
Command Window
For noise power of -80 Hz/dBm The power deviation is -0.95131
The bit error rate is 0
The number of cycles is 1643
fx >>
```

Figure 4.1: The performance of our SISO system. The number of cycles taken to transmit the bits is of particular importance to us.

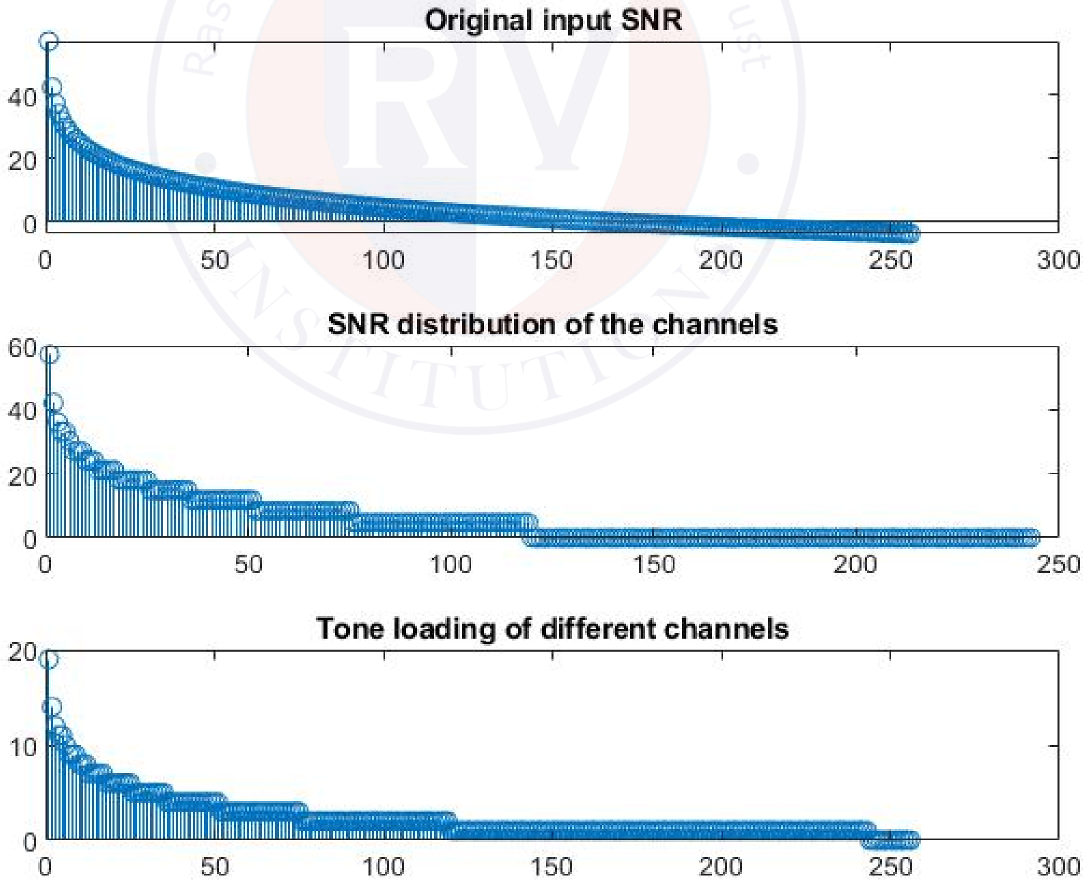



Figure 4.2: The tone loading profile of various subchannels for SISO mode.

## 4.3 SIMO System Results

The result for the SIMO simulation is shown in figure 4.3. The BER is observed to be 0, which is within the expected range. Also, the total power deviation due to rounding of the number of bits per tone is $-1.82$ dB which is less than our threshold value of $\pm 2$ dB.

We observe in figure 4.4 that the subchannels with higher SNR have more bits loaded onto them which is the expected behavior of our tone loading algorithm.

To transmit $10^6$ bits, we need a total of 1051 cycles of transmitting bits as per the tone loading profile in 4.4. This is done again in diversity mode. We shall see how using MIMO systems improve this rate.

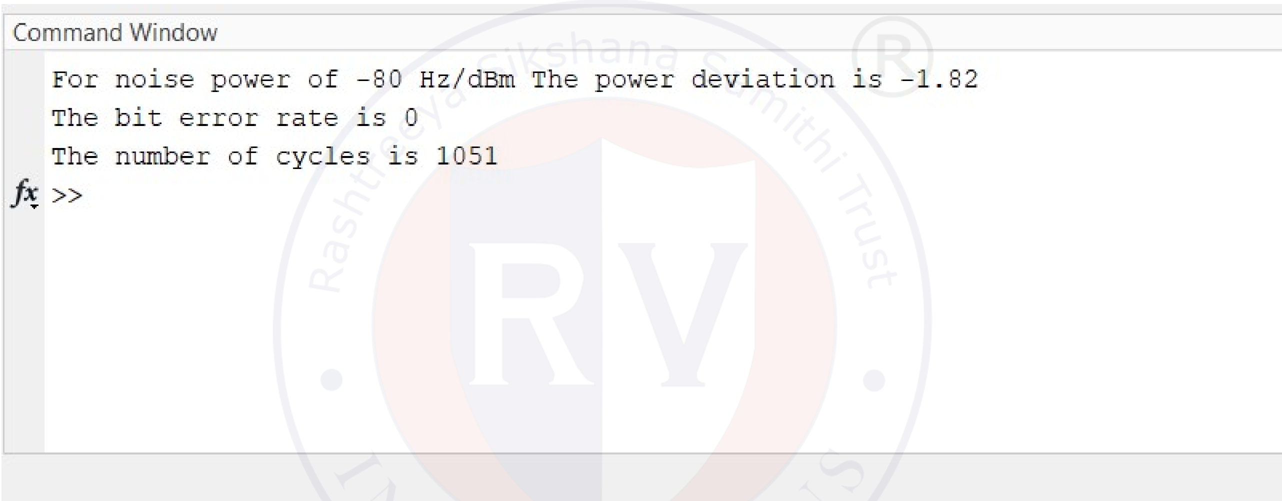



Figure 4.3: The performance of our SIMO system. The number of cycles taken to transmit the bits is of particular importance to us.

## 4.4 MISO System Results

The result for the MISO simulation is shown in the figure 4.5. The BER is observed to be 0, which is within the expected range. We do not perform any tone loading as we use a Alamouti precoding scheme. It takes only 98 cycles to transmit the $10^6$ bits.

## 4.5 MIMO System Results

### 4.5.1 MIMO Diversity Case

The result for the MIMO simulation in diversity case is shown in figure 4.7. The BER is observed to be 0, which is within the expected range. Also, the total power deviation due to rounding of the number of bits per tone is $-1.3892$ dB which is less than our

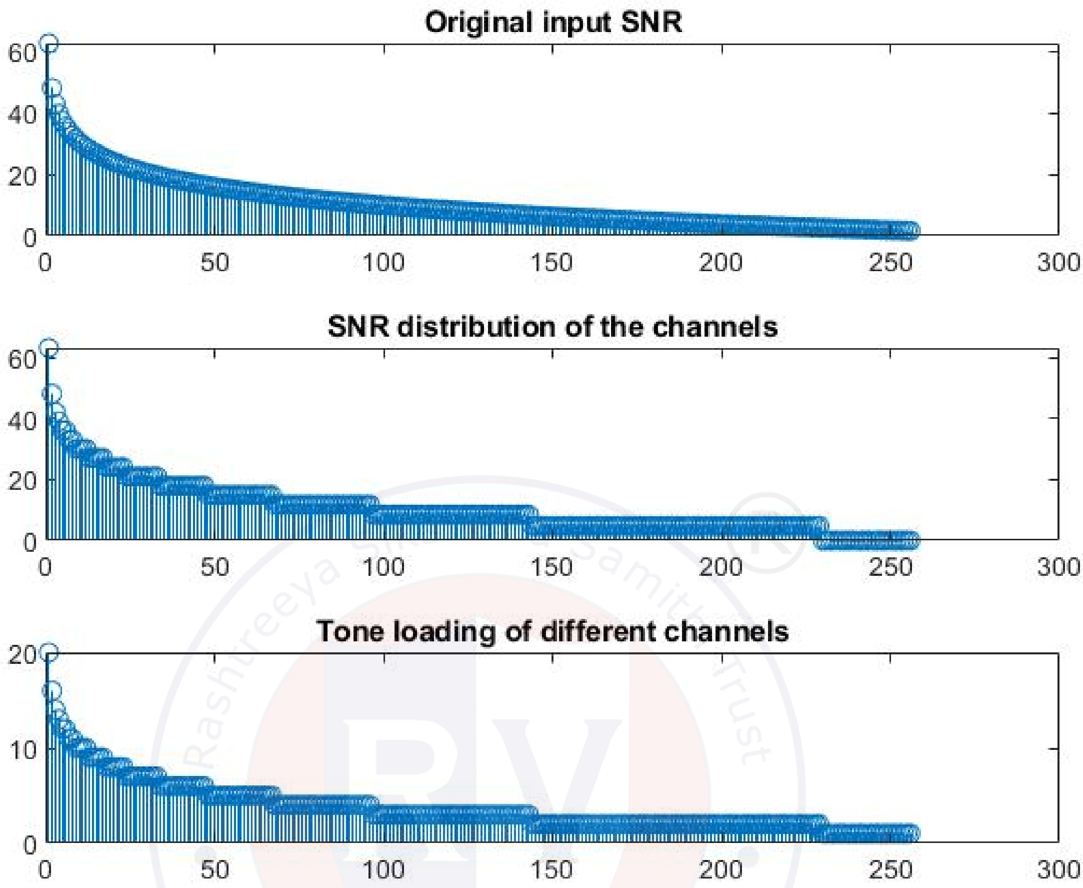



Figure 4.4: The tone loading profile of various subchannels for SIMO mode.

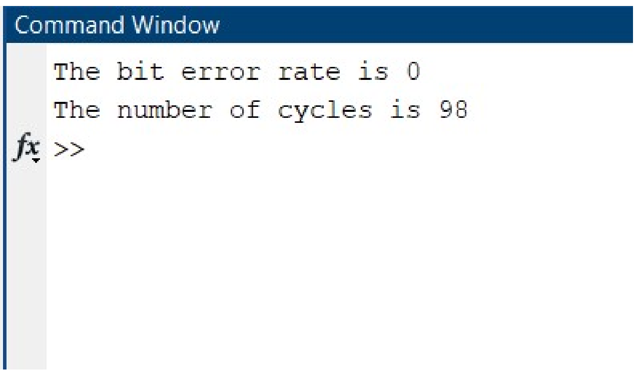



Figure 4.5: MISO System Performance.

threshold value of ±2 dB.

We observe in figure 4.6 that the subchannels with higher SNR have more bits loaded onto them which is the expected behavior of our tone loading algorithm.

Although we have many antenna paths to transmit $10^6$ bits, since we are operating in diversity mode we need a total of 1303 cycles of transmitting bits as per the tone loading profile in 4.6. We shall see how operating MIMO in multiplexing mode can vastly improve this system performance.

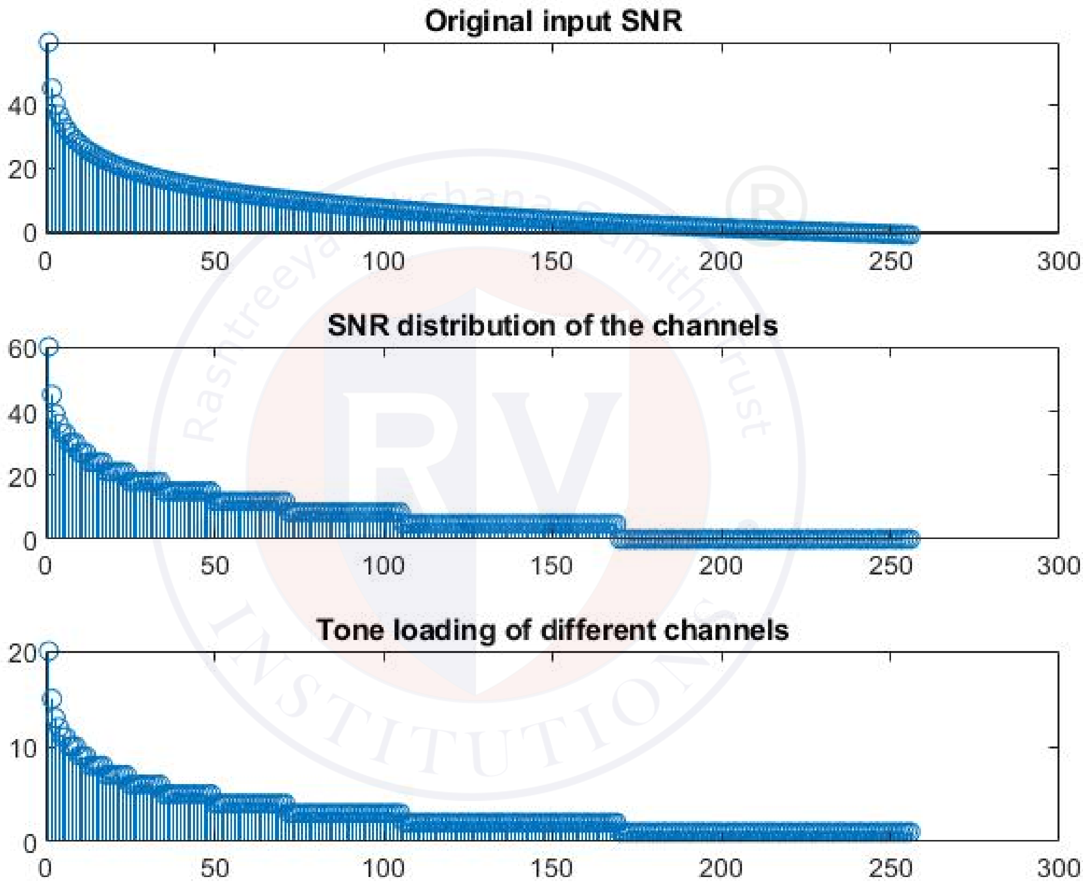



Figure 4.6: The tone loading profile of various subchannels for MIMO in diversity mode.

### 4.5.2 MIMO Multiplexing Case

The result for the MIMO simulation in multiplexing case is shown in figure 4.9. The BER is observed to be 0, which is within the expected range. Also, the total power deviation due to rounding of the number of bits per tone is −0.65038 dB which is less than our threshold value of ±2 dB.

We observe in figure 4.8 that the subchannels with higher SNR have more bits loaded

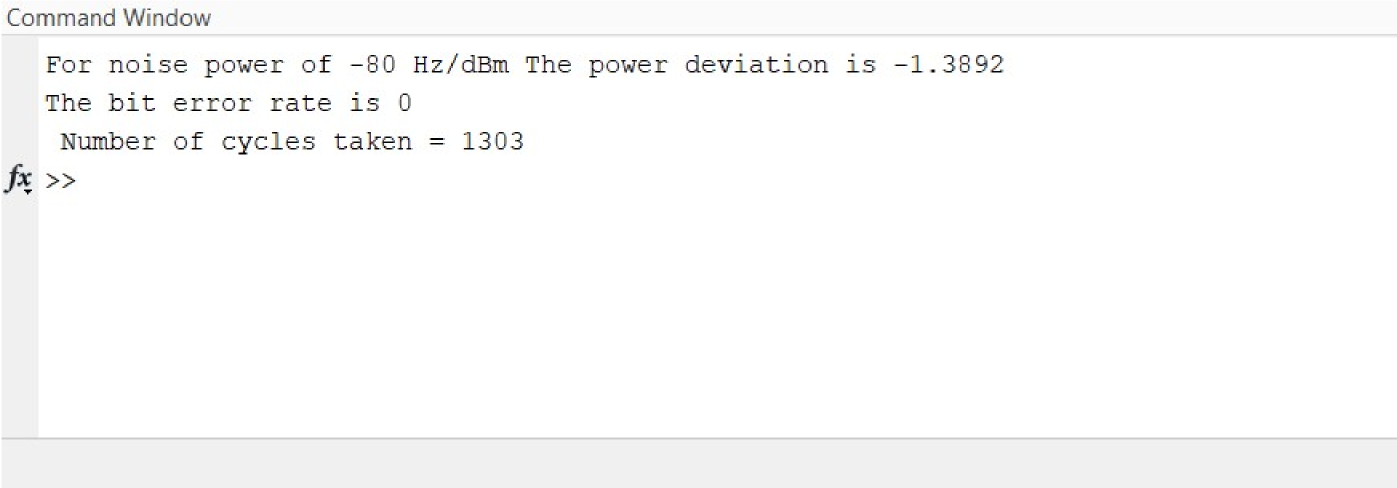



Figure 4.7: The performance of our MIMO system. The number of cycles taken to transmit the bits is of particular importance to us.

onto them which is the expected behavior of our tone loading algorithm.

Since we have many antenna paths to transmit $10^6$ bits, we only 797 cycles of transmitting bits as per the tone loading profile in 4.6. As we see, in the multiplexing case, the number of cycles have reduced considerably directly interfering higher data rates.

### 4.5.3 MIMO Multiplexing with Inverse Channel Estimation Precoder

The result for the MIMO simulation for multiplexing case with inverse channel estimation precoder is shown in the figure 4.10. The BER is observed to be 0, which is within the expected range. We do not perform any tone loading as we use a Inverse Channel Estimation precoding scheme. It takes only 98 cycles to transmit the $10^6$ bits. We notice how by using suitable precoding the number of cycles reduce drastically.

### 4.5.4 MIMO Multiplexing with Singular Value Decomposition Precoder

The result for the MIMO simulation for multiplexing case with singular value decomposition precoder is shown in the figure 4.11. The BER is observed to be 0, which is within the expected range. We do not perform any tone loading as we use a Singular Value Decomposition precoding scheme. It takes only 98 cycles to transmit the $10^6$ bits. We notice how by using suitable precoding the number of cycles reduce drastically.

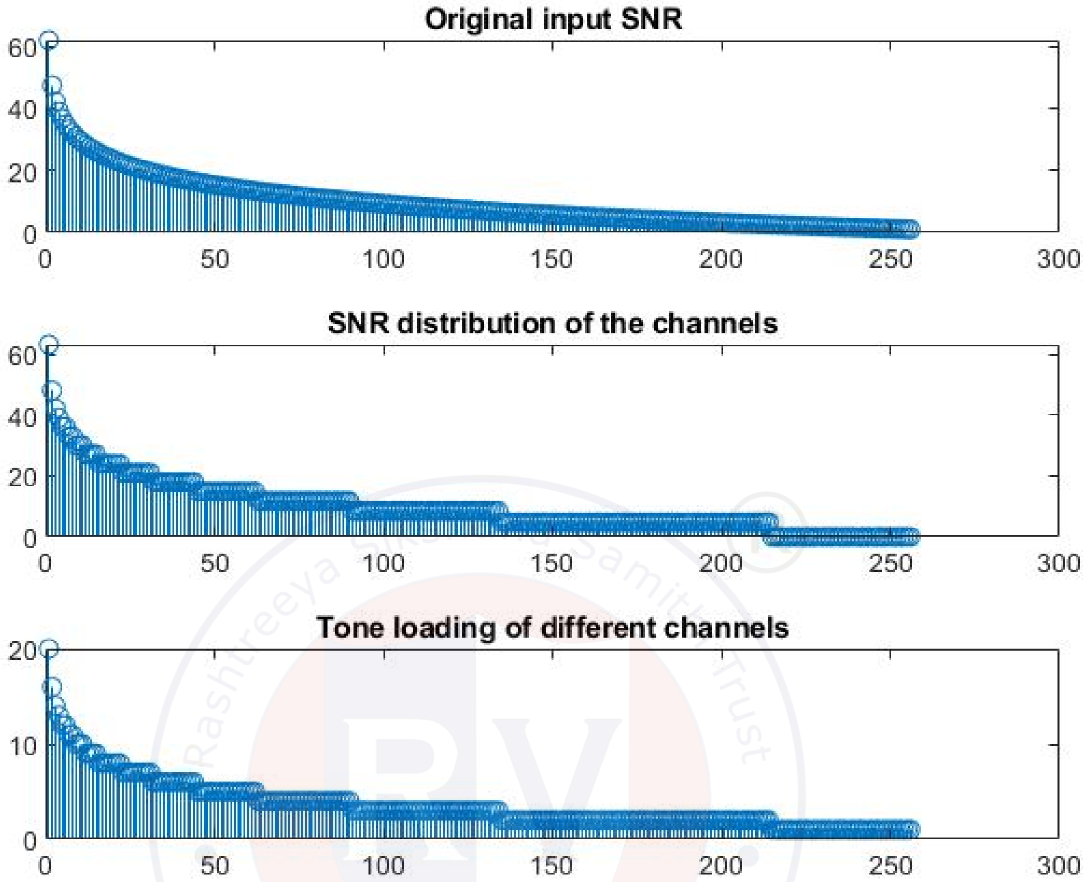



Figure 4.8: The tone loading profile of various subchannels for MIMO in diversity mode.

```
Command Window
For noise power of -80 Hz/dBm The power deviation is -1.2775
The power deviation is -0.65038
The bit error rate is 0
 Number of cycles taken = 797
fx >>
```

Figure 4.9: The performance of our MIMO system. The number of cycles taken to transmit the bits is of particular importance to us.

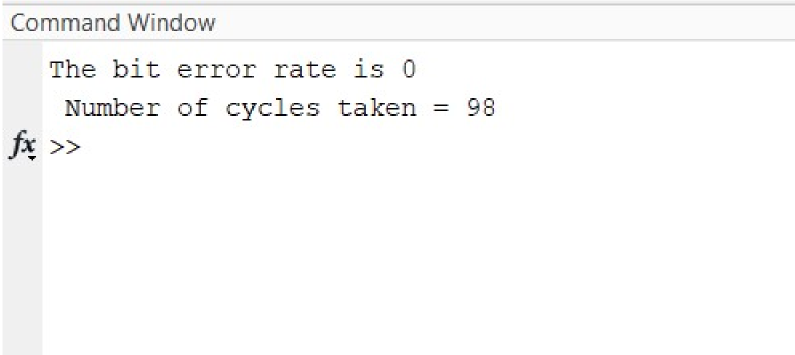



Figure 4.10: MIMO System Performance with Inverse Channel Estimation Precoder.

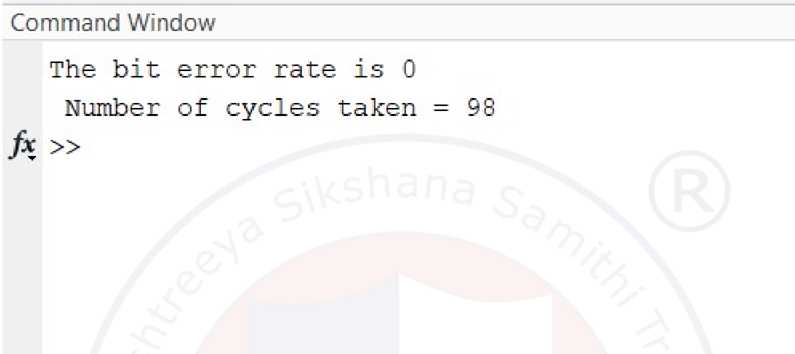



Figure 4.11: MIMO System Performance with Singular Value Decomposition Precoder.

## Summary

In this section we discussed the results of the simulations of our system in various configurations. We clearly see that data rates increase with multiplexing mode and also with precoding. Finally, in the last section we conclude our report and talk about the future scope of the report and how further improvements can be made to our system.

# Chapter 5

# Conclusion and Future Scope

# CHAPTER 5

# CONCLUSION AND FUTURE SCOPE

We end this report by stating that we have definitively shown in this report through our simulations, that MCM and MIMO can be effectively used to improve user capacity and data rates. We have shown how switching to diversity in low SNR regimes and multiplexing in high SNR regimes can maintain good Quality of Service for users. Thus, we can build upon existing 4G and 5G systems and expand them to be used in multiplexing scheme along with diversity.

## 5.1 Future Scope

For readers, we suggest further improvements can be done by improving upon the channel modeling by introducing more real world phenomenon like shadowing and use more complex path loss functions like Ricean distribution.
Another scope for improvisation is in the scope of the system. Here, we have limited ourselves to $2 \times 2$ MIMO systems. We encourage the reader to implement large systems leading to massive MIMO systems.

# BIBLIOGRAPHY


[1] D. George and T. Hatt, "Global Mobile Trends," *GSMA Intelligence*, 2017. [Online]. Available: https://www.gsmaintelligence.com/research/?file=3df1b7d57b1e63a0cbc3d585 download.

[2] S. Weinstein and P. Ebert, "Data transmission by frequency-division multiplexing using the discrete fourier transform," *IEEE Transactions on Communication Technology*, vol. 19, no. 5, pp. 628–634, 1971. DOI: 10.1109/TCOM.1971.1090705.

[3] Yiyan Wu and W. Y. Zou, "Orthogonal frequency division multiplexing: A multicarrier modulation scheme," *IEEE Transactions on Consumer Electronics*, vol. 41, no. 3, pp. 392–399, 1995. DOI: 10.1109/30.468055.

[4] F. Bellili, A. Methenni, and S. Affes, "Closed-form crlbs for cfo and phase estimation from turbo-coded square-qam-modulated transmissions," *IEEE Transactions on Wireless Communications*, vol. 14, pp. 2513–2531, May 2015. DOI: 10.1109/TWC.2014.2387855.

[5] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998. DOI: 10.1109/49.730453.

[6] V. Klema and A. Laub, "The singular value decomposition: Its computation and some applications," *IEEE Transactions on Automatic Control*, vol. 25, no. 2, pp. 164–176, 1980. DOI: 10.1109/TAC.1980.1102314.

[7] L. Hanlen and M. Fu, "Wireless communication systems with-spatial diversity: A volumetric model," *IEEE Transactions on Wireless Communications*, vol. 5, no. 1, pp. 133–142, 2006. DOI: 10.1109/TWC.2006.1576537.

[8] ITU, *Asymmetric digital subscriber line transceivers 2 (adsl2)*, 2009.

[9] A. Peinado and A. Fúster-Sabater, "Generation of pseudorandom binary sequences by means of linear feedback shift registers (lfsrs) with dynamic feedback," *Mathematical and Computer Modelling*, vol. 57, no. 11, pp. 2596–2604, 2013, Information System Security and Performance Modeling and Simulation for Future Mobile Networks, ISSN: 0895-7177. DOI: https://doi.org/10.1016/j.mcm.2011.07.023.

[Online]. Available: http://www.sciencedirect.com/science/article/pii/S0895717711004341.

[10] P. S. Chow, J. M. Cioffi, and J. A. C. Bingham, "A practical discrete multitone transceiver loading algorithm for data transmission over spectrally shaped channels," *IEEE Transactions on Communications*, vol. 43, no. 2/3/4, pp. 773–775, 1995. DOI: 10.1109/26.380108.

[11] C. E. Shannon, "A mathematical theory of communication," *The Bell System Technical Journal*, vol. 27, no. 3, pp. 379–423, 1948. DOI: 10.1002/j.1538-7305.1948.tb01338.x.

[12] A. Ghosh, J. Zhang, J. G, and R. Muhammad, *Fundamentals of LTE.* Prentice Hall, 2010.