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Development of MCM-MIMO Processing for Urban Cellular Link

A Project Report

Submitted by,

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In partial fulfillment of the requirements for the degree of

Bachelor of Engineering in

Electronics and Communication Engineering

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RV College of Engineering®, Bengaluru

(Autonomous institution affiliated to VTU, Belagavi)

Department of Electronics and Communication Engineering

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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.

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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. In this report, a methodology is developed 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 to address this problem through MCM and MIMO.

MIMO however is too broad a term as it consists of various configurations and setups. A system which can be operated in two modes is designed, namely diversity and multiplexing. Diversity is suitable for low SNR regimes where, 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 the option exists to maximize data rates and capacity by transmitting differing data over good channels. that are already providing good BER.

This report shows the simulations of the work with the help of MATLAB. The ultimate goal of this report is to design a 2×2 MIMO system and in this regard, at first a SISO system is designed to lay the foundation for multi carrier communication systems. Further, a 1×2 SIMO and 2×1 MISO system is also designed to operate in diversity mode. Finally, a 2×2 MIMO system is designed to work in both diversity and multiplexing modes to improve the data rates and capacities. The design of this system employs unique precoding schemes like Alamouti coding, Inverse Channel Estimation precoding and SVD precoding. This report also demonstrates the use of Rayleigh fading and Friis' path loss formula for real world simulation purposes.

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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

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

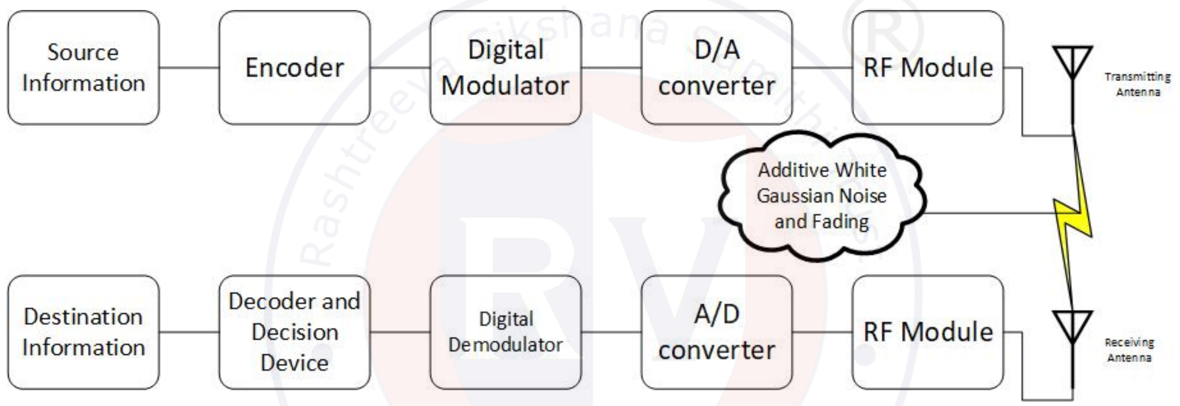

Figure 1.1: Wireless Digital Communication System

In further chapters the discussion is on the various components of this system and the different techniques used in implementing them in MATLAB. In this report the concern is only with the digital aspects of the system and not much attention is paid 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 this report tries to address is the improvement of capacity and data rates in wireless communication systems. Using SISO systems, theoretically one can achieve high rates. However, there is a current discomfort with the design of these systems as there is a need to design complex equalizers, allocate large power budgets or have cost prohibitive modems all of which make SISO systems unviable for communication.

1.4 Objectives

The objectives of the project is to initially build a SISO system which is used as a reference for further 2 antenna SIMO, MISO systems. Finally a 2×2 MIMO systems is developed to examine ways to improve SNR for 2 antenna systems and capacity for high SNR regimes by using MCM-MIMO systems.

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. This report is built upon the work of Weinstein and Ebert [2] where a low cost and easy to implement solution is offered 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, the decision is made to use QAM as it is best suited for the purposes of this report. However, to achieve effective higher order QAM constellations this report follows 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 2×1 MISO systems where the choice is made to go for spatial diversity scheme, this report includes some precoding measures as suggested by Alamouti [5] so that the burden on the system is eased and overall system performance is improved. Apart from this this report also uses precoding schemes like inverse channel coders and singular value decomposers as suggested by Klema and Laub [6] as huge improvements are noticed in speed by using these methods.

1.5.3 Channel Modeling

In terms of modeling the real world channel, one must consider various random processes to accurately define the channel. However, for the sake of simplicity this report models multipath systems as previously shown by Hanlen and Fu [7] where more importance is placed on Rayleigh fading and ignore other effects like those of shadowing. Although, Rayleigh fading is a statistically simple model, it does a good job 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, this report also take into consideration the aspects of noise that the channel adds to our data signal. Similarly as before, this report has chosen AWGN type of noise to represent an accurate but simplistic model. In the survey of literature it was noticed that most research scholars stick to a similar approach and this reports follows in the same footsteps.

1.5.4 Transceiver Architecture and Channel Loading Methods

Transceiver Architecture

In the design of the transmitter and receiver systems, this report relies upon standards set by the ITU as per their technical document ITU [8]. This report builds 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]. This report also follows the same ITU [8] standard in designing the 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]. The claim is 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. While studying the existing literature it was found that the method followed by Chow, Cioffi, and Bingham [10] was effective but unsuitable as it is rate adaptive in nature. Therefore, this report draws inspiration from this tone loading algorithm to define a new 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 the requirements well while also being highly optimal.

1.6 Brief Methodology of the project

The basic methodology of this project is

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

To help achieve our objectives this report are follows the steps as stated below.

- A SISO system is developed for reference and this shows the performance of single channel systems to firmly establish the need for MCM-MIMO systems.
- Using this SISO system as a foundatio SIMO and MISO systems are built which operate in diversity modes to elaborate how BER can be improved for 2 antenna systems.
- Rayleigh fading is introduced in the channel and modelling of LOS path loss function is done with the help of Friis' formula.

- The transmitter is assumed to be operating on a power budget of $1mW$.
- Then a MIMO system is designed which is capable of operating in both diversity and multiplexing modes to finally observe the improvement in data rates and capacity over SISO systems.

1.7 Organization of the report

This report is organized as follows.

- Chapter 2 discusses the fundamentals of MCM and MIMO systems. The discussion is on the key technologies in MCM and MIMO that enable it to be an effective solution for modern cellular systems. Along with this the chapter discusses some of the challenges faced in their implementation.
- Chapter 3 informs the reader about the steps taken to design the communication system delving into the details of the design parameters and algorithms used.
- Chapter 4 shows the results obtained by performing simulations of our system on MATLAB. Comparison of performance between existing systems and this system is shown and the effectiveness of this system is highlighted.
- Chapter 5 is the final chapter where the report is concluded and the scope for future research is mentioned. This section also lists some additional features that can be added to the 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. This report firmly establishes some of the prerequisite learning required before the report can discuss the actual design of the system in the next chapter. This report begins by looking at the shortcomings of single channel systems and how they can be overcome with the help of MCM. This report also highlights how some of the shortcomings of single channel systems can be used to our advantage in MCM-MIMO systems. This report also spends 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, a simple Line Of Sight path loss function (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, one must come up with large scale and complex systems of transmitters and receivers to meet the demand. In this report, the implementation of various versions of MIMO upto 2×2 is shown. MIMO itself can be used in various ways namely multiplexing and diversity. In the following sections this report takes a closer look at these configurations.

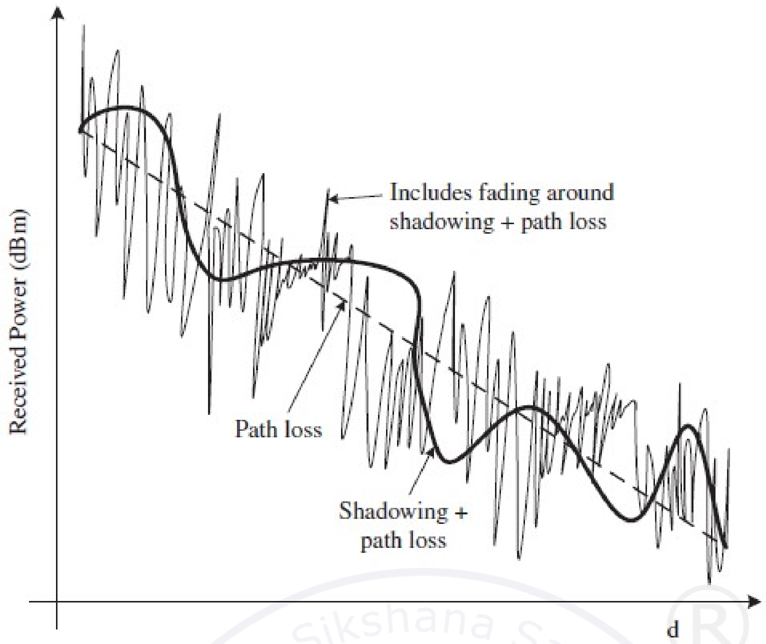

Figure 2.1: Variation of Received Signal Power with Distance of separation (d) between transmitter and receiver. Source Ghosh, Zhang, G, *et al.* [12]

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 this report refers 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-

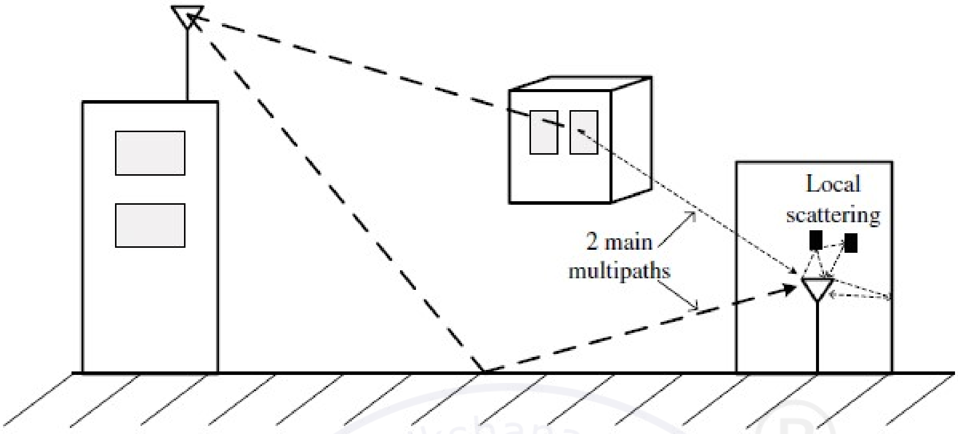

Figure 2.2: Multipath Propagation in a typical urban setting. Source Ghosh, Zhang, G, *et al.* [12]

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 one is in a high SNR regime, instead of sending multiple copies of the same data, one 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 one 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 one is given the various options for multiplexing, one 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, one sees the significant advantages MIMO has enabled for us by opening the doors to MIMO and MCM.

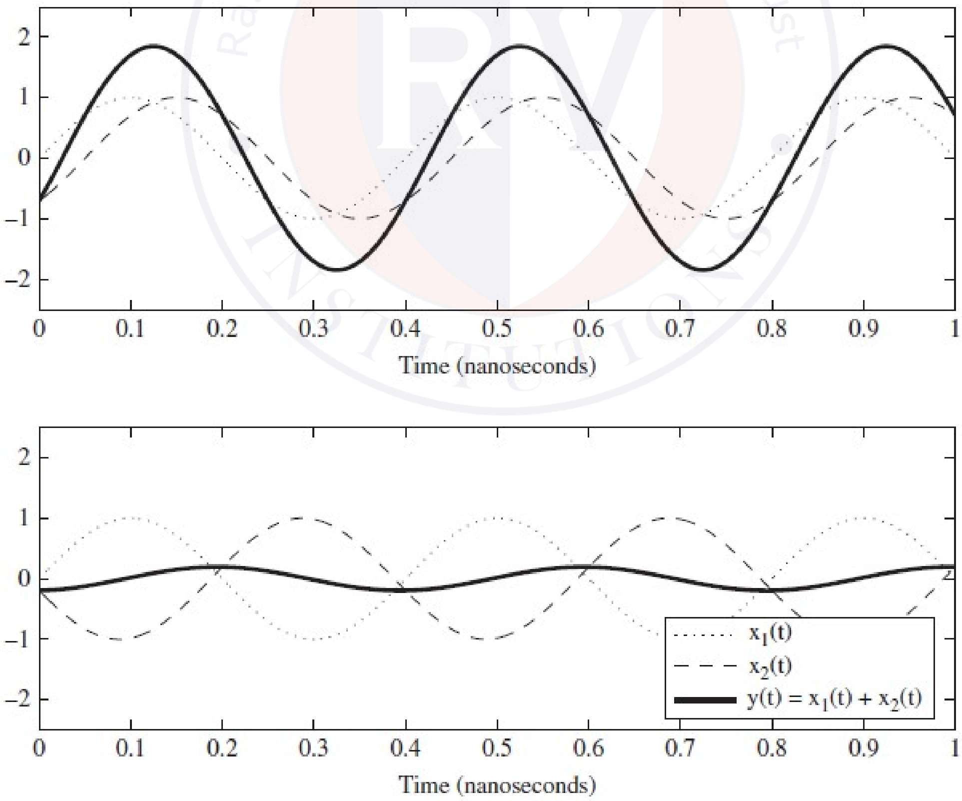

Figure 2.3: Constructive and Destructive Interference leading to large variation in received signal power. Source Ghosh, Zhang, G, *et al.* [12]

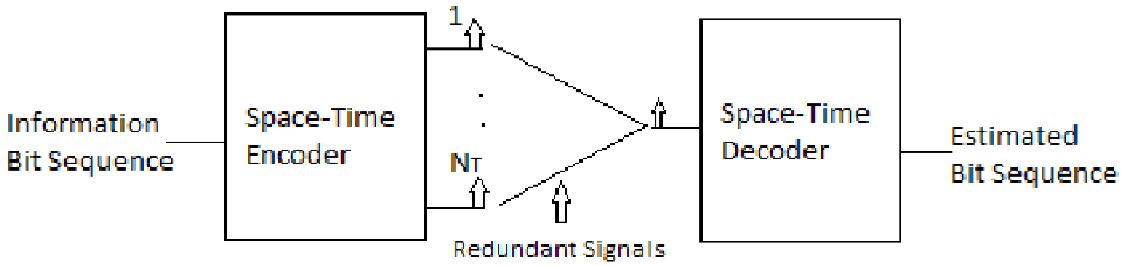

Figure 2.4: Spatial Diversity. SourceGhosh, Zhang, G, *et al.* [12]

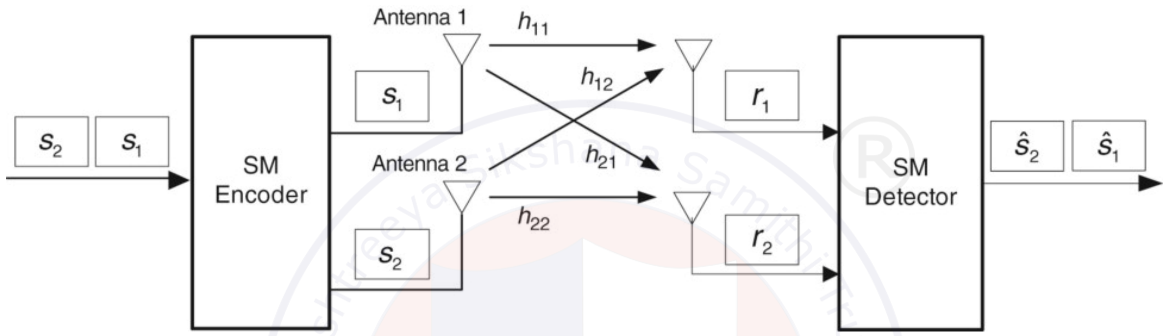

Figure 2.5: Spatial Multiplexing

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

In the previous section readers 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 one realizes that one 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, one is 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.

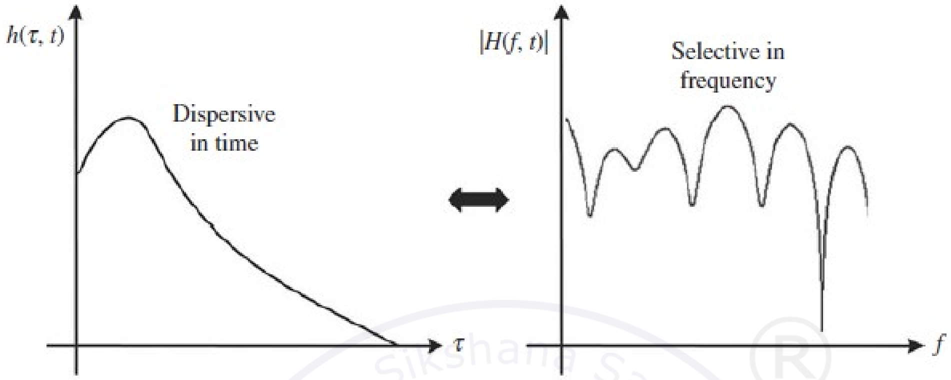

Figure 2.6: Frequency Selective Fading which occurs because the message is longer than the delay spread of the channel. Source Ghosh, Zhang, G, *et al.* [12]

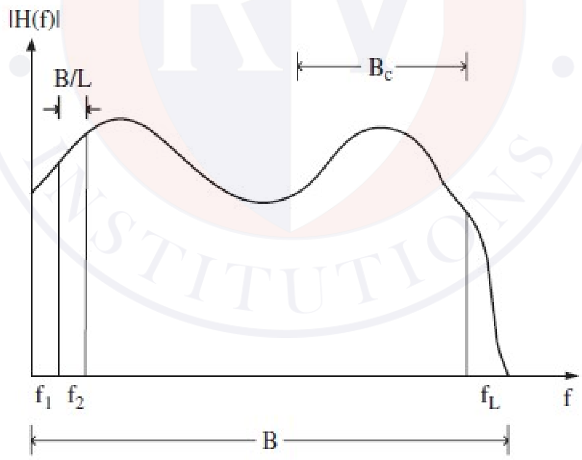

Figure 2.7: By breaking the large bandwidth into smaller subchannels, one can achieve an almost flat fading subchannel which is desirable. Source Ghosh, Zhang, G, *et al.* [12]

2.5 Shortcomings of simple MCM and the need for OFDM

Having shown the implementation of a simple MCM system, this report now addresses some of the shortcomings of this. Primarily,

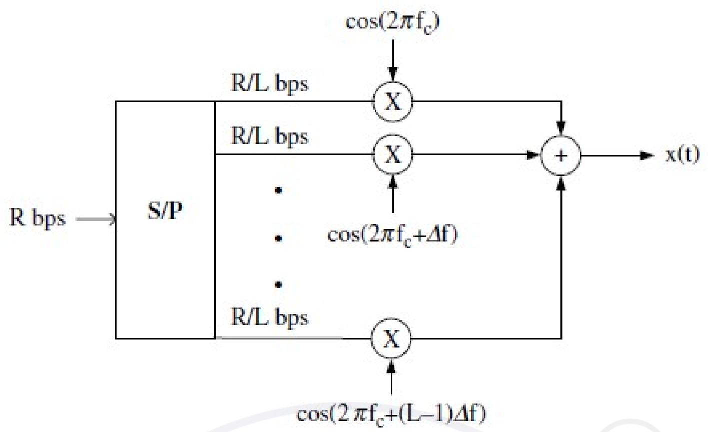

Figure 2.8: An MCM transmitter with an IFFT block to split the given bandwidth into smaller L subchannels. Source Ghosh, Zhang, G, *et al.* [12]

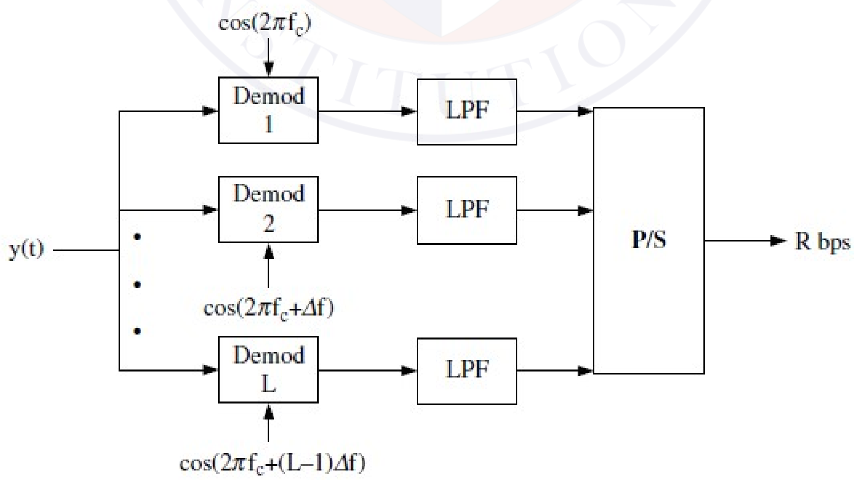

Figure 2.9: An MCM transmitter with an FFT block to reverse the effects of IFFT block at the transmitter. Source Ghosh, Zhang, G, *et al.* [12]

- 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 the reader shall 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, one clubs 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.

One knows 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, one knows 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.

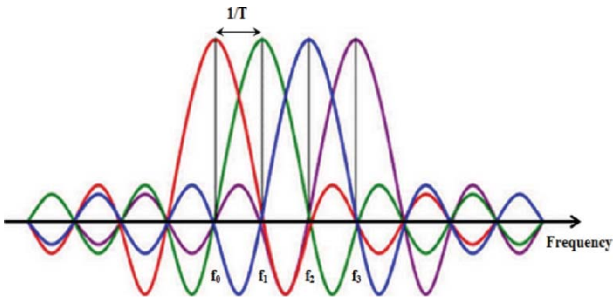

Figure 2.10: An OFDM symbol where different coloured waves correspond to different bits. Notice how when one wave peaks, all the other waves are at their null points. Source Ghosh, Zhang, G, *et al.* [12]

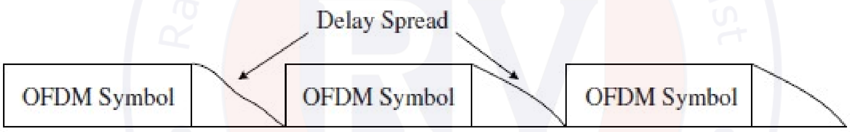

Figure 2.11: A delay of T_g is introduced between the symbols to avoid interference between the OFDM symbols. Notice that this does not do anything to combat ISI within the OFDM symbol itself.

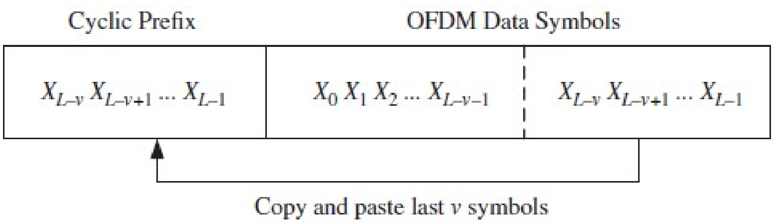

Figure 2.12: The cyclic prefix in an OFDM symbol. Source Ghosh, Zhang, G, *et al.* [12]

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, the different concepts are all combined to create an OFDM transceiver which is capable of sending and receiving data bits packaged in OFDM symbols.
In figure 2.13 one can 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

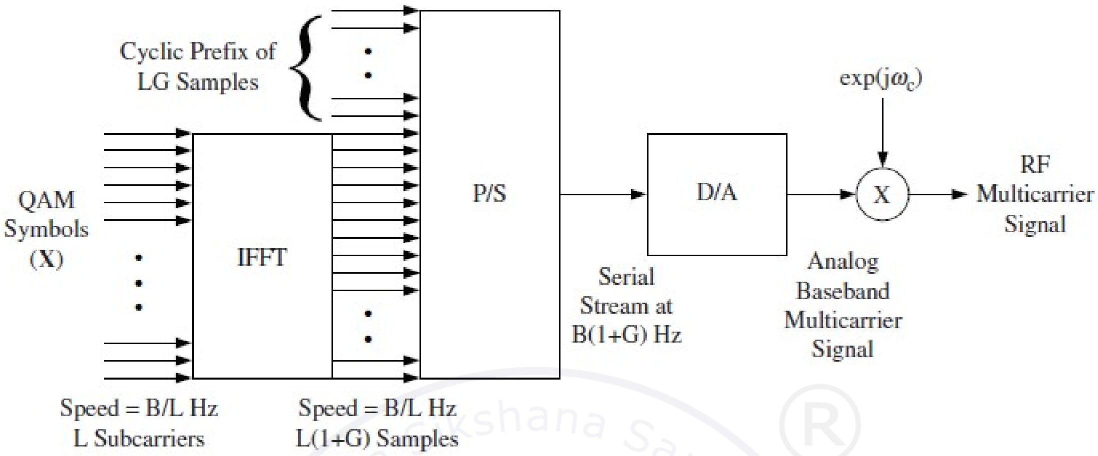

Figure 2.13: OFDM Transmitter. Source Ghosh, Zhang, G, *et al.* [12]

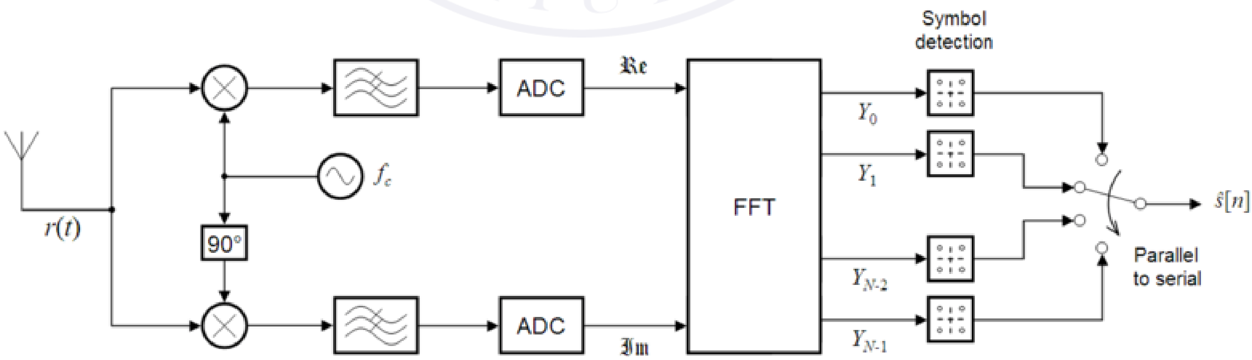

Figure 2.14: OFDM Receiver. Source Ghosh, Zhang, G, *et al.* [12]

transmitter need not know the channel information before sending the data. This section describes the coding scheme.

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.

$$y_1 = \begin{bmatrix} h_1 & h_2 \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + w_1 \tag{2.1}$$

$$y_2 = \begin{bmatrix} h_1 & h_2 \end{bmatrix} \times \begin{bmatrix} -x_2{}^* \\ x_1^* \end{bmatrix} + w_2 \tag{2.2}$$

This can be further simplified as,

$$y = \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = c_1 x_1 + c_2 x_2 + w \tag{2.3}$$

Where,

$$c_1 = \begin{bmatrix} h_1 \\ h_2^* \end{bmatrix} \tag{2.4}$$

$$c_2 = \begin{bmatrix} h_2 \\ -h_1^* \end{bmatrix} \tag{2.5}$$

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 the matrix y is obtained, x_1 and x_2 can be recovered as follows,

$$\frac{c_1^H}{||c_1||} \cdot y = ||c_1||x_1 + \overline{w_1} \tag{2.6}$$

$$\frac{c_2^H}{||c_2||} \cdot y = ||c_2||x_2 + \overline{w_2} \tag{2.7}$$

Here, c_1^H and c_2^H are the result obtained after performing the Hermitian operator on the c matrices. It is noticed 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 2×1 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

$$\begin{bmatrix} y \end{bmatrix} = \begin{bmatrix} x \end{bmatrix} \times \begin{bmatrix} h \end{bmatrix} + \begin{bmatrix} n \end{bmatrix} \tag{2.8}$$

where $\begin{bmatrix} n \end{bmatrix}$ is the AWGN noise vector.
From this, one 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.

$$\begin{bmatrix} y \end{bmatrix} \times \begin{bmatrix} h \end{bmatrix}^{-1} = \begin{bmatrix} x \end{bmatrix} + \begin{bmatrix} w_1 \end{bmatrix} \tag{2.9}$$

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 that us faced is that $\begin{bmatrix} w_1 \end{bmatrix}$ is no longer AWGN but becomes colored noise. Therefore, to overcome this hindrance, precoding of the transmitted symbols vector $\begin{bmatrix} x \end{bmatrix}$ is done by multiplying it with $\begin{bmatrix} h \end{bmatrix}^{-1}$. The received vector $\begin{bmatrix} y \end{bmatrix}$ then becomes

$$\begin{bmatrix} y \end{bmatrix} = \begin{bmatrix} x \end{bmatrix} \times \begin{bmatrix} h \end{bmatrix}^{-1} + \begin{bmatrix} n \end{bmatrix} \tag{2.10}$$

Finally, when one tries and extracts the transmitted symbols at the receiver by multiplying with $\begin{bmatrix} h \end{bmatrix}$ one gets

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

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 readers 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 it is required to have high speed modems which do not take more than a few microseconds to make the necessary computations, one must look to faster ways of inverting the channel coefficient matrix.

In this effort this report uses the singular value decomposition technique where one decomposes 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 one multiplies the transmitted symbol vector $\begin{bmatrix} x \end{bmatrix}$ with $\begin{bmatrix} V \end{bmatrix}$ and similarly at the receiver one multiplies 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

This chapter has elaborated on the motivations behind MCM and MIMO. The authors have also clearly elaborated on the key technologies that enable them. The next chapter discusses the implementation details of the MCM-MIMO system and explains the different algorithms used. Finally, in Chapter 4 the results obtained after simulations are discussed and conclusions are drawn 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.

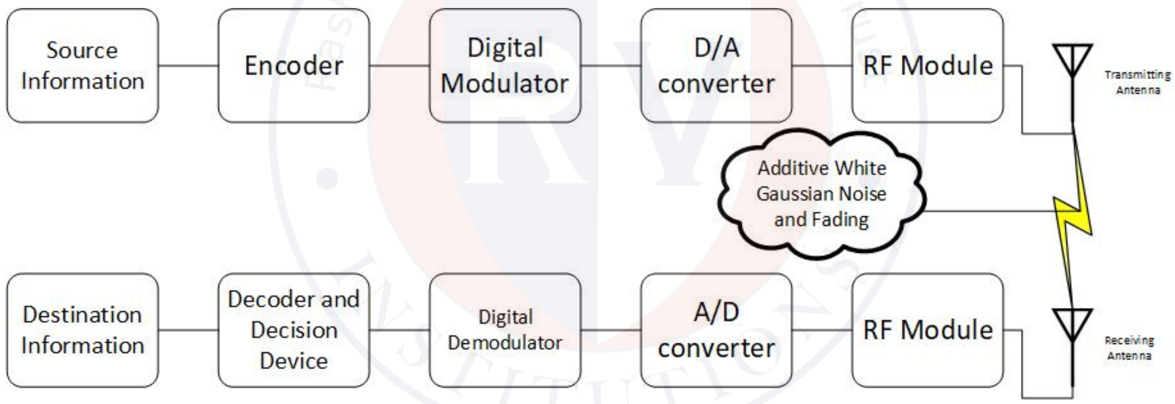

Figure 3.1: General Wireless Communication System Block Diagram

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

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

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 σ 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

λ = 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

This chapter looks at the various results of the simulations the models have gone through. It is shown that the system parameter, BER is within the required limits (less than 10^{-5}) and the report also discusses the time taken to transmit 10^6 bits in the various schemes. Comparisons and contrasts are drawn between the results obtained across different schemes and conclusions are drawn.

4.1 List of Simulations and their Parameters

The list of various simulations and their parameters is given in 4.1.

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
- 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 ± 2 dB.

It is observed 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.

Inference:

Table 4.1: List of Simulations and Parameters

Simulation Parameters				
Simulation Mode	Number of bits	Precoding Scheme	BER	Number of cycles
SISO	10^6	-	0	1643
SIMO	10^6	Alamouti Precoding	0	1051
MISO	10^6	-	0	98
MIMO	10^6	Inverse Channel Estimation Precoding and Singular Value Decomposition Precoding	0	98

Since there is only one antenna path to transmit 10^6 bits, there is a need of a total of 1643 cycles of transmitting bits as per the tone loading profile in 4.2. Due to the lack of multiple antenna paths, it takes a long time to transmit the bits. To improve the speed (data rate), one must either improve the SNR of the channel to improve the channel capacity or go for MCM-MIMO system. Since the first option is not in our control, it is discussed in the future sections how MCM-MIMO can improve the data rates and capacity.

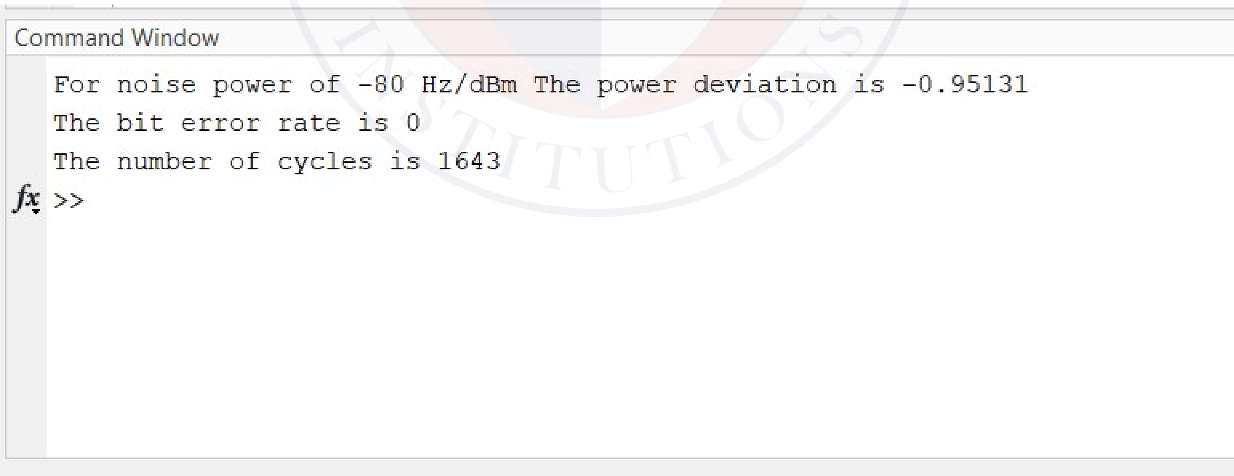

Figure 4.1: The performance of our SISO system. The number of cycles taken to transmit the bits is of particular importance to us.

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

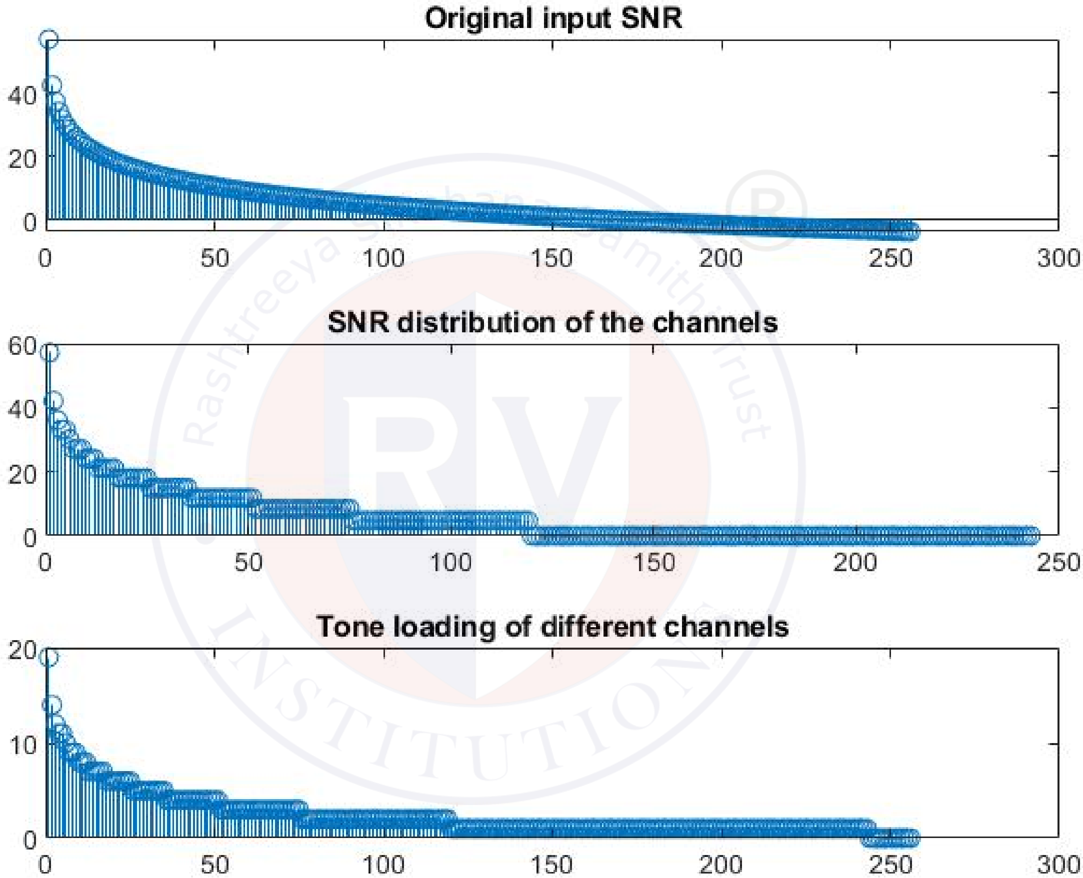

Figure 4.2: The tone loading profile of various subchannels for SISO mode.

of the number of bits per tone is -1.82 dB which is less than our threshold value of ± 2 dB.

It is observed 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.

Inference:

To transmit 10^6 bits, one needs a total of 1051 cycles of transmitting bits as per the tone loading profile in 4.4. This case is also known as receiver diversity, wherein one chooses the best path between the transmitter and receiver and use that path for the transmission of data. By periodically checking for the best path, it is possible to maintain a good quality link between transmitter and receiver that despite bad channel conditions.

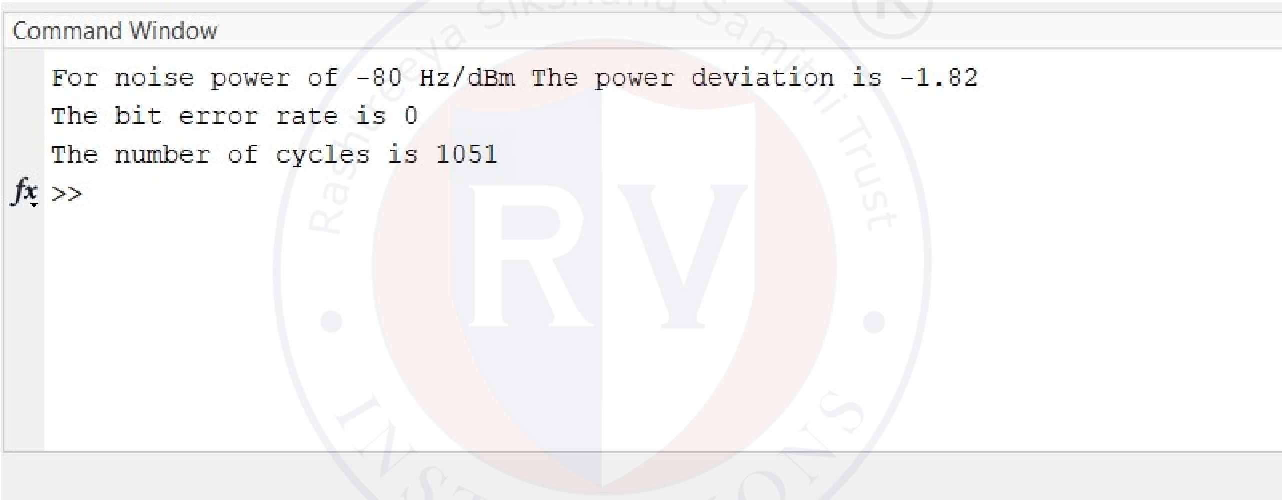

Figure 4.3: The performance of our SIMO system. The number of cycles taken to transmit the bits is of particular importance to us.

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. One need not perform any tone loading as Alamouti precoding scheme is used.

Inference:

It takes only 98 cycles to transmit the 10^6 bits. Since there are multiple transmitting antennas that use Alamouti coding, one is able to send 2 symbols in 2 time intervals, however with increase in the number of antennas the efficiency of the precoding falls. One can use this system to accommodate 2 sets of symbols from the same user thus improving

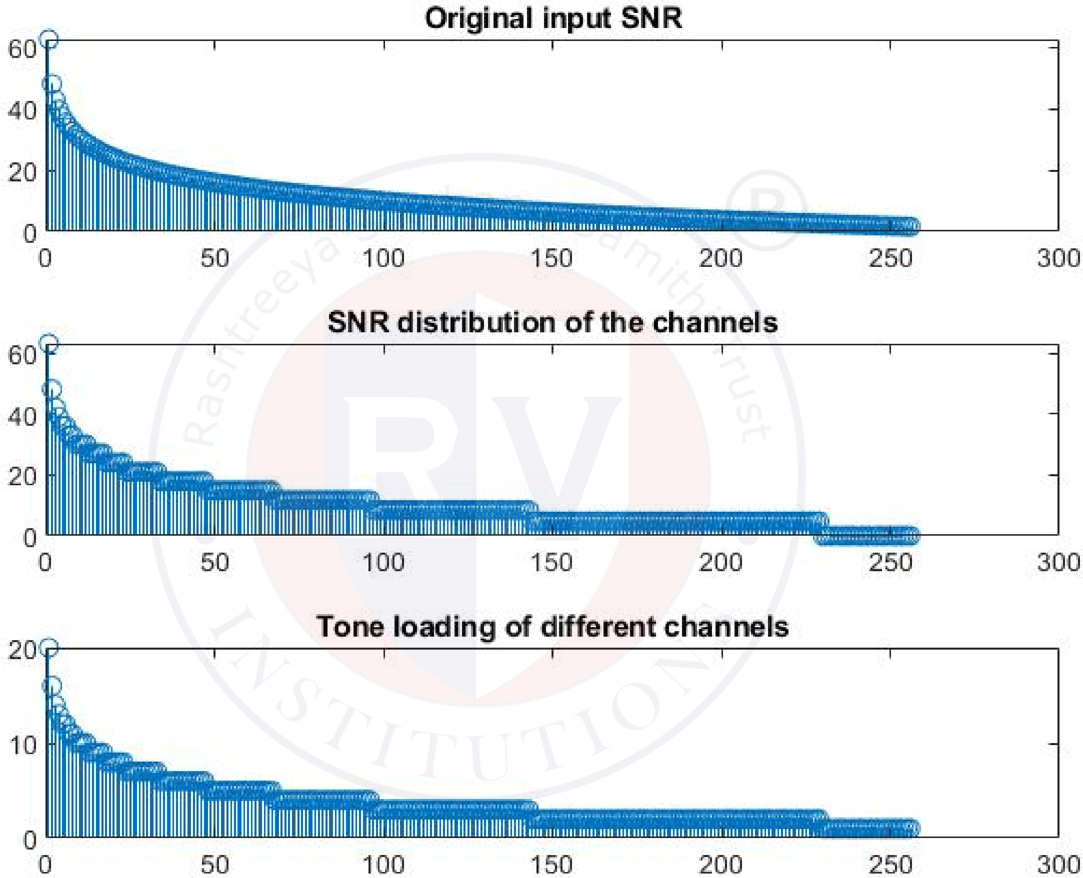

Figure 4.4: The tone loading profile of various subchannels for SIMO mode.

the data rate or symbols from 2 different users thus improving the capacity of the system.

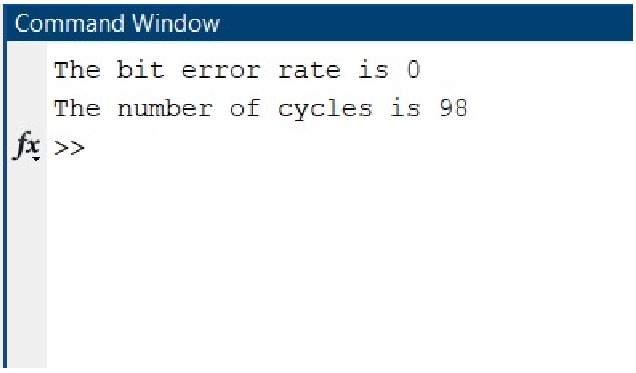

Figure 4.5: MISO System Performance.

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 threshold value of ± 2 dB.

It is observed 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. One needs a total of 1303 cycles of transmitting bits as per the tone loading profile in 4.6

Interference:

Although one has many antenna paths to transmit 10^6 bits, since one is operating in diversity mode, the system is only using the best channel between these two to transmit our data, hence one does not seeing much improvement in speed. It is seen how operating MIMO in multiplexing mode can vastly improve this system performance.

4.5.2 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 4.8. The BER is observed to be 0, which is within the expected range. There is no need to perform any tone loading as the system uses a Inverse Channel Estimation precoding scheme.

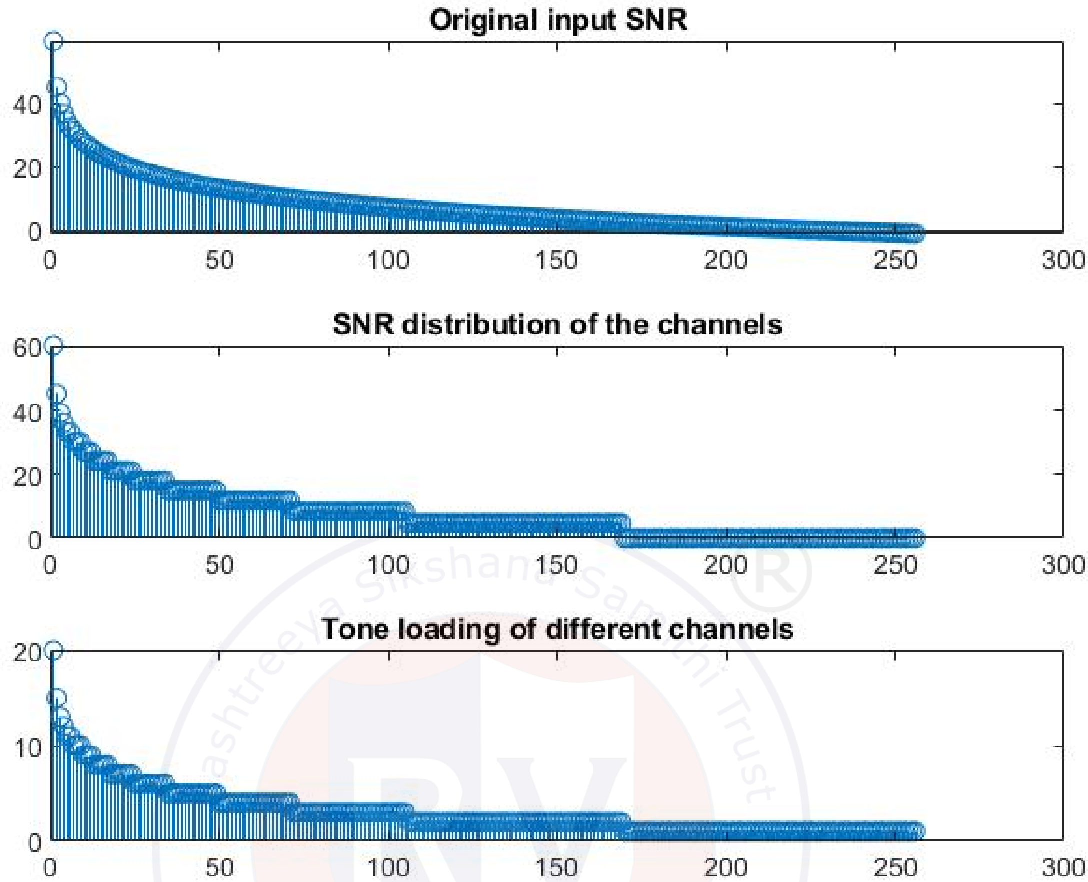

Figure 4.6: The tone loading profile of various subchannels for MIMO in diversity mode.

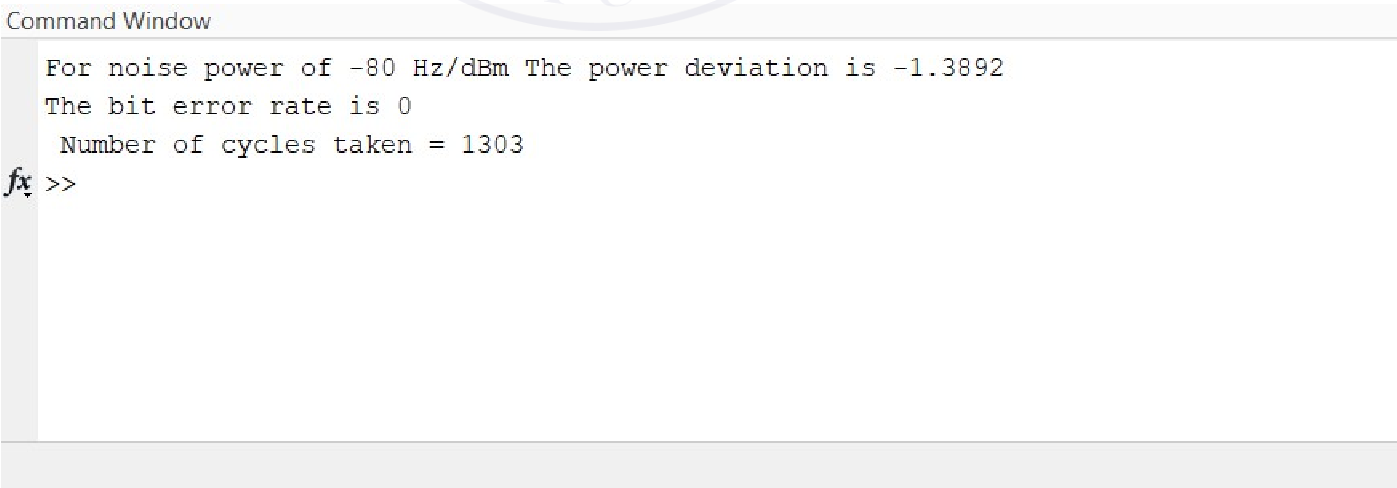

Figure 4.7: The performance of our MIMO system. The number of cycles taken to transmit the bits is of particular importance to us.

Inference:

It takes only 98 cycles to transmit the 10^6 bits. One notices how by using suitable precoding the number of cycles reduce drastically. Since the system is using Inverse Channel Estimation precoding, there is no need for a decoder at the receiver as the channel effects itself nullify the effect of the precoding. By using multiple antenna paths, data rates and capacities are vastly improved.

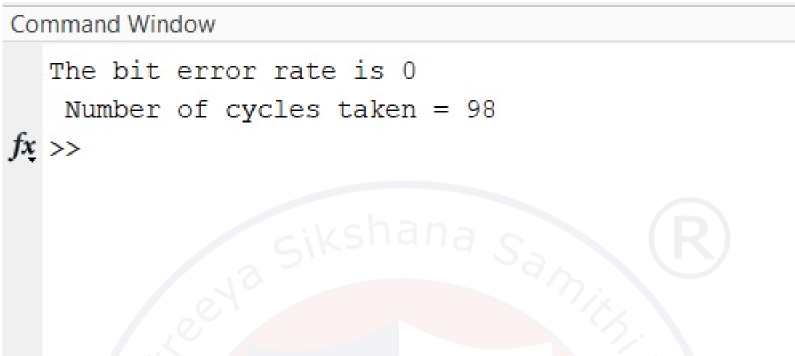

Figure 4.8: MIMO System Performance with Inverse Channel Estimation Precoder.

4.5.3 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 4.9. The BER is observed to be 0, which is within the expected range. One does not perform any tone loading as the system uses a Singular Value Decomposition precoding scheme. It takes only 98 cycles to transmit the 10^6 bits. It is noticed how by using suitable precoding the number of cycles reduce drastically.

Inference:

Although the speed of SVD decomposition precoding is similar to that of Inverse Channel Estimation precoding, the speed of execution is noticed to be faster because it is computationally simpler to find the SVD of the matrix than to invert it. This is especially true when the size of the matrix is much larger than 2×2.

Summary

In this chapter the results of the simulations of our system in various configurations was discussed. Readers clearly see that data rates increase with multiplexing mode and

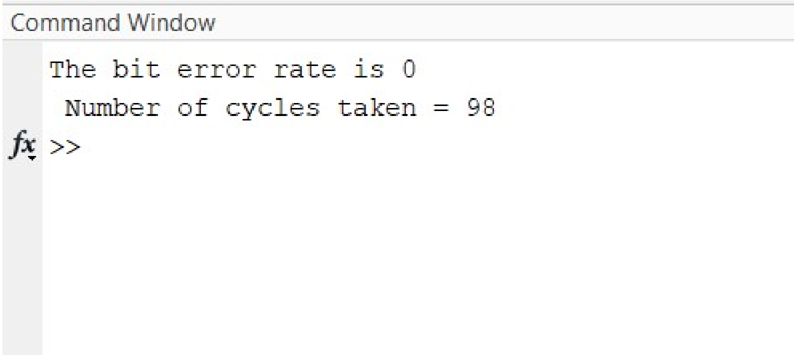

Figure 4.9: MIMO System Performance with Singular Value Decomposition Precoder.

also with precoding. Finally, in the last section the report is concluded and the future scope of the report is discussed and how further improvements can be made to our system is also mentioned.

Chapter 5

Conclusion and Future Scope

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

This report has examined how one can improve upon the capacity and data rates of existing 4G and future 5G systems with the help of MCM-MIMO systems.

In this report a system is designed which can be operated in two modes as stated, namely in diversity and multiplexing modes. It is shown how diversity is suitable for low SNR regimes, so multiple copies of the same data needs to be sent to maintain a feasible Quality of Service(QoS). This report also shows how multiplexing is suitable in high SNR regimes where one has the option of maximizing data rates and capacity by transmitting differing data over good channels that are already providing good BER.

The ultimate goal of this report was to design a 2×2 MIMO system and in this regard, at first a SISO system was designed to lay the foundation for multi carrier communication systems. Further, a 1×2 SIMO and 2×1 MISO system was also designed to operate in diversity mode. Finally, a 2×2 MIMO system was designed to work in both diversity and multiplexing modes to improve the data rates and capacities. The design of this system employed unique precoding schemes like Alamouti coding, Inverse Channel Estimation precoding and SVD precoding. This report also demonstrated the use of Rayleigh fading and Friis' path loss formula for real world simulation purposes.

Summary

For readers, it is suggested 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, the report is limited to 2×2 MIMO systems. Readers are encouraged to implement large systems leading to massive MIMO systems.

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