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EFFECTIVE CHANNEL STATE INFORMATION (CSI) FEEDBACK FOR MIMO SYSTEMS IN WIRELESS BROADBAND COMMUNICATIONS

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Submitted in fulfilment of the requirements for the degree of

Master of Engineering (Research)

School of Electrical Engineering and Computer Science

Science and Engineering Faculty

Queensland University of Technology

2014

Keywords

Bit Error Rate (BER)
Channel State Information
Energy per bit to Noise power spectral density ratio (Eb/No)
Fading
Frequency-division duplex
MIMO
Multi-User MIMO
Single-User MIMO
Time-division duplex
Wireless Communication

Abstract

Multiple Input Multiple Output (MIMO) is seen as one of the key technologies in wireless communication industry that offers significant increase in data throughput and link range without additional bandwidth or increased transmit power. Such systems have the potential to spread the same total transmit power over the antennas to achieve an array gain that improves the spectral efficiency and/or to achieve a diversity gain that improves the link reliability. The availability of Channel State Information (CSI) at the transmitter end in MIMO system has been a popular research topic in recent years. The knowledge of accurate and timely CSI at the transmitter is becoming increasingly important in wireless communication systems. While it is often assumed that the receiver needs to know the channel for accurate power control, scheduling, and data demodulation, it is now known that the transmitter (especially, the base station) can also benefit greatly from this information.

The CSI makes it possible to adapt transmissions to current channel conditions, which is crucial for achieving reliable communication with high data rates in multi antenna systems.
The channel capacity of MIMO system increases linearly with the increase in the number of antenna pairs between transmitter and receiver. In addition, several works have shown that the capacity in MIMO can be further improved if the forward Channel State Information (CSI) is made available at the transmitter. Basically, there are two methods that allow the transmitter to obtain CSI from the receiver. The first one is based on the channel reciprocity principle and the second one uses feedback from the receiver.

This research has analysed both reciprocity and feedback mechanisms and has presented the basis of an effective CSI feedback mechanism that efficiently provides the transmitter with minimum CSI to allow the accurate knowledge of a rapidly changing channel. The simulations have been conducted using MATLAB to measure the performance degradation when the channel is imperfectly estimated at the receiver in a 2 X 2 MIMO systems and compared to the case of perfect channel knowledge at the receiver. The simulation results show that with 8 pilot symbols for each 100 symbols of data, channel estimation causes about a 1 dB degradation in performance for the selected Eb/No range when compared to feedback CSI at the transmitter end. Also the channel estimation causes about a 2.45 dB degradation in performance for the selected Eb/No range as compared to the feedback channel when Rician fading channel was added to the simulation process. Furthermore, the research has analysed the channel capacity of a MIMO

system with and without the CSI at the transmitting end. It has been observed that the capacity of the MIMO system was increased significantly with the available of CSI at the transmitting end.

The research has led to one publication to date, namely:

Sharma, Maneesha (2013) Novel Adaptive Channel State Information Feedback for Multiuser MIMO in Wireless Broadband Communications. In: IEEE Fourteenth International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2013), 4 – 7th June 2013, Madrid, Spain. (Published).

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List of Abbreviations

ACMA	Australian Communications and Media Authority
BER	Bit Error Rate
BS	Base Station
CDMA	Code Division Multiple Access
CCI	Co-Channel Interference
CFR	Channel Frequency Response
CIR	Channel Impulse Response
CSI	Channel State Information
DoA	Direction of Arrival
DoD	Direction of Departure
FDM	Frequency Division Multiplexing
FDD	Frequency Division Duplex
IID	Independent Identically Distributed
ISI	Inter Symbol Interference
LOS	Line of Sight
MAI	Multiple Access Interference
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood Algorithm
MPC	Multi Path Components
MS	Mobile Station
MUD	Multi User Detection
MU-MIMO	Multi User Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
RF	Radio Frequency
SDMA	Space Division Multiple Access

SISO	Single Input Single Output
SM	Spatial Multiplexing
STBC	Space Time Block Code
TDDS	Time Division Duplex System
UT	User Terminal
WLAN	Wireless Local Area Networks
ZF	Zero Forcing

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: QUT Verified Signature

Date: May 2014

Acknowledgments

First of all, I would like to thank my principal supervisor Dr. Karla Ziri-Castro for her help, advice, guidance and encouragement throughout the candidature. Also I would like to extend my sincere thanks to my associate supervisors, Dr. Dhammika Jayalath and Dr. Hajme Suzuki (CSIRO- Rural Broadband Access Project Leader) for their valuable advices, discussions and useful suggestions that I received throughout this research.

I gratefully acknowledge the financial support given by QUT, by providing the EECS school based scholarship from July, 2013 to December, 2013 to carry out this research.

I would also like to extend thanks to all academic and non-academic staff of the faculty for the support given in many ways. I am grateful to my colleagues at QUT for sharing their knowledge and for their encouragement.

Finally, thanks to my parents, rest of the family, my husband and my son, who all helped make this thesis possible through their constant support and encouragement.

Chapter 1: Introduction

In wireless communications, radio spectrum is a scarce resource and hence imposes a high cost on the high data rate transmission. Fortunately, the emergence of multiple input multiple output (MIMO) system has opened another very resourceful dimension i.e. space for information transmission. MIMO is the use of multiple antennas at both the transmitter and receiver to improve communication performance. Multi-antenna systems currently play and are expected to keep playing a very important role in future multimedia wireless communication system. Future MIMO systems are predicted to provide tremendous improvement in spectrum utilization.

The knowledge of accurate and timely channel state information (CSI) at the transmitter is becoming increasingly important in wireless communication systems and also in MIMO systems[4]. While it is often assumed that the receiver (whether base station or mobile) needs to know the channel for accurate power control, scheduling, and data demodulation, the transmitter (especially the base station) can also benefit greatly from this information[4]. Recent results have shown that large throughput gains are possible when the base station uses multiple antennas and a known channel to transmit distinct messages simultaneously and selectively to many single-antenna users [4]. In time-division duplex systems, the base station and the user terminal share the same frequency band for data transmission. Hence, the base station can exploit reciprocity to obtain the forward channel from pilots received over the reverse channel. But the frequency-division duplex systems are different and more difficult because the base station transmits and receives on different frequencies. Therefore cannot use the received pilot to infer anything about the multi antenna transmit channel [4].

This chapter outlines the motivation (Section 1.1) and background (Section 1.2) of the research, the overarching objectives of the research (Section 1.3), and the significance of this research (Section 1.4). Finally, it includes an outline of the remaining chapters of the thesis (Section 1.5).

1.1 MOTIVATION

In recent years the telecommunications industry has experienced phenomenal growth, particularly in the area of wireless broadband communication. This growth has been fuelled by the widespread popularity of mobile phones and wireless computer networking. The upgrading of mobile networks to support 4G services and the expansion of Wi-Fi networks, have been key facilitators for the development of the smart phones and tablets around the world.

The take up of smart phones and mobile internet use has been exploded in Australia according to new research from the Australia Communications and Media Authority (ACMA) [5]. According to ACMA, almost half of Australia's adult population now own a Smartphone and many of them are harnessing 3G or 4G services to access the internet while on the move [5]. The functionality and ease of internet access provided by these smart phones and tablets has been a key factor for the increase in the number of users day by day.

ACMA research shows that an estimated 92 per cent of the adult population (those aged 18 years and over) used a mobile phone as of May 2012. Mobile phone usage ranged from a comparative low of 77 per cent for people aged 65 years and over to a high of 99 per cent for those aged 18–24 years[5]. The usage of mobile phone, smart phone and tablet in the year 2012 can be illustrated in Figure 1.

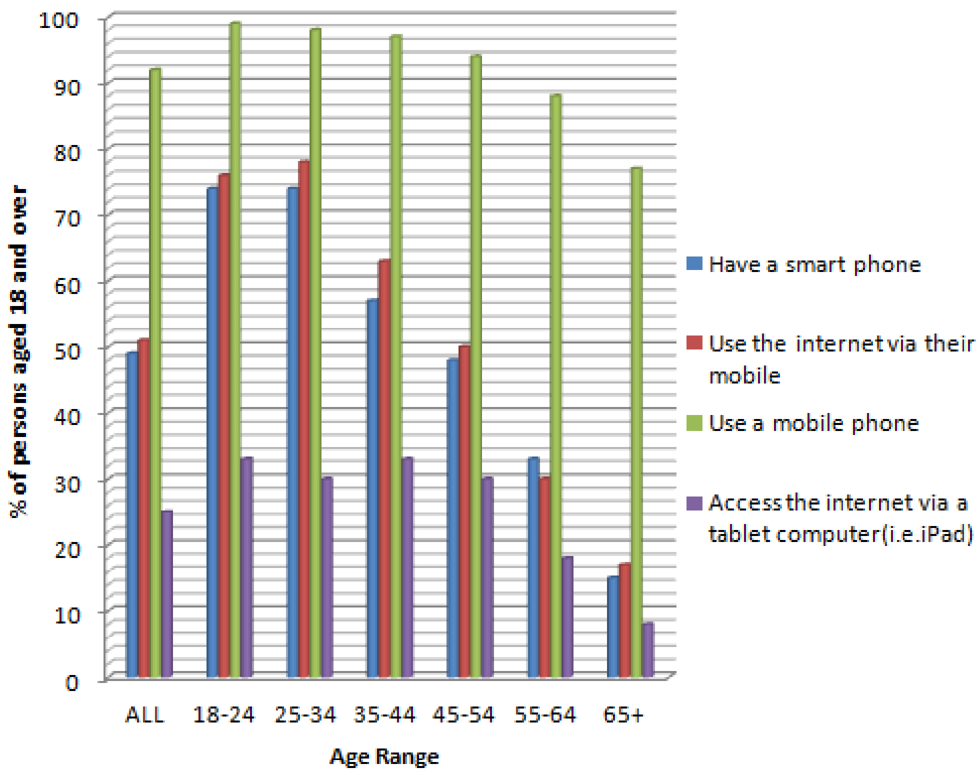

Figure 1 :Mobile phone, smart phone and tablet usage [5]

Nowadays, people use Internet for every sort of things such as communication, research, socialising, shopping and entertainment. The internet is used by every sector either the government or private sector to deliver services such as health, education and energy to the public.

At present it is estimated that there are around 5 billion mobile phone users in the world and with the increase in number of users each day, the demand of high-speed wireless Internet access is also growing. However, there are limits to the growth, and the radio spectrum used for wireless communications is a finite resource. Therefore, considerable effort has been invested in making more efficient use of it. Using the spectrum more efficiently caters for the ever increasing demand for faster communications since more bits per second can be transmitted using the same bandwidth.

Recently, a major research focus in this area has been the use of MIMO technology instead of the traditional single antenna systems[6]. Researchers [6, 7] have shown that systems with multiple antennas at the transmitter and receiver can significantly enhance the system throughput, reliability and coverage, without extra bandwidth and power.

Basically, there are three basic parameters that completely describe the quality and usefulness of any wireless link. They are classified as Speed, Range and Reliability. Prior to the development of MIMO technology these three parameters were interrelated according to strict rules. The speed could be increased only by sacrificing the range and the reliability. Similarly, the range could be extended at the expense of speed and reliability. Reliability could be improved by reducing speed and range. The MIMO OFDM (Orthogonal Frequency Division Multiplexing) has redefined the trade-offs clearly demonstrating that it can boost all these three parameters simultaneously [6]. Hence, MIMO technology has found significant importance in telecommunication systems. But still there are so many open problems in this technology that need to be fully exploited in coming years.

The capacity of a MIMO channel is influenced by the degree of CSI (channel-state information) available to both transmitter and receiver [8]. In most instances of multi-antenna communication, the receiver can accurately track the instantaneous state of the channel from pilot signals that are typically embedded within the transmissions [8]. In terms of CSI at the transmitter, on the other hand, several scenarios are possible such as either using reciprocity principle or the feedback from the receiver. The challenge lies on whether and what type of CSI can be made practically available to the transmitter in a MIMO OFDM systems, where fading channels are randomly varying.

1.2 BACKGROUND

The last few years have witnessed the transition of MIMO communication from a theoretical concept to a practical technique for enhancing performance of wireless networks [9]. Multiple antennas, when used at both the transmitter and the receiver, create a MIMO propagation channel. Using sophisticated coding at the transmitter and substantial signal processing at the receiver, the MIMO channel can be provisioned for higher data rates, resistance to multipath fading, lower delays, and support for multiple users [3]. MIMO technology is becoming immensely popular at the recent time due to its high performance enhancing capabilities and is already an important part of every modern wireless communication standards such as IEEE 802.11n (Wi-Fi), 4G, 3GPP Long Term Evolution, Wi MAX and HSPA+.

Furthermore, in MIMO technology it is found that between the transmitter and the receiver the signal can take multiple paths [3]. Previously, these multiple paths only serve to introduce interference, but by using MIMO these additional paths may serve as advantage as they can be used to provide additional robustness to the radio link. The two coding methods or algorithms used in MIMO are Spatial Diversity and Spatial Multiplexing [3]. Multiple-antenna channels provide spatial diversity, which can be used to improve the reliability of the link. The basic idea is to supply to the receiver multiple independently faded replicas of the same information symbol, so that the probability that the entire signal components fade simultaneously is reduced [10]. Spatial multiplexing is used to provide additional data capacity by utilising the different paths to carry additional traffic, i.e. increasing the data throughput capability [3].

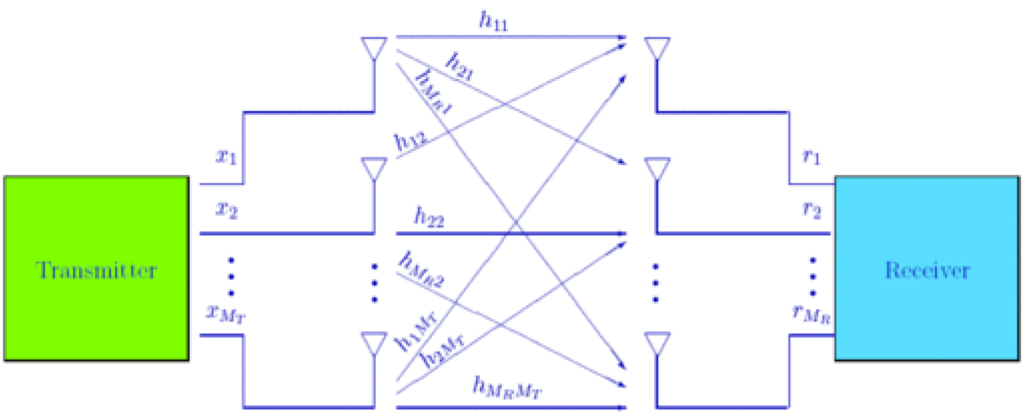

Figure 2: Example of MIMO system [3]

Basically, there are two operational modes that are considered in MIMO systems i.e. single user and multi user MIMO technologies.

Single User MIMO (SU-MIMO):

A SU-MIMO system sends data to only a single user in the spatial domain as shown in the Figure 3. In SU-MIMO, each user has to take turns for sharing the channel.

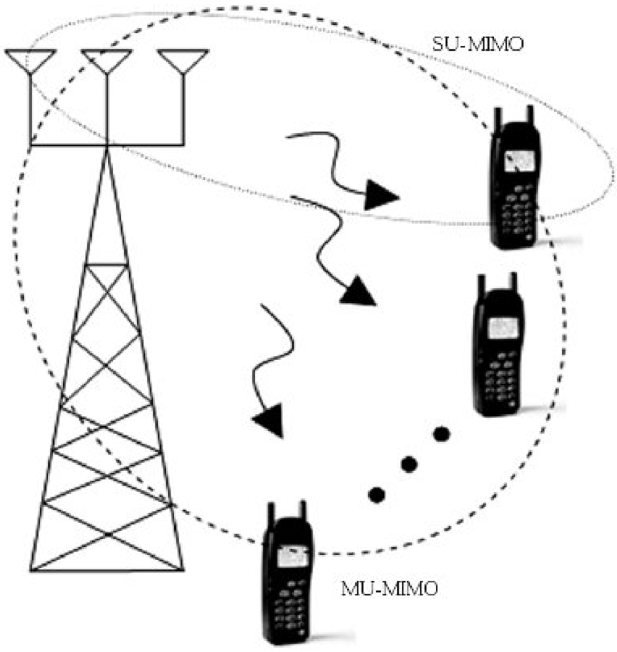

Figure 3 : SU-MIMO and MU-MIMO

In SU-MIMO, since the base station is serving only one particular user at one time the data rate is increased for a single User Equipment (UE) as illustrated from Figure 4.

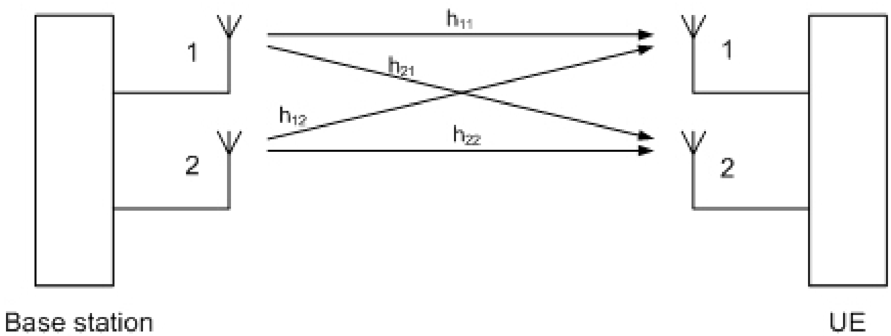

Figure 4: SU-MIMO

Multiuser MIMO (MU-MIMO)

In the MU-MIMO scenario, the access point (AP) is equipped with multiple antennas to communicate with a group of users. Each of these users is also equipped with multiple antennas. It is possible to send a separate stream to each user, as long as the transmitter knows the channel matrix H and pre-cancels the interference caused by users 2 and 3 to user 1 and so on.

This mode is particularly useful in the uplink because the complexity on the UE side can be kept at a minimum by using only one transmit antenna as illustrated in Figure 5. This is also called 'collaborative MIMO'.

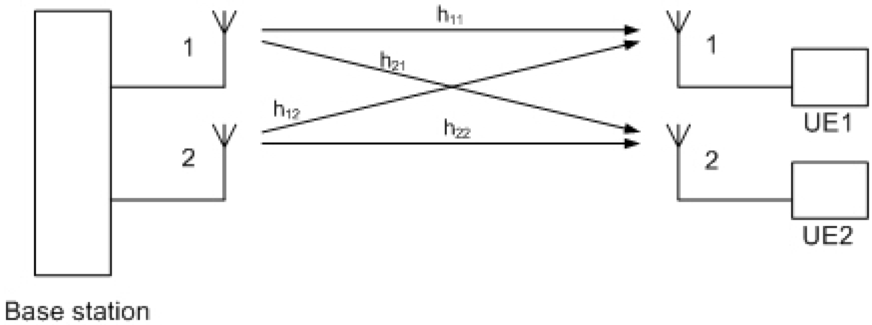

Figure 5: MU-MIMO

Point-to-point (single user) MIMO communication promises large gains for both channel capacity and reliability, essentially via the use of space-time codes (diversity gain oriented) combined with stream multiplexed transmission (rate maximization oriented) [9]. In such a traditional single user view of MIMO systems, the extra spatial degrees of freedom brought by the use of multiple antennas are exploited to expand the dimensions available for signal processing and detection, thus acting mainly as a physical (PHY) layer performance booster [9]. In this approach the link layer protocols for multiple accesses (uplink and downlink) indirectly reap the performance benefits of MIMO antennas in the form of greater per-user rates, or more reliable channel quality, despite not requiring full awareness of the MIMO capability[9].

Mostly there are two challenges in a MU-MIMO scenario: uplink (where users transmit simultaneously to single base station) and downlink (where the base station transmits to multiple independent users) [11]. The uplink challenge is addressed using array processing and multi-user detection techniques by the base station in order to separate the signals transmitted by the users. The downlink challenge is somewhat different and difficult to address. As the receiver antennas are distributed among different users it is practically impossible to achieve the level of coordination between all users. A number of different techniques to address the issue of MIMO downlink transmission and reception have already been proposed. Almost all of these proposed techniques that have been used for addressing the MIMO downlink challenge employ processing of data symbols at the transmitter and it requires the transmitter to know the downlink CSI [11]. So the availability of CSI at the transmitter end in MIMO has been a popular research topic at the recent time.

The need for CSI feedback places a significant burden on uplink capacity in most systems, exacerbated in systems with wideband (e.g. OFDM) communication or high mobility (such as 3GPP-LTE, WiMax , etc.) [9].

There are two methods that allow the transmitter to obtain CSI from the receiver. The first one is based on the channel reciprocity principle and the second one uses feedback from the receiver [3]. In the first method, the radio propagation channel is reciprocal between two antennas. Ideally, the forward and reverse channels are assumed to be the same. Therefore, the transmitter can realize the forward CSI by estimating the reverse CSI instead. In the second one, the forward channel is estimated at receiver and then it is sent back to the transmitter through the reverse channel. This method does not function properly if the channel is changing rapidly. In order to realize the correct CSI at transmitter, more frequent estimations and feedbacks are required. As a result, the overheads for the reverse channel become prohibitive [12]. Hence, it is very important to carefully consider how the feedback mechanism will be designed and used to support MIMO. This research will analyse both the feedback and reciprocity mechanisms and perform a performance comparison between these methods. An effective CSI feedback mechanism in MIMO system can be designed so it can provide the transmitter with minimum CSI to allow for accurate knowledge of a time-varying channel. Figure 6 and Figure 7 illustrates the reciprocity mechanism and feedback mechanism respectively.

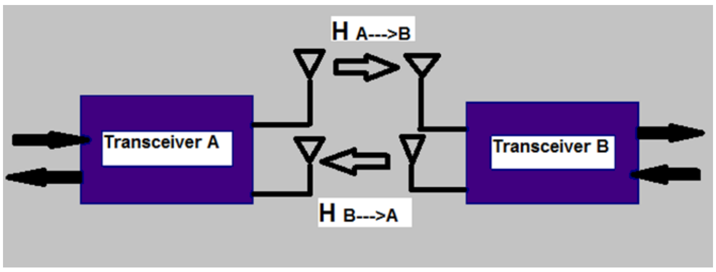

Figure 6: Reciprocity Mechanism [3]

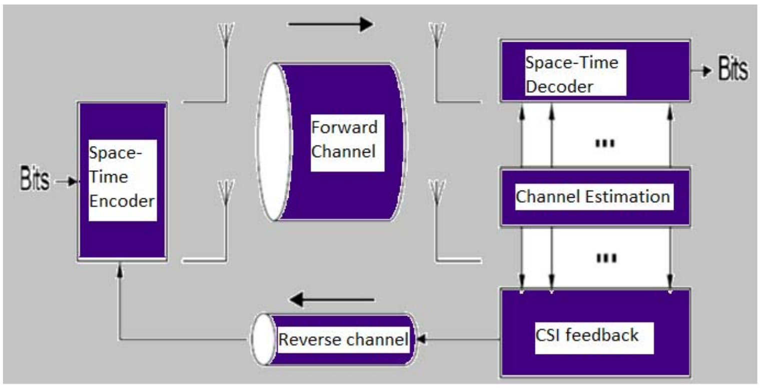

Figure 7 : Feedback Mechanism [3]

1.3 OBJECTIVES

This program of research aims to fulfil the following objectives:

- To analyse the performance of feedback and reciprocity mechanisms when the channel remains unchanged and also when channel exhibits Rician fading.
- To provide a performance comparison between the feedback and reciprocity mechanisms.
- To determine the channel capacity of MIMO systems with and without the CSI at the transmitting end.

1.4 SIGNIFICANCE

Despite the fact that wireless MIMO communications have attracted the immense attention from both the academic and the industrial communities over fifteen years, the impact and design of an optimal form of CSI feedback using minimal bandwidth in MIMO system is still an open problem. The use of MIMO techniques can significantly increase downlink throughput without requiring large numbers of antennas at the user terminal [13]. However, it is crucial that the transmitter have accurate CSI in order to realize these gains. In fact, the availability of CSI appears to be the critical issue that will determine the feasibility of MIMO techniques in future wireless communication systems [14].

Single-user MIMO systems benefit from having CSI at the transmitter when (Number of transmitting antennas) i.e. $n_T > n_R$ (number of receiving antennas) and also at low signal-to-noise ratio (SNR) [11]. A base station transmitting to multiple co-channel users will almost always benefit from CSI [11]. This is because the CSI is not only useful in achieving high SNR at the desired receiver, but also in reducing the interference produced at other points in the network by the desired user's signal [11]. The most common method for obtaining CSI at the transmitter is through the use of training or pilot data in the uplink (e.g., for time-division duplex systems) or via feedback of the receiver's channel estimate found using downlink training data (e.g., for frequency-division duplex transmission) [11]. In either case, obtaining CSI at the transmitter can be a very challenging and costly problem, but is justifiable for both single user and multi-user channels [11]. Accurate CSI may be easy to obtain when the channel is changing slowly (e.g., as in indoor scenarios), but it is much more difficult in situations where the channel is changing rapidly [11].

The two most likely applications of MIMO technology are wireless local area networks (WLANs) and cellular telephony. Wireless LANs are a natural fit for MIMO technology because the rich multipath environment in which they are usually deployed (indoors, office or college campuses, etc.) is an important criterion for achieving high capacity [11]. In this type of channel, user mobility is likely to be very slow, and the channel can be viewed as quasi-static [11]. The use of multiple antennas on the cellular telephone applications are more challenging and problematic due to higher user mobility, and the small size and cost constraints of manufacturing mobile devices [11]. Time-varying channel models have not been considered in most of the research on MIMO systems to date; simple quasi-static models have been assumed [11]. Further research on techniques for obtaining and tracking channel state information is needed for highly mobile scenarios[11].

Recent research suggests that the prediction horizon for MIMO systems may be much longer than in the single-input single-output (SISO) case, which has usually proven to be too short to be useful, since multiple antennas reveal more information about the physical structure of the channel [11].Moreover, the capability of OFDM systems to cope with highly time-variant wireless channel characteristics makes the rapid employment of OFDM systems in the latest wireless communications, so as with MIMO system [15].

This research aims to develop an effective CSI feedback mechanism that will allow obtaining CSI efficiently at the transmitter of a MIMO system. It is very important to carefully consider how feedback is designed and used to support MIMO. The challenge lies on whether and what type of CSI can be made practically available to the transmitter in a wireless setting, where fading channels are randomly varying. This research focuses on the following key factors:

- the performance of CSI feedback mechanism when the channel remains unchanged for the duration of data packet
- the performance of CSI feedback mechanism when the channel exhibits the Rician fading distribution,

- and the performance comparison of MIMO channel capacity with and without the CSI at the transmitting end.

1.5 THESIS OUTLINE

The organisation of the remainder of this thesis is as follows:

Chapter 2 presents a literature review and describes the basic concepts of wireless communications system. It discusses the Multiple Input Multiple Output (MIMO) system and the principal concepts of MIMO architecture such as spatial multiplexing, diversity, array and diversity gain and interference reduction and avoidance. It also describes the available methods for providing Channel State Information (CSI) at the transmitting end in MIMO systems, which has a strong influence on the development of new wireless systems. It discusses the MIMO channel capacity and also provides the comparison between single user and multi-user MIMO. Finally this chapter provides an overview of BER, Eb/No, OSTC in wireless communication system.

Chapter 3 describes the research methodology that has been used throughout the research to achieve the research objectives. It presents in detail the simulation carried out in MATLAB to obtain CSI at the transmitter end in MIMO system. It also describes simulations done to measure the channel capacity of MIMO systems with and without the availability of CSI at the transmitter end. Furthermore, this chapter presents the block diagrams of both the feedback and reciprocity mechanisms that have been simulated in MATLAB and also describes each component that has been used in the transmitter and receiver models.

Chapter 4 presents the results of simulation conducted in MATLAB to design a feedback mechanism to obtain CSI at the transmitter end in MIMO system and also to determine the channel capacity of MIMO with and without CSI. Furthermore, this chapter analyses the graphs of BER vs Eb/No (dB) obtained while performing simulation over a range of Eb/No points to generate BER results for different feedback mechanisms. Also it analyses the graphs of Capacity (bits/sec/Hz) vs SNR (dB) obtained while performing simulation over a range of SNR (dB) points to generate Capacity (bit/sec/Hz) results with varying number of transmitter and receiver antennas. The simulation is being performed using both the feedback and reciprocity mechanisms that allow comparing the different results. It also provides a measure of the performance degradation when the channel is imperfectly estimated at the receiver, compared to the case of perfect channel knowledge at the receiver.

Chapter 5 is the final chapter and summarises the results and contributions of the thesis.

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Chapter 2: Literature review

This chapter provides a comprehensive literature review on the availability of channel state information for multi-input multi-output (MIMO) systems which has a strong influence on the development of new wireless systems. This chapter will review literature on the following topics:

The first part of the literature review provides a brief outline of wireless communication and also describes some of the key terms and technologies of wireless communication.

The second part of the literature review discusses MIMO technology , the channel capacity of MIMO technology and also provide the comparison between single user and multi user MIMO.

The third part of the chapter performs the key role in the literature survey discussing channel state information and the methods of obtaining CSI at the tranmsitting end.

Finally, the chapter ends with the discussion of BER, Eb/No and OSTBC.

2.1 INTRODUCTION TO WIRELESS COMMUNICATION

The performance of wireless communication systems mainly depends on the the wireless channel environment. In wireless communication, radio propagation is simply defined as the behavior of radio waves when they are propagated from transmitter to receiver. In the course of propagation , radio waves are mainly affected by three different modes of physical phenomenon :reflection, diffraction, and scattering [2].

Reflection is the physical phenomena that occurs when a propagating electromagnetic wave impinges upon an object with very large dimensions compared to the wavelength , for example, surface of the earth and building. It forces the transmit signal power to be reflected back to its origin rather than being passed all the way along the path to the receiver.

Diffraction refers to various phenomena that occur when the radio path between the transmitter and receiver is obstructed by a surface with sharp irregularities or small openings. It appears as a bending of waves around the small obstacles and spreading out of waves past small openings. The secondary waves generated by diffraction are useful for establishing a path between the transmitter and receiver, even when a line-of-sight path is not present.

Scattering is the physical phenomenon that forces the radiation of an electromagnetic wave to deviate from a straight path by one or more local obstacles, with small dimensions compared to the wavelength. Those obstacles that induce scattering, such as foliage, street signs, and lamp posts, are referred to as the scatters.In other words , the propagation of a radio wave is a complicated and less predictable process that is governed by reflection, diffraction, and scattering, whose intensity varies with different environments at different instances.

The following section sets out a brief outline of fading and other different terms related with wireless communication.

2.1.1 Fading

Wireless communication is primarily limited by fading. In wireless communication, fading is simply defined as the variation of the signal amplitude over time and frequency and is often modeled as a random process. In contrast with the additive noise as the most common source of signal degradation , fading is another source of signal degradation that is characterized as a non-additive signal disturbance in the wireless channel[2]. Fading can occur either due to multipath propagation which is referred as multipath induced fading. Also it can occur due to shadowing from obstacles affecting the wave propagation which is referred as shadow fading.

The fading phenomenon can be broadly classified into two different types: large-scale fading and small scale fading. Large-scale fading is either caused by path loss of signal as a function of distance or shadowing by large objects such as buildings, intervening terrains, and vegetation. Shadowing is a slow fading process which is characterized by variation of median path loss between the transmitter and receiver in fixed locations. Hence large-scale fading is characterized by average path loss and shadowing. On the other hand, small-scale fading refers to the rapid variation of signal levels due to the constructive and destructive interference of multiple signal paths or multi-paths when mobile station moves short distances[2]. Small-scale fading can be further classified into frequency selective fading and flat fading depending on the relative extent of a multipath. Also depending on the time variation in a channel due to mobile speed small-scale fading can be classified as either fast fading or slow fading.

- Slow fading arises when the coherence time of the channel is large relative to the delay constraint of the channel. In this type of fading, the amplitude and phase change imposed by the channel can be considered roughly constant over the period of use. Slow fading can be caused by events such as shadowing, where a large obstruction such as a hill or large building obscures the main signal path between the transmitter and the receiver[16].

- Fast fading occurs when the coherence time of the channel is small relative to the delay constraint of the channel. In this type of fading, the amplitude and phase change imposed by the channel varies considerably over the period of use[16].

The coherence time of the channel is related to a quantity known as the **Doppler spread** of the channel. When a user is moving, the user's velocity causes a shift in the frequency of the signal transmitted along each signal path. This phenomenon is known as the Doppler shift. Signals travelling along different paths can have different Doppler shifts, corresponding to different rates of change in phase. The difference in Doppler shifts between different signal components contributing to a single fading channel tap is known as the Doppler spread[16]. Channels with a large Doppler spread have signal components that are each changing independently in phase over time. Since fading depends on whether signal components add constructively or destructively, such channels have a very short coherence time.

In general, coherence time is inversely related to Doppler spread, typically expressed as

$$T_C \approx 1/D_S \tag{1}$$

where T_C is the coherence time, D_S is the Doppler spread.

- Selective fading or frequency selective fading is a radio propagation anomaly caused by partial cancellation of a radio signal by itself — the signal arrives at the receiver by two different paths, and at least one of the paths is changing (lengthening or shortening). In frequency-selective fading, the coherence bandwidth of the channel is smaller than the bandwidth of the signal. Different frequency components of the signal therefore experience uncorrelated fading[16].

- Flat fading is a type of fading where the coherence bandwidth of the channel is larger than the bandwidth of the signal. Therefore, all frequency components of the signal will experience the same magnitude of fading[16].

The following Figure 7 classifies the types of fading channels.

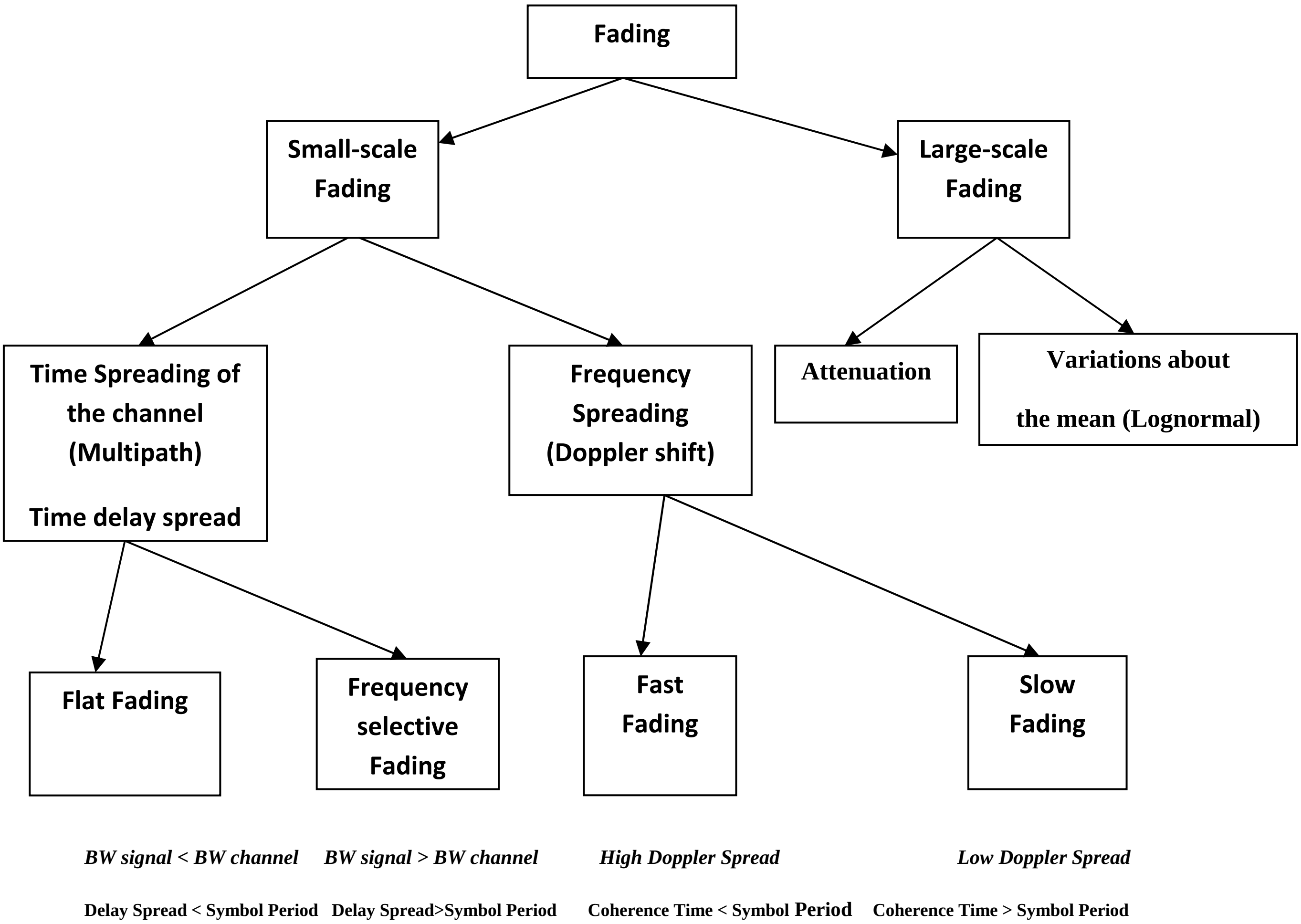


Figure 8 : Types of fading channel [2]

2.2 INTRODUCTION TO MIMO SYSTEM

Ever since Guglielmo Marconi[16] sent the first telegraph across the English Channel in 1897, new wireless communication methods and services have been implemented throughout the world. As a result, more and more information has become accessible through radio, television, and the internet. Therefore, the demand for higher data rates, better quality of service, and higher network capacity is ever increasing[16].

Wireless communication technology has become more popular compared to wired communication technology due to its enormous benefits such as easier deployment, low costs and greater flexibility. Furthermore, it enables mobility to access information anywhere, anytime[17].

Wireless communication technologies use the atmosphere as the communication medium and utilize the vast radio spectrum for transmission of different communication channels such as television, radio and wireless broadband. However, due to increasing demand for wireless services the frequency spectrum has become a scarce resource[18].

Therefore, researchers try to identify better methods for efficient use of radio frequency spectrum. Using the complex modulation schemes is one approach to improve the efficiency for a given bandwidth. Unfortunately, this approach increases the complexity and the cost of the radio system.

In recent years, Multiple Input Multiple Output (MIMO) systems gained significant attention both in academia and industry as a promising solution to improve spectral efficiency[10]. Multiple Input Multiple Output systems use multiple transmitter antenna elements in the transmitter end and multiple receiver antenna elements at the receiver end. Researchers[6, 7] have shown that systems with multiple antennas at the transmitter and receiver can significantly enhance the system throughput, reliability and coverage, without extra bandwidth and power. In addition to 'time' which is known as the natural dimension to digital data communication, the use of multiple antennas introduces a new dimension called 'space to digital communication systems[1, 10]. Therefore, MIMO technology is known as 'space-time' wireless technology.

The emergence of MIMO systems began in early 1990s[10] . In 1994, Paulraj and Kailath[19] introduced a technique to increase the capacity of wireless channels using multiple antennas at both the transmitter and receiver ends. Telatar[20] further illustrated the ability of capacity improvement in wireless systems by using multiple antennas. Furthermore, Foschini et al. developed the 'BLAST' architecture[21] which can achieve spectral efficiencies up to 10-20 bits/s/Hz. Since then, MIMO technology has become a popular research area in both academia and industry. Basically there are two operational modes that are considered in MIMO technology which are Single User MIMO (SU-MIMO) and Multi User MIMO (MU-MIMO). The availability of CSI at the transmitting end in MIMO technology has been a popular research topic in recent time.

The use of MIMO techniques can increase downlink throughput without requiring large numbers of antennas at the user terminal . However, it is important that the transmitter has exact CSI in order to realize these gains. In fact, the availability of CSI appears to be the critical issue that will determine the feasibility of MIMO techniques in future wireless communication systems. The single-user MIMO systems benefit from having CSI at the transmitter when $n_T > n_R$ and also at low signal-to-noise ratio (SNR).But the challenge lies on the way CSI can be made available at the transmitting end.

Furthermore the channel capacity of MIMO system increases linearly with the increase of number of antennas. In addition several works have shown that the capacity can be further improved if the forward Channel State Information (CSI) is known at the transmitter . When forward CSI is known at the transmitter, the transmitted signals are able to be adjusted according to the known CSI in order to achieve the maximum capacity . However, the transmitter is not able to know forward CSI unless the receiver sends it back via reverse channel . The different methods to realize CSI at transmitter in both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) are being discussed and new feedback mechanism has been proposed. However, according to the feedback mechanism proposed by Nataphat Promsuvana and Peerapong Uthansakul , it has been shown that more estimations and feedbacks are needed to realize the correct CSI at transmitter in FDD mode [22].

The following diagram defines the basic building blocks of MIMO system:

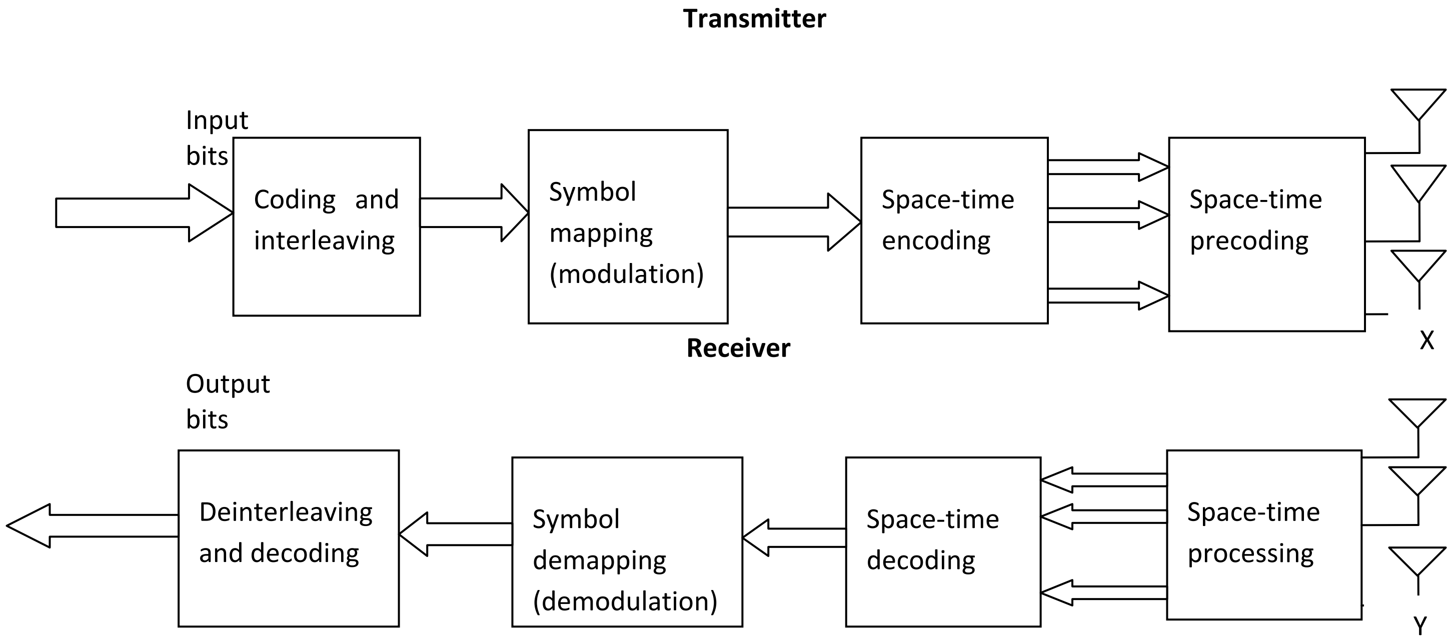


Figure 9 : Basic Building Blocks of MIMO system [3]

The classical MIMO system equation can be defined as :

$$y = \boldsymbol{H}.x + n \quad (2)$$

where, x, y, n and **H** represent the input vector, the output vector, the noise vector, and the channel matrix, respectively. Figure 10 illustrates a MIMO channel with multiple antenna elements at the transmitter and the receiver ends.

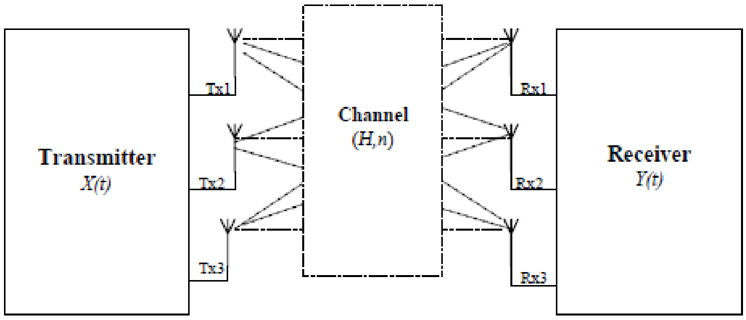


Figure 10 : MIMO channel illustration

Since, MIMO systems are equipped with multiple antennas at both transmitter and receiver ends, MIMO channel is defined with respect to all transmitter and receiver antenna pairs. Considering m transmit antennas and n receiver antennas, a linear time-variant MIMO channel matrix $\mathbf{H}_{nxm}$ can be defined as below:

$$\mathbf{H}_{n\,x\,m} = \begin{bmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nm} \end{bmatrix} \quad (3)$$

where h_{nm} represents the time variant impulse response between the mth transmit antenna and nth receive antenna.

2.2.1 Principles of Space-Time (MIMO) Systems

Oestges and Clerckx[10] stated that MIMO systems use the spatial domain to improve the data rate and reduce the bit-error-rate (BER). Spatial multiplexing improves the data rate (capacity) of a MIMO system while diversity improves the received signal quality (less bit-error-rates)[10].

2.2.1.1 Spatial Multiplexing

Winters [23] showed that the data rate (capacity) is improved in Space-time systems by transmitting different streams of information through independent parallel channels. This principle is known as spatial multiplexing[1] . Gesbert et al.[1] presented a basic spatial multiplexing (SM) scheme with three transmitters and three receivers, which can improve the spectral efficiency by three-fold.

The explanation of the three-fold capacity increment by Gesbert et al.[1] can be expressed as follows. As shown in Figure 11, initially, the bit stream is decomposed into three sub sequences which are transmitted simultaneously using three antennas. Therefore, only one third of the nominal spectrum is used. Since all three antennas operate in the same frequency spectrum, the signals are naturally mixed together in the wireless channel. By detecting the mixing channel matrix from training symbols, the individual bit streams are separated and estimated at the receiver. The separation process is similar to solving three unknowns from a linear system of three equations. Furthermore, the above solution is derived assuming the flat fading conditions, that is, each pair of transmit and receive antennas yields to a single scalar channel coefficient [1].

The separation is possible provided the equations are independent from each other. This implies that the bit streams can be detected and merged to yield the original bit stream, given each receiver antenna "seeing" a sufficiently different channel from the transmitter antenna array. Gesbert et al. stated further that, although flat fading assumption is used in this scenario, the extension to frequency selective cases is also possible using the multiple-carrier approach or combining the MIMO space-time detector with an equaliser in the time domain. Therefore, under favourable conditions such as rich-scattering scenarios MIMO systems can reach higher spectral efficiencies[21].

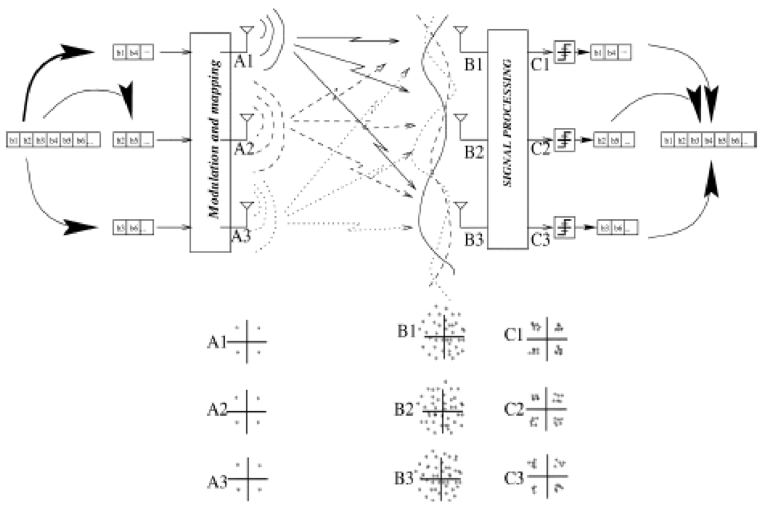


Figure 11: An illustration of Spatial Multiplexing [1]

2.2.1.2 Diversity

Rappaport[16] stated that, wireless links experience random fluctuations of the signal level in time, space and frequency. These fluctuations are known as fading, and can affect the quality of a wireless system. The diversity techniques are employed, to reduce the impact of fading on signal quality [16]. If these copies are affected by independent fading conditions, the probability of fading all the copies at the same time decreases [10]. Therefore, the diversity helps to improve the quality of a wireless system.

Since fading is obvious in space, time and frequency domains, diversity techniques have also been exploited in those domains [10]. The most common diversity technique is spatial diversity [24] in MIMO systems, whereby multiple antennas are spatially separated and the receiver selects the best signal at a given time. The time diversity can be obtained through proper coding and interleaving [10]. Furthermore, frequency diversity is obtained using equalization techniques[25] or muti-carrier modulations. Time and frequency diversity techniques introduce a loss in time or bandwidth when providing redundancy[10]. However, spatial or polarization diversity does not introduce a loss in time or bandwidth, because it is provided using multiple antennas at the transmitter and receiver ends.

2.2.1.3 Array and Diversity Gain

As stated by Oestges et al.[10] the array and diversity gain are two important parameters, which reflect the merit of a diversity scheme. The array gain (g_a) can be determined as the average output Signal to Noise Ratio (ρ_{out}), to the single branch average SNR (ρ). Therefore, the array gain can be defined as :

$$g_a = \rho_{out}/\rho \tag{4}$$

The diversity gain g_{od} (ρ) can be defined as the negative slope of the log-log plot of the average error probability P' to the Signal to Noise Ratio (ρ). Therefore, the diversity gain can be defined as :

$$g_{od}(\rho) = -\log P' / \log \rho \tag{5}$$

In this section, the key features of MIMO systems were examined. According to the information stated, it is obvious that MIMO systems can offer significant improvements in the data rate and quality-of-service (QOS) through the principles of spatial multiplexing and diversity. As discussed in this section a key feature of MIMO systems is capacity improvement. Therefore, the following section will focus on the MIMO channel capacity.

2.2.2 MIMO Channel Capacity

According to the pioneering work carried out by Foschini [21, 26] and Telatar[20] it was shown that a significant capacity improvement of MIMO systems is possible under favourable conditions. These favourable conditions include rich scattering environments and independent transmission paths from each transmit and receive antenna. Furthermore, Goldsmith et al.[27] showed that, the capacity gain achieved from the multiple antennas depends on the reliable channel state information (CSI) at the transmitter and the receiver, the channel SNR and the correlation between the channel gains on each antenna. Therefore, this section of the literature review will investigate the MIMO channel capacity, with and without the channel state information (channel knowledge) at the transmitter.

The Shannon-Hartley theorem provides the theoretical maximum rate of error free data that can be transmitted via an Additive White Gaussian Noise (AWGN) channel for a given received signal power [16] The Shannon's capacity formula is given by [16]

$$C = B\log_2[1 + P(N_O B)] = B\ \log_2[1 + \frac{S}{N}] \tag{6}$$

where C is the channel capacity, P is the received signal power and N_O is the noise power density. Furthermore, S=N is considered as the signal-to-noise ratio (SNR). The Shannon's capacity formula is the baseline for the derivation of MIMO channel capacity equations.

2.2.2.1 MIMO Capacity: Channel Unknown at the Transmitter

Foschini [21] derived the generalised (Channel unknown at the transmitter) capacity equation for time-space architectures. The following equation is derived, using the Shannon's capacity formula for M transmitter and N receiver antennas. The transmitter only knows the channel statistics such as the distribution of the channel (eg Rayleigh) and distribution parameters in this scenario. The famous capacity equation derived by Foschini is given as [21]

$$C_{EP} = \log_2 |\, I_N + (\rho/M)HH(\dagger)| b/s/Hz \tag{7}$$

where (†), H, I_N and ρ represent the determinant, transpose-conjugate , NxM channel matrix, NxN identity matrix and SNR, respectively. This equation is based on M equal power (EP) uncorrelated sources. According to the above equation, both Foschini[21] and Telatar [20] showed that capacity of a MIMO system improves linearly with m fold where m = min(M, N).

2.2.2.2 MIMO Capacity: Channel Known at the Transmitter

According to the information theoretic analysis by Gesbert et al.[1] it has been shown that the additional performance gain can be achieved in MIMO systems with the channel state information at the transmitter (CSIT). This scenario considers that the transmitter knows the random channel outcome and adjusts the transmit signal accordingly [28]. If Q denotes the covariance matrix of the transmitted M-D vector Gaussian signal of total radiated power P, then the Shannon's capacity for a fading MIMO channel with additive white Gaussian noise (AWGN) is given as below

$$C = \log_2 | I_N + HQH \dagger | \, b/s/Hz \tag{8}$$

where |.|, (†), H and I_N represent the determinant, transpose-conjugate , NxM channel matrix and NxN identity matrix, respectively. Furthermore, for the equal power uncorrelated sources (where CSIT is not available), Q = $(\rho/M)I_N$.

2.2.3 Comparison between Single-User (SU) MIMO and Multi-User (MU) MIMO Systems

A basic Multi-User MIMO system is illustrated in Figure 12. In MU-MIMO systems, base station (BS) coordinates with multiple user terminals (UT) in order to achieve an increased downlink capacity. Furthermore, to achieve this increased downlink capacity, accurate Channel State Information (CSIT) is needed at the BS [29]. As stated by Bauch et al.[30], introduction of the spatial domain into the scheduling process enables an additional degree of freedom, which allows improved exploitation of multi-user diversity.

In MU-MIMO systems, the BS calculates the downlink beamforming matrix based on the predicted user channels. Since many users are attached to a single BS, it selects a subset of users to be served at each point in time. This selection and relevant rate allocation is known as scheduling [30].

Another difference between SU-MIMO and MU-MIMO is that, in SU-MIMO the number of spatial domains that can be used is limited by the number of antennas at the receiver terminal. Potential spatial dimensions can be wasted in a SU-MIMO system in a situation where the receiver terminal has smaller number of antennas compared to the BS [30]. Moreover, in MU-MIMO, the total number of spatial dimensions can be exploited.

Therefore, MU-MIMO systems may achieve considerable gains in terms of sum capacity over SU-MIMO systems [30].

By extending the classical MIMO system equation defined in [31], the MU-MIMO system equation for the signal received by the kth user can be defined as below,

$$y_k = H_k . x_k + n_k \quad (9)$$

where H_k, x_k and y_k is the propagation channel for k^{th} user, transmitted signal and received signal by the kt^{h} user, respectively. Furthermore, n_k represents AWGN noise component experienced by the k^{th} user.

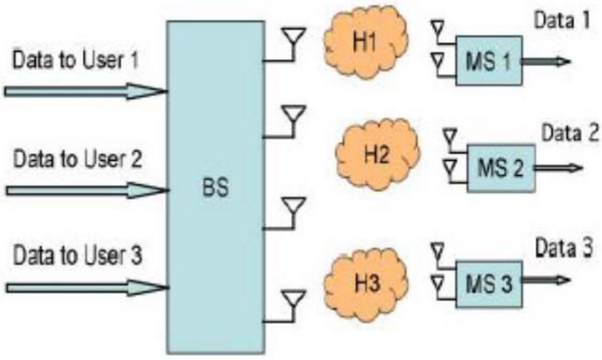


Figure 12: A Multi- user MIMO system

As shown by Spencer et al. [11], there are two communication problems to consider in multiuser MIMO systems. Those are the 'uplink' through which all users transmit data to the same base station, and the 'downlink' through which the base station transmits data to multiple users simultaneously. A comprehensive illustration of the multiuser downlink MIMO system is provided in the reference [11]. Furthermore, as stated by Spencer et al., single user MIMO systems benefit from the co-ordination between all transmitters and receivers. However, in multiuser MIMO systems it is assumed that there is no co-ordination between the users (receivers). Therefore, multiuser MIMO systems are more complex compared to the single user MIMO systems.

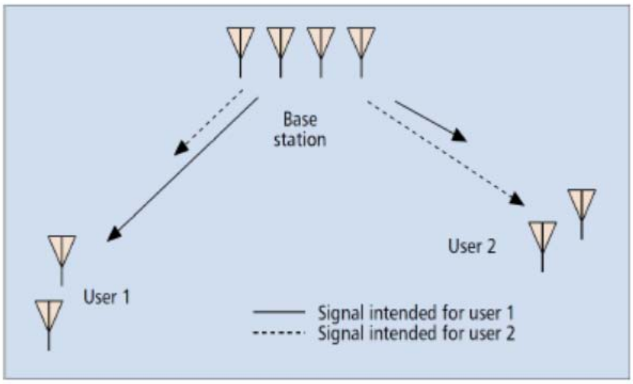


Figure 13 : An illustration of Multi-user MIMO Downlink[11]

The challenge at the uplink is that users transmit data to the base station over the same channel and the base station has to separate the users using methods such as array processing and multi-user detection (MUD) [11]. Furthermore, in the downlink channel, the base station transmits the data simultaneously to many users. As shown in Figure 13, the base station may attempt to transmit data over the same channel to two users, causing inter-user interference for user 1 generated by the signal sent to user 2 and vice versa. By using the methods such as multiuser detection (MUD), such interference can be avoided [11]. Spencer et al. stated that techniques such as MUD are too costly to use at the receiver and recommended avoiding the multiple access interference by intelligently designing the transmitted signal at the transmitter. Therefore, if the channel state information (CSI) is available at the transmitter, it has knowledge about the level of interference created by the relevant users, and can take measures to eliminate those effects via intelligent beam forming or the use of dirty paper codes [11].

Research shows that, only a few multiuser MIMO feedback mechanisms [32, 33] have been proposed in the area of MIMO feedback mechanism. In the previous subsection, it has been stated that the inter-user interference in multiuser MIMO systems is a great concern. Nihar Jindal and Sean Ramprashad [34] argued that the most critical factor affecting the throughput gains provided by MU-MIMO is the feedback mechanism that allows the transmitting basestation to periodically receive CSI from mobiles. The authors further presented the design options within the CSI feedback mechanism for downlink MU-MIMO in FDD systems. In particular the authors consider how best to use feedback resources by approximately choosing the time and frequency intervals T and F at which to send CSI feedback, the feedback quantization level B (in bits) per mobile, and the number of mobiles K sending CSI feedback in each F x T interval. The results demonstrate that the time period of feedback T is a critical aspect for a system such as LTE-A. This is due to the relatively stronger correlation in time than in frequency, and smaller influence T has on the CSI error, and thus MU-MIMO efficiency, when compared to parameters such as F and B.

Another message presented by the authors show that a well designed MU-MIMO system should have mobiles quantize their channels sufficiently accurately with respect to their SNR, even at the expense of K and multi-user diversity in the system. Furthermore the inaccuracy in the CSI provided to channel and not (substantially) by channel quantization errors. The results also show that having each mobile directly quntize its own channel vector (and then choosing beams based on these quantized vectors) is strongly preferred over indirect quantization approaches such as opportunistic (random) beamforming.

Gregory Morozov, Alexei Davydov and Apostolos Papathanassiou [35] propose a novel CSI feedback mechanism which combines two existing CSI feedback schemes to achieve significant system performance improvements in MU-MIMO beamforming for OFDMA systems operating in Time Division Duplex(TDD). The employed CSI reporting schemes are the quantized, codebook-based feedback scheme and the sounding based feedback scheme. It is shown in the paper that for accurate calculation of the MU-MIMO beamforming weights, the sounding based CSI feedback scheme is preferable in deployment scenarios with low noise and interference levels. Gregory Morozov, Alexei Davydov and Apostolos Papathanassiou evaluated the sytem- level performance of TDD- OFDMA with MU-MIMO beamforming under quantized and sounding-based CSI feedback schemes. The extensive evaluation results indicate that the combination of the two feedback mechanisms using a simple feedback selection scheme performs close to the system with perfect CSI feedback, which renders the proposed approach as an excellent candidate for practical TDD-OFDMA system deployments with MU-MIMO beamforming. Few research papers related with feedback mechanism by different authors [36-38] were also studied and it was concluded that the optimal and novel CSI feedback mechanism is needed for MU-MIMO to properly serve the spatially seperated users.

2.3 CHANNEL STATE INFORMATION

In wireless communication, channel state information (CSI) simply represents the properties of a communication link between the transmitter and receiver. The CSI describes how a signal propagates from the transmitter to the receiver and represents the combined effect of, for example, scattering, fading, and power decay with distance. The CSI makes it possible to adapt transmissions to current channel conditions, which is crucial for achieving reliable communication with high data rates in multi antenna systems. The channel state information (CSI) at the transmitter is vital in MIMO systems in order to increase the transmission rate, to enhance coverage, to improve spectral efficiency and to reduce receiver complexity[3].

The CSI is usually estimated at the receiving end and then quantized and fed back to the transmitting side. Basically there are two ways that the transmitter can obtain CSI from the receiving end. The transmitter and receiver can have different CSI. There are basically two levels of CSI, namely instantaneous CSI and statistical CSI. The following section describes both, the instantaneous and statistical CSI.

2.3.1 Instantaneous CSI

Instantaneous CSI is also known as short-term CSI. Instantaneous CSI means that the current conditions of the channel are known, which can be viewed as knowing the impulse response of a digital filter[16]. This gives an opportunity to adapt the transmitted signal to the impulse response and thereby optimize the received signal for spatial multiplexing or to achieve low bit error rates.

2.3.2 Statistical CSI

Statistical CSI is also known as long-term CSI. Statistical CSI means that a statistical characterization of the channel is known. This description can include the type of fading distribution, the average channel gain, the line-of-sight component, and the spatial correlation[16]. As with instantaneous CSI, this information can be used for transmission optimization.

The CSI acquisition is practically limited by how fast the channel conditions are changing. In fast fading systems where channel conditions vary rapidly under the transmission of a single information symbol, only statistical CSI is reasonable. On the other hand, in slow fading systems instantaneous CSI can be estimated with reasonable accuracy and used for transmission adaptation for some time before being outdated. In practical systems, the available CSI often lies in between these two levels; instantaneous CSI with some estimation/quantization error is combined with statistical information.

The capacity of a MIMO (multi-input multi-output) channel is influenced by the degree of CSI (channel-state information) available to both transmitter and receiver[2]. In most instances of multi-antenna communication, the receiver can accurately track the instantaneous state of the channel from pilot signals that are typically embedded within the transmissions. In terms of CSI at the transmitter, on the other hand, several scenarios are possible:

In frequency-duplexed systems, where uplink and downlink are apart in frequency, the link fading is not reciprocal and thus the CSI must be conveyed through feedback, which may incur round-trip delays that are non negligible with respect to the coherence time of the CSI being reported[3]. Consequently, the transmitter is usually deprived of instantaneous CSI.

In time-duplexed systems, in contrast, the links are reciprocal as long as the coherence time of the fading process exceeds the duplex time. Thus, the transmitter may have access to reliable CSI at low and moderate levels of mobility.

At high levels of mobility, even in time-duplexed systems the CSI becomes rapidly outdated.

In terms of the characterization of the single-user capacity, these various scenarios are usually mapped onto distinct operational regimes:

(a) The transmitter has instantaneous CSI.

(b) The transmitter has only statistical CSI.

(c) The transmitter has no CSI.

In a narrowband flat-fading channel with multiple transmit and receive antennas (MIMO), the system is modeled as

$$y = \boldsymbol{H}.x + n \tag{10}$$

where y and x are the receive and transmit vectors, respectively, and **H** and n are the channel matrix and the noise vector, respectively. Let us suppose the noise is modeled as circular symmetric complex normal with

$$n \sim CN(0, S) \tag{11}$$

where the mean value is zero and the noise covariance matrix S is known.

- Instantaneous CSI

Ideally, the channel matrix H is known perfectly. Due to channel estimation errors, the channel information can be represented as

$$Vec\ (H_{estimate}) \sim CN(vec(H), R_{error}) \tag{12}$$

where Hestimate is the channel estimate and Rerror is the estimation error covariance matrix. The vectorization vec ( ) was used to achieve the column stacking of H, as multivariate random variables are usually defined as vectors.

- Statistical CSI

In this case, the statistics of H are known. In a Rayleigh fading channel, this corresponds to knowing that

$$Vec(H) \sim CN(0, R) \tag{13}$$

for some known channel covariance matrix R.

2.3.3 Estimation of the channel:

Since the condition of the channel always vary, instantaneous CSI needs to be estimated on a short-term basis. A popular approach to estimate the channel is called training sequence (or pilot sequence). In the training sequence or pilot sequence a known signal is transmitted from the transmitting side and the channel matrix H is estimated in the receiving side using the combined knowledge of the transmitted and received signal[2].

Let the training sequence be denoted as $x_1, \ldots\ldots\ldots, x_n$ where the vector x_i is transmitted over the channel as

$$y_i = \boldsymbol{H}.x_i + n_i \tag{14}$$

By combining the received training signals yi for i =1,..., N the total training signaling becomes

$$Y = [y_1, \ldots \ldots \ldots., y_N] = H.X + N \tag{15}$$

with the training matrix X = $[x_1, \ldots.., x_N]$ and the noise matrix N=$[n_1, \ldots., n_N]$.

With this notation, channel estimation means that H should be recovered from the knowledge of Y and X when noise is ignored.

Training symbols can be used for channel estimation, usually providing a good performance. However, their transmission efficiencies are reduced due to the required overhead of training symbols such as preample or pilot tones that are transmitted in addition to data symbols. The least square (LS) and minimum-mean-square-error (MMSE) techniques are widely used for channel estimation when training symbols are available. The following section describes these two methods:

- Least-square estimation

If the channel and noise distributions are unknown, then the least-square estimation method (also known as the minimum-variance unbiased estimator) finds the channel estimate in following way

$$H_{LS-estimate} = Y.X.H(X.X.H)^{-1} \quad (16)$$

where ( ) H denotes the conjugate transpose. The estimation Mean Square Error (MSE) is proportional to tr $(XXH)^{-1}$

(where t_r denotes the trace. The error is minimized when XXH is a scaled identity matrix. This can only be achieved when N is equal to (or larger than) the number of transmit antennas. The simplest example of an optimal training matrix is to select X as a (scaled) identity matrix of the same size that the number of transmit antennas.

- MMSE estimation

If the channel and noise distributions are known, then this a priori information can be exploited to decrease the estimation error. This approach is known as Bayesian estimation and for Rayleigh fading channels it exploits that

$$vec(H) \sim CN(0, R) \quad (17)$$

$$vec(N) \sim CN(0, S) \quad (18)$$

The MMSE estimator is the Bayesian counterpart to the least-square estimator and becomes

$$Vec(H_{MMSE-estimate} = (R - 1 + (XT \otimes I)HS^{-1}(XT \otimes I))^{-1} \left(XT \otimes I\right) HS^{-1} vec(Y) \quad (19)$$

where $\otimes$ denotes the Kronecker product and the identity matrix I has the dimension of the number of receive antennas. The estimation Mean Square Error (MSE) is

$$t_r(R - 1 + (XT \otimes I)HS^{-1}(XT \otimes I))^{-1} \quad (20)$$

and is minimized by a training matrix X that in general can only be derived through numerical optimization. But there exist heuristic solutions with good performance based on water filling. As opposed to least-square estimation, the estimation error for spatially correlated channels can be minimized even if N is smaller than the number of transmit antennas. Thus, MMSE estimation can both decrease the estimation error and shorten the required training sequence. It needs however additionally the knowledge of the channel correlation matrix R and noise correlation matrix S. In absence of an accurate knowledge of these correlation matrices, robust choices need to be made to avoid MSE degradation. A Correlation matrix simply describes correlation among N variables. It is a square symmetrical NxN matrix with the (ij) th element equal to the correlation coefficient r_ij between the (i) th and the (j) th variable. The diagonal elements (correlations of variables with themselves) are always equal to 1.00.

2.3.4 Methods of Obtaining CSI at transmitter in MIMO

The design and implementation of MIMO faces significant challenges, one of the most relevant is the availability of CSI at the transmitter. The transmitter can only acquire CSI indirectly, since the signal enters the channel only after leaving the transmitter[3]. The receiver, however, can estimate the channel directly from the channel modified received signal. Pilots are usually inserted in the transmitted signal to facilitate channel estimation by the receiver. Basically there are two methods that allow the transmitter to obtain CSI from the receiver. The first one is based on the channel reciprocity principle and the second one uses feedback from the receiver.

The reciprocity principle is usually applicable in Time Division Duplex (TDD) systems where the forward and reverse links occur at the same frequency, the same time and same antenna locations. The feedback mechanism is often applicable in FDD systems and is not limited by reciprocity requirements.

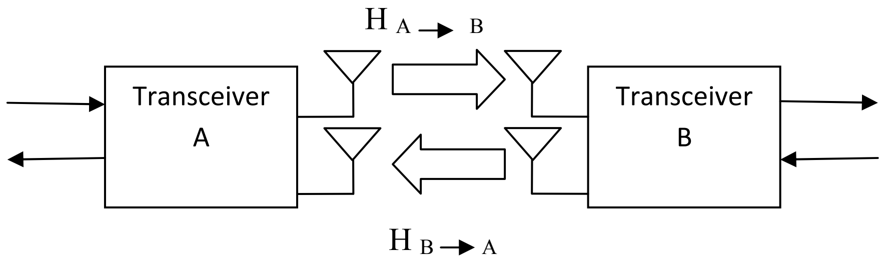


Figure 14: Reciprocity mechanism

The reciprocity principle in wireless communication states that the channel from an antenna A to another antenna B is identical to the transpose of the channel from B to A. Reciprocity hold, provided both forward and reverse links occur at the same frequency, the same time and same antenna locations. Since communication systems are often full-duplex, the reciprocity principle suggests that the transmitter can obtain the forward (A to B) channel from the reverse (B to A) channel measurements, which the receiver (at A) can measure, as shown in figure below .

In practical full-duplex communications, however the forward and reverse links cannot use all identical frequency, time, and spatial instances. The reciprocity principle may still hold approximately if the difference in any of these dimensions is relatively small, compared to the channel variation across the referenced dimension[3]. In the temporal dimension, this condition implies that any time lag Δt between the forward and reverse transmissions must be much smaller than the channel coherence time T_C :

$$\Delta t < T_C \tag{21}$$

Similarly, any frequency offset Δf must be much smaller than the channel coherence bandwidth B_C:

$$\Delta f < B_C \tag{22}$$

And the antenna location differences on the two links must be much smaller than the channel coherence distance D_C.

One complication in using reciprocity methods is that the principle only applies to the radio channel between the antennas, while in practice; the "channel" is measured and used at the baseband processor. This fact means that different transmit and receive radio-frequency (RF) hardware chains become part of the forward and reverse channels. Since these chains have different frequency transfer characteristics, reciprocity requires transmit-receive chain calibration.

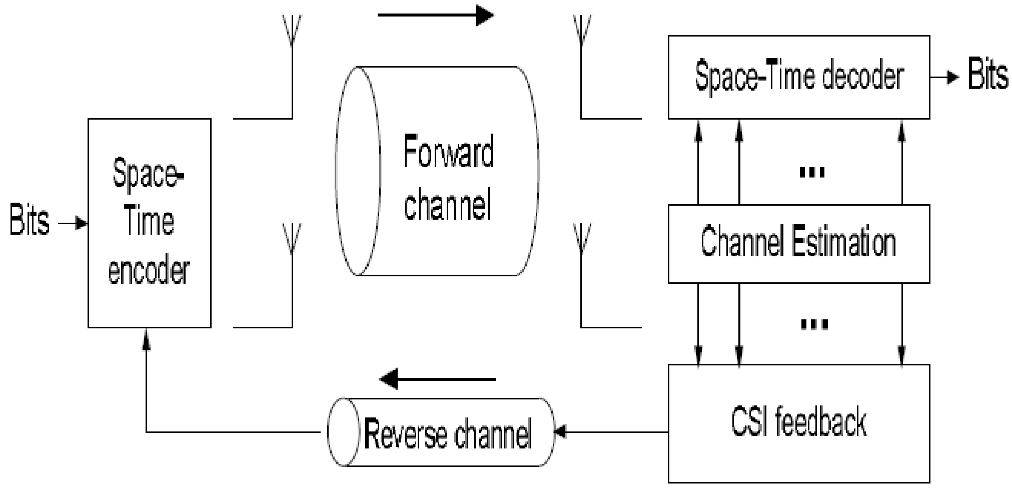


Figure 15: Feedback Mechanism

For this approach, the receiver estimates the channel and then feeds it back to the transmitter through reverse channel[3]. The configuration of feedback approach is shown in Figure 15. In Figure 15, the receiver uses the estimated channel to extract the data and to generate the feedback CSI. The feedback CSI is sent back to the transmitter using the feedback control channel. It is assumed that channel state information is perfectly known at the transmitter. The transmitter, in turn, uses this information to customize the transmitted signal for the channel.

In a practical system, errors from feedback link which influences to channel knowledge cannot be neglected. This effect can degrade the capacity performance and it is more pronounced when feedback link contain errors excessively, under this assumption the available CSI at transmitter can be expressed as

$$H_T = \boldsymbol{H} + \epsilon_E + \epsilon_F \tag{23}$$

Or,

$$H_T = H' + \epsilon_F \tag{24}$$

where H is the forward channel and ε_F is the $N_R \times N_T$ error matrix from feedback link assumed as complex Gaussian distribution with zero mean and variance σ_F^2 .

The channel is measured at the receiver at B during the forward link (A to B) transmission, and the information is sent to the transmitter at A on the reverse-link. Feedback is not limited by the reciprocity requirements. However, the time lag Δlag between the channel measurement at B and its use by the transmitter at A can be a source of error, unless it is much smaller than the channel coherence time:

Feedback can also be used to send channel statistics that change much slower in time compared to the channel itself. In such cases, the time lag requirement for valid feedback can be relaxed significantly.

Channel acquisition using feedback is referred to as the closed-loop method and is more common in FDD systems[3]. Although not subjected to transmit-receive calibration, feedback imposes another system overhead by using up transmission resources. Therefore, methods of reducing feedback overhead, such as quantizing feedback information, are both important and necessary. Within a bound on feedback resources these parameters can determine how best to use such resources to optimize MIMO spectral efficiency[3]. The results obtained by authors in show that spectral efficiency is often maximized if users quantize their channels very accurately but perform feedback at moderate intervals in time, such that CSI inaccuracy is primarily determined by the variation of the channel in time and frequency rather than being dominated by quantization errors. A number of complementary approaches geared toward feedback reduction were proposed, which may restore the robustness of MIMO techniques with respect to a wider range of application and environments. The impact and design of an optimal form of CSI feedback mechanism is still an open and exciting problem. Therefore, the main contribution of this research is to develop an effective CSI feedback mechanism suitable for MIMO systems in time-varying channel.

2.4 BIT ERROR RATE (BER), ENERGY PER BIT TO NOISE POWER SPECTRAL DENSITY RATIO (EB/NO) AND ORTHOGONAL SPACE TIME BLOCK CODING (OSTBC)

2.4.1 Bit Error Rate (BER)

Bit error rate, BER is a key parameter that is used in assessing systems that transmit digital data from one location to another [39].

Bit Error Rate (BER) is defined as the rate at which errors occur in a transmission system. If the transmission medium between the transmitter and receiver is good and also the signal to noise ratio is high, then the bit error rate will be very small - possibly insignificant and having no noticeable effect on the overall system. However if noise can be detected, then there is chance that the bit error rate will need to be considered[16].

Mathematically, BER is defined as the ratio of number of errors occured to the total number of bits sent which is

$$BER = Number\ of\ Errors/Total\ Number\ of\ bits\ sent \qquad (25)$$

The main reasons for the degradation of a data channel and the corresponding bit error rate, BER is noise and changes to the propagation path (where radio signal paths are used). Both effects have a random element to them, the noise following a Gaussian probability function while the propagation model follows a Rayleigh model. This means that analysis of the channel characteristics are normally undertaken using statistical analysis techniques[16].

In this research ,BER has been used to analyse the performance of feedback mechanism, reciprocity mechanism and also the performance of both the feedback and reciprocity mechanisms when Rician channel was being added to the simulation.

2.4.2 Energy per bit to Noise power spectral density ratio (Eb/No)

Eb/N0 (the energy per bit to noise power spectral density ratio) is an important parameter in digital communication or data transmission. It is a normalized signal-to-noise ratio (SNR) measure, also known as the "SNR per bit". It is especially useful when comparing the bit error rate (BER) performance of different digital modulation schemes without taking bandwidth into account [16]. Eb/N0 is a non-dimensional ratio.

Eb/N0 is commonly used with modulation and coding designed for noise-limited rather than interference-limited communication, since additive white noise (with constant noise density N0) is assumed[16].

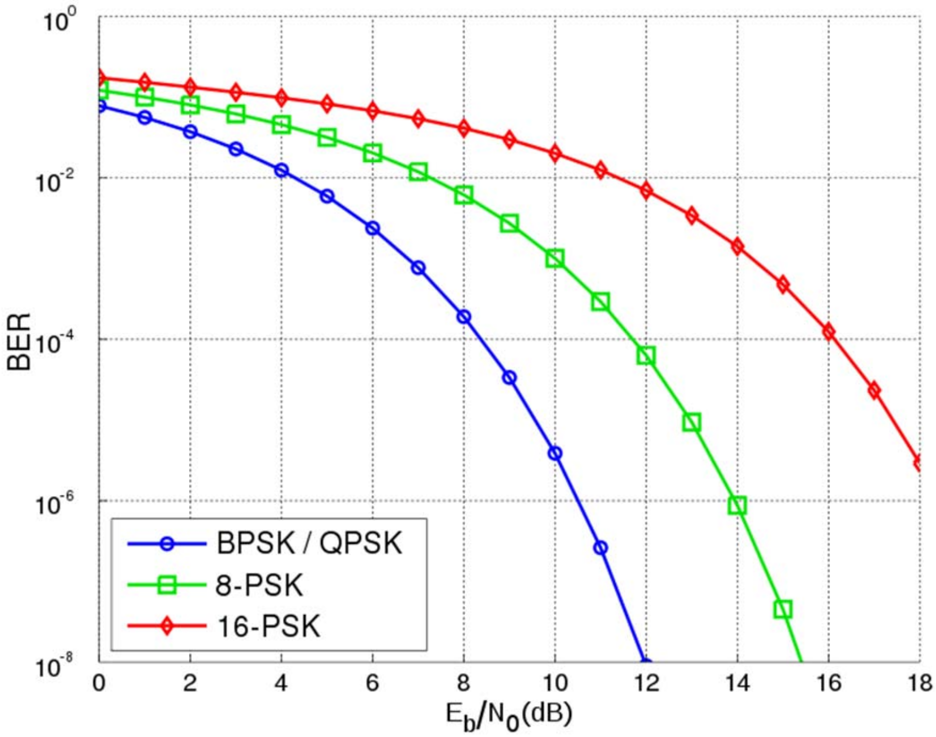


Figure 16: Bit-error rate (BER) vs Eb/N0 curves for different digital modulation

2.4.3 Space-time block code

Space-time block codes are used for MIMO systems to enable the transmission of multiple copies of a data stream across a number of antennas and to exploit the various received versions of the data to improve the reliability of data-transfer[40]. Space-time coding combines all the copies of the received signal in an optimal way to extract as much information from each of them as possible.

Space time block coding uses both spatial and temporal diversity and in this way enables significant gains to be made[40].

Space-time coding involves the transmission of multiple copies of the data. This helps to compensate for the channel problems such as fading and thermal noise.

Although there is redundancy in the data some copies may arrive less corrupted at the receiver [41].

When using space-time block coding, the data stream is encoded in blocks prior to transmission. These data blocks are then distributed among the multiple antennas (which are spaced apart to decorrelate the transmission paths) and the data is also spaced across time [41].

A space time block code is usually represented by a matrix. Each row represents a time slot and each column represents one antenna's transmissions over time.

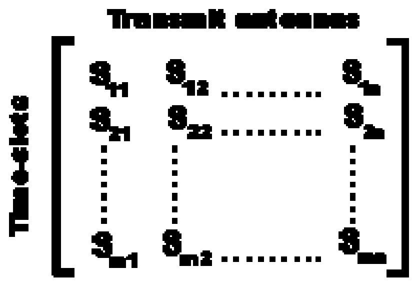


Figure 17:Space-time block code

Within this matrix, S_{ij} is the modulated symbol to be transmitted in time slot i from antenna j. There are to be T time slots and n_T transmit antennas as well as n_R receive antennas. This block is usually considered to be of 'length' T [41].

2.4.3.1 MIMO Alamouti coding

A particularly elegant scheme for MIMO coding was developed by Alamouti. The associated codes are often called MIMO Alamouti codes or just Alamouti codes [42].

The MIMO Alamouti scheme is an ingenious transmit diversity scheme for two transmit antennas that does not require transmit channel knowledge. The MIMO Alamouti code is a simple space time block code that he developed in 1998.

2.4.3.2 Differential space time block code

Differential space time block coding is a form of space time block coding that does not need to know the channel impairments in order for the signal to be decoded. The differential space time block codes are normally based upon the more standard space-time block codes. One block-code is transmitted from a set in response to a change in the input signal. This enables the system to work because the differences among the blocks in the set are designed to allow the receiver to extract the data with good reliability.

Chapter 3: Research design

3.1 INTRODUCTION

This chapter of the thesis outlines the design and methodology of the research. It describes the methodology that has been used throughout the research to achieve the research objectives discussed in Chapter 1. It describes in detail the simulations carried out in MATLAB to obtain CSI at the transmitter end in MIMO system. It also describes the simulations conducted to measure the channel capacity of MIMO systems with and without the availability of CSI at the transmitter end. Furthermore, this chapter presents the block diagrams of both the feedback and reciprocity mechanisms that have been simulated in MATLAB and also describes each component that has been used in the block diagrams of the transmitter and receiver MATLAB models. This chapter also presents the general simulation set up that has been used in the research. The description of most of the components presented in this chapter has been done with the help of MATLAB and MATHWORKS.

3.2 RESEARCH METHODOLOGY

This section gives a brief overview of the research methodology that has been implemented throughout the research. It is divided into three different phases as follows:

- Phase 1

The first phase of the research includes the comprehensive literature review in the research field to obtain a solid background and identify the knowledge gap.

- Phase 2

The second phase of the research consists of the simulation of the feedback mechanisms in MIMO systems. Both the reciprocity principle, applicable in TDD system and the feedback mechanism, applicable in FDD system have been simulated.

- Phase 3

The last phase of the research consists of analysing the trade-offs between the amount of CSI fed back to the transmitter and the gain available from using the CSI. Also, the graphs of BER vs Eb/No (dB) for the known, estimated and feedback CSI are analysed for comparing performance improvement.

The different topics that were studied in literature review have already been provided in t Chapter 2. The following section will describe the simulation of feedback mechanisms in more detail. The next chapter will analyse the results obtained from the simulation of feedback mechanisms.

3.3 SIMULATION OF FEEDBACK MECHANISMS IN MATLAB

In order to design the feedback mechanisms in MIMO systems and also to calculate the channel capacity, several simulations have been carried out in MATLAB. The simulation started by defining some common simulation parameters such as frame length, number of packets, maximum number of errors, Eb/No (energy per bit to noise power spectral density ratio) , number of transmitting antennas, number of receiving antennas, number of pilots symbols per frame and orthogonal set per transmit antenna. The simulation was set up by creating different system objects such as BPSK Modulator, BPSK Demodulator, QPSK Modulator, QPSK Demodulator, OSTBC Encoder, OSTBC Combiner, AWGN channel, Error Rate calculator and MIMO channel and also modulation order was defined. With the number of transmitting and receiving antennas being considered two BPSK modulator and demodulator were created. For the increase in the number of transmitting and receiving antennas QPSK or QAM modulator and demodulator could be created as BPSK does not support more than two transmitting and receiving antennas. As this research has used only two transmitting and two receiving antennas only BPSK modulator and demodulator were used for simulation. The variables were pre-allocated for speed. Also the figure has been set up for visualizing BER results. Finally a “for” loop has been implemented so that the simulation is run over a range of Eb/No points to generate BER results that allow comparing the known, estimated and feedback channel at the transmitting end. The loop function has been set up till the number of errors exceed 'maxNumErrs' or the maximum number of packets have been simulated.

The simulation is carried out by considering both the feedback and reciprocity mechanisms for different number of antennas at the transmitting and receiving ends. The reciprocity mechanism is only applicable in TDD systems as the channel is the same (same frequency etc). Feedback mechanism can be used in either TDD or FDD systems. Both of these approaches look at the quality of the channel obtained at the base station needed for beamforming, space-time signalling, maximizing capacity and precoding.

3.3.1 Block Diagram of feedback mechanism

This section describes the block diagrams of the feedback mechanism with a detailed explanation of each component.

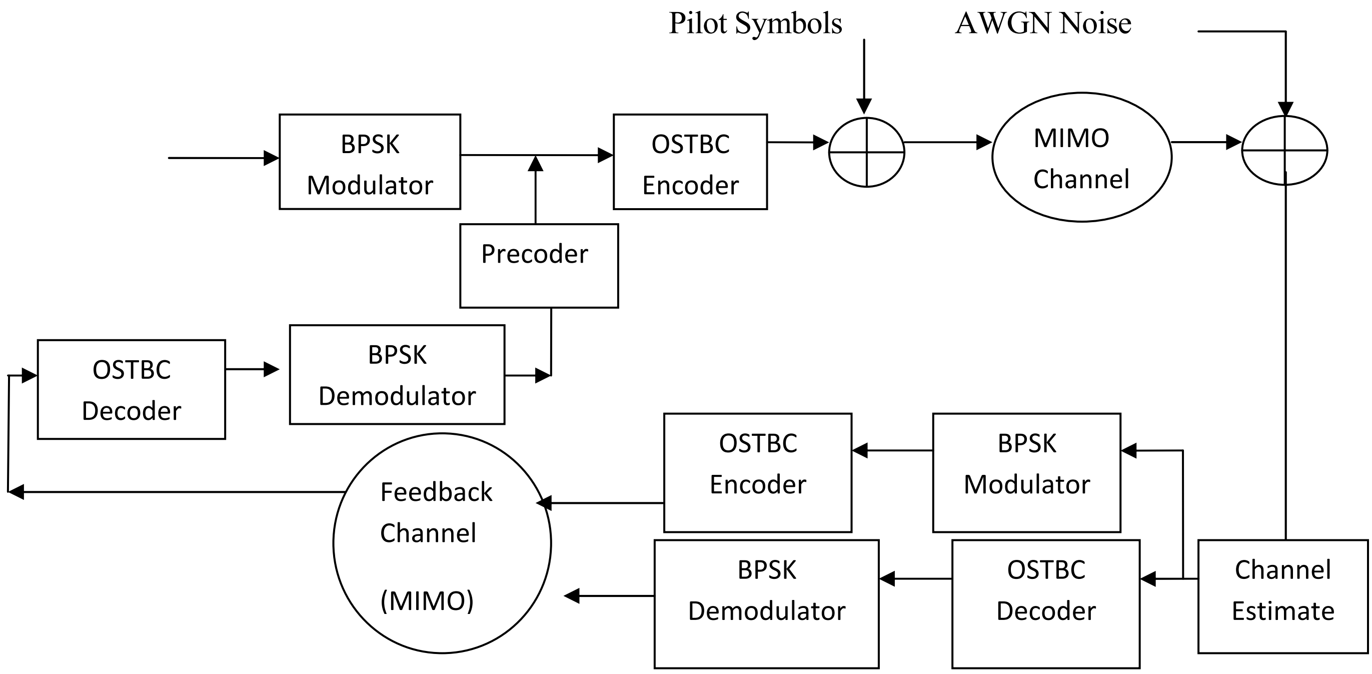


Figure18: Block diagram of simulated feedback mechanism in a MIMO system

Figure 18 represents the block diagram of feedback mechanism that has been implemented in MATLAB to obtain the CSI at the transmitter end. For the effective transmission of the generated data, first it is being sent through the BPSK modulator. The generated data is simply the mix of 0s and 1s and is in the form of column vector. The BPSK Modulator modulates the data using the binary phase shift keying method. The output is a baseband representation of the modulated signal. It accepts a column vector input signal. The input must be a discrete-time binary-valued signal. If the input bit is 0 or 1, respectively, then the modulated symbol is exp (jθ) or -exp (jθ), respectively, where θ represents the Phase offset parameter. This output is now sent through the OSTBC encoder. The OSTBC Encoder encodes an input symbol sequence using orthogonal space-time block code (OSTBC). The OSTBC Encoder block encodes the information symbols from the BPSK Modulator by using either the Alamouti code for two transmit antennas or other generalized complex orthogonal codes for three or four transmit antennas. The number of transmit antennas is given to this block as an input. The output of this block is an (Ns x Nt) variable-size matrix, where the number of columns (N_t) corresponds to the number of transmit antennas and the number of rows (N_s) corresponds to the number of orthogonal code samples transmitted over each transmit antenna in a frame. The number of transmit and receive antennas are adaptive and change either manually or according to an adaptation algorithm, based on the difference between target and actual frame-error rates of the overall system. For the proper estimation of the channel characteristics at the receiver end, the pilot symbols are prepended for each frame in the transmitter side and then finally the data is being transmitted through the channel. The MIMO channel system object is being created to simulate the 2 X 2 spatially independent flat-fading Rayleigh channel. The different properties of MIMO channel such as the SampleRate, PathDelays, AveragePathGains, MaximumDopplerShift, DopplerSpectrum, NumTransmitAntennas, NumbeRecAntennas, TransmitCorrelation Matrix, ReceiveCorrelation Matrix, Fading distribution, KFactor, DirectPathDoppler shift, DirectPathInitial Phase, RandomStream, Seed, NormalizePathGains, NormalizeChannelOutputs, PathGainsOutputPort were created according to the need and requirement for the simulation process. After data was passed through the MIMO channel, the channel was estimated at the receiving end. Through interpolation, it is possible to estimate the channel across an arbitrary number of frames. As there is always unwanted signal present at the channel, the AWGN is being added to the channel as noise before the estimation was done. At the receiver end, the channel is being estimated using the channel estimator. At this stage for making simulation process bit easier it is assumed the channel remains unchanged for the length of the packet (i.e., it undergoes slow fading).

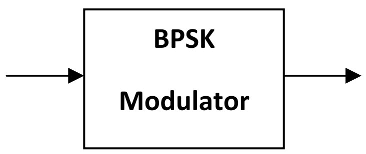
The main problem in designing MIMO systems is demodulating the received signals to recover the transmitted bits. Typically, each received signal contains components of all transmitted signals, making demodulation more complicated than in a SISO system. To address this issue, many receivers employ linear equalization to separate the received signals. This approach is attractive for its low computational complexity but it introduces a substantial performance penalty, resulting in significantly reduced data rates or ranges compared to what may otherwise be possible. For better performance ML detection has been used in simulation. Given a MIMO system described by $y = \mathbf{H}x+n$, where y is the received signal vector , H is the known (or estimated) channel matrix and n is additive noise, an ML detector searches over all possible transmit symbol vectors x to find the vector x which minimizes $||y - Hx||^2$. In a system with N_t spatial streams, each employing an M^2 point constellation, this requires calculating M^2N_t distance metrics.

After the proper estimation of the channel at the receiver end, the CSI is sent back to the transmitter through the feedback channel. The feedback channel is the MIMO channel itself. Both the magnitudes as well as phase of the estimated channel were fed back simultaneously. Again for the effective transmission of the estimated channel, it is sent through the BPSK modulator and then OSTBC encoder before passing through the feedback channel. Now for the successful retrieving of the channel information at the transmitter side the estimated channel is passed through the decoder and demodulator respectively. The transmitter finally receives CSI from the receiver using the feedback channel. The main advantage of having CSI at the transmitter is that the transmitter can adapt its transmission strategies according to the channel condition which is crucial in receiving the high data rates in multi antenna systems. The graphs of BER vs Eb/No (dB) for the known, estimated and feedback CSI are shown in the next results and analysis chapter.

The explanation of each of the components that has been used in the block diagram of feedback mechanism has been discussed below.

3.3.2 Transmitter Side

3.3.2.1 BPSK Modulator



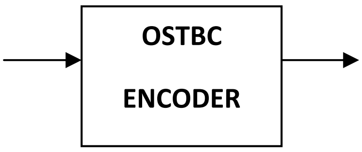
The BPSK Modulator modulates the signal using the binary phase shift keying method. The output is a baseband representation of the modulated signal. It accepts a column vector input signal. The input must be a discrete-time binary-valued signal. If the input bit is 0 or 1, respectively, then the modulated symbol is exp (jθ) or -exp(jθ), respectively, where θ represents the Phase offset parameter.

The BPSK Modulator supports the following data types:

Table 1: Supported Data Types by BPSK Modulator

Port	Supported Data Types
Input	Double-precision floating point Single-precision floating point Boolean 8-, 16-, and 32-bit signed integers 8-, 16-, and 32-bit unsigned integers ufix(1)
Output	Double-precision floating point Single-precision floating point Fixed point (signed only)

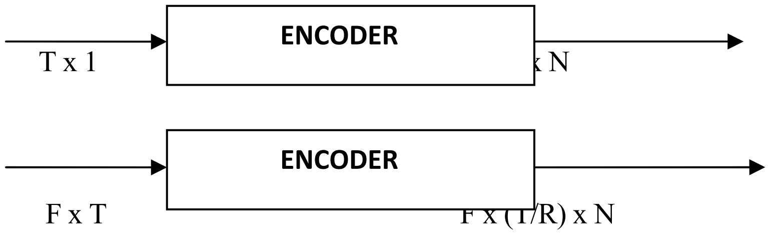
3.3.2.2 OSTBC Encoder



The OSTBC Encoder block encodes the information symbols from the BPSK or QPSK Modulator by using either the Alamouti code for two transmit antennas or other generalized complex orthogonal codes for three or four transmit antennas. The number of transmit antennas is given to this block as an input. The output of this block is an (Ns x Nt) variable-size matrix, where the number of columns (Nt) corresponds to the number of transmit antennas and the number of rows (Ns) corresponds to the number of orthogonal code samples transmitted over each transmit antenna in a frame. This block is a MATLAB Function block that uses the comm.OSTBCEncoder System object to implement the encoding algorithm for selected transmit antennas.

Dimension:

The block supports time and spatial domains for OSTBC transmission. It also supports an optional dimension, over which the encoding calculation is independent. This dimension can be thought of as the frequency domain. The following illustration indicates the supported dimensions for the inputs and output of the OSTBC Encoder block.



The following table describes the different variables with their description supported by OSTBC encoder:

Table 2: Variables with description supported by OSTBC encoder

Variable	Description
F	The additional dimension; typically the frequency domain. The encoding does not depend on this dimension.
T	Input symbol sequence length for the time domain.
R	Symbol rate of the code.
N	Number of transmit antennas.

Note: F can be any positive integer. N can be 2, 3 or 4, indicated by Number of transmit antennas. For N = 2, R must be 1. For N = 3 or 4, R can be 3/4 or 1/2, indicated by Rate. The time domain length T must be a multiple of the number of symbols in each codeword matrix. Specifically, for N = 2 or R = 1/2, T must be a multiple of 2 and when R = 3/4, T must be a multiple of 3.

To understand the block's dimension propagation, the following table needs to be referred.

Dimension	Input	Output
F=1	Column vector	2-D

F>1	2-D	3-D

OSTBC Encoding Algorithms:

The OSTBC Encoder supports five different OSTBC encoding algorithms. Depending on the selection for Rate and Number of transmit antennas, the encoder implements one of the algorithms in the following table:

Table 3: OSTBC encoding algorithms

Transmit Antenna	Rate	OSTBC Codeword Matrix
2	1	$\begin{pmatrix} s1 & s2 \\ -s2* & s1* \end{pmatrix}$
3	½	$\begin{pmatrix} s1 & s2 & 0 \\ -s2* & s1* & 0 \\ 0 & 0 & s1 \\ 0 & 0 & -s2* \end{pmatrix}$
3	¾	$\begin{pmatrix} s1 & s2 & s3 \\ -s2* & s1* & 0 \\ s3* & 0 & -s1* \\ 0 & s3* & -s2* \end{pmatrix}$
4	½	$\begin{pmatrix} s1 & s2 & 0 & 0 \\ -s2* & s1* & 0 & 0 \\ 0 & 0 & s1 & s2 \\ 0 & 0 & -s2* & s1* \end{pmatrix}$
4	¾	$\begin{pmatrix} s1 & s2 & s3 & 0 \\ -s2* & s1* & 0 & s3 \\ s3* & 0 & -s1* & s2 \\ 0 & s3* & -s2* & -s1 \end{pmatrix}$

3.3.2.3 Pilot Symbols

To facilitate the estimation of the channel characteristics, the specific reference signals (pilot symbols) are inserted for each frame in the transmitter side. These pilot symbols provide an estimate of the channel at the receiving end. Through interpolation, it is possible to estimate the channel across an arbitrary number of frames.

3.3.3 Channel

- MIMO Channel

The MIMO Channel System object filters an input signal through a multiple-input multiple-output (MIMO) multipath fading channel.

- Construction

1. H = comm.MIMOChannel creates a multiple-input multiple-output (MIMO) frequency selective or frequency flat fading channel System object, H. This object filters a real or complex input signal through the multipath MIMO channel to obtain the channel impaired signal.

2. H = comm.MIMOChannel(Name, Value) creates a MIMO channel object, H, with the specified property Name set to the specified Value. One can specify additional name-value pair arguments in any order as (Name1, Value1,..., NameN,ValueN).

Properties of the MIMO Channel System object:

The following section describes the properties that could be assigned to the MIMO channel system object according to the need of the program.

- SampleRate

Specify the sample rate of the input signal in hertz as a double-precision, real, positive scalar. The default value of this property is 1 Hz.

- PathDelays

Specify the delays of the discrete paths in seconds as a double-precision, real, scalar or row vector. The default value of this property is 0. When you set PathDelays to a scalar, the MIMO channel is frequency flat. When you set PathDelays to a vector, the MIMO channel is frequency selective.

- AveragePathGains

Specify the average gains of the discrete paths in decibels as a double-precision, real, scalar or row vector. The default value of this property is 0. AveragePathGains must have the same size as PathDelays.

- MaximumDopplerShift

Specify the maximum Doppler shift for all channel paths in hertz as a double precision, real, nonnegative scalar. The default value of this property is 0.001 Hz.

The Doppler shift applies to all the paths of the channel. When one set the MaximumDopplerShift to 0, the channel remains static for the entire input. You can use the reset method to generate a new channel realization.

The MaximumDopplerShift must be smaller than SampleRate/10/fc for each path, where fc represents the cutoff frequency factor of the path. For a Doppler spectrum type other than Gaussian and BiGaussian, the value of fc is 1. For these two Doppler spectrum types, fc is dependent on the Doppler spectrum object properties. Refer to the algorithm section of this page for more details about how fc is defined.

- DopplerSpectrum

Specify the Doppler spectrum shape for all channel paths as a single object from the Doppler spectrum package or a row vector of such objects. The default value of this property is a Jakes Doppler spectrum object.

The maximum Doppler shift value necessary to specify the Doppler spectrum/spectra is given by the MaximumDopplerShift property. This property applies when the MaximumDopplerShift property value is greater than 0.

If one assign a single Doppler spectrum object to DopplerSpectrum, all paths have the same specified Doppler spectrum. Select from the following:

doppler.jakes

doppler.flat

doppler.rjakes (...)

doppler.ajakes(...)

doppler.rounded(...)

doppler.bell(...)

doppler.gaussian(...)

doppler.bigaussian(...)

One can assign DopplerSpectrum a vector of Doppler spectrum objects, which can be chosen from any of those in the previous list. Each path has the Doppler spectrum specified by the corresponding Doppler spectrum object in the vector. In this case, the length of DopplerSpectrum must be equal to the length of PathDelays.

- NumTransmitAntennas

Specify the number of transmit antennas as a numeric, real, positive integer scalar between 1 and 8, inclusive. The default value of this property is 2.

- NumReceiveAntennas

Specify the number of receive antennas as a numeric, real, positive integer scalar between 1 and 8, inclusive. The default value of this property is 2.

- TransmitCorrelationMatrix

Specify the spatial correlation of the transmitter as a double-precision, real or complex, 2-D matrix or 3-D array. The default value of this property is [1 0;0 1].

If the channel is frequency flat, i.e., PathDelays is a scalar, TransmitCorrelationMatrix is a 2-D Hermitian matrix of size Nt-by-Nt. Nt represents the number of transmit antennas, i.e., the NumTransmitAntennas property value. The main diagonal elements must be all ones. The off-diagonal elements must be real or complex numbers with a magnitude smaller than or equal to one.

If the channel is frequency selective, i.e., PathDelays is a row vector of length Np, you can specify TransmitCorrelationMatrix as an Nt-by-Nt matrix. In this case, each path has the same transmit spatial correlation matrix. Alternatively, you can specify the value as a

3-D array of size Nt-by-Nt-by-Np. In this case, each path can have its own transmit spatial correlation matrix.

- ReceiveCorrelationMatrix

Specify the spatial correlation of the receiver as a double precision, real or complex, 2-D matrix or 3-D array. The default value of this property is [1 0;0 1].

If the channel is frequency flat, i.e., PathDelays is a scalar, ReceiveCorrelationMatrix is a 2-D Hermitian matrix of size Nr-by-Nr. Nr represents the number of receive antennas, i.e., the NumReceiveAntennas property value. The main diagonal elements must be all ones. The off-diagonal elements must be real or complex numbers with a magnitude smaller than or equal to one.

If the channel is frequency selective, i.e., PathDelays is a row vector of length Np, one can specify ReceiveCorrelationMatrix as an Nr-by-Nr matrix. In this case, each path has the same receive spatial correlation matrix. Alternatively, one can specify the value as a 3-D array of size Nr-by-Nr-by-Np. In this case, each path can have its own receive spatial correlation matrix.

- FadingDistribution

Specify the fading distribution of the channel as one of Rayleigh| Rician. The default value of this property is Rayleigh, i.e., the channel is Rayleigh fading.

- KFactor

Specify the K factor of a Rician fading channel as a double-precision, real, positive scalar or nonnegative, nonzero row vector of the same length as PathDelays. This property applies when one set the FadingDistribution property to Rician. The default value of this property is 3.

If KFactor is a scalar, the first discrete path is a Rician fading process with a Rician K factor of KFactor. The remaining discrete paths are independent Rayleigh fading processes. If KFactor is a row vector, the discrete path corresponding to a positive element of the KFactor vector is a Rician fading process with a Rician K factor specified by that element. The discrete path corresponding to a zero-valued element of the KFactor vector is a Rayleigh fading process.

- DirectPathDopplerShift

Specify the Doppler shifts for the line-of-sight components of a Rician fading channel in hertz as a double-precision, real scalar or row vector. The default value of this property is 0. This property applies when one set the FadingDistribution property to Rician.

DirectPathDopplerShift must have the same size as KFactor. If DirectPathDopplerShift is a scalar, this value represents the line-of-sight component Doppler shift of the first discrete path. This path exhibits a Rician fading process. If DirectPathDopplerShift and KFactor are row vectors, the discrete path corresponding to a positive element of the KFactor vector is a Rician fading process. Its line-of-sight component Doppler shift is specified by the corresponding element of DirectPathDopplerShift.

- DirectPathInitialPhase

Specify the initial phases of the line-of-sight components of a Rician fading channel in radians as a double precision, real scalar or row vector. The default value of this property is 0. This property applies when you set the FadingDistribution property to Rician.

DirectPathInitialPhase must have the same size as KFactor. If DirectPathInitialPhase is a scalar, this value represents the line-of-sight component initial phase of the first discrete path. This path exhibits a Rician fading process. If DirectPathInitialPhase and KFactor are row vectors, the discrete path corresponding to a positive element of the KFactor vector is a Rician fading process. Its line-of-sight component initial phase is specified by the corresponding element of DirectPathInitialPhase.

- RandomStream

Specify the source of random number stream as one of Global stream | mt19937ar with seed. The default value of this property is Global stream. If one set RandomStream to Global stream, the current global random number stream is used for normally distributed random number generation. In this case, the reset method only resets the filters. If one set RandomStream to mt19937ar with seed, the mt19937ar algorithm is used for normally distributed random number generation. In this case, the reset method not only resets the filters but also reinitializes the random number stream to the value of the Seed property.

- Seed

Specify the initial seed of a mt19937ar random number generator algorithm as a double precision, real, nonnegative integer scalar. The default value of this property is 73. This property applies when you set the RandomStream property to mt19937ar with seed. The Seed reinitializes the mt19937ar random number stream in the reset method.

- NormalizePathGains

Set this property to true to normalize the fading processes such that the total power of the path gains, averaged over time, is 0 dB. The default value of this property is true. When one set this property to false, there is no normalization on path gains. The average powers of the path gains are specified by the AveragePathGains property.

- NormalizeChannelOutputs

Set this property to true to normalize the channel outputs by the number of receive antennas. The default value of this property is true. When one set this property to false, there is no normalization for channel outputs.

- PathGainsOutputPort

Set this property to true to output the channel path gains of the underlying fading process. The default value of this property is false.

3.3.3.1 AWGN Channel

The AWGN Channel adds white Gaussian noise to a real or complex input signal. When the input signal is real, this channel adds real Gaussian noise and produces a real output signal. When the input signal is complex, this channel adds complex Gaussian noise and produces a complex output signal. This channel inherits its sample time from the input signal.

This block accepts a scalar-valued, vector, or matrix input signal with a data type of type single or double. The output signal inherits port data types from the signals that drive the block.

- Rayleigh Fading Channel with AWGN

The multipath Rayleigh fading is added to an AWGN channel. Since a transmitted signal propagates along several paths in multipath channel to reach to the receiver, it may lead to different time delays.

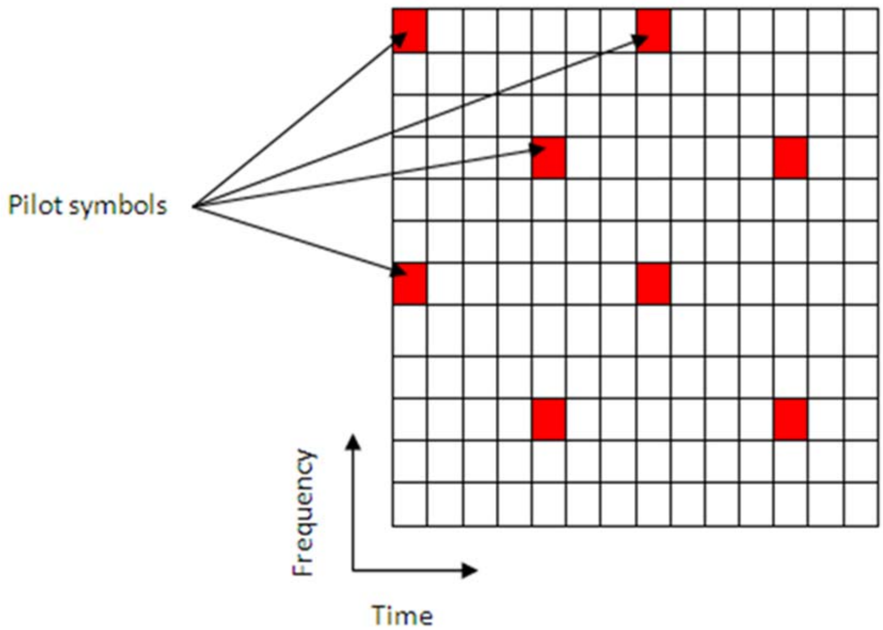
3.3.4 Receiver Side

3.3.4.1 Channel Estimator

The LTE System uses orthogonal frequency division multiplexing (OFDM) as its digital multicarrier modulation scheme. Channel estimation plays an important part in an OFDM system. It is used for increasing the capacity of orthogonal frequency division multiple access (OFDMA) systems by improving the system performance in terms of bit error rate.

To facilitate the estimation of the channel characteristics, LTE uses cell-specific reference signals (pilot symbols) inserted in both time and frequency. These pilot symbols provide an estimate of the channel at given locations within a subframe. Through interpolation, it is possible to estimate the channel across an arbitrary number of subframes.

The pilot symbols prepended in the transmitted signal are assigned positions within a subframe depending on the eNodeB cell identification number and which transmit antenna is being used, as shown in the following figure.



The unique positioning of the pilots ensures that they do not interfere with one another and can be used to provide a reliable estimate of the complex gains imparted onto each resource element within the transmitted grid by the propagation channel.

LTE assigns each antenna port a unique set of locations within a subframe to which to map reference signals. This means that no other antenna transmits data at these locations in time and frequency. This allows channel estimation for multi-antenna configurations to be performed. The channel estimation algorithm extracts the reference signals for a transmit/receive antenna pair from the received grid. The least squares estimates of the channel frequency response at the pilot symbols are calculated. The least squares estimates are then averaged to reduce any unwanted noise from the pilot symbols. Virtual pilot symbols are created to aid the interpolation process near the edge of the subframe where no pilot symbols may be located. Using the averaged pilot symbol estimates and the calculated virtual pilot symbols, interpolation is then carried out to estimate the entire subframe.

3.3.4.2 OSTBC Decoder

The OSTBC Combiner object combines the input signal (from all of the receive antennas) and the channel estimate signal to extract the soft information of the symbols encoded by an OSTBC. The input channel estimate does not need to be constant and can vary at each call to the step method. The combining algorithm uses only the estimate for the first symbol period per codeword block. A symbol demodulator or decoder would follow the Combiner object in a MIMO communications system.

3.3.4.3 BPSK Demodulator

The BPSK Demodulator demodulates a signal that was modulated using the binary phase shift keying method. The input is a baseband representation of the modulated signal. This modulator accepts a scalar or column vector input signal. The input signal must be be a discrete-time complex signal. The block maps the points exp(jθ) and -exp(jθ) to 0 and 1, respectively, where θ is the Phase offset parameter.

3.3.5 Feedback Side

3.3.5.1 BPSK Modulator

The BPSK Modulator modulates the signal using the binary phase shift keying method. The output is a baseband representation of the modulated signal. It accepts a column vector input signal. The input must be a discrete-time binary-valued signal. If the input bit is 0 or 1, respectively, then the modulated symbol is exp (jθ) or -exp (jθ), respectively, where θ represents the Phase offset parameter.

3.3.5.2 OSTBC Encoder

The OSTBC Encoder block encodes the information symbols from the BPSK or QPSK Modulator by using either the Alamouti code for two transmit antennas or other generalized complex orthogonal codes for three or four transmit antennas.

3.3.5.3 Feedback Channel

The feedback channel is simply the MIMO Channel. The noise is being added to the channel. The AWGN Channel adds white Gaussian noise to a real or complex input signal. When the input signal is real, this channel adds real Gaussian noise and produces a real output signal. When the input signal is complex, this channel adds complex Gaussian noise and produces a complex output signal. This channel inherits its sample time from the input signal.

3.3.5.4 OSTBC Decoder

The OSTBC Combiner object combines the input signal (from all of the receive antennas) and the channel estimate signal to extract the soft information of the symbols encoded by an OSTBC. The input channel estimate does not need to be constant and can vary at each call to the step method. The combining algorithm uses only the estimate for the first symbol period per codeword block. A symbol demodulator or decoder would follow the Combiner object in a MIMO communications system.

3.3.5.5 OSTBC Demodulator

The BPSK Demodulator demodulates a signal that was modulated using the binary phase shift keying method. The input is a baseband representation of the modulated signal. This modulator accepts a scalar or column vector input signal. The input signal must be be a discrete-time complex signal. The block maps the points exp(jθ) and -exp(jθ) to 0 and 1, respectively, where θ is the Phase offset parameter.

3.3.6 Block Diagram of Reciprocity Mechanism

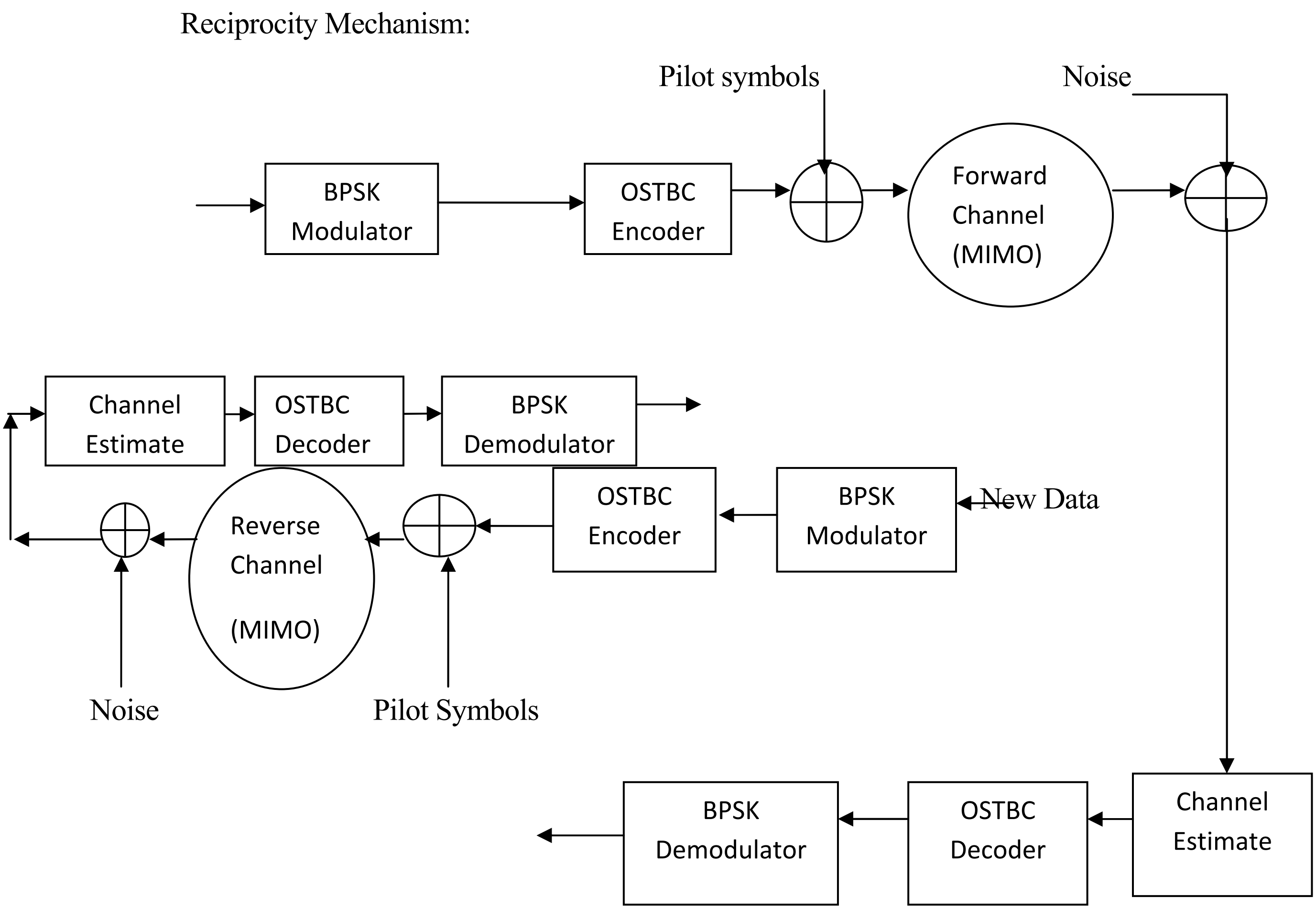


Figure 19: Block diagram of simulated reciprocity mechanism in a MIMO system

Figure 19 represents the general block diagram of reciprocity mechanism that has been implemented in mat lab to estimate the CSI at the transmitter end. For the effective transmission of the generated data, first it is being sent through the BPSK modulator. The generated data is simply the mix of 0s and 1s and is in the form of column vector. The BPSK Modulator modulates the data using the binary phase shift keying method. The output is a baseband representation of the modulated signal. It accepts a column vector input signal. The input must be a discrete-time binary-valued signal. If the input bit is 0 or 1, respectively, then the modulated symbol is exp(jθ) or -exp(jθ), respectively, where θ represents the Phase offset parameter. This output is now sent through the OSTBC encoder. The OSTBC Encoder encodes an input symbol sequence using orthogonal space-time block code (OSTBC). The OSTBC Encoder block encodes the information symbols from the BPSK Modulator by using either the Alamouti code for two transmit antennas or other generalized complex orthogonal codes for three or four transmit antennas. The number of transmit antennas is given to this block as an input. The output of this block is an (Ns x Nt) variable-size matrix, where the number of columns (Nt) corresponds to the number of transmit antennas and the number of rows (Ns) corresponds to the number of orthogonal code samples transmitted over each transmit antenna in a frame. The number of transmit and receive antennas are adaptive and change either manually or according to an adaptation algorithm, based on the difference between target and actual frame-error rates of the overall system. For the proper estimation of the channel at the receiver end, the pilot symbols are prepended for each frame and then finally the data is being transmitted through the channel. The MIMO channel system object is being created to simulate the 2 X 2 spatially independent flat-fading Rayleigh channel. The different properties of MIMO channel such as the SampleRate, PathDelays, AveragePathGains, MaximumDopplerShift, DopplerSpectrum, NumTransmitAntennas, NumbeRecAntennas, TransmitCorrelation Matrix, ReceiveCorrelation Matrix, Fading distribution, KFactor, DirectPathDoppler shift, DirectPathInitial Phase, RandomStream, Seed, NormalizePathGains, NormalizeChannelOutputs, PathGainsOutputPort were created according to the need and requirement for the simulation process. After data was passed through the MIMO channel, the channel was estimated at the receiving end. As there is always unwanted signal present at the channel, the AWGN is being added to the channel as noise. At the receiver end, the forward channel is being estimated using the channel estimator. For better performance ML detection has been used in simulation. At this stage for making simulation process bit easier it is assumed the channel remains unchanged for the length of the packet (i.e., it undergoes slow fading). And the original data is retrieved after sending through the decoder and demodulator. Again for comparing both the forward channel and reverse channel are similar or not, a new set of data is being sent from the receiver side. For the effective transmission of the data it is sent through the modulator and encoder and then the pilot symbols are added for the channel estimation purposes. The AWGN is also being added to the reverse channel and finally the channel is estimated at the transmitter side using the channel estimator. Both the forward channel and reverse channel are compared. The graphs of BER vs Eb/No (dB) for the known, estimated and feedback CSI are shown in the next chapter of results and analysis.

Most of the components used in the block diagram of reciprocity mechanism are similar to that of the feedback mechanism and are already explained above.

3.4 CONCLUSION

This chapter describes the research methodology that has been used throughout the research. It also describes in detail the simulation carried out in MATLAB to implement the feedback mechanisms in MU-MIMO system. The simulation done for analysing the performance of MIMO system with and without CSI at the transmitter end is also presented in this chapter. In practice, however, full CSI may not be directly available due to feedback overhead and feedback delay. In particular, CSI for the time-varying channel cannot be tracked completely by the transmitter and thus, only partial information (e.g., the statistical information) can be exploited.

Also the block diagrams of both the feedback and reciprocity mechanisms have been presented and each of the components has been explained in detail.

The next chapter presents the result obtained in each of the simulations described in this chapter.

Chapter 4: Results

4.1 INTRODUCTION

This chapter presents the results of simulations conducted in MATLAB to design a feedback mechanism to obtain CSI at the transmitter end in MIMO systems and also to determine the channel capacity of MIMO with and without CSI. Furthermore, this chapter analyses the graphs of BER vs Eb/No (dB) obtained while performing simulations over a range of Eb/No points to generate BER results in feedback mechanisms. Also, it analyses the graphs of Capacity (bits/sec/Hz) vs SNR (dB) obtained while performing simulations over a range of SNR (dB) points to generate Capacity (bit/sec/Hz) results with varying number of transmitter and receiver antennas. The simulations were performed using both the feedback and reciprocity mechanisms that allow comparing the different results. It also provides a measure of the performance degradation when the channel is imperfectly estimated at the receiver, compared to the case of perfect channel knowledge at the receiver.

4.2 SIMULATION RESULTS

This section presents results obtained while performing simulation in Matlab. The results obtained through simulation have been categorized into different parts:

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- Performance evaluation of CSI feedback mechanism when channel remains unchanged for the length of the packet (i.e., it undergoes slow fading).
- Performance evaluation of CSI feedback mechanism when Rician fading channel is introduced with different values of K factors.
- Performance evaluation of CSI feedback when using reciprocity principle.
- Performance evaluation of MIMO system with and without the availability of CSI at the transmitter end.

4.3 PERFORMANCE EVALUATION OF CSI FEEDBACK MECHANISM WHEN CHANNEL REMAINS UNCHANGED FOR THE LENGTH OF THE PACKET:

This section evaluates the performance of MIMO system when CSI was made available at the transmitter end and also analyses the graph obtained after simulation. The simulation was carried out in 2 X 2 MIMO systems with and without the channel estimation. It is assumed that the channel remains unchanged for the length of the packet (i.e., it undergoes slow fading).

For the simulation process, different parameters have been set as shown in Table 4. These parameters were selected as it is a common approach for evaluating the performance of the given system in terms of BER vs Eb/No in telecommunication system. Also the most common values were assigned to these parameters for making the simulation process easier and simpler so that later more complex variables can be assigned to check performance evaluation.

Table 4 : Simulation parameters when channel remains unchanged

Frame Length	100
Maximum Number of Errors	300
Maximum Number of Packets	3000
Eb/No	12 dB
Number of Pilot symbols per frame	8

Further, a MIMO channel system object was created to simulate the 2x2 spatially independent flat-fading Rayleigh channel. The maximum Doppler shift has been set to 0.001 when the sample rate was 1 Hz.

A MIMO fading channel object has different properties and has already been explained in chapter 3. The following table details the values of different properties of MIMO channel that has been set for the simulation process.

Table 5 : Properties of MIMO Channel set for simulation

Property	Description
NumTxAntennas(N)	2
NumRxAntennas(M)	2
MaxDopplerShift	0

TxCorrelationMatrix	eye(N)
RxCorrelationMatrix	eye(M)
PathGainsOutputPort	true

After all the parameters were set up the simulation was carried out. When the CSI is not known at the receiver, this has to be extracted from the received signal. It was assumed that the channel estimator performs this using orthogonal pilot signals that were prepended to every packet. At first the comparison is done between the known channel and the estimated channel and the following graph demonstrates the performance of known channel and the estimated channel with 8 pilot symbols/frame.

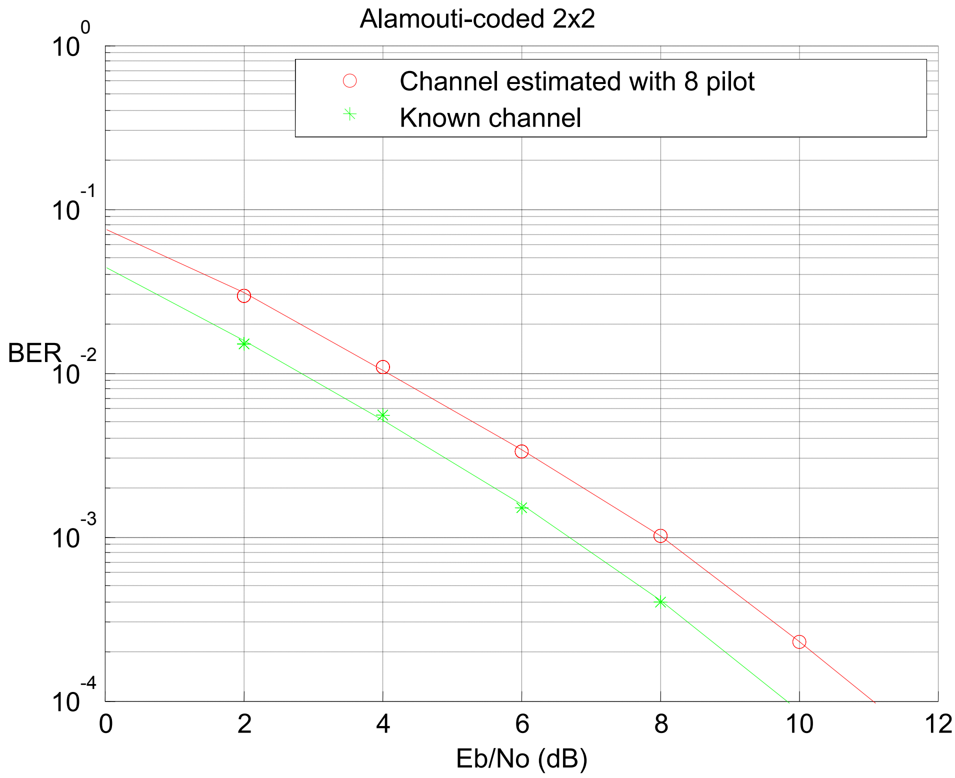

Figure 20: BER vs Eb/No (dB) between known channel and channel estimation with 8 pilot symbols/frame

It should be noted here from Figure 20 that with 8 pilot symbols for each 100 symbols of data, channel estimation causes about a 1 dB degradation in BER for the selected Eb/No range. This improves with an increase in the number of pilot symbols per frame but adds to the overhead of the link. In this comparison, we keep the transmitted SNR per symbol to be the same in both cases.

Addition of feedback channel;

A feedback channel was being added to the original code to compare the performance of known, feedback and estimated channel. This feedback channel was used to feed back the estimated CSI to the transmitting end in 2 X 2 MIMO systems when the channel remains unchanged. At first the magnitude component of the estimated CSI was being fed back to the transmitting end and Figure 19 shows demonstrate the output obtained after the simulation. The code abs (Hest) has been used to obtain the magnitude component of the estimated channel.

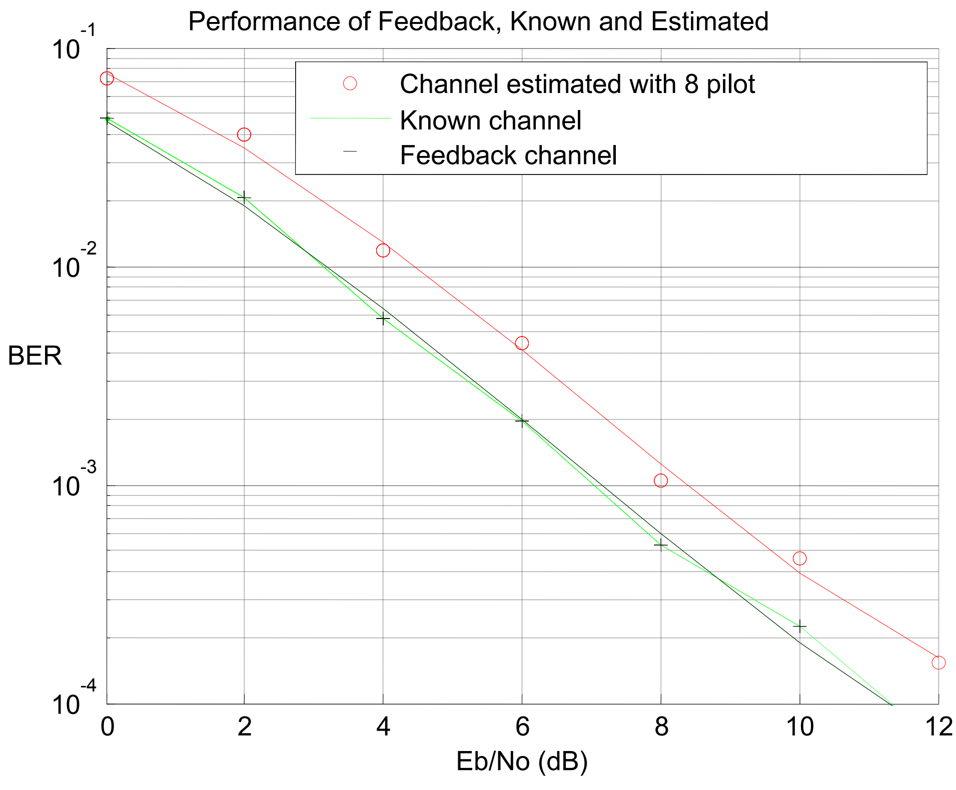

Figure 21: BER vs Eb/No (dB) while feed backing the magnitude of the channel

It can be observed from Figure 21 that when CSI was being fed back to the transmitting end the performance of MIMO system is being improved. It can be seen that channel estimation causes about a 1 dB degradation in BER for the selected Eb/No range as compared to feedback channel. The graph of feedback channel and known channel almost overlaps with each other. Also the BER has been improved by 2% with the feedback channel.

The phase component of the estimate channel (HEst) was fed back to the transmitter and the performance comparison was made between the known, feedback and estimate channel. The code angle (H_{Est}) has been used to feedback the phase of Hest. Figure 22 demonstrates the figure obtained after the simulation process.

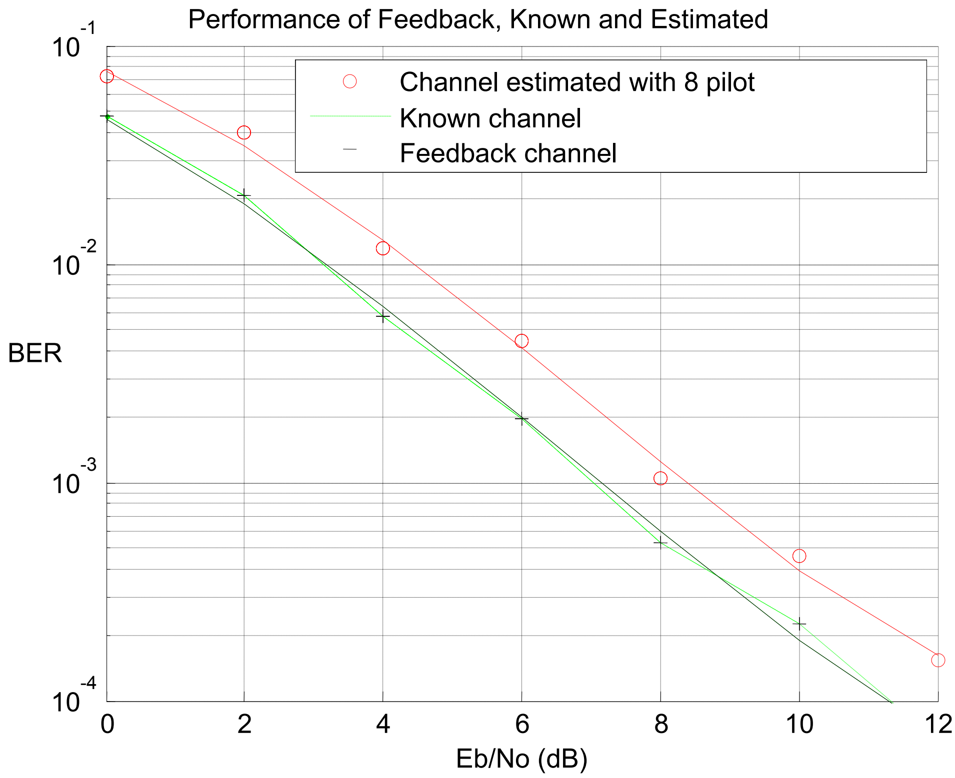

Figure 22: BER vs Eb/No (dB) while feed backing the phase of the channel

It can be observed from Figures 21 and 22 that the graph looks similar when the magnitude and the phase of the channel was fed back to the transmitter end when the channel remains unchanged for the period of data transfer. Hence, it can be said that when the channel remains unchanged for the duration of data transfer the performance of a 2 X 2 MIMO system does not change either we fed back the magnitude or the phase component to the transmitting end.

4.4 PERFORMANCE EVALUATION OF CSI FEEDBACK MECHANISM WHEN RICIAN FADING CHANNEL IS USED WITH DIFFERENT VALUES OF K FACTORS.

This section evaluates the performance of MIMO system when Rician fading channel was introduced to the MATLAB code with different values of K factor. For the simulation process the parameters were exactly set up as in section 4.3 with the addition of few other parameters in the MIMO channel system object and as shown on the table below:

Table 6: Simulation parameters set for Rician fading channel

Property	Description
MaximumDopplerShift	5
NumTxAntennas(N)	2
NumRxAntennas(M)	2
TxCorrelationMatrix	eye(N)
RxCorrelationMatrix	eye(M)
PathGainsOutputPort	true
SampleRate	5000
FadingDistribution	'rician'
PathDelays	2e-9, 4e-9, 6e-9..........
AveragePathGains	0.8, 1.0, 2.0, ...
KFactor	0,1,2,3.....

The values of path delays, average path gains and K factor have been changed for different cases.

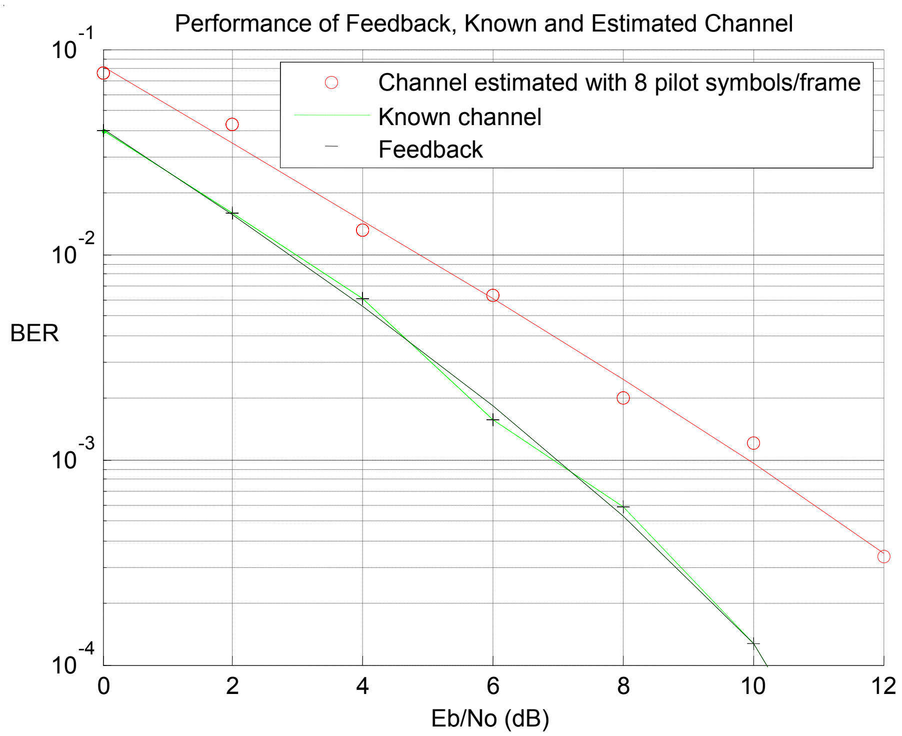

Figure 23: BER vs Eb/No (dB) in Rician fading channel when K factor =0.5

It can be observed from Figure 23 that with 8 pilot symbols for each 100 symbols of data, channel estimation causes about a 2.45 dB degradation in performance for the selected Eb/No range as compared to the feedback channel. Also there is a degradation of 3% in BER performance while the channel is estimated as compared to the feedback channel. This clearly indicates that if the estimated channel would be fed back to the transmitter it will definitely improve the system overall performance.

Let us see the graph of BER vs Eb/No when the value of Kfactor is changed to 1.

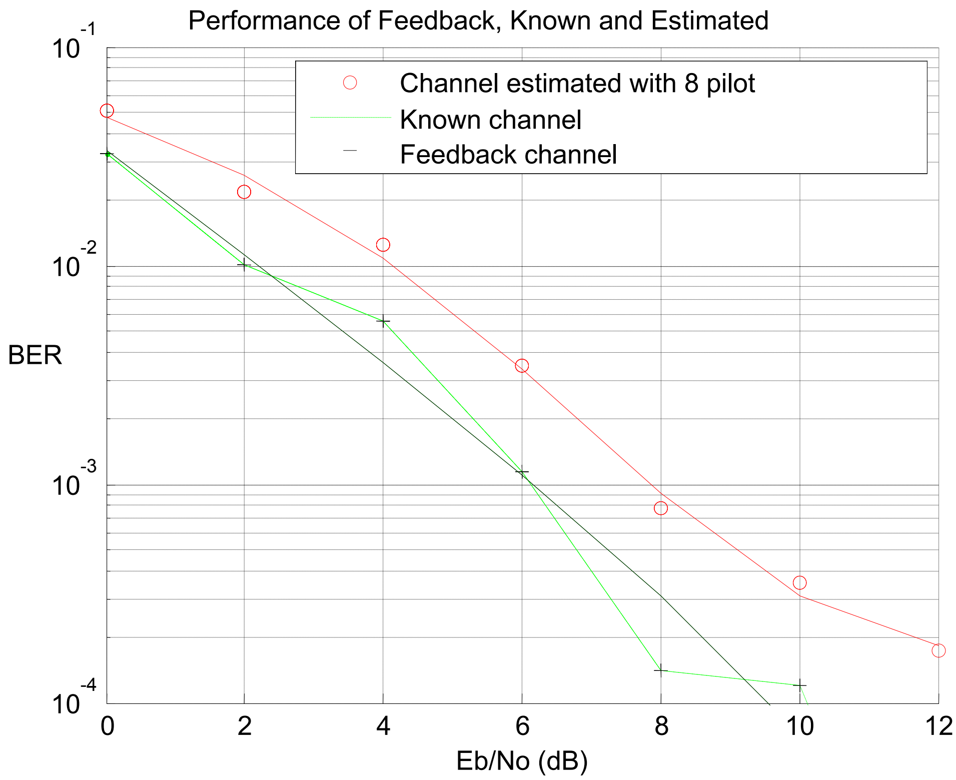

Figure 24: BER vs Eb/No (dB) in Rician fading channel when KFactor =1

It can be observed from Figure 24 that with 8 pilot symbols for each 100 symbols of data, channel estimation causes about 2.45 dB degradation in performance for the selected Eb/No range as compared to the feedback channel. Also there is a degradation of 3% in BER performance while the channel is estimated as compared to the feedback channel. Also with the increase in the value of K the graph of known channel gets distorted more.

4.5 PERFORMANCE EVALUATION OF CSI FEEDBACK WHEN USING RECIPROCITY PRINCIPLE

This section provides the performance evaluation of CSI feedback when using reciprocity principle. As the reciprocity principle states, the base station can exploit reciprocity to obtain the forward channel from pilots received over the reverse channel. Figure 25 illustrates the performance of MIMO system when reciprocity principle is used to estimate the forward channel.

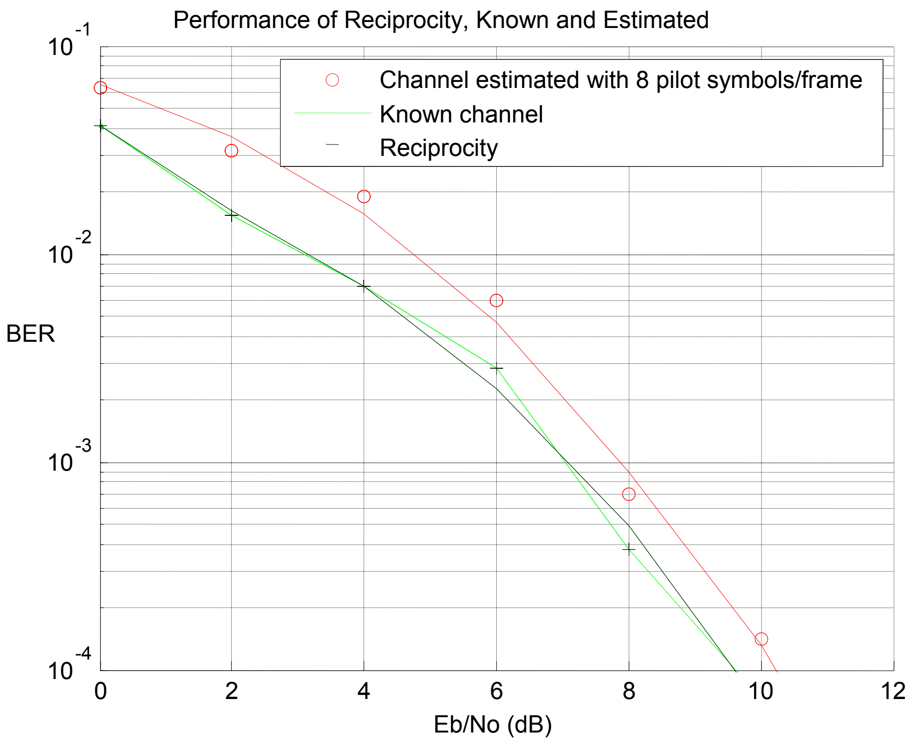

Figure 25: BER vs Eb/No (dB) while using reciprocity to feedback the channel

It should be noted here from Figure 25 that with 8 pilot symbols for each 100 symbols of data, channel estimation causes about a 1 dB degradation in performance for the selected Eb/No range as compared to the reciprocity mechanism.

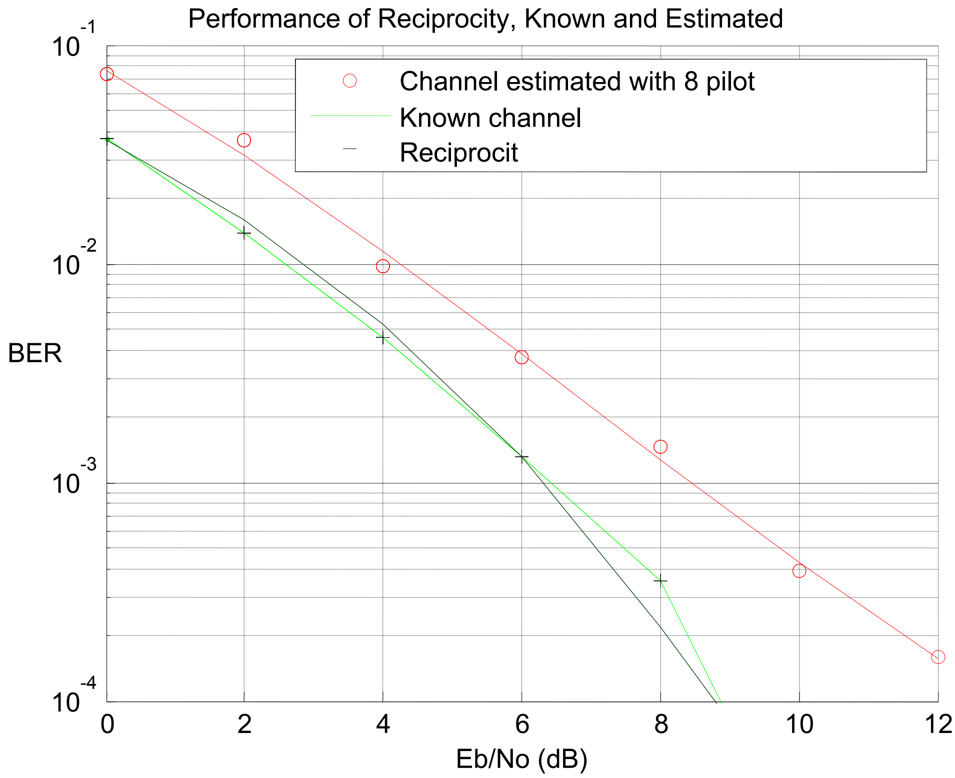

Figure 26: BER vs Eb/No (dB) using reciprocity mechanism when K factor =1

Figure 26 illustrates the performance curve when reciprocity mechanism was used to estimate the forward channel and when Kfactor is equal to 1. It can be observed that there is nearly a 3 dB degradation in performance in channel estimation as compared to the feedback channel.

4.6 PERFORMANCE EVALUATION OF MIMO SYSTEM WITH AND WITHOUT THE AVAILABILITY OF CSI AT THE TRANSMITTER END.

This section evaluates the performance of MIMO system with and without the availability of CSI at the transmitting end. Figure 23 illustrates the performance of MIMO system with and without CSI. The X-axis shows the SNR in dB and the Y-axis shows the Capacity in bits/s/Hz. It has already been discussed in literature review that the capacity of MIMO will increase with the availability of CSI as can been seen from the equation 8. It can be observed from Figure 23 that the capacity of MIMO system is increased when CSI is available at the transmitter end. The capacity is around 69 bits/s/Hz when CSI is available at the transmitter end and the capacity is 42 bits/s/Hz when CSI is not available at the transmitter end in 4X 4 MIMO system. The capacity has been increased by 64 % with the availability of CSI at the transmitting end.

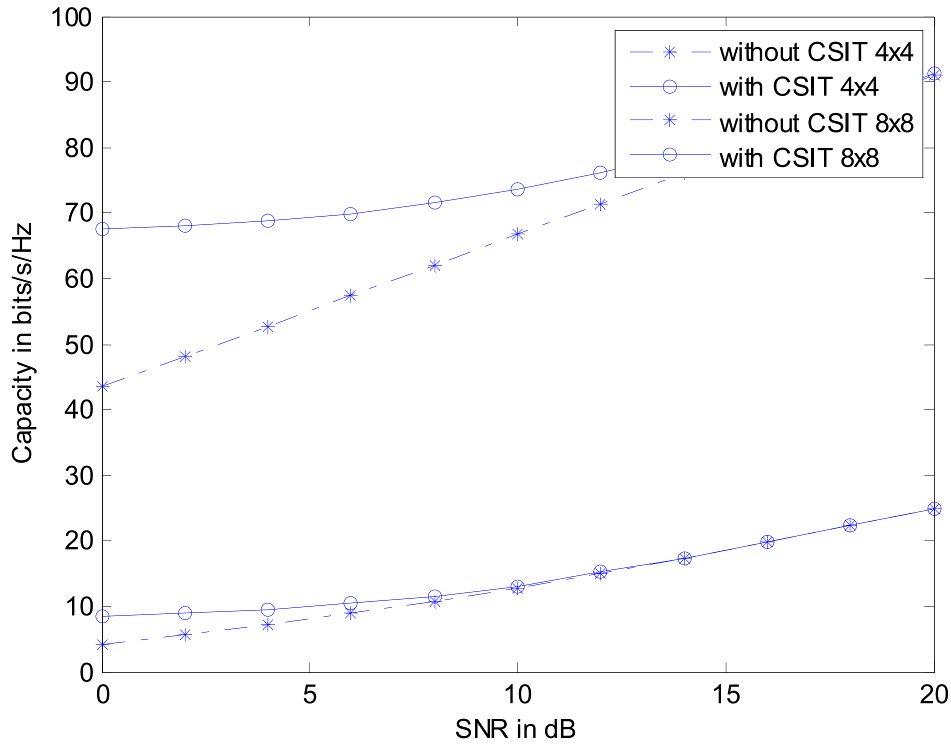

Figure 27: Capacity vs SNR in MIMO

4.7 PERFORMANCE COMPARISON BETWEEN FEEDBACK MECHANISM AND RECIPROCITY MECHANISM

This section evaluates and compares the performance of feedback and reciprocity mechanisms.

The Simulated performance curves (BER Vs Eb/No) for feedback and reciprocity mechanisms were provided in Figures 21 and 25 when the channel remains unchanged for the length of the packet and when it is flat- fading Rayleigh channel. Also the performance curves (BER Vs Eb/No) were provided in Figures 24 and 26 when the Rician fading channel is considered. It can be observed from Figure 21 that channel estimation causes about 1 dB degradation in performance for the selected Eb/No range as compared to feedback channel. The same results were found for the reciprocity mechanism. It should be noted from Figure 23 that with 8 pilot symbols for each 100 symbols of data, channel estimation causes about 1 dB degradation in performance for the selected Eb/No range as compared to the reciprocity mechanism. But the value of Eb/No for feedback channel is 11 dB in compared to channel estimation of 12 dB as can be seen from Figure 21. For the reciprocity the value of Eb/No is 9 dB as compared to 10 dB of channel estimation as can be seen from Figure 23. It can be observed from Figure 24 that with 8 pilot symbols for each 100 symbols of data, channel estimation causes about 2.45 dB degradation in performance for the selected Eb/No range as compared to the feedback channel. It can be observed from Figure 26 that there is nearly 3 dB degradation in performance in channel estimation as compared to the reciprocity when Kfactor is equal to 1.

Hence it was found that when Rician fading channel was considered during simulation the performance of MIMO system has degraded.

4.8 CONCLUSION

This chapter presents the results of simulation conducted in MATLAB to design a feedback mechanism to obtain CSI at the transmitter end in MIMO system and also to determine the channel capacity of MIMO with and without the CSI at the transmitting end. Furthermore this chapter analyses BER vs Eb/No (dB) results obtained while performing simulations over a range of Eb/No points to generate BER results for different feedback mechanisms. It was found that channel estimation causes about 1 dB degradation in performance for the selected Eb/No range as compared to feedback channel. The same result was found for the reciprocity mechanism as well. The performance of MIMO system degraded when Rician fading channel was considered during simulation. Also it analyses the graphs of Capacity (bits/sec/Hz) vs SNR (dB) obtained while performing simulations over a range of SNR (dB) points to generate Capacity (bit/sec/Hz) results with varying number of transmitter and receiver antennas. With the comparison of different graphs obtained after the simulations it was observed and proved that the performance of MIMO significantly improved with the available of CSI at the transmitter end. Also the channel capacity of MIMO system increases when CSI was made available at the transmitter end.

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Chapter 5: Conclusions

The results and contributions of this thesis are summarised in this final chapter. The first part of the thesis provides a brief introduction of the research and discussed the motivation behind the research, the research objectives and the research problems. Specifically, a feedback mechanism and reciprocity mechanism have been simulated in MATLAB to obtain CSI at the transmitter end and a performance comparison was conducted between these two methods. A review of the theory on multi-path fading, MIMO and OFDM and the relevant literature review on feedback mechanism are also presented. The next section presents a chapter by chapter summary of the thesis.

A detailed overview of multipath fading, MIMO wireless communications systems, CSI and the methods for obtaining CSI at the transmitter end, feedback mechanism and reciprocity mechanism are provided in Chapter 2. Furthermore a detailed overview of BER, Eb/No, OSTBC are also presented. The literature review helped to understand the current state of the research area and identify the knowledge gaps in the research field.

The methodology for carrying out the research in three different phases is discussed in Chapter 3. This chapter presents in detail the simulation carried out in MATLAB to obtain CSI at the transmitter end in MIMO system. It also narrates simulation done to check the channel capacity of MIMO systems with and without the availability of CSI at the transmitter end. Furthermore this chapter presents the block diagrams of both the feedback and reciprocity mechanisms that have been simulated in MATLAB and also describes each component that has been used in the block diagrams.

Chapter 4 presents the results of simulation conducted in MATLAB to design a feedback mechanism to obtain CSI at the transmitter end in MIMO system and also to determine the channel capacity of MIMO with and without the CSI at the transmitting end. Furthermore this chapter analyses the graphs of BER vs Eb/No (dB) obtained while performing simulation over a range of Eb/No points to generate BER results in feedback mechanisms. Also it analyses the graphs of Capacity (bits/sec/Hz) vs SNR (dB) obtained while performing simulation over a range of SNR (dB) points to generate Capacity (bit/sec/Hz) results with varying number of transmitter and receiver antennas. The simulation is being performed using both the feedback and reciprocity mechanisms that allow comparing the different results. It also provides a measure of the performance degradation when the channel is imperfectly estimated at the receiver, compared to the case of perfect channel knowledge at the receiver.

5.1 SUMMARY OF RESEARCH FINDINGS AND CONTRIBUTIONS

The research presented in this thesis discusses the feedback mechanisms which provide the transmitter with CSI to allow the knowledge of the time-varying channel in MIMO systems. Both the feedback mechanisms and reciprocity mechanisms were simulated and the performance comparison was made between these two methods. The simulated results show that the feedback mechanism will improve the performance of MIMO system when the CSI has been made available at the transmitter end. Also, the channel capacity of MIMO system is improved when CSI is made available at the transmitter end.

The simulated performance curves (BER Vs Eb/N0) for feedback and reciprocity mechanisms were provided in Chapter 4. At first the channel was assumed to remain unchanged for the length of the packet and later Rician fading channel was considered. It was observed that channel estimation causes about 1 dB degradation in performance for the selected Eb/No range as compared to feedback channel when the channel remains unchanged. The same results were found for the reciprocity mechanism i.e channel estimation causes about 1dB degradation in performance for the selected Eb/No range as compared to the reciprocity mechanism. Furthermore, it was observed with 8 pilot symbols for each 100 symbols of data, channel estimation causes about 2.45 dB degradation in performance for the selected Eb/No range as compared to the feedback channel when the Rician fading channel is considered and also the K factor is equal to 1. When the reciprocity mechanism was considered it was found that there was nearly 3 dB degradation in performance in channel estimation when K factor is equal to 1. Hence it was found that when Rician fading channel was considered during simulation the performance of MIMO system has degraded.

Regarding the channel capacity of MIMO systems it was observed that the capacity of MIMO system increased when CSI is available at the transmitter end. The capacity is around 69 bits/s/Hz when CSI is available at the transmitter end and the capacity is 42 bits/s/Hz when CSI is not available at the transmitter end in a 4 X 4 MIMO system. The capacity has been increased by 64 % with the availability of CSI at the transmitting end.

5.2 SUGGESTED FUTURE WORKS

In recent times there are so many research works going on Multiuser MIMO (MU-MIMO) technology. The performance of MU-MIMO system has begun to be intensely investigated because of several key advantages over single user MIMO communications. MU-MIMO schemes allow for a direct gain in multiple access capacity (proportional to the number of base station (BS) antennas) thanks to so-called multiuser multiplexing schemes[9] .MU-MIMO appears more immune to most of propagation limitations plaguing single user MIMO communications such as channel rank loss or antenna correlation. Although increased correlation still affects per-user diversity, this may not be a major issue if multiuser diversity can be extracted by the scheduler instead[9]. Additionally, line of sight propagation, which causes severe degradation in single user spatial multiplexing schemes, is no longer a problem in multiuser setting [9]. MU-MIMO allows the spatial multiplexing gain at the base station to be obtained without the need for multiple antenna terminals, thereby allowing the development of small and cheap terminals while intelligence and cost is kept on the infrastructure side [9].

The most important fact for MU-MIMO is that it requires channel state information (CSI) at transmitter end to properly serve the spatially multiplexed users. In MU-MIMO, CSI not only helps in achieving high SNR at the desired receiver but also reduces the interference produced at other point in the network by the desired user's signal [11]. But the challenge lies on whether and what type of CSI can be made practically available to the transmitter in a MU-MIMO OFDM systems, where fading channels are randomly varying.

Another challenge related to MU-MIMO cross-layer design lies in the complexity of the scheduling procedure associated with the selection of a group of users that will be served simultaneously [9]. Optimal scheduling involves exhaustive search whose complexity is exponential in the group size, and depends on the choice of precoding, decoding, and channel state feedback technique [9].

5.2.1 Extensions

Some of the work presented in this thesis can be further extended. This research has designed the feedback mechanism in MIMO system in time –varying channel and analysed the channel capacity. Since the availability of CSI at the transmitter (Tx) end plays a vital role in MU-MIMO technology than SU-MIMO, the best approach is to design the feedback mechanism in MU-MIMO OFDM system.

Also the latest and modern technologies such as LTE Advanced, Wimax and 802.11 ac standards could benefit from this feedback mechanism. These advanced technologies naturally perform better with the availability of the channel state information at the transmitter end. As this feedback mechanism provides the transmitting end with all the combined effect such as scattering, fading and power decay with distance, the transmitted signal can adapt to the current channel conditions. This will definitely increase the data rate of the system. The simulation results in this thesis have shown that the channel capacity and also the performance of MIMO systems have been increased with the design of feedback mechanism. Similarly the performance of these advanced technologies will increase with the introduction of feedback mechanism. The recommendations from the simulation results on these future standards could be the design of the precoding matrices intelligently such that even a very small number of feedback bits will be sufficient to keep the distortion level small (typically 3 -8 bits).

It is very important to carefully consider how feedback is designed and used to support MU-MIMO OFDM system. Some of the questions that may arise during the design of the feedback mechanism in MU-MIMO systems are as follows:

- how often should users feedback CSI considering a range of time-varying channel conditions
- the most efficient method to minimize bandwidth usage during feedback,
- and the optimum number of users and OFDM subcarriers to consider when providing feedback

As already been discussed in the thesis, the CSI can be obtained at the transmitter by using two techniques. The first method is to use the pilot or training data in the uplink for time division duplex systems. The second mechanism uses the feedback from the receivers channel estimate obtained by the training data in the downlink. The latter is suitable for frequency-division duplex transmission systems. In each scenario, it is not only a technical challenge, but also not economical to obtain the CSI at the transmitter.

However, it is justifiable for multi-user channels. Therefore, the CSI obtained by the feedback mechanism in this thesis can be further extended to the MU-MIMO OFDM system.

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Appendices

6.1 APPENDIX A –PUBLICATION 1

Sharma, Maneesha (2013) **Novel Adaptive Channel State Information Feedback for Multiuser MIMO in Wireless Broadband Communications.** In: IEEE Fourteenth International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2013), 4 – 7th June 2013, Madrid, Spain. (Published).

6.2 APPENDIX B – MATLAB CODE

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http://dx.doi.org/10.1109/WoWMoM.2013.6583428

6.2 Matlab code

```
clc,clear all
close all
%numPackets = 10;  % number of packets
% Create comm.BPSKModulator and comm.BPSKDemodulator
System objects
P = 2;     % modulation order
hMod   = comm.BPSKModulator;
hDemod = comm.BPSKDemodulator('OutputDataType','double');

% Create comm.OSTBCEncoder and comm.OSTBCCombiner System
objects
hAlamoutiEnc = comm.OSTBCEncoder;
hAlamoutiDec = comm.OSTBCCombiner;

% Create two comm.AWGNChannel System objects for one and
two receive
% antennas respectively. Set the NoiseMethod property of
the channel to
% 'Signal to noise ratio (Eb/No)' to specify the noise
level using the
% energy per bit to noise power spectral density ratio
(Eb/No). The output
% of the BPSK modulator generates unit power signals; set
the SignalPower
% property to 1 Watt.
hAWGN1Rx = comm.AWGNChannel('NoiseMethod', 'Signal to
noise ratio (Eb/No)',...
                            'SignalPower', 1);
hAWGN2Rx = clone(hAWGN1Rx);

% Create comm.ErrorRate calculator System objects to
evaluate BER.
hErrorCalc1 = comm.ErrorRate;
hErrorCalc2 = comm.ErrorRate;
hErrorCalc3 = comm.ErrorRate;
hErrorCalc4 = comm. ErrorRate;

% Since the comm.AWGNChannel System objects as well as
the RANDI function
% use the default random stream, the following commands
are executed so
% that the results will be repeatable, i.e., same results
will be
% obtainedhhhh
% for every run of the demo. The default stream will be
restored at the end
% of the demo.
s = RandStream.create('mt19937ar', 'seed',55408);
prevStream = RandStream.setGlobalStream(s);
```

```
frmLen = 100;             % frame length
maxNumErrs = 300;         % maximum number of errors
maxNumPackets = 3000;     % maximum number of packets
EbNo = 0:2:12;            % Eb/No varying to 12 dB
N = 2;                    % number of Tx antennas
M = 2;                    % number of Rx antennas
pLen = 8;                 % number of pilot symbols per
frame
W = hadamard(pLen);
pilots = W(:, 1:N);       % orthogonal set per transmit
antenna

pLen1 = 8;
W1 = hadamard(pLen1);
pilots1 = W1(:, 1:N);



%and set up the simulation.
% Create a comm.MIMOChannel System object to simulate the
2x2 spatially
% independent flat-fading Rayleigh channel
%hChan = comm.MIMOChannel('MaximumDopplerShift',      0,
...
                        % 'NumTransmitAntennas',       N,
...
                        % 'NumReceiveAntennas',        M,
...
                        % 'TransmitCorrelationMatrix',
eye(N), ...
                        % 'ReceiveCorrelationMatrix',
eye(M), ...
                        % 'PathGainsOutputPort',
true);
hChan = comm.MIMOChannel('MaximumDopplerShift',   5, ...
                       'NumTransmitAntennas',       N,...
                        'NumReceiveAntennas',        M,
...
                        'TransmitCorrelationMatrix',
eye(N), ...
                        'ReceiveCorrelationMatrix',
eye(M), ...
                        'PathGainsOutputPort',
true,...
                         'SampleRate',
5000,...
                         'FadingDistribution',
'rician', ...
                         'PathDelays',               2e-
9, ...
```

```
                         'AveragePathGains',
0.8,...
                         'KFactor',                  1);
                         %'PathDelays',
2e-9, ...
                         %'AveragePathGains',
0.8,...
                         %'FadingDistribution',
'rician', ...
                         %'KFactor',
100000);

% Change the NumReceiveAntennas property value of the
hAlamoutiDec System
% object to M that is 2
release(hAlamoutiDec);
hAlamoutiDec.NumReceiveAntennas = M;

% Release the hAWGN2Rx System object
release(hAWGN2Rx);

% Set the global random stream for repeatability
s = RandStream.create('mt19937ar', 'seed',55408);
prevStream = RandStream.setGlobalStream(s);

% Pre-allocate variables for speed
HEst = zeros(frmLen, N, M);
ber_Estimate = zeros(3,length(EbNo));
ber_Known    = zeros(3,length(EbNo));
ber_Feedback = zeros(3,length(EbNo));


% Set up a figure for visualizing BER results
h= gcf; grid on; hold on;
set(gca,'yscale','log','xlim',[EbNo(1),
EbNo(end)],'ylim',[1e-4 1e-1]);
xlabel('Eb/No (dB)'); ylabel('BER');
set(h,'NumberTitle','off');
set(h,'Name','Orthogonal Space-Time Block Coding');
set(h, 'renderer', 'zbuffer');  title('Performance of
Feedback, Known and Estimated Channel');

% Loop over several EbNo points
for idx = 1:length(EbNo)
    reset(hErrorCalc1);
    reset(hErrorCalc2);
    reset(hErrorCalc3);
    hAWGN2Rx.EbNo = EbNo(idx);

    % Loop till the number of errors exceed 'maxNumErrs'
```

```
    % or the maximum number of packets have been
simulated
    while (ber_Estimate(2,idx) < maxNumErrs) && ...
          (ber_Known(2,idx) < maxNumErrs) && ...
          (ber_Feedback(2,idx)< maxNumErrs) && ...
          (ber_Estimate(3,idx)/frmLen < maxNumPackets)
          (ber_Feedback(3,idx)/frmLen < maxNumPackets)

        % Generate data vector per frame
        data = randi([0 P-1], frmLen, 1);

        % Modulate data
        release(hMod);
        modData = step(hMod, data);

        % Alamouti Space-Time Block Encoder
        encData = step(hAlamoutiEnc, modData);

        % Prepend pilot symbols for each frame
        txSig = [pilots; encData];

        % Pass through the 2x2 channel
        reset(hChan);
        [chanOut, H] = step(hChan, txSig);

        % Add AWGN
        release (hAWGN2Rx);
        rxSig = step(hAWGN2Rx, chanOut);

        % Channel Estimation
        %   For each link => N*M estimates
        HEst(1,:,:) = pilots(:,:).' * rxSig(1:pLen, :) /
pLen;
        %   assume held constant for the whole frame
        HEst = HEst(ones(frmLen, 1), :, :);

        % Combiner using estimated channel
        decDataEst = step(hAlamoutiDec,
rxSig(pLen+1:end,:), HEst);

        % Combiner using known channel
        decDataKnown = step(hAlamoutiDec,
rxSig(pLen+1:end,:), ...

squeeze(H(pLen+1:end,:,:,:)));

        % ML Detector (minimum Euclidean distance)
        demodEst   = step(hDemod, decDataEst);      %
estimated
        demodKnown = step(hDemod, decDataKnown);    %
known
```

```
        % Calculate and update BER for current EbNo value
        %   for estimated channel
        ber_Estimate(:,idx) = step(hErrorCalc1, data, 
demodEst);
        %   for known channel
        ber_Known(:,idx)    = step(hErrorCalc2, data, 
demodKnown);

        %feedback

% Generate new data vector per frame

        release (hMod);
       % a1 =int16(abs (HEst)*10000);
        %b1 = de2bi (a1,15);
        %a1 = int16(abs(angle(HEst)*10000));
        %b1=de2bi(a1,15);
        %data1 = reshape (b1,6000,1);

        %data1 = reshape(dec2bin(abs(HEst),4),1600,1);
        %data2 = double(data1);
        data1 = data;

        % Modulate data
        new_modData = step(hMod, data1);

        % Alamouti Space-Time Block Encoder
        encData1 = step(hAlamoutiEnc, new_modData);

        % Prepend pilot symbols for each frame
        txSig1 = [pilots; encData1];

        % Pass through the 2x2 channel
        reset(hChan);
        [chanOut1, Hf] = step(hChan, txSig1);

        % Add AWGN
        release (hAWGN2Rx);
        rxSig1 = step(hAWGN2Rx, chanOut1);

        % Channel Estimation
        %   For each link => N*M estimates
        HEst(1,:,:) = pilots(:,:).' * rxSig(1:pLen, :) / 
pLen;
        %   assume held constant for the whole frame
        HEst = HEst(ones(frmLen, 1), :, :);
        HEst1 = abs(HEst);

        % Combiner using estimated channel
```

```
        decDataEst = step(hAlamoutiDec,
rxSig(pLen+1:end,:), HEst);

        % Combiner using known channel
        decDataKnown = step(hAlamoutiDec,
rxSig(pLen+1:end,:), ...

squeeze(H(pLen+1:end,:,:,:)));

        % Combiner using feedback
        decDataFeedback = step(hAlamoutiDec,
rxSig(pLen+1:end,:),...

squeeze(H(pLen+1:end,:,:,:)));


        % ML Detector (minimum Euclidean distance)
        demodEst   = step(hDemod, decDataEst);      %
estimated
        demodKnown = step(hDemod, decDataKnown);    %
known
        demodFeedback = step(hDemod, decDataFeedback);
% feedback

        % Calculate and update BER for current EbNo value
        %   for estimated channel
        ber_Estimate(:,idx) = step(hErrorCalc1, data,
demodEst);
        %   for known channel
        ber_Known(:,idx)    = step(hErrorCalc2, data,
demodKnown);
        % for feedback channel
        ber_Feedback(:,idx)   = step(hErrorCalc3, data,
demodFeedback);

    end % end of FOR loop for numPackets

    % Plot results
    semilogy(EbNo(1:idx), ber_Estimate(1,1:idx), 'ro');
    semilogy(EbNo(1:idx), ber_Known(1,1:idx), 'g--');
    semilogy (EbNo (1:idx), ber_Feedback(1,1:idx), 'k+');
    legend(['Channel estimated with ' num2str(pLen) '
pilot symbols/frame'],...
           'Known channel','Reciprocity');
    drawnow;
end  % end of for loop for EbNo

% Perform curve fitting and replot the results
fitBEREst   = berfit(EbNo, ber_Estimate(1,:));
fitBERKnown = berfit(EbNo, ber_Known(1,:));
fitBERFeedback = berfit(EbNo, ber_Known(1,:));
```

```
semilogy(EbNo, fitBEREst, 'r', EbNo, fitBERKnown,
'g',EbNo, fitBERFeedback, 'k'); hold off;

% Restore default stream
RandStream.setGlobalStream(prevStream);
```