LINEAR DECODING OF QO-STBC UNDER IMPERFECT CHANNEL ESTIMATION CONDITIONS

Thesis submitted towards the partial fulfilment of the requirements for the award of degree of

MASTER OF ENGINEERING
IN
WIRELESS COMMUNICATION

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DECLARATION

I, Bhupinder Singh, hereby declare that the work, which is being presented in the thesis entitled **"Linear Decoding of QO-STBC under Imperfect Channel Estimation Conditions"** by me in partial fulfillment of the requirements for the award of degree of Master of Engineering in Wireless Communication from Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. Amit Kumar Kohli**, Associate Professor, Electronics and Communication Engineering Department.

The matter presented in this thesis has not been submitted in any other University/ Institute for the award of any other degree.

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ABSTRACT

Quasi-orthogonal space-time block-code (QO-STBC) was developed to overcome the transmission rate drawbacks of orthogonal-space-time block-code (O-STBC) for more than two transmit antennas. QO-STBC scheme achieves full transmission rate and partial diversity order, but with increase in decoding complexity. This is due to the presence of interference terms in its detection matrix.

Matrix manipulation methods known as Givens rotation (GR) and Eigen value decomposition (EVD) have been applied to the channel matrix of conventional QO-STBC (C-QO-STBC) scheme to generate the interference free detection matrix. It results into simple linear decoding of the conventional QO-STBC scheme. Givens rotation and Eigen value decomposition methods result into two new QO-STBC schemes known as Givens rotation QO-STBC scheme (GR-QO-STBC) and Eigen value decomposition QO-STBC scheme (EVD-QO-STBC).

Both new QO-STBC schemes have been analyzed in terms of its bit error rate performance (BER) under the condition that the receiver has perfect knowledge of channel state information (CSI). But, in realistic environment, it is not possible for channel estimator to estimate the channel without estimation error. Therefore, we analyze the performance of both new QO-STBC schemes in terms of BER under the condition of imperfect CSI at the receiver side. The Rayleigh flat fading channel is used for this analysis.

Simulation results are provided to show the impact of channel estimation errors on the performance of both new QO-STBC schemes.

We also analyze the performance of GR-QO-STBC scheme and EVD-QO-STBC scheme under MIMO system using 4×2 and 3×2 antenna systems along with the simulation results.

Keywords: Space-time block-code (STBC), channel state information (CSI), Eigen value decomposition (EVD), Givens rotation (GR), signal-to noise ratio (SNR).

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LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLAST	Bell Laboratory Layered Space Time
CI	Coordinate Interleaved
CIOD	Coordinate Interleaved Orthogonal Design
CPM	Continuous Phase System
CSI	Channel State Information
dB	Decibel
EO-STBC	Extended Orthogonal Space-time Block-Code
EVD	Eigen Value Decomposition
GR	Givens Rotation
LOS	Line of Sight
LS	Least Square
LTE-A	Long Term Evolution Advanced
MCM	Multi Carrier Modulation
MDC	Minimum Decoding Complexity
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum Likelihood
MPSK	Multiple Phase Shift Keying
MRRC	Maximum Ratio Receiver Combining

MSE	Mean Square Error
OFDM	Orthogonal Frequency Division Multiplexing
O-STBC	Orthogonal Space-Time Block-Code
PAM	Pulse Amplitude Modulation
PAPR	Peak-to-Average Power Ratio
PSK	Phase Shift Keying
PWM	Pulse Width Modulation
QAM	Quadrature Amplitude Modulation
QO-STBC	Quasi-Orthogonal Space-Time Block-Code
SER	Symbol Error Rate
SIMO	Single Input Multiple Output
SQOHLSTTC	Super Quasi Orthogonal Horizontal Layered Space-Time Trellis Code
STBC	Space-Time Block-Code
STTC	Space-Time Trellis Code

LIST OF FIGURES

Chapter 1

INTRODUCTION

This chapter includes the discussion about wireless communication and its development along with its basic block diagram. We also discuss about the different challenges that come in successful implementation of wireless communication.

1.1. Wireless Communication

Wireless communication is one of the exponentially rising sectors of communication field. As such, it has seized the thought of the media and the vision of the public. Wireless systems have experienced a rapid growth over the last two decades and been used as many applications such as wireless sensor networks, automated highways and factories, etc. Parallel progress of both the wireless techniques and wireless devices ensures a bright future for wireless communication.

In early years of wireless communication, different types of signals such as smoke signals, torch signaling, flashing mirrors were used for exchange of information [1]. As the time passes, development of different techniques has made it possible to send electrical signals using wireless devices over wireless channels from one place to another place. These different techniques involve the development of modulation, source encoding and channel encoding techniques.

Modulation, source encoding and channel encoding techniques are the fundamental techniques for every wireless communication system. Along with these techniques, different types of transmission strategies are also developed to provide reliable wireless communication. Transmission strategies such as single input multiple output (SIMO), multiple input single output (MISO), multiple input multiple output (MIMO), MISO and MIMO with space-time block-coding (STBC) and orthogonal frequency division multiplexing (OFDM) are evolved to provide wireless communication with high quality.

Combination of STBC with MISO and MIMO systems [18] is used to neutralize the severe effects of multipath fading environment on the wireless communication. STBC is also known as transmitter diversity scheme. Two different types of space-time block-codes are derived.

1. Orthogonal space-time block-code (O-STBC)
2. Quasi-orthogonal space-time block-code (QO-STBC)

In short, STBC scheme is a method of generating the copies of each symbol to be transmitted and then transmit these copies from each of the transmitting antenna in such a way that the received symbol is free from the impact of multipath propagation i.e., fading. It is just brief introduction to STBC scheme and it is completely described in chapter 4.

OFDM is a transmission technique and it is just enhancement to the multi-carrier modulation method (MCM). In OFDM, multiple carriers, orthogonal to each other, are used to carry the data symbols. OFDM is developed for transmission over frequency selective fading channels. OFDM changes frequency selective fading channel into frequency flat fading channel. Now days, combination of both STBC and OFDM is used in wireless communication systems for more reliable and efficient transmission.

This is just brief discussion about various transmission techniques and strategies used in wireless communication systems.

Next, we will discuss about the fundamental block diagram of a wireless communication system.

1.2. Basic Block Diagram of a Wireless Communication System

To understand the complete process of wireless communication, a fundamental block diagram, which includes the important blocks of wireless communication system, is given below

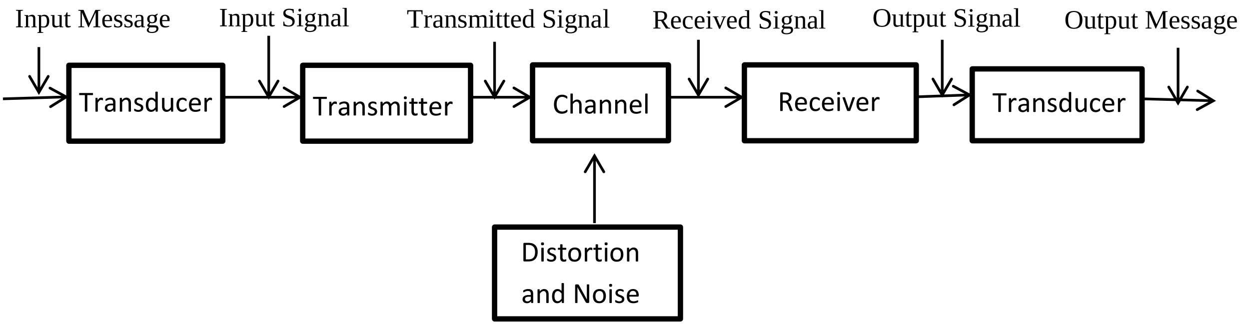

Fig. 1.1. Fundamental block diagram of a wireless communication system [5].

First block is of transducer and it converts one form of energy into other form of energy. Here, it is used for converting the message signal from an information source into an electrical signal.

1.2.1. Transmitter

Transmitter converts the information signal into a form which is suitable for transmission over a wireless channel. At transmitter, various tasks are performed such as modulation, source coding and channel coding. Each of them is briefly explained below

- **Modulation**

Modulation techniques have made it possible to send information signals through wireless channels by transferring the characteristics of message signals and make them suitable to be transmitted over wireless channels. Modulation techniques are also used for multiplexing the number of users on to a single channel to provide multiple access of a wireless channel to the number of users.

Different types of modulation techniques have been developed for wireless communication which are mentioned below

Analog Modulation Techniques

1. Amplitude Modulation
2. Frequency Modulation
3. Phase Modulation

In analog modulation techniques, both message and carrier signals are in continuous form. Analog modulation techniques are still in use today, but because of the development of digital wireless communication systems, they are in less use as compared to digital modulation techniques. Wireless communication shifts from analog form to digital form because of the following reasons

1. Development of digital signal processing techniques at large extent as compared to analog one.
2. Digital signals are easy to store and process as compared to analog signals.
3. Digital signals are more immune to noise as compared to analog signals.
4. Different encryption and decryption techniques are available to secure the digital signals i.e., digital communication is more secure as compared to analog communication.

Digital Modulation Techniques

In digital modulation techniques, carrier signal is in continuous form, but the message signal is in digital form or converted into digital form by using sampling and quantization methods.

Different digital modulation techniques are

1. Amplitude Shift Keying (ASK)
2. Phase Shift Keying (PSK)
3. Quadrature Phase Shift Keying (QPSK)
4. Differential Phase Shift Keying (DPSK)
5. Frequency Shift Keying (FSK)
6. Quadrature Amplitude Modulation (QAM)

The choice of a particular modulation technique will depend on the type of application. There are two factors which mostly affected the choice of modulation technique.

(i). Power efficiency

(ii). Bandwidth efficiency.

Some of the modulation techniques mentioned above are more bandwidth efficient and some of them are more power efficient.

- **Source Coding**

Source coding techniques are developed to remove the redundant information coming from the information source. Removal of redundant information decreases the bandwidth requirement which is a very limited source available for wireless communication. Some of the source coding techniques available are given below

1. Shannon-Fano Coding
2. Huffman Coding

Source coding techniques discussed above encode a particular information symbol by using its probability of occurrence. These techniques assign more number of bits to a symbol with very less probability of occurrence and lower number of bits to a symbol with high probability of occurrence. This is just brief explanation of the working principle of source coding techniques mentioned above.

- **Channel Coding**

Channel coding techniques are used to shield the transmitted data from errors when it passes through the channel. Channel coding techniques are used to detect as well as correct the errors present in the received data. In channel coding technique, each symbol is represented with some extra number of bits to protect it from the errors. Different channel coding techniques are developed and some of them are given below

1. Parity Check Codes

2. 2-D Parity Check Codes
3. Linear Block Codes
4. Convolutional Codes
5. Turbo Codes

1.2.2. Channel

Channel is the medium through which a signal passes. Fidelity of the received signal will depend upon the characteristics of the channel through which the transmitted signal passes. A wireless channel can be represented as a filter with impulse response $h(t)$. Mathematically, the received signal is denoted as

$$y(t) = x(t)*h(t) \tag{1.1}$$

where * denotes the convolution of the transmitted signal x(t) with channel impulse response h(t).

Ideal channel response is represented as

$$y(t) = K\,x(t-t_0) \tag{1.2}$$

where t_0 is the delay introduced by the channel and in frequency domain, channel response is given as

$$Y(f) = K\,X(f)\,e^{-j2\pi f t_0} \tag{1.3}$$

$$H(f) = K\,e^{-j2\pi f t_0} \tag{1.4}$$

where K is the magnitude response of the channel and $\theta = -2\pi f t_0$ represents its phase response. Magnitude and phase response of an ideal channel are given below

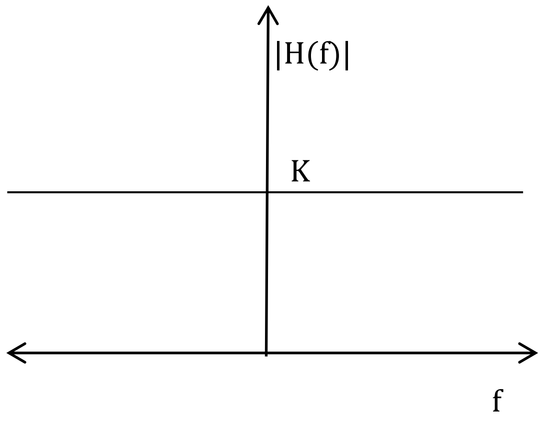

Fig. 1.2. Magnitude response of an ideal channel.

Channel given in equation (1.2) is an ideal channel whose magnitude is constant over all frequencies and phase is a linear function of frequency. In general, we don't require a

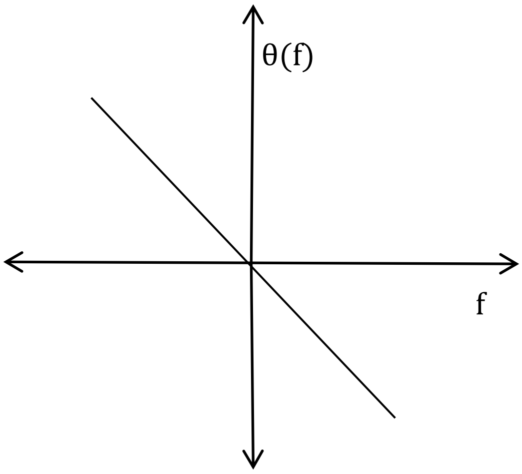

Fig. 1.3. Phase response of an ideal channel.

channel, which has a uniform magnitude and linear phase response over the entire frequency range. But, channel over which a signal is transmitted should has a uniform magnitude and linear phase response over the frequency range of the transmitted signal otherwise signal will get distorted i.e., received signal will lose its fidelity.

1.2.3. Distortion and Noise

- **Distortion**

Distortion in the transmitted signal occurs when there is a characteristic impairment between the transmitted signal and the channel. In case of distortion, the transmitted signal will lose its shape i.e., shape of the transmitted signal will get changed.

There are two different types of distortion introduced by a wireless channel.

1. Amplitude Distortion
2. Phase Distortion

Amplitude Distortion

Amplitude distortion introduces when the channel's magnitude response is not constant over the frequency range of the transmitted signal i.e., channel scaled different frequency components with different scaling factors.

Phase Distortion

Phase distortion introduces in the transmitted signal due to nonlinear phase response of the channel over the bandwidth of transmitted signal i.e., phase does not remain linear function of frequency. Different frequency components delayed by different amount.

- **Noise**

Noise can be defined as an unwanted signal that interferes with an information signal or a modulated signal. Noise present in the communication channel degrades the quality of the received signal at the receiver side; hence cause errors in decoding of the transmitted signals and it also affects the capacity of a wireless channel. Noise signal can be regarded as an information signal which gives information about the source of noise. Noise signal is generally regarded as a random signal i.e., it can’t be measured or predicted. Therefore, modeling of the noise present in wireless communication system is an important and difficult process. Various types of noise is present in the wireless communication as mentioned below

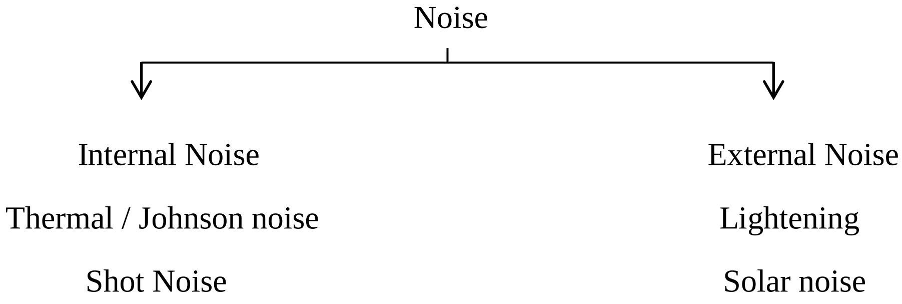

Fig. 1.4. Types of noise.

Internal noise is because of the arbitrary motion of electrons in the electronic circuit of the receiver and the transmitter terminals.

This type of noise can’t be avoided whereas external noise is due to the manmade sources and natural sources as shown in the Fig. 1.4.

As it is clear from Fig. 1.1 given above that during the transmission of an information signal or a modulated signal, noise of various types is combined with the transmitted signal. Since, noise is a random signal therefore by using central limit theorem [3]; noise in a communication system is modeled using Gaussian distribution. Gaussian distribution function is given as

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{1.5}$$

where μ denotes the mean of noise and σ^2 gives the variance of noise.

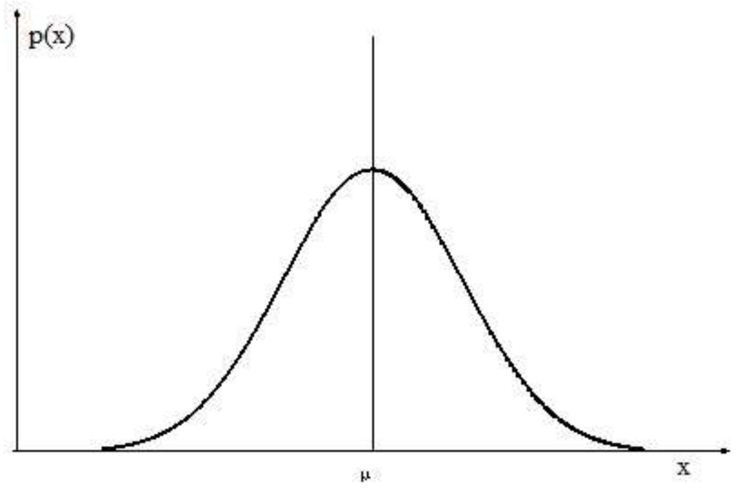

Fig. 1.5. Gaussian distribution [3].

1.2.4. Receiver

At the receiver side, exactly the inverse operation of the transmitter side is performed to recover the original transmitted signal and then output transducer converts the decoded signal into the form in which an information source generates the signal.

- **Equalization**

To eliminate the distortion introduced by the wireless channel, received signal at the receiver side is multiplied by the inverse of the channel response $H(f)$. This method of removing the effects of distortion from the received signal is known as equalization and it is done as

$$Y_{eq}(f) = \frac{Y(f)}{H(f)} \tag{1.6}$$

where $Y_{eq}(f)$ is the equalized received signal in the frequency domain and $Y(f)$ is the received distorted signal in the frequency domain.

- **Demodulation**

Demodulation is a technique of separating the information signal from the modulated carrier signal. Demodulator is an electronic circuit present at the receiver side and it recovers the information signal from the modulated carrier waveform. Number of demodulation methods is same as that of modulation methods. As an example to demodulation process, a diagram representing the amplitude demodulation method is given below

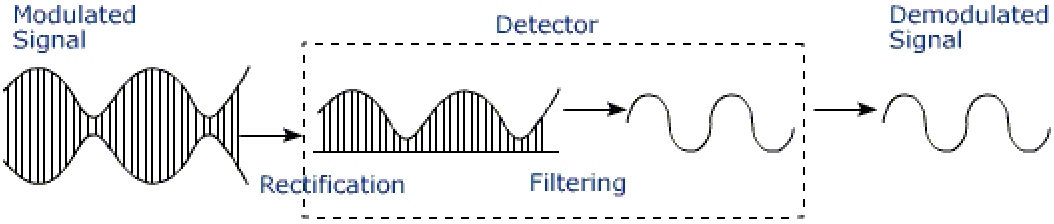

Fig. 1.6. Amplitude demodulation process [4].

This is just the brief explanation of a wireless communication system and the fundamental techniques which are used for successful propagation of an information signal over a wireless channel from the transmitter to the receiver along with the discussion on distortion and noise which impacts the performance of a wireless communication system.

After discussing the block diagram of a wireless communication system, we will discuss about another important topic of wireless communication – Capacity of Wireless Channels.

1.3. Capacity of Wireless Channels

Sharp increase in demand for wireless communication has made it critically necessary to define the capacity limits of a wireless channel. Channel capacity is the maximum data rate that can be transferred over a wireless channel with very small probability of errors, by having no conditions on the complexity of the encoder and decoder [1]. Channel capacity was first given by Claude Shannon in 1940 which is developed using a mathematical theory based on the concept of mutual information between the input and output of a wireless channel. We will discuss about the capacity of both time-invariant and time-variant wireless channels.

1.3.1. Capacity of Time-Invariant Channels

Time-invariant channels are additive white Gaussian noise (AWGN) channels and capacity of an AWGN channel is provided by Shannon’s theorem as mentioned below

$$C = B\ \log_2(1 + \frac{P}{N_0 B}) \tag{1.7}$$

where B is bandwidth of an AWGN channel, P is the power of the transmitted signal and N_0 is power spectral density of AWGN noise.

1.3.2. Capacity of Time-Variant Channels

Capacity of time-varying wireless channels will depend on two different scenarios.

(1) Channel state information only at the receiver side.

(2) Channel information both at the transmitter and receiver side.

Depending on these two different scenarios, there are different definitions of a channel's capacity.

1.3.2.1. Channel Information only at the Receiver Side

In this case, receiver has the knowledge of channel distribution $p(\gamma)$ and γ is signal-to noise ratio defined as $\frac{P}{N_0 B}$. In this case, two different definitions of channel capacity are given as

- **Shannon (Ergodic) Capacity**

Shannon capacity of a time-varying wireless communication channel is given as

$$C = \int_0^\infty B \log_2(1+\gamma) p(\gamma) d\gamma \qquad (1.8)$$

Thus Shannon capacity is defined as an AWGN channel capacity averaged over channel distribution $p(\gamma)$. Therefore, it is also known as ergodic capacity.

In this case, since only the receiver has the knowledge of instantaneous value of γ. Therefore, data transmitted over the channel remains constant irrespective of the value γ.

- **Outage Capacity**

Capacity with outage is defined for slowly varying channels. In this case, the transmitter selects the minimum value of signal-to noise ratio $\gamma_{\min}$ and then transmits data according to the value of $B \log_2(1+\gamma_{\min})$.

If the instantaneous value of γ at the receiver side is greater than or equal to $\gamma_{\min}$ $(\gamma \geq \gamma_{\min})$ then the transmitted data can be decoded with almost zero probability of error. But, if the received instantaneous SNR is less than the $\gamma_{\min}$ $(\gamma \leq \gamma_{\min})$ then the transmitted data can only be decoded with probability of error approaching to one and the receiver declares an outage.

1.3.2.2. Channel Information both at the Transmitter and Receiver Side

In this case, both the transmitter and receiver have the knowledge of channel state information (CSI). As the CSI is available at the transmitter, so the transmitter can vary the transmission rate according to the available CSI. In this case, the transmitter will not send data until it cannot be decoded correctly.

In this case, Shannon capacity is given based on the optimal power and rate adaptation corresponding to the channel state information.

$$\mathrm{C} = \int_0^\infty \mathrm{B}\log_2\left(1 + \frac{\mathrm{P}(\gamma)\gamma}{\overline{\mathrm{P}}}\right)\mathrm{p}(\gamma)\mathrm{d}\gamma \tag{1.9}$$

where $\overline{\mathrm{P}}$ is the average power constraint and $\mathrm{P}(\gamma)$ denotes the power transmitted for SNR γ.

Average power constraint $\overline{\mathrm{P}}$ is given as

$$\int_0^\infty \mathrm{P}(\gamma)\, \mathrm{p}(\gamma)\mathrm{d}\gamma \ \leq \overline{\mathrm{P}} \tag{1.10}$$

1.4. Challenges in Wireless Communication

The major challenges that come in wireless communication are given below

- One of the major challenges is the availability of limited bandwidth for wireless communication.
- To achieve higher data rates with available limited bandwidth for sharing of information such as text, videos, video calling, voice calls etc.
- To overcome from the effects of multipath propagation i.e., multipath fading and noise for reliable communication of information.
- Selection of optimal power level for transmission of signal to avoid interference with other communication systems.

These are the major challenges that come in the progress of wireless communication. The most difficult challenge is to deal with the multipath fading and its effects on the wireless communication. Therefore, in next chapters, our main topic of discussion will be space-time block-codes which are developed to nullify the effects of fading on wireless communication.

1.5. Thesis Objective

- To discuss about various space-time block-codes (O-STBC and QO-STBC), which are developed to provide consistent wireless communication over highly faded channels along with their development and principle of design.
- To provide the analysis of QO-STBC schemes under the constraint of imperfect channel state information at the receiver side along with simulation results.

1.6. Organization of the Thesis

Chapter-1 (Introduction), includes the discussion about wireless communication and different techniques which have made the wireless communication possible. This chapter also includes the discussion on various challenges of wireless communication.

Chapter-2 (Literature Survey), consists of literature review i.e., brief discussion on different techniques or methods which are related to the field of our research work.

Chapter-3 (Multipath Propagation, Fading, Fading Parameters and Diversity Methods), has discussion about multipath propagation along with its mathematical model. This chapter also includes discussion on fading parameters, fading distributions and on various diversity methods to avoid the destructive effects of fading.

Chapter-4 (Space-Time Block-Coding and Design Criterion), includes introduction to space-time block-coding scheme (STBC) along with its design criterion. We also discuss about Alamouti scheme which is fundamental for all other STBC schemes along with some important terms related to space-time block-codes.

Chapter-5 (Analysis and Methodology), introduces various QO-STBC schemes along with their complete mathematical analysis. This chapter also includes the analysis of QO-STBC schemes under imperfect channel state information at the receiver side.

Chapter-6 (Simulation Results), presents the simulation results performed in MATLAB for various QO-STBC schemes discussed in chapter 5.

Chapter-7 (Concluding Remarks and Future Scope), includes the concluding statements and future scope of the research work done in the thesis.

Chapter 2

LITERATURE SURVEY

This chapter will provide insight regarding various orthogonal space-time block-coding schemes (O-STBC) and quasi-orthogonal block coding-schemes (QO-STBC).

Space-Time Codes: Performance Criterion and Code Construction

In [6], Tarokh and Seshadri discusses about the design of space-time codes to improve the wireless communication over fading channels along with enhanced data rate. Channel encoder encodes the data into n streams and these are transmitted at the same time using n transmitting antennas. Performance criteria is developed assuming the condition that channel is a slow flat fading channel. Matrices, consist of a pair of different code sequences regulate the performance. The diversity gain is described by the minimum rank among these matrices and the minimum determinant defines the coding gain. Analysis also includes the fast fading channel. The design criterion is used to develop trellis code for high speed wireless communication. The codes designed in this paper give the best adjustment between trellis complexity, data rate and diversity.

Examination of multi-element array (MEA) technology has been done in [7] to improve the wireless capacities in particular applications. Some results based on the information theory are also presented in this paper to ensure the great benefits of MEAs in WLANs and building to building wireless communication links. An important case is also considered in which channel characteristics subjected to Rayleigh fading are available only at the receiver side, but not at the transmitter side. By fixing the overall transmitted power, capacity offered by MEA technology is also given in this paper.

Orthogonal Space-Time Block-Codes (O-STBC)

Orthogonal space-time block-coding schemes are developed to improve the quality and the capacity of mobile communication. The word ‘orthogonal’ specifies that their design is inspired from orthogonal design criterion. Orthogonal characteristics of space-time block-coding schemes result into simple linear decoding (maximum likelihood decoding) at the receiver side along with other advantages such as improvement in diversity gain and coding gain.

Alamouti [8], presents the first space-time block-code for two transmitting antennas and one receiving antenna. Its design is inspired from orthogonal design criterion therefore it is also known as orthogonal space-time block-code (O-STBC). It achieves the diversity order (2N, where N is number of receiving antennas) of MRRC (Maximal Ratio Receiver Combining) technique, which is a receiver diversity scheme. Due to orthogonal characteristics of O-STBC, transmitted symbols are decoded using simple linear detection method i.e., maximum likelihood decoder (ML) works with a single symbol at the time of decoding. It is a rate one code and it can be generalized for two transmit antennas with any number of receiving antennas. This method suffers from -3 dB performance loss as compared to MRRC due to the use of half power for each transmitted symbol in comparison to the full power in case of MRRC scheme. Alamouti scheme is only for two transmitting antennas and it cannot be used for more than two transmitting antennas.

Performance of STBC scheme is analyzed by Tarokh and Jafarkhani [9]**.** Space-time block-codes present a way to deal with destructive effects of multipath fading during the transmission of information from the transmitter to the receiver. In STBC, symbols are encoded in space and time domain which results in an encoding matrix of size n × n i.e., for n transmit antennas and n time slots. At the receiver side, the received signal is a linear combination of n transmitted symbols plus AWGN noise. Orthogonal structure of space-time block-codes allow simple linear detection of transmitted symbols i.e., maximum likelihood decoder has a one symbol at a time to work with. It is shown that use of multiple transmits antennas along with space-time block-codes provide great performance under the effect of multipath fading, but without any increase in bandwidth and in decoding complexity.

An effective approach to generalize the orthogonal space-time block-coding (O-STBC) for any number of transmitting antennas is given by Tarokh and Jafarkhani [10]. Space-time block-coding (STBC) technique is used to overcome the effects of multipath fading. Orthogonal characteristics of space time block coding helps to decouple the transmitted signals and it results into simple maximum likelihood decoding (ML). Generalized orthogonal designs are used to provide orthogonal space-time block-codes for any number of transmitting antennas for both complex and real signal constellations. These codes give maximum possible transmission rate for real signal constellations such as pulse amplitude modulation (PAM), pulse width modulation (PWM) etc. Similarly, for complex signal constellations such as PSK and QAM, space-time block-codes are provided to achieve $\frac{1}{2}$ of the maximum possible transmission rate for any number of transmitting antennas. For two, three and four transmitting antennas, space-time block-codes are proposed to achieve full, $\frac{3}{4}$ and $\frac{3}{4}$ of the maximum possible transmission rate respectively.

A new family of space-time codes is presented in [11]. A serial concatenated coding scheme is used in these codes with a standard space-time code as the outer code and a very simple rate 1 recursive code as the inner code. A very negligible increase in complexity is introduced to the transmitter by rate 1 recursive code as compared to the conventional space-time codes. An interleaver is inserted between the inner code and the outer code. Substantial gain can be achieved with this new scheme by tolerating some delay.

In [12], discussion is about space-time codes developed for multiple antenna wireless communication. Space-time codes provide full diversity over fading channels along with simple linear encoding and decoding methods. As they achieve full diversity with low complexity, but it is shown that they also cause a capacity loss because they convert a matrix channel into a scalar AWGN channel which has a low capacity than original one. In this letter, loss in capacity is defined in terms of number of receiver antennas, rate of transmission and channel rank.

Quasi-Orthogonal Space-Time Block-Codes (QO-STBC)

As we have discussed above that space-time block-codes from orthogonal design criterion achieve full diversity order and full transmission rate, but only for two transmitting antennas. For more than two transmitting antennas, space-time block-codes achieve full diversity order, but lack in transmission rate. To overcome this limitation, orthogonal characteristics of space-time block-codes are relaxed and new codes, known as quasi-orthogonal space-time block-codes (QO-STBC) are developed.

Jafarkhani [13**],** presents a space-time block-code (STBC) developed for more than two transmitting antennas by easing the condition of orthogonality and it is known as quasi-orthogonal space-time block-code (QO-STBC). This code achieves full transmission rate, but with partial diversity order as comparison to orthogonal space-time block-codes for more than two transmitting antennas. Due to quasi-orthogonal characteristics of the code, decoding complexity at the receiver side increases i.e., maximum likelihood decoder works with a pair of transmitted signals in place of a single symbol as in case of orthogonal space-time block-coding (O-STBC) scheme. This is because of the presence of interfering terms in the detection matrix which is used for the detection of transmitted signals at the receiver side.

A turbo-coding scheme that comprises parallel concatenated space-time codes is studied in [14]. It is referred as turbo space-time coded modulation (turbo-STCM). Along with full rate, this scheme also provides full diversity. Performance is also analyzed with recursive as well as non-recursive space-time constituent codes. In this paper, it is also proved that turbo-STCM performs better than standard space-time codes of similar complexity.

Quasi-orthogonal space-time block-codes with full transmission rate and full diversity order are discussed in [15]. Initially, orthogonal space-time block-codes are provided by Alamouti and Tarokh for two and more than transmit antennas respectively. Orthogonal space-time block-codes for more than two transmit antennas achieve full diversity order and fast ML decoding, but lacks in transmission rate. To achieve full rate, condition of orthogonality is relaxed and quasi-orthogonal space-time block-codes are given by Jafarkhani. QO-STBC scheme achieves full rate, but with partial diversity order. To achieve full diversity for QO-STBC scheme, a new scheme is discussed in this paper. In this scheme, half of the transmitted signals are selected from constellation A and other half is selected from rotated constellation $Ae^{j\Phi}$. Rotation angle is properly chosen for different modulation schemes and in result, this scheme has full transmission rate and full diversity order.

It is shown in [16] that by properly deviating the phase of constellation space, performance of QO-STBC scheme can be improved. Optimum phase deviation of constellation space increases the minimum distance of the correlating space-time codewords and as a result of it, performance of a QO-STBC scheme gets enhanced.

A full transmission rate space-time code for 3+ Tx antennas is proposed in [17]. This scheme reduces the non-orthonormality which increases when code rate crosses the maximum allowable limit. Iterative interference cancellation based linear decoding scheme is used which approaches the ML decoding performance.

Alamouti scheme is able to achieve the channel capacity with two transmitting and one receiving antenna. After that no such scheme is developed for the case of more than two transmitting antennas. In [18], a family of space-time codes, designed for four transmitting antennas is presented and these codes are shown to achieve a significant fraction of the open-loop Shannon capacity of the channel.

In [19], a new set of space-time codes known as super-orthogonal space-time trellis codes is given. Combination of set partitioning and a super set of orthogonal space-time block-codes is used in a logical manner to provide full diversity order and improved coding gain over previous space-time trellis code constructions.

In [20], it is shown that with the help of phase feedback, it is possible to have ML decoding of a single symbol at a time for linear complex space-time block-codes for up to eight transmitting antennas with transmission rate of $\frac{6}{8}$. For full transmission rate i.e., rate one code, two-phase feedback system reduces the interference from three symbols to only one symbol. Therefore, it results in less complex maximum likelihood decoding.

Quasi-orthogonal space-time block-code with least decoding complexity is discussed by Yuen and Guan in [21]. Structure of this code (MDC-QO-STBC) is such that maximum likelihood decoder has two real symbols at a time to detect. Proper constellation rotation angles are chosen for QAM and for MPSK to achieve full diversity order and coding gain for MDC-QO-STBC. It is shown that transmission rate for MDC-QO-STBC is one for three and four transmitting antennas and $\frac{3}{4}$ for five to eight transmitting antennas. MDC-QO-STBC has better power distribution between transmitting antennas and is more flexible in adjusting to number of transmitting antennas as compared to coordinate interleaved orthogonal design (CIOD) and asymmetric CIOD codes.

In [22], performance of antenna selection scheme for multiple antenna transmission systems under the condition of correlated fading is analyzed. It is considered that CSI is only available at the receiver side and antenna selection is also performed only at the receiver side. Antenna selection scheme is based only on the instantaneous received signal power.

In [23], performance of the concatenation of an outer channel code with an orthogonal space-time block-code is analyzed. Outer code can be a convolutional code or a trellis-coded modulation code (TCM). Upper bounds on the bit error rate performance of this scheme are derived with receiver antenna selection scheme. Several assumptions are made during the analysis of this scheme and these upper bounds can be extended in a simple way for other types of outer codes and fading channels.

In [24], a generalization of extended orthogonal space-time block-codes (EO-STBCs) for MIMO systems using four transmit antennas over quasi-static flat fading channels is presented. As full transmission rate orthogonal space-time block-codes present only for two transmit antennas, so a new STBC scheme based on phase feedback is presented. In this scheme, using the feedback from the receiver, phases of some of the symbols are rotated. Simulation results proved that this new STBC scheme based on phase feedback achieves a reasonable performance and it outperforms the closed-loop space-time block-codes.

Till now, we have discussed about the different space-time block-codes to enhance the performance of wireless communication systems under the severe effects of multipath fading along with different decoding methods. Next, we are going to discuss a new layered space-time code which is a combination of Bell Laboratory Layered Space-Time architecture (BLAST) and special Space-Time Trellis codes (STTC).

New layered space-time codes as a combination of BLAST and STTC Codes are presented by Ferr$\acute{e}$ and Pierre in [25]. System proposed is named as Super Quasi-Orthogonal Horizontal Layered Space-Time Trellis Code (SQOHLSTTC). It presents in a Space-Time Trellis Code based on a powerful space-time block-code which is primarily advanced for a three transmit antenna communication system along with an original block based decoding algorithm. Group interference cancellation and group interference suppression are combined in the decoding algorithm of SQOHLSTTC. A low complexity hard decision repetitive decoding scheme is proposed to implement the system. System performance ensures the great interest in the proposed transmission scheme.

A new decoding scheme based on array processing is proposed in [26]. New decoding scheme works with single symbol at a time and can decrease the decoding time of decoder as well as decoding complexity. Null space is used in this technique to separate the transmitted signals from different antennas, and then these symbols are decoded linearly. Mathematical analysis proved that this proposed decoding method greatly reduce the decoding complexity. The computational complexity of new method with 256-QAM is lower than in comparison to conventional decoder with 16-QAM.

In [27], an issue of choosing best decoding method for QO-STBC scheme is discussed. During the analysis, a generic maximum likelihood metric expression is used which is more capable of reducing the decoding complexity. It is proved that for small number of antennas, exhaustive search has considerable benefit over sphere decoding.

As we have discussed above that a QO-STBC scheme provides full rate transmission, but results in increase in decoding complexity due to its quasi-orthogonal characteristics. In QO-STBC scheme, linear ML decoding is not possible because of the presence of interference terms from neighboring signals during the decoding of a transmitted signal.

Next, we will discuss some new methods which greatly reduce the decoding complexity of QO-STBC scheme by modifying its channel matrix. Resulting new channel matrix is orthogonal in characteristics which makes the linear decoding of transmitted signals possible i.e., ML decoder works with single signal with no interference from the neighboring transmitted signals at the time of decoding.

A quasi-orthogonal space-time block-coding (QO-STBC) scheme with simple linear detection is presented by Park in [28]. A traditional QO-STBC scheme achieves the full rate transmission, but at the expense of increase in decoding complexity. Along with decoding complexity, diversity gain of the conventional QO-STBC scheme also gets affected. All these drawbacks of the conventional QO-STBC scheme are due to the interference from the adjacent signals at the decoding time of a signal. Proposed QO-STBC scheme will eliminate the interference terms by manipulating the decoding matrix of conventional QO-STBC scheme using Givens rotation method and therefore it will result in decrease in decoding complexity as compared to the conventional QO-STBC scheme. This new scheme will also enhance the diversity gain along with decrease in decoding complexity.

An array processing based decoder for quasi-orthogonal space-time block-code (QO-STBC) under imperfect CSI at the receiver side (i.e., CSI with some channel estimation error) is analyzed by Zhang and Yuan in [29]. Array processing based decoder for QO-STBC has been analyzed under the condition of perfect CSI at the receiver side in terms of symbol error rate (SER) and complexity level. In this paper, impression of imperfect CSI on the performance of QO-STBC scheme is examined and it is evaluated that imperfect CSI reduces the performance of QO-STBC scheme in terms of symbol error rate especially in high signal-to noise ratio (SNR) regime. Mean square error (MSE) is utilized to relate the degradation of performance with correctness of the channel estimator.

Space-time block-codes with high transmission rate, full diversity and low ML decoding for multi input multi output systems employing three and four transmit antennas are discussed in [30]. In this, empty slots in the transmission matrices of present space-time block-codes from coordinate interleaved orthogonal designs (CIODs) are filled by additional symbols. It uses the conditional ML decoding which greatly diminishes the decoding complexity of non-orthogonal space-time block-codes. Two proposed schemes with transmission rate of 1.5 and 2 are given for MIMO systems employing four transmitting antennas. It is proved that low complexity scheme with transmission rate of 2 outdoes the best proposed STBC because of its coding gain. STBC scheme with rate of 1.5 outperforms the full diversity QO-STBC scheme. These two schemes with transmission rate of 1.5 and 2 are also employed on three transmit antennas systems and both these schemes outperform the analogous full diversity QO-STBC schemes.

In [31], performance of QO-STBC coded OFDM systems employing array processing based decoder is evaluated under the condition of imperfect CSI at the receiver side. The least square (LS) channel estimator is used to estimate the CSI. Mean square error is used to analyze the performance of the LS channel estimator over the frequency selective fading channels. Its influence on the SER is also analyzed in this paper.

Shang $et\ al.$ in [32] evaluates some QO-STBC schemes for four transmit antennas. Some analyses are made on MDC-QO-STBC scheme and it is shown that the encoding matrix of MDC-QO-STBC scheme is similar to the conventional QO-STBC scheme and this scheme can be linearly decoded at the receiver side.

Alamouti space-time block-code discussed above is mainly for PSK and QAM modulation techniques. It is then simplified for continuous phase modulation (CPM), known as OST-CPM, by preserving its orthogonality for fast ML decoding. Next, we are going to discuss the orthogonal-like space-time coded CPM systems for three and four transmit antennas inspired from orthogonal and quasi-orthogonal designs.

Wang and Su in [33], presents orthogonal-like space-time coded continuous phase (CPM) systems for three and four transmit antennas. These codes are inspired from orthogonal and quasi-orthogonal space-time codes. Since the symbols transmitted from antennas in the suggested orthogonal-like space-time coded CPM systems are not orthogonal, but fast ML decoding is maintained as that it is for two transmitting antennas. It is shown that suggested orthogonal-like space-time coded CPM systems for four transmit antennas outperforms the orthogonal space-time coded continuous phase systems for two transmitting antennas.

In [34], space-time block-coded communication systems using the numeric-variable-forgetting-factor (NVFF) least squares (LS) channel estimator are analyzed. The polynomial model is used in LS algorithm in conjuction with NVFF to improve the performance of the channel tracking under the non-stationary wireless environment.

QO-STBC scheme with Eigen value decomposition (EVD) manipulation is discussed in [35]. This new scheme achieves the less complex ML decoding as comparison to the QO-STBC scheme proposed by Jafarkhani in [4]. Eigen value decomposition manipulation is applied to the detection matrix of conventional QO-STBC scheme which results in a new channel matrix which is orthogonal in nature. Therefore, no interference terms are present during the detection of a symbol from neighboring antennas. This results in a simple linear decoding of transmitted symbols at the receiver side. This new scheme has improved BER performance as compared to the conventional QO-STBC scheme.

An enhanced QO-STBC scheme with full transmission rate, full diversity order and with linear decoding is proposed by Pham and Qi in [36]. This QO-STBC scheme has better peak-to-average power ratio (PAPR). In this scheme, to achieve full diversity order, constellation rotation scheme is applied to the message symbols along with the coordinate interleaving. Information symbols are pre-grouped using Givens rotation matrix. Bit error rate performance of the proposed scheme is better than that of O-STBC scheme proposed by Tarokh, QO-STBC scheme proposed by Jafarkhani and QO-STBC scheme proposed by Park. Its bit error rate performance is slightly better than that of coordinate interleaved QO-STBC (CI-QO-STBC) and minimum decoding complexity QO-STBC (MDC-QO-STBC) schemes. It also has reduced decoding complexity as compared to that of MDC-QO-STBC scheme.

In [37], space-time block-code for long term evolution advanced systems (LTE-A) is presented. In LTE-A, mobile stations have two transmit antennas and data is send using three time slots. Therefore, a new STBC scheme is proposed for two transmitting antennas and three time slots. Proposed space-time block-code has following properties.

1. It can have full transmission rate and full diversity order.
2. ML decoding has joint detection of three real symbols.
3. It is compatible with single antenna transmission mode.
4. By increasing signal constellation size, minimum determinant values (MDVs) do not die out.

An orthogonal frequency division multiplexing technique using QO-STBC scheme is analyzed in [38]. In conventional QO-STBC scheme, there is some interference terms present in the detection matrix. Therefore, it is impossible to achieve full diversity with conventional QO-STBC scheme. STBC schemes have completely diagonal detection matrices and enables simple linear decoding. But, it is not the case with conventional QO-STBC scheme. In this paper, a method of removing the interfering terms from the detection matrix of QO-STBC scheme for an OFDM system is discussed. It is shown that elimination technique provides a 2 dB BER gain for a QO-STBC system.

A QO-STBC scheme based on the Hadamard matrix [40-41] is discussed in [39]. Property of Hadamard matrix is used to achieve the full diversity for a QO-STBC scheme. Hadamard matrix diagonalize the quasi-cyclic matrix and consequently, a decoding matrix so that linear decoding is achieved. The results of this scheme give full diversity and enhanced performance as compared to the interference free QO-STBC scheme. Proposed scheme achieves a gain of 4 dB is achieved with respect to the interference free QO-STBC scheme.

Chapter 3

MULTIPATH PROPAGATION, FADING, FADING PARAMETERS AND DIVERSITY METHODS

This chapter presents the discussion about multipath propagation, fading and diversity methods. We also discuss about the different fading distributions, multipath fading parameters and fading channels along with the mathematical model of multipath propagation channel.

3.1. Multipath Propagation Channel

In wireless communication, it is not always likely to have a line of sight (LOS) path between the transmitter and the receiver due to the presence of large no. of obstructions such as buildings, trees, vehicles etc. Because of the presence of such obstructions, there is a multipath propagation channel between the transmitter and the receiver. All these obstructions act as a scatterer for a signal from the transmitter to the receiver. An example of multipath propagation environment is given below

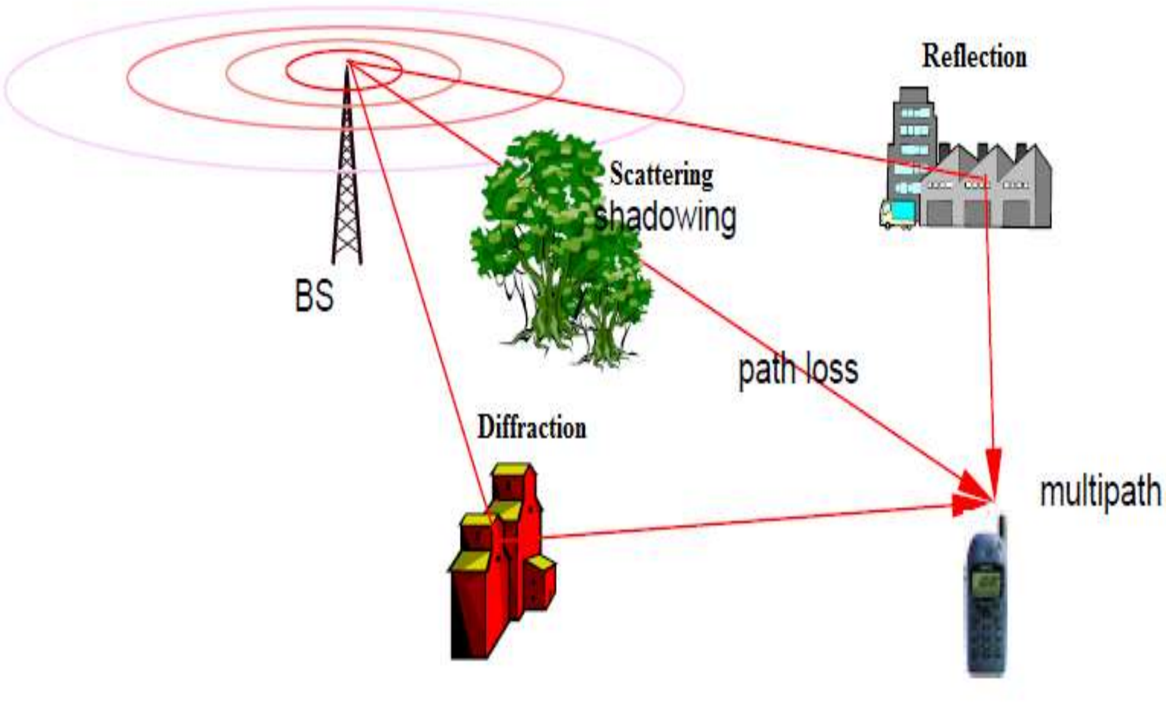

Fig. 3.1. Multipath propagation environment [4].

If a short duration pulse is transmitted over a multipath channel then the received signal will be a pulse train with each pulse in a train corresponds to the line of sight component or a distinct multipath component related with a distinct scatterer. Due to the presence of multipath propagation channel, signal energy gets spread in time known as time delay spread of the channel. Generally, time difference between the first arrival pulse and the last arrival pulse is known as time delay spread of the channel. If the time delay of the channel is small as compared to the inverse of the signal duration then there is little time spreading of the received signal.

However, if the time delay is larger than the inverse of the signal bandwidth then there is significant time spreading of the received signal and it results into significant signal distortion.

Another characteristic of the multipath propagation channel is its time varying nature due to movement of the transmitter or the receiver. Motion causes the variations in the location of reflectors and it results in changes in the characteristics of multipath channel. Thus, if we repeatedly transmit pulses from a moving transmitter, we will spot changes in the amplitudes, delays and in the number of multipath components corresponding to each pulse.

This time varying nature of multipath propagation channel due to movement of the transmitter or the receiver is shown below in the diagram.

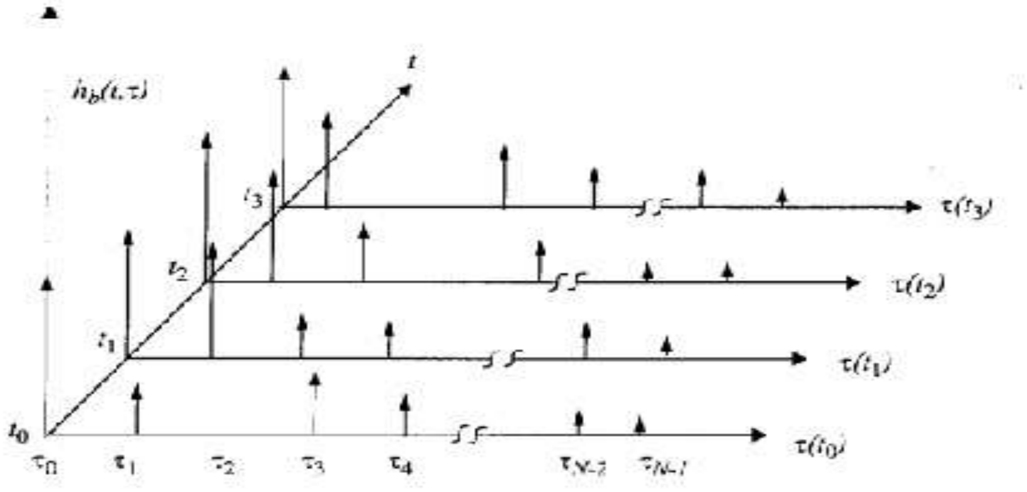

Fig. 3.2. Time varying multipath channel model [4].

3.2. Mathematical Model of Multipath Channel

Physical channels such as under-water acoustic channels and ionospheric radio channels, which results in time-variant multipath propagation of the transmitted signal may be modeled as time-variant linear filters. Such filters are characterized by time-variant impulse response $h(\tau\,;t)$.

where $h(\tau\,;t)$ is the response of the channel at time t due to an impulse applied at time t-τ.

For an input signal s(t), the channel output signal is

$$r(t) = s(t)^{*}\, h(\tau\,;t) + n(t) \tag{3.1}$$

and time-variant impulse response $h(\tau\,;t)$ is given as

$$h(\tau; t) = \sum_{k=1}^{L} a_k(t)\, \delta(t - \tau_k) \tag{3.2}$$

where $a_k(t)$ gives the time-variant attenuation factor of the L propagation paths and τ_k represents the delay associated with k^{th} propagation path at time t.

If equation (3.2) is used in equation (3.1), then the received signal is given as

$$r(t) = \sum_{k=1}^{L} a_k(t)\, s(t - \tau_k) + n(t) \tag{3.3}$$

and the received signal is consist of L multipath components and each component is attenuated by factor a_k and has a delay of τ_k.

Let us consider the transmission of an un-modulated carrier

$$s(t) = A\cos(2\pi f_c t) \tag{3.4}$$

By using the equations (3.3) and (3.4), the received signal in the absence of noise is given as

$$r(t) = A \sum_{k=1}^{L} a_k(t) \cos[2\pi f_c(t - \tau_k(t))] \tag{3.5}$$

$$= A\,\mathrm{Re}\left[\sum_{k=1}^{L} a_k(t)\, e^{j2\pi f_c t}\, e^{-j2\pi f_c \tau_k(t)}\right] \tag{3.6}$$

From equation (3.6), the complex valued signal

$$z(t) = \sum_{k=1}^{L} a_k(t)\, e^{-j2\pi f_c \tau_k(t)}$$

$$= \sum_{k=1}^{L} a_k(t)\, e^{j\phi_k(t)} \tag{3.7}$$

represents the response of the channel to the complex valued signal $e^{j2\pi f_c t}$. Input to the channel is a monochromatic signal, but the received signal is consist of large number of different frequency components. These different frequency components are generated because of the time variations in the response of channel. Bandwidth of $z(t)$ is called the Doppler frequency spread of the channel and denoted as B_d and it is a measure of the fact that how rapidly a channel changes. From equation (3.7), it is quite clear that whenever $\tau_k(t)$ changes by $\frac{1}{f_c}$, the overall phase $\phi_k(t)$ changes by 2π and $\frac{1}{f_c}$ is a small quantity. Equation (3.7) represents the multipath propagation model of the channel and it results in signal fading. Sometimes $z(t)$ adds destructively to decrease the power level of the received signal and sometimes adds constructively to enhance the power level of the received signal.

Now, the changes in the received signal power due to the multipath propagation of the transmitted signal represent the multipath fading effect. Multipath fading effect limits the data carrying capacity of the wireless channel as it increases the probability of symbol error or bit error at the receiver side.

In next section, we will discuss about the different fading distributions.

3.3. Fading Distributions

3.3.1. Rayleigh Distribution

If all the multipath components of the received signal have approximate same amplitude i.e., there is no line of sight (LOS) component then amplitude of the received signal will follow the Rayleigh distribution.

From equation (3.7), $z(t)$ can be represented as a sum of real and imaginary parts as given below

$$z(t) = z_r(t) + jz_i(t) \tag{3.8}$$

where both $z_r(t)$ and $z_i(t)$ represents the Gaussian random processes and $z_r(t)$ and $z_i(t)$ are statistically independent.

$z(t)$ is represented as

$$z(t) = a(t)e^{j\phi(t)} \tag{3.9}$$

where

$$a(t) = \sqrt{z_r^2(t) + z_i^2(t)}$$

$$\phi(t) = \tan^{-1}\frac{z_i(t)}{z_r(t)}$$

In this representation, if both $z_r(t)$ and $z_i(t)$ are Gaussian with zero-mean values, the amplitude $a(t)$ is characterized statistically by the Rayleigh probability distribution and $\phi(t)$ is uniformly distributed over the interval of 0 to 2π. Due to Rayleigh probability distribution, channel is known as Rayleigh fading channel and Rayleigh probability distribution is given as

$$f(a) = \frac{a}{\sigma^2} e^{\frac{-a^2}{2\sigma^2}} \quad , a \geq 0 \tag{3.10}$$

and the parameter $\sigma^2 = E(z_r^2) = E(z_i^2)$.

The graphical representation of Rayleigh fading distribution is given below in the diagram.

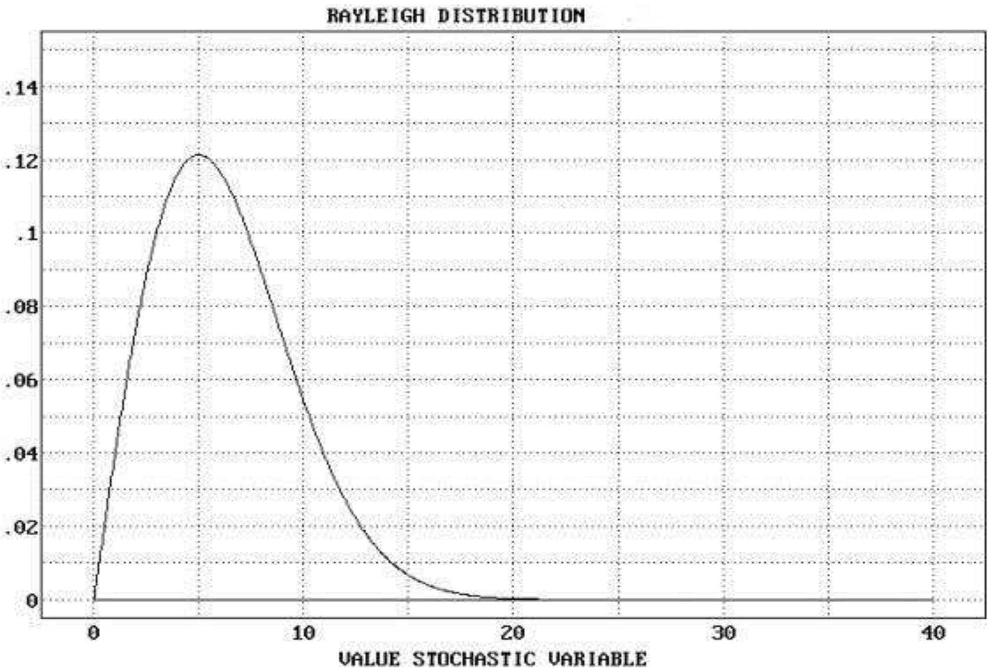

Fig. 3.3. Rayleigh fading distribution [4].

3.3.2. Ricean Distribution

The received signal amplitude in case of multipath propagation will follow the Ricean distribution if one of the components of the received signal is a line of sight component. Mathematical description of Ricean distribution is given below

$$f(a) = \frac{a}{\sigma^2} e^{-\frac{a^2+v^2}{2\sigma^2}} I_0\left(\frac{av}{\sigma^2}\right), \ (a \geq 0, v \geq 0) \tag{3.11}$$

where v defines the maximum amplitude of the LOS component and I_0 is the zeroth order Bessel function of the first kind.

As the amplitude of dominant component decreases, Ricean distribution converges into Rayleigh distribution.

Ricean distribution is generally defined by a parameter K which is given as

$$K = 10\log\left(\frac{v^2}{2\sigma^2}\right)\ \text{dB} \tag{3.12}$$

If K>>1, Ricean distribution tends to Gaussian distribution about the mean. The graphical representation of Ricean distribution is given below in the Fig. 3.4.

3.4. Parameters of Multipath Channel

Important parameters of multipath fading channel are given below

1. Time Dispersive Parameters
2. Coherence Bandwidth
3. Doppler Spread and Coherence Time

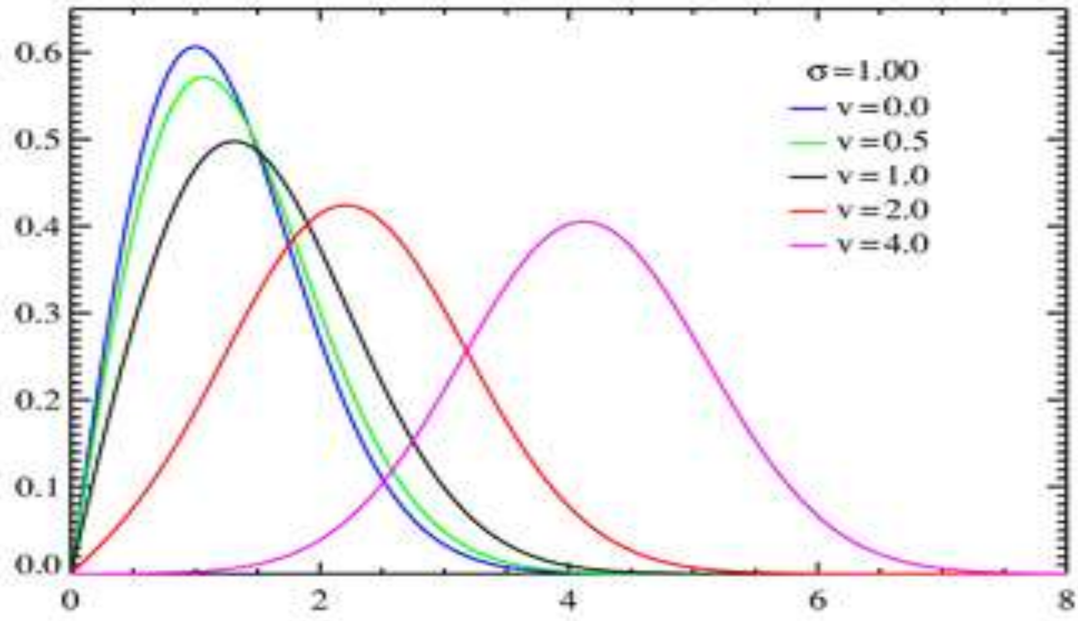

Fig. 3.4. Ricean fading distribution [4].

3.4.1. Time Dispersive Parameters

Time dispersive parameters of a multipath channel include the following three parameters

1. Mean Excess Delay
2. RMS Delay Spread
3. Excess Delay Spread

All three parameters mentioned above can be defined by using the power delay profile. The mean excess delay is the first moment of power delay profile and gives as

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\, \tau_k}{\sum_k P(\tau_k)} \tag{3.13}$$

where a_k is the amplitude of k^{th} multipath and a_k^2 represents the power associated with the k^{th} multipath.

The root mean square (RMS) delay spread is the second moment of power delay profile and given as

$$\sigma_\tau = \sqrt{\overline{\tau^2} - \bar{\tau}^2} \tag{3.14}$$

$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\, \tau_k^2}{\sum_k P(\tau_k)} \tag{3.15}$$

Both the delays discussed above are measured with respect to the first arriving signal at the receiver at $\tau_0 = 0$.

Excess delay spread (X dB) parameter of a multipath channel is defined as the time delay over which multipath signal energy falls X dB below the maximum arriving signal energy.

It is defined as

$$\text{excess delay spread (X dB)} = \tau_X - \tau_0 \tag{3.16}$$

where τ_0 represents the arrival time of maximum energy signal at the receiver side and τ_X is arrival time of signal whose energy is within the X dB of maximum energy signal.

3.4.2. Coherence Bandwidth

As discussed above that the time dispersive parameters are used to characterize the multipath propagation channel in time domain. In the frequency domain, coherence bandwidth is used to characterize the multipath channel.

Coherence bandwidth is defined as the range of frequencies over which the channel response remains same i.e., channel responds to each frequency component within the coherence bandwidth with same amplitude and also with linear phase response. Two signals at two different frequencies within the coherence bandwidth of the channel are assumed to highly correlated in amplitude. Coherence bandwidth of the channel is inversely related to RMS delay spread of the channel. If the frequency correlation function is above 0.9 then the coherence bandwidth is given as

$$B_c = \frac{1}{\sigma_\tau} \tag{3.17}$$

Now, if the frequency correlation function is above 0.5 then the coherence bandwidth is given as

$$B_c = \frac{1}{5\sigma_\tau} \tag{3.18}$$

3.4.3. Doppler Spread and Coherence Time

Doppler spread and coherence time parameters of the channel are used to define the time varying nature of the channel whereas the parameters discussed above give the time dispersive nature of the channel. Time varying nature of the channel is due to the relative motion between the mobile and the base station or due to the movements of the surrounding objects of mobile or base station.

Doppler spread B_D, is a measure of the broadening of the spectrum of the transmitted signal which is initially transmitted as a sinusoidal signal with a single frequency component f_c.

At the receiver side, the received signal will have frequency components within the range of f_c - f_d to f_c+f_d. Here, f_d is the Doppler shift and it is directly proportional to the relative motion between the base station and the mobile and also proportional to the angle of arrival of the received signal. Doppler shift is given as

$$f_d = \frac{v}{\lambda}\cos\theta \tag{3.19}$$

If the baseband signal bandwidth is greater than the Doppler spread B_D then the effect of Doppler spread is negligible i.e., slow fading channel.

Another parameter which is used to give the time varying nature of multipath channel is coherence time. Coherence time is inversely related to the Doppler spread and is given as

$$T_C = \frac{1}{f_m} \tag{3.20}$$

where f_m represents the maximum Doppler shift.

Coherence time is defined as the time interval over which the response of the channel remains invariant i.e., two signals are transmitted within the coherence time of the channel are highly correlated in amplitude.

3.5. Multipath Channel Types

Depending on the relation between the transmitted signal parameters (such as bandwidth and symbol duration) and the channel parameters (such as rms delay spread and Doppler spread), different transmitted signals undergo different types of fading i.e., relationship between the parameters of transmitted signal and of channel results into the different type of fading channels. These different fading channels are discussed below

3.5.1. Flat Fading Channel

If a multipath mobile radio channel has coherence bandwidth greater than the transmitted signal bandwidth then a multipath channel is known as a flat fading channel. In flat fading channel, channel responds to the transmitted signal with constant gain and linear phase over the entire signal bandwidth i.e., response of the channel is flat over the entire signal bandwidth. In flat fading channel, spectral characteristics of the transmitted signal are preserved at the receiver side, but the gain of channel can vary with time.

In a flat fading channel, multipath time delay spread is very small as compared to the time duration of the transmitted signal and flat fading channel can be assumed to have impulse response $h_b(t,\tau)$ with zero excess delay i.e., $\tau = 0$.

Flat fading channels are also known as amplitude varying channels and also known a narrowband channels, since the bandwidth of the transmitted signals is less the bandwidth of channel.

The amplitude distribution of flat fading channels is very important parameter in design of radio links. Most commonly used distribution is Rayleigh distribution i.e., instantaneous amplitude of the received signal will vary according to the Rayleigh distribution.

Mathematically, a signal will undergo flat fading if

$$B_S \ll B_C$$

and

$$\sigma_\tau \ll T_S$$

where B_S and B_C represents the signal bandwidth and the coherence bandwidth of the channel respectively. σ_τ and T_S represents the multipath delay spread of the channel and the signal duration of the transmitted signal respectively.

The characteristics of a flat fading channel are shown below in Fig. 3.5.

3.5.2. Frequency Selective Channel

In frequency selective channel, bandwidth over which channel has constant gain and linear phase response is less than the bandwidth of the transmitted signal i.e., in frequency selective channel, the reciprocal bandwidth of the transmitted signal is less than the multipath time delay spread of the channel. Thus frequency selective fading results in time dispersion of the transmitted signal within the channel and it results in inter symbol interference (ISI).

In case of frequency selective fading, each frequency component of the transmitted signal has different value of channel gain. Frequency selective channel is also known as wideband channel because the bandwidth of the transmitted signal is wider than the coherence bandwidth of the channel. Frequency selective channel is very difficult to model as compared to the flat fading channel and mathematically, a signal will undergo frequency selective fading if

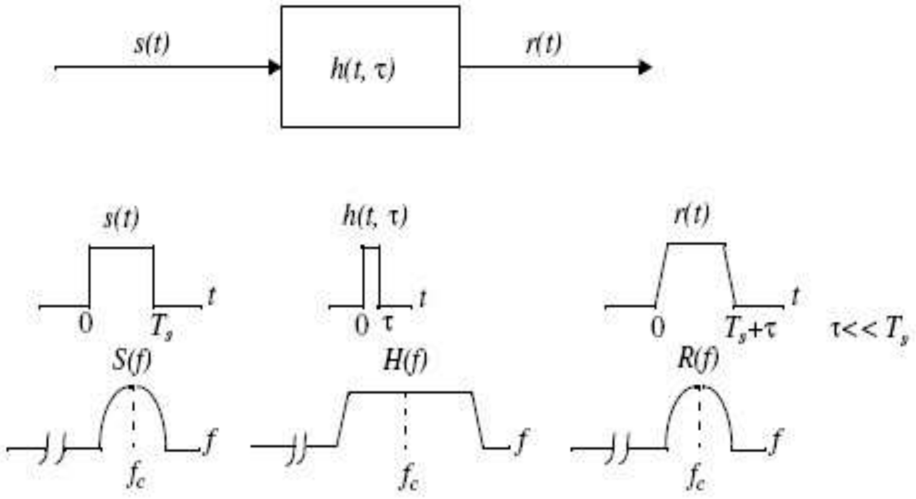

Fig. 3.5. Characteristics of flat fading channel [4].

$$B_S \gg B_C$$

and

$$\sigma_\tau \gg T_S$$

The characteristics of a frequency selective fading channel are given below in the Fig. 3.6.

Depending upon how the baseband signal varies as compared to the variations in the channel, a channel is classified as a fast fading channel or as a slow fading channel. Both types of channel are given below

3.5.3. Fast Fading Channel

In fast fading channel, variations in the channel within in the symbol duration are high i.e., the coherence time of the channel is smaller than the symbol duration and this causes the frequency spread due to the Doppler spread. Fast fading results in signal distortion and signal distortion increases with increase in Doppler spread.

When a channel is specified as a fast fading channel then it is not specified that whether a channel is frequency selective or flat fading. Fast fading only means that the channel variations are more as compared to the symbol or signal variations.

Mathematically, a signal will undergo fast fading if

$$T_C \ll T_S$$

and

$$B_S \ll B_D$$

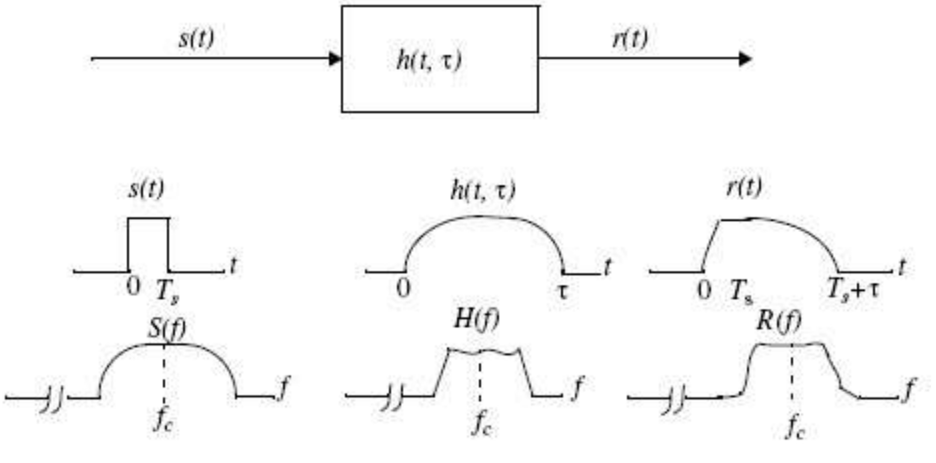

Fig. 3.6. Characteristics of frequency selective fading channel [4].

where T_C and T_S represents the coherence time and the symbol duration respectively. B_S and B_D represents the signal bandwidth and the Doppler spread of the channel respectively.

3.5.4. Slow Fading Channel

If the coherence time of the channel is greater than the symbol duration then a symbol will undergo slow fading and a channel is described as a slow fading channel. In slow fading, rate of change of channel is lower than that of transmitted symbol i.e., Doppler spread is lower than the transmitted symbol bandwidth.

Mathematically, a symbol will undergo slow fading if

$$T_C \gg T_S$$

and

$$B_S \gg B_D$$

In next section, we will discuss about different diversity techniques to overcome the effects of multipath fading.

3.6. Diversity Methods

To improve the performance of a communication system in the presence of multipath fading, different diversity methods are implemented [42]. Diversity methods can be applied at the transmitter side as well as at the receiver side. The objective of the diversity method is to generate the copies of the transmitted signal, which are differently responded by the multipath fading channel and then select the best available copy of the transmitted signal using different combining techniques.

Different types of diversity methods are given below

1. Frequency Diversity
2. Time Diversity
3. Polarization Diversity
4. Spatial Diversity

3.6.1. Frequency Diversity

In frequency diversity technique, a signal is transmitted at two different carrier frequencies which are separated from each other greater than the coherence bandwidth of the channel. When a signal is transmitted at two different carrier frequencies, it is going to be responded differently by the channel. Therefore, receiver has an option to select the best available copy of the transmitted signal.

3.6.2. Time Diversity

It is very much similar to the frequency diversity technique, but the difference is that in this technique, a signal is transmitted at same carrier frequency, but at two different time slots separated from each other greater than the coherence time of the channel. Coherence time of the channel is the time duration over which channel response remains constant. Therefore, when a signal is transmitted at two different time slots, both copies of the signal received at the receiver are uncorrelated to each other and best available copy is selected by the receiver.

3.6.3. Polarization Diversity

This technique of diversity is different from both the techniques discussed above. In this technique, a signal and its copy are transmitted using two different polarizations i.e., one is transmitted using horizontal polarization and other is using vertical polarization. Use of two different polarization techniques will give two uncorrelated signals at the receiver side i.e., channel response is different for both the signals and the receiver will select the best available signal.

3.6.4. Spatial Diversity

In spatial diversity [43] technique, multiple antennas are used at the receiver side to receive the multipath components of transmitted signal. Antenna spacing at the receiver side is such that the different multipath components of transmitted signal are independent from each other. By using the suitable combining technique, much improved version of the transmitted signal which will free from the effects of multipath fading is generated at the receiver output. As multiple antennas are separated from each other spatially therefore this technique is known as spatial diversity technique.

Similar technique can be applied at the transmitter side as receiver terminals are smaller in wireless communication as compared to the transmitter. So, it is much easier and cost efficient to use multiple antennas at the transmitter side. When multiple antennas are used at the transmitter side, it is known as transmitter diversity technique.

Chapter 4

SPACE-TIME BLOCK-CODING AND DESIGN CRITERION

In this chapter, we discuss about space-time block-coding (STBC) scheme, a transmitter diversity scheme to deal with the effects of multipath fading on wireless communication. Design criterion of STBC is also discussed in this chapter along with the first space-time block-code which is known as Alamouti code.

4.1. Space-Time Block-Coding

Space-time block-coding (STBC) [44] is a transmitter diversity scheme which employs multiple antennas at the transmitter side to transfer message symbols. In STBC scheme, transmitted symbols are encoded in both space and time domain. This diversity scheme is very much similar to the receiver diversity scheme in terms of performance in which multiple antennas are employed at the receiver side to obtain multiple independent copies of the transmitted symbol. But, the problem with receiver diversity scheme is that in wireless communication, receiver terminals are small in size and therefore it is not feasible to maintain enough spacing between the antennas to obtain independent paths.

STBC i.e., transmitter diversity scheme is much more feasible as compared to the receiver diversity scheme because of the size of the transmitters. Moreover, it is much more cost efficient to use multiple antennas at the transmitter side as each transmitter provides services to the large number of users.

As we discussed above that in the transmitter diversity scheme, there are multiple antennas at the transmitter side. But, the most important issue is the method to transmit symbols from the multiple antennas so that maximum diversity gain as well as maximum diversity order could be achieved for each of the transmitted symbol.

Space-time block-codes (STBC) provide a method to transmit symbols from multiple antennas with maximum achievable performance. A large number of space-time block-codes are developed for different number of antennas to transmit symbols. A block diagram of a wireless communication system using a space-time block-coder is given below in Fig. 4.1.

To design a space-time code, two most important design criterions [45] are given as

1. It should achieve full diversity.
2. Its decoding should be simple and fast.

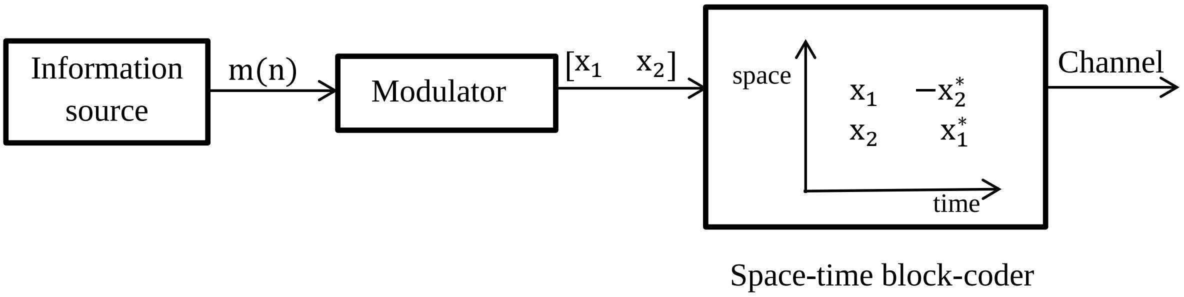

Fig. 4.1. A communication system with space-time block-coder.

First space-time block-code was given in 1998 by Alamouti [8], for two transmitter antennas and one receiver antenna. As its design is developed from orthogonal design criterion therefore it is known as an orthogonal space-time block-code (O-STBC). This new scheme achieves the same diversity order as that of maximum ratio receiver combining technique (MRRC) with simple linear decoding at the receiver side. This scheme is fundamental for all other space-time block-codes. As Alamouti scheme is only for two transmit antennas, so for more than two transmit antennas at the transmitter side, new space-time block-codes are developed which are briefly discussed below.

For more than two transmit antennas at the transmitter side, an O-STBC scheme was given by Tarokh [10]. It achieves full diversity order ,, but lacks in transmission rate i.e., for more than two transmit antennas, it is not possible to design an orthogonal space-time block-code for complex modulated signals which have full diversity order as well as full rate. To achieve rate one transmission, a new encoding scheme known as quasi-orthogonal space-time block-code (QO-STBC) was proposed was by Jafarkhani [13]. This scheme achieves rate one transmission with partial diversity order. But, due to non-orthogonal nature of encoding matrix, decoding complexity gets increases at the receiver side i.e., maximum-likelihood (ML) decoder has to work with a pair of transmitted symbols instead of a single symbol because of the presence of interference terms in the decoding matrix i.e., linear decoding could not be used.

To overcome the limitations of QO-STBC scheme proposed by Jafarkhani, a new QO-STBC scheme with Givens rotation (GR) and Eigen value decomposition (EVD) was proposed by Park [28] and Ping [35] respectively. Both these techniques are used to remove the interfering terms from the decoding matrix which results in linear decoding of QO-STBC scheme at the receiver side. Due to decrease in decoding complexity, new QO-

STBC schemes achieve better diversity gain and coding gain as compared to the conventional QO-STBC scheme.

In next section we will discuss the design criterion of space-time block-codes.

4.2. Design Criterion of Space – Time Block-Code

Let assume that we transmit a code word $\mathbf{C1}$. An error occurs if the decoder mistakenly decides that we have transmitted another code word $\mathbf{C2}$. The pair-wise error probability P($\mathbf{C1} \rightarrow \mathbf{C2}$) is an important measure of performance for the code. A good design criterion is to minimize the maximum pair-wise error probability.

Using the union bound, the probability of error when we transmit $\mathbf{C1}$ is upper bounded by

$$\text{P(error}|\ \mathbf{C1}\text{ is sent)} <= \sum_{2}^{I} \mathrm{P}(\mathbf{C1} \rightarrow \mathbf{C2}) \tag{4.1}$$

where I represents set of code words contain in the codebook.

The received signal vector is given as

$$\mathbf{R} = \mathbf{CH} + \mathbf{N} \tag{4.2}$$

$\mathbf{N}$, $\mathbf{M}$ and $\mathbf{T}$ are no. of transmit antennas, no. of receiver antennas and no. of time slots.

$\mathbf{R}$ = Received matrix (T×M) $\mathbf{C}$ = Code word matrix (T×N)

$\mathbf{H}$ = Channel matrix (N×M) $\mathbf{N}$ = noise matrix (T×M)

Also, here we assume a quasi-static channel i.e., path gains remain constant over a frame of length T.

Consider, distribution of received signals for known code word **C** and channel matrix **H** is given by

$$\mathrm{f}(\mathbf{R}|\ \mathbf{C}, \mathbf{H}) = \frac{1}{(\pi \mathrm{N}_0)^{\mathrm{T}\times\frac{\mathrm{M}}{2}}} \mathrm{e}^{-\frac{\{[(\mathbf{R}-\mathbf{CH})(\mathbf{R}-\mathbf{CH})^{\mathrm{H}}]\}}{\mathrm{N}_0}} \tag{4.3}$$

where N_0variance of noise sample.

Maximum likelihood decoding will decide in favor of a code word that maximizes the $\mathrm{f}(\mathbf{R}|\ \mathbf{C}, \mathbf{H})$.

Equivalently, ML decoding will find a code word $\mathbf{C}'$ that solves the following minimization given below

$$\mathbf{C}' = \arg_{\mathrm{c}} \min\{[\ (\mathbf{R} - \mathbf{CH})(\mathbf{R} - \mathbf{CH})^{\mathbf{H}}]\} \tag{4.4}$$

4.3. Alamouti Space-Time Block-Code

The Alamouti scheme [8] is historically the first STBC scheme to provide full diversity order for communication systems with two transmit antennas. This scheme provides the same diversity order as provided by MRRC with one transmit and two receiver antennas. This scheme can be generalized to any number of receiver antennas. Alamouti scheme uses two symbol period for transmission of two symbols. Encoding matrix for Alamouti scheme is given below

$$\mathbf{X} = \begin{bmatrix} s_0 & s_2 \\ -s_2^* & s_0^* \end{bmatrix} \tag{4.5}$$

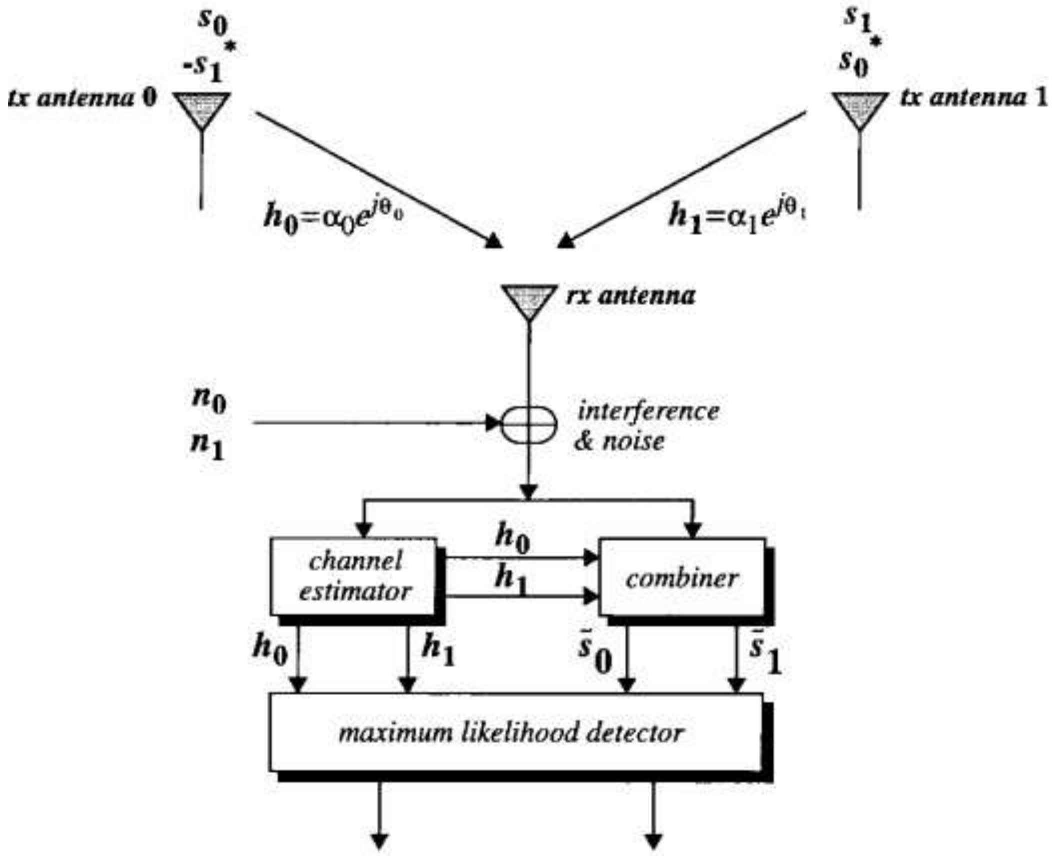

Fig. 4.2. Representation of Alamouti scheme [8].

Fading across two antennas is supposed to be constant over two symbol periods and for two transmit antenna, fading coefficients are given as

$$h_1(t) = h_1(t+T) = \alpha_1 e^{j\theta_1} \tag{4.6}$$

$$h_2(t) = h_2(t+T) = \alpha_2 e^{j\theta_2} \tag{4.7}$$

where T is the symbol duration, α_1 and α_2 represents the attenuation factors associated with their respective channels and θ_1, θ_2 represents the phase factors of their respective channels.

At the receiver side, received signal vector over two symbol durations is given as

$$\mathbf{R} = \mathbf{HX}+\mathbf{N} \tag{4.8}$$

where $\mathbf{H}$ is the channel matrix, $\mathbf{X}$ is the encoding matrix and $\mathbf{N}$ is the noise matrix of complex Gaussian noise coefficients of zero mean and unit variance.

$$\mathbf{R} = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix} \tag{4.9}$$

Now, transmitted symbols are detected as

$$\widehat{\mathbf{X}} = \begin{bmatrix} \widehat{s_0} \\ \widehat{s_1} \end{bmatrix} = \mathbf{H^H R} = \mathbf{H^H HX}+\mathbf{H^H N} \tag{4.10}$$

where

$$\widehat{s_0} = ({\alpha_1}^2+ {\alpha_2}^2)\, s_0+h_1^* n_1+h_2 n_2^*$$

$$\widehat{s_1} = ({\alpha_1}^2+ {\alpha_2}^2)\, s_1-h_1 n_2^*+h_2^* n_1$$

Detected signals are then send to the maximum likelihood detector, which work on the decision rule given as

$$d^2\,(\widehat{s_0}, s_i) \leq d^2\,(\widehat{s_0}\,, s_k) \quad , \quad \forall\ i \neq k \tag{4.11}$$

where $d^2(x, y)$ is the squared Euclidean distance given as

$$d^2(x, y) = (x-y)\,(x^*-y^*)$$

4.4. Important Terms of Space-Time Block-Codes

In this section, some important terms related to space-time block-codes are presented. These terms are

1. Diversity Order
2. Diversity Gain

4.4.1. Diversity Order

Diversity order [1] is one of the fundamental parameter of a wireless communication system employing diversity scheme. Diversity order of a wireless communication system is defined as the total number of independent paths over which a symbol or a signal will travel between the transmitter and the receiver i.e., number of paths that exist between the transmitter and the receiver.

Diversity order of a communication system should be as high as possible to minimize the error probability as it determines the slope of the curve which represents the probability of bit error with respect to signal-to noise ratio (SNR).

In case of transmitter diversity scheme, consider, at the transmitter side, we have N transmit antennas and L time slots. In this case, a transmitted code word will be given as

$$\mathrm{C} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1L} \\ c_{21} & c_{22} & \cdots & c_{2L} \\ \vdots & \vdots & \ddots & \vdots \\ c_{N1} & c_{N2} & \cdots & c_{NL} \end{bmatrix}_{N\times L} \tag{4.12}$$

Now, according to rank criterion or diversity criterion [45], rank of the code word difference matrix for any pair of transmitted signal matrices C and $\tilde{\mathrm{C}}$ should be as high as possible.

where $\tilde{\mathrm{C}}$ is given as

$$\tilde{\mathrm{C}} = \begin{bmatrix} \widetilde{c_{11}} & \widetilde{c_{12}} & \cdots & \widetilde{c_{1L}} \\ \widetilde{c_{21}} & \widetilde{c_{22}} & \cdots & \widetilde{c_{2L}} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{c_{N1}} & \widetilde{c_{N2}} & \cdots & \widetilde{c_{NL}} \end{bmatrix}_{N\times L} \tag{4.13}$$

and the code word difference matrix is given as

$$\Delta\mathrm{C} = \mathrm{C} - \tilde{\mathrm{C}} \tag{4.14}$$

Now, if the rank of the $\Delta\mathrm{C}$ is N and the number of receiver antennas at the receiver side is M then the diversity order of a communication system is $\mathrm{N}\times\mathrm{M}$.

4.4.2. Diversity Gain

In case of transmitter diversity scheme, at the receiver side, combination of multiple independent fading paths gives more favorable distribution of signal-to noise ratio (SNR). This favorable distribution of SNR leads to decrease in average bit error rate. This decrease in average bit error rate is known as diversity gain of the system. Mathematically, average bit error rate is given as

$$\overline{P_e}\,(\gamma) = \int_0^\infty P_e(\gamma)\; p(\gamma)\; d\gamma \tag{4.15}$$

Chapter 5

ANALYSIS AND METHODOLOGY

In this chapter, we discuss quasi-orthogonal space-time block-coding (QO-STBC) schemes along with their complete mathematical analysis. This chapter also represents the analysis of Givens rotation quasi-orthogonal space-time block-code (GR-QO-STBC) and Eigen value decomposition quasi-orthogonal space-time block-code (EVD-QO-STBC) under imperfect CSI at the receiver side.

5.1. Conventional Quasi-Orthogonal Space-Time Block-Code (C-QO-STBC)

Conventional QO-STBC is the first quasi-orthogonal space-time block-coding scheme designed to achieve rate one transmission for four and three transmission antenna systems. This is given by Jafarkhani in [13]. As we mentioned above that this scheme is for both three and four transmission antenna systems. So, first we describe this method for four transmission antenna system and then for three transmission antenna system as it is easy to derive 3×1 system from 4×1 system.

Consider a 4×1 system and its encoding matrix is given as

$$\mathbf{X_4} = \begin{bmatrix} \mathbf{X_{12}} & \mathbf{X_{34}} \\ \mathbf{X_{34}} & \mathbf{X_{12}} \end{bmatrix} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ x_3 & x_4 & x_1 & x_2 \\ -x_4^* & x_3^* & -x_2^* & x_1^* \end{bmatrix} \tag{5.1}$$

Channel is supposed to be quasi-static Rayleigh flat fading i.e., channel remains constant during the transmission of four symbols. In four time slots, four different symbols are transmitted from the transmitter side and received symbols are given as

$$\mathbf{R} = \mathbf{H_4}\mathbf{X} + \mathbf{N} \tag{5.2}$$

where $\mathbf{R}$ is the vector of received symbols during four time slots, $\mathbf{H_4}$ is the channel matrix of Rayleigh flat fading coefficients, $\mathbf{X}$ is the vector of transmitted symbols and $\mathbf{N}$ is the noise matrix of complex Gaussian coefficients with zero mean and unit variance.

Now, equation (5.2) can be written as

$$\mathbf{R} = [r_1 \quad r_2^* \quad r_3 \quad r_4^*] = \mathbf{H_4} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \\ n_3 \\ n_4^* \end{bmatrix} \tag{5.3}$$

where r_i is the symbol received during i^{th} time slot, x_i is the symbol transmitted during i^{th} time slot and similarly, n_i is the additive noise coefficient during i^{th} time slot. For four transmit antennas, channel matrix $\mathbf{H_4}$ is given below

$$\mathbf{H_4} = \begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ h_2^* & -h_1^* & h_4^* & -h_3^* \\ h_3 & h_4 & h_1 & h_2 \\ h_4^* & -h_3^* & h_2^* & -h_1^* \end{bmatrix} \tag{5.4}$$

where h_i is the Rayleigh channel coefficient between the i^{th} transmitting antenna and receiving antenna.

Transmitted symbols are decoded using a detection matrix $\mathbf{D} = \mathbf{H_4}^{\mathbf{H}}\mathbf{H_4}$. In case of an orthogonal space-time block-coding scheme (O-STBC), detection matrix is diagonal in characteristics. Therefore, it is possible to use linear decoding to decode the transmitted symbols. But, in case of C-QO-STBC scheme, detection matrix is not diagonal and it is given as

$$\mathbf{D_4} = \mathbf{H_4}^{\mathbf{H}}\mathbf{H_4} = \begin{bmatrix} \alpha & 0 & \beta & 0 \\ 0 & \alpha & 0 & \beta \\ \beta & 0 & \alpha & 0 \\ 0 & \beta & 0 & \alpha \end{bmatrix} \tag{5.5}$$

α is the diagonal element and it represents the sum of individual channel gains and β represents the interference terms from adjacent symbols. Mathematically, both α and β are given as

$$\alpha = \sum_{i=0}^{4} |h_i|^2 \tag{5.6}$$

$$\beta = h_1 h_3^* + h_2 h_4^* + h_3 h_1^* + h_4 h_2^* \tag{5.7}$$

Now, because of the presence of interference terms β in the detection matrix, more complicated decoding method known as pseudo inverse method is used at the receiver side to decode the transmitted symbols and the method is given below

$$\begin{aligned} \widehat{\mathbf{X}} &= (\mathbf{H_4}\,\mathbf{H_4^H})^{-1}\mathbf{H_4^H}\mathbf{R} \\ &= (\mathbf{H_4}\,\mathbf{H_4^H})^{-1}\mathbf{H_4^H}\,\mathbf{H_4}\,\mathbf{X} + (\mathbf{H_4}\,\mathbf{H_4^H})^{-1}\mathbf{H_4^H}\,\mathbf{N} \end{aligned} \tag{5.8}$$

where $\widehat{\mathbf{X}}$ is the vector of decoded transmitted symbols. $\mathbf{H_4}$, $\mathbf{X}$ and $\mathbf{N}$ are same as defined above in equation (5.2).

For 3×1 antenna systems, equations (5.2), (5.3), (5.5) and (5.8) will remain same except the encoding, detection and channel matrices, which are given below

$$\mathbf{X_3} = \begin{bmatrix} x_1 & x_2 & x_3 \\ -x_2^* & x_1^* & -x_4^* \\ x_3 & x_4 & x_1 \\ -x_4^* & x_3^* & -x_2^* \end{bmatrix} \tag{5.9}$$

$$\mathbf{H_3} = \begin{bmatrix} h_1 & h_2 & h_3 & 0 \\ h_2^* & -h_1^* & 0 & -h_3^* \\ h_3 & 0 & h_1 & h_2 \\ 0 & -h_3^* & h_2^* & -h_1^* \end{bmatrix} \tag{5.10}$$

$$\mathbf{D_3} = \mathbf{H_3^H H_3} = \begin{bmatrix} \alpha & 0 & \gamma & 0 \\ 0 & \alpha & 0 & \gamma \\ \gamma & 0 & \alpha & 0 \\ 0 & \gamma & 0 & \alpha \end{bmatrix} \tag{5.11}$$

where $\mathbf{X_3}$, $\mathbf{H_3}$ and $\mathbf{D_3}$ are encoding, channel and detection matrices for 3×1 antenna systems respectively.

In equation (5.11), α represents the sum of channel gains and γ denotes the interference due to the presence of adjacent symbols.

$$\alpha = \sum_{i=1}^{3} |h_i|^2 \tag{5.12}$$

$$\gamma = h_1 h_3^* + h_3 h_1^* \tag{5.13}$$

As shown above that the presence of interference terms in the detection matrix results in more complex decoding method which results in performance degradation of C-QO-STBC scheme.

In next section, a new QO-STBC technique is discussed with new channel matrix which gives a detection matrix with no interference terms.

5.2. Givens Rotation Quasi-Orthogonal Space-Time Block-Code (GR-QO-STBC)

A new QO-STBC scheme with new channel matrix is given by Park in [28]. This new QO-STBC scheme is named as GR-QO-STBC scheme. In this scheme, Givens rotation manipulation is used on the detection matrix of C-QO-STBC scheme to remove the interference terms. Givens rotation is a method of matrix manipulation in which plane of the detection matrix is rotated to eliminate the interference terms.

First we consider the detection matrix of 4×1 antenna systems given in equation (5.5). Interference terms β are eliminated by using two steps in succession. In this method, two rotation matrices are defined and named as $\mathbf{R_1}$ and $\mathbf{R_2}$. $\mathbf{R_1}$ is used to exclude the interference terms from the detection matrix $\mathbf{D_4}$ present at $d_{13}$and d_{31}. Similarly, $\mathbf{R_2}$ is used to remove the interference terms from d_{24} and d_{42} locations in the detection matrix $\mathbf{D_4}$. Rotation matrix $\mathbf{R_1}$ is given below

$$\mathbf{R_1} = \begin{bmatrix} \cos(\frac{\pi}{4}) & 0 & \sin(\frac{\pi}{4}) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\frac{\pi}{4}) & 0 & \cos(\frac{\pi}{4}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.14}$$

and similarly, $\mathbf{R_2}$ is given as

$$\mathbf{R_2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\frac{\pi}{4}) & 0 & \sin(\frac{\pi}{4}) \\ 0 & 0 & 1 & 0 \\ 0 & -\sin(\frac{\pi}{4}) & 0 & \cos(\frac{\pi}{4}) \end{bmatrix} \tag{5.15}$$

By applying $\mathbf{R_1}$ and $\mathbf{R_2}$ in succession on the detection matrix $\mathbf{D_4}$, a new detection matrix $\mathbf{D_{n4}}$ is derived and it is given as

$$\mathbf{D_{n4}} = \mathbf{R_2^T}\ \mathbf{R_1^T}\ \mathbf{D_4}\ \mathbf{R_1}\ \mathbf{R_2} \tag{5.16}$$

$$\mathbf{D_{n4}} = \begin{bmatrix} \alpha-\beta & 0 & 0 & 0 \\ 0 & \alpha-\beta & 0 & 0 \\ 0 & 0 & \alpha+\beta & 0 \\ 0 & 0 & 0 & \alpha+\beta \end{bmatrix} \tag{5.17}$$

A new channel matrix can be derived from the new detection matrix by using following equations

$$\begin{aligned} \mathbf{D_{n4}} &= \mathbf{R_2^T}\ (\ \mathbf{R_1^T}\ \mathbf{D_4}\ \mathbf{R_1}\ )\ \mathbf{R_2} \\ &= \mathbf{R_2^T}\ (\ \mathbf{R_1^T}\ \mathbf{H_4^H}\ \mathbf{H_4}\ \mathbf{R_1}\ )\ \mathbf{R_2} \\ &= (\ \mathbf{R_2^T}\ \mathbf{R_1^T}\ )\ \mathbf{H_4^H}\ \mathbf{H_4}\ (\ \mathbf{R_1}\ \mathbf{R_2}) \\ &= (\ \mathbf{H_4}\ \mathbf{R_1}\ \mathbf{R_2}\ )^{\mathbf{H}}\ (\ \mathbf{H_4}\ \mathbf{R_1}\ \mathbf{R_2}\ ) \end{aligned} \tag{5.18}$$

From equation (5.17), a new channel matrix is given as

$$\mathbf{H_{n4}} = \mathbf{H_4}\ \mathbf{R_1}\ \mathbf{R_2} \tag{5.19}$$

$$\mathbf{H_{n4}} = \begin{bmatrix} h_1-h_3 & h_2-h_4 & h_1+h_3 & h_2+h_4 \\ h_2^*-h_4^* & h_3^*-h_1^* & h_2^*+h_4^* & -h_1^*-h_3^* \\ h_3-h_1 & h_4-h_2 & h_1+h_3 & h_2+h_4 \\ h_4^*-h_2^* & h_1^*-h_3^* & h_2^*+h_4^* & -h_1^*-h_3^* \end{bmatrix} \tag{5.20}$$

From equation (5.17) and (5.18), it is quite clear that new channel matrix $\mathbf{H_{n4}}$ is orthogonal in characteristic as there are no interference terms present in the detection matrix $\mathbf{D_{n4}}$. Therefore, it leads to simple linear decoding of transmitted symbols at the receiver side i.e., maximum likelihood decoder (ML) works with a single symbol at a time instead of a pair of transmitted symbols.

A new encoding matrix related to the new channel matrix $\mathbf{H_{n4}}$ can be derived by using the relationship between them as given in equation (5.3). By using equation (5.3), a new encoding matrix is given as

$$\mathbf{X_{n4}} = \begin{bmatrix} x_1 + x_3 & x_2 + x_4 & x_3 - x_1 & x_4 - x_2 \\ -x_2^* - x_4^* & x_1^* + x_3^* & x_2^* - x_4^* & x_3^* - x_1^* \\ x_3 - x_1 & x_4 - x_2 & x_1 + x_3 & x_2 + x_4 \\ x_2^* - x_4^* & x_3^* - x_1^* & -x_2^* - x_4^* & x_1^* + x_3^* \end{bmatrix} \tag{5.21}$$

New channel matrix $\mathbf{H_{n4}}$ is orthogonal in characteristics. Therefore, transmitted symbols are decoded as mentioned below

$$\mathbf{R} = \mathbf{H_{n4}X} + \mathbf{N} \tag{5.22}$$

$$\hat{\mathbf{X}} = \mathbf{H_{n4}^{H}}\,\mathbf{R} = \mathbf{H_{n4}^{H}}\,\mathbf{H_{n4}X} + \mathbf{H_{n4}^{H}}\,\mathbf{N} \tag{5.23}$$

Equation (5.23) is known as a simple linear decoding scheme and it is only possible because of orthogonal characteristics of new channel matrix $\mathbf{H_{n4}}$. Therefore, GR-QO-STBC scheme has better performance as compared to the C-QO-STBC scheme discussed earlier. It is because of the simplicity of the decoding process used in GR-QO-STBC scheme.

Now, for 3×1 antenna systems, implementation of equations (5.14), (5.15) and (5.16) will remain same, but it results in new channel and encoding matrices. Both the matrices are given below

$$\mathbf{H_{n3}} = \mathbf{H_3}\,\mathbf{R_1}\,\mathbf{R_2} \tag{5.24}$$

$$\mathbf{H_{n3}} = \begin{bmatrix} h_1 - h_3 & h_2 & h_1 + h_3 & h_2 \\ h_2^* & h_3^* - h_1^* & h_2^* & -h_1^* - h_3^* \\ h_3 - h_1 & -h_2 & h_1 + h_3 & h_2 \\ -h_2^* & h_1^* - h_3^* & h_2^* & -h_1^* - h_3^* \end{bmatrix} \tag{5.25}$$

$$\mathbf{X_{n3}} = \begin{bmatrix} x_1 + x_3 & x_2 + x_4 & x_3 - x_1 \\ -x_2^* - x_4^* & x_1^* + x_3^* & x_2^* - x_4^* \\ x_3 - x_1 & x_4 - x_2 & x_1 + x_3 \\ x_2^* - x_4^* & x_3^* - x_1^* & -x_2^* - x_4^* \end{bmatrix} \tag{5.26}$$

where $\mathbf{H_{n3}}$ is the new channel matrix and $\mathbf{X_{n3}}$ is the new encoding matrix for 3×1 antenna systems.

In next section, a QO-STBC based on the Eigen value decomposition method will be discussed.

5.3. Eigen Value Decomposition Quasi-Orthogonal Space-Time Block-Code (EVD-QO-STBC)

A new QO-STBC scheme based on the Eigen value decomposition method is given by Ping in [35]. Eigen value decomposition method is used to eliminate the interference terms from the detection matrix of conventional QO-STBC scheme. Similar to the QO-STBC scheme discussed above, this scheme is also for four and three transmit antenna systems.

Consider a 4×1 communication system and the detection matrix for four antenna systems is given by equation (5.5).

$$\mathbf{D_4} = \mathbf{H_4}^{\mathbf{H}}\mathbf{H_4} = \begin{bmatrix} \alpha & 0 & \beta & 0 \\ 0 & \alpha & 0 & \beta \\ \beta & 0 & \alpha & 0 \\ 0 & \beta & 0 & \alpha \end{bmatrix} \tag{5.27}$$

where α signifies channel gain and β gives the interference terms from neighboring antennas.

$$\alpha = \sum_{i=0}^{4} |h_i|^2$$

$$\beta = 2\,\mathrm{Re}\,[\mathrm{h_1 h_3^* + h_2 h_4^*}]$$

Because of the presence of interference terms β in the detection matrix, it is not suitable to use maximum likelihood decoding (ML) technique to detect the transmitted symbols. Due to the presence of interference terms, ML decoder has to work with a pair of transmitted symbols which results in increased bit error rate (BER).

The maximum likelihood matrix is given as

$$\widehat{\mathbf{X}} = \arg\{\min(\|\ \mathbf{R} - \mathbf{XH}\ \|)\} \tag{5.28}$$

where ||*|| denotes the Euclidean norm and arg{ } denotes the solution satisfying the conditions. To remove the interference terms present in the detection matrix $\mathbf{D_4}$, EVD manipulation is apply to the $\mathbf{D_4}$ as given below

$$\mathbf{D_4} = \mathbf{U_4}\ \mathbf{D_{n4}}\ \mathbf{U_4^{-1}} \tag{5.29}$$

where $\mathbf{U_4}$ is 4×4 eigen matrix consist of eigenvectors of $\mathbf{D_4}$ and $\mathbf{D_{n4}}$ is 4×4 matrix of eigen values of $\mathbf{D_4}$.

By using the theory of matrix analysis, eigen matrix $\mathbf{U_4}$ is given as

$$\mathbf{U_4} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \tag{5.30}$$

From equation (5.29), a new detection matrix independent from the interference terms β is given as

$$\mathbf{D_{n4}} = \mathbf{U_4^{-1}}\ \mathbf{D_4}\ \mathbf{U_4} \tag{5.31}$$

$$= \begin{bmatrix} \alpha+\beta & 0 & 0 & 0 \\ 0 & \alpha+\beta & 0 & 0 \\ 0 & 0 & \alpha-\beta & 0 \\ 0 & 0 & 0 & \alpha-\beta \end{bmatrix} \tag{5.32}$$

From equation (5.31), a new channel matrix is derived which is given below

$$\begin{aligned} \mathbf{D_{n4}} &= \mathbf{U_4^{-1}}\ \mathbf{D_4}\ \mathbf{U_4} \\ &= \mathbf{U_4^H}\ \mathbf{H_4^H}\ \mathbf{H_4}\ \mathbf{U_4} \\ &= (\mathbf{H_4 U_4})^{\mathbf{H}}\ (\mathbf{H_4 U_4}) \end{aligned} \tag{5.33}$$

A new channel matrix is now defined as

$$\mathbf{H_{n4}} = \mathbf{H_4 U_4} \tag{5.34}$$

$$= \begin{bmatrix} \mathbf{G_1} & \mathbf{W_1} \\ \mathbf{C_1} & \mathbf{K_1} \end{bmatrix} \tag{5.35}$$

where

$$\mathbf{G_1} = \begin{bmatrix} h_1 + h_2 + h_3 + h_4 & h_1 - h_2 + h_3 - h_4 \\ h_2^* - h_1^* + h_4^* - h_3^* & h_2^* + h_1^* + h_4^* + h_3^* \end{bmatrix}$$

$$\mathbf{W_1} = \begin{bmatrix} h_1 + h_2 - h_3 - h_4 & h_1 - h_2 - h_3 + h_4 \\ h_2^* - h_1^* - h_4^* + h_3^* & h_2^* + h_1^* - h_4^* - h_3^* \end{bmatrix}$$

$$\mathbf{C_1} = \begin{bmatrix} h_1 + h_2 + h_3 + h_4 & h_1 - h_2 + h_3 - h_4 \\ h_2^* - h_1^* + h_4^* - h_3^* & h_2^* + h_1^* + h_4^* + h_3^* \end{bmatrix}$$

$$\mathbf{K_1} = \begin{bmatrix} -h_1 - h_2 + h_3 + h_4 & -h_1 + h_2 + h_3 - h_4 \\ -h_2^* + h_1^* + h_4^* - h_3^* & -h_2^* - h_1^* + h_4^* + h_3^* \end{bmatrix}$$

From equation (5.32), new detection matrix $\mathbf{D_{n4}}$ is completely diagonal in characteristics. Therefore, new channel matrix $\mathbf{H_{n4}}$ is orthogonal in characteristics. A new encoding matrix $\mathbf{X_{n4}}$ is derived from the new channel matrix $\mathbf{H_{n4}}$ by using the relation between them as given in equation (5.3).

A new encoding matrix $\mathbf{X_{n4}}$ is

$$\mathbf{X_{n4}} = \begin{bmatrix} \mathbf{E_1} & \mathbf{F_1} \\ \mathbf{F_1} & \mathbf{E_1} \end{bmatrix} \tag{5.36}$$

where

$$\mathbf{E_1} = \begin{bmatrix} x_1 + x_2 + x_3 + x_4 & x_1 + x_3 - x_2 - x_4 \\ -x_1^* + x_2^* - x_3^* + x_4^* & x_1^* + x_2^* + x_3^* + x_4^* \end{bmatrix}$$

$$\mathbf{F_1} = \begin{bmatrix} x_1 + x_2 - x_3 - x_4 & x_1 - x_3 - x_2 + x_4 \\ -x_1^* + x_2^* + x_3^* - x_4^* & x_1^* + x_2^* - x_3^* - x_4^* \end{bmatrix}$$

Orthogonal characteristics of the new channel matrix $\mathbf{H_{n4}}$ allow the use of simple linear decoding at the receiver side to estimate the transmitted symbols. Transmitted symbols are estimated as

$$\mathbf{R} = \mathbf{H_{n4}X} + \mathbf{N}$$

$$\mathbf{\widehat{X}} = \mathbf{H_{n4}^H}\,\mathbf{R} = \mathbf{H_{n4}^H}\,\mathbf{H_{n4}X} + \mathbf{H_{n4}^H}\,\mathbf{N} \tag{5.37}$$

where

$\mathbf{R} = [r_1 \quad r_2^* \quad r_3 \quad r_4^*]^T$, $\mathbf{X} = [x_1 \quad x_2 \quad x_3 \quad x_4]^T$ and $\mathbf{N} = [n_1 \quad n_2^* \quad n_3 \quad n_4^*]^T$

r_i and x_i are the symbols received and transmitted at i^{th} time slot respectively. n_i is the additive Gaussian noise coefficient added to the received symbol at time t = i.

For 3×1 antenna systems, method of equations (5.29), (5.30), (5.31), (5.32) and (5.33) will remain same and it results in new channel and encoding matrices for three antenna systems.

$$\mathbf{H_{n3}} = \mathbf{H_3 U_3}$$

$$= \begin{bmatrix} \mathbf{G_2} & \mathbf{W_2} \\ \mathbf{C_2} & \mathbf{K_2} \end{bmatrix} \tag{5.38}$$

where

$$\mathbf{G_2} = \begin{bmatrix} h_1 + h_2 + h_3 & h_1 - h_2 + h_3 \\ h_2^* - h_1^* - h_3^* & h_2^* + h_1^* + h_3^* \end{bmatrix}$$

$$\mathbf{W_2} = \begin{bmatrix} h_1 + h_2 - h_3 & h_1 - h_2 - h_3 \\ h_2^* - h_1^* + h_3^* & h_2^* + h_1^* - h_3^* \end{bmatrix}$$

$$\mathbf{C_2} = \begin{bmatrix} h_1 + h_2 + h_3 & h_1 - h_2 + h_3 \\ h_2^* - h_1^* - h_3^* & h_2^* + h_1^* + h_3^* \end{bmatrix}$$

$$\mathbf{K_2} = \begin{bmatrix} -h_1 - h_2 + h_3 & -h_1 + h_2 + h_3 \\ -h_2^* + h_1^* - h_3^* & -h_2^* - h_1^* + h_3^* \end{bmatrix}$$

and

$$\mathbf{X_{n3}} = \begin{bmatrix} \mathbf{E_2} & \mathbf{F_2} \\ \mathbf{F_2} & \mathbf{E_2} \end{bmatrix} \tag{5.39}$$

where

$$\mathbf{E_2} = \begin{bmatrix} x_1 + x_2 + x_3 + x_4 \\ -x_1^* + x_2^* - x_3^* + x_4^* \end{bmatrix}$$

$$\mathbf{F_2} = \begin{bmatrix} x_1 + x_2 - x_3 - x_4 \\ -x_1^* + x_2^* + x_3^* - x_4^* \end{bmatrix}$$

$\mathbf{H_{n3}}$ and $\mathbf{X_{n3}}$ are the new channel matrix and the new encoding matrix for three antenna systems respectively.

5.4. Analysis of GR-QO-STBC and EVD-QO-STBC Schemes under Imperfect Channel State Information (CSI) Condition

In section 5.2 and 5.3, we have discussed GR-QO-STBC and EVD-QO-STBC schemes with their complete mathematical analysis. Analysis of both QO-STBC schemes has been done under the condition that the receiver has perfect knowledge of channel state information (CSI). But, in wireless communication scenarios, it is impossible to get the perfect knowledge of channel state information. So, it is useful to analyze the performance of wireless communication systems assuming the condition that channel is not perfectly known at the receiver as it is done in [29], [31] and [46].

In this section, we analyze the performance of linear decoder for GR-QO-STBC and EVD-QO-STBC schemes under imperfect channel state information condition i.e., channel estimator at the receiver side estimate the channel with some errors. Channel estimation errors will certainly going to have some impact on the BER performance of both QO-STBC schemes.

First of all, consider the linear decoder for both QO-STBC schemes under the condition of perfect channel state information at the receiver side.

From equations (5.23) and (5.37), linear decoder for both QO-STBC schemes is given as

$$\mathbf{R} = \mathbf{H_n}\,\mathbf{X} + \mathbf{N} \tag{5.40}$$

$$\hat{\mathbf{X}} = \mathbf{H_n^H}\,\mathbf{R} = \mathbf{H_n^H}\mathbf{H_n}\,\mathbf{X} + \mathbf{H_n^H}\,\mathbf{N} \tag{5.41}$$

where $\mathbf{H_n}$ is the new channel matrix for GR-QO-STBC and EVD-QO-STBC schemes from equations (5.20), (5.25), (5.35) and (5.38) respectively, $\hat{\mathbf{X}}$ is the vector of decoded symbols and both $\mathbf{X}$ and $\mathbf{N}$ are the vector of transmitted symbols and the vector of additive complex Gaussian noise coefficients respectively.

But, in case of imperfect channel state condition at the receiver side, receiver does not have perfect knowledge of CSI and the channel matrix which is used by the receiver to decode or to estimate the transmitted symbols is given as

$$\hat{\mathbf{H}}_\mathbf{n} = \mathbf{H_n} + \boldsymbol{\delta}\mathbf{h} \tag{5.42}$$

where $\hat{\mathbf{H}}_\mathbf{n}$ is the estimated channel matrix and from equation (5.42), it is given as sum of the original channel matrix $\mathbf{H_n}$ and the channel coefficient error matrix $\boldsymbol{\delta}\mathbf{h}$. $\boldsymbol{\delta}\mathbf{h}$ represents the errors made by channel estimator during the estimation of channel coefficients.

Each element of the channel coefficient error matrix $\boldsymbol{\delta}\mathbf{h}$ is complex Gaussian random variable with zero mean and unit variance as given below

$$\delta h_k = a_k + j b_k \tag{5.43}$$

So, under imperfect CSI condition, transmitted symbols are decoded using the channel matrix $\hat{\mathbf{H}}_\mathbf{n}$ and simple linear decoding will be given as

$$\hat{\mathbf{X}} = \hat{\mathbf{H}}_\mathbf{n}^\mathbf{H}\,\mathbf{R} = \hat{\mathbf{H}}_\mathbf{n}^\mathbf{H}\,\mathbf{H_n}\,\mathbf{X} + \hat{\mathbf{H}}_\mathbf{n}^\mathbf{H}\,\mathbf{N} \tag{5.44}$$

$$\begin{aligned} &= (\mathbf{H_n} + \boldsymbol{\delta}\mathbf{h})^\mathbf{H}\mathbf{H_n}\,\mathbf{X} + (\mathbf{H_n} + \boldsymbol{\delta}\mathbf{h})^\mathbf{H}\,\mathbf{N} \\ &= \mathbf{H_n^H}\,\mathbf{H_n}\,\mathbf{X} + \boldsymbol{\delta}\mathbf{h}^\mathbf{H}\,\mathbf{H_n}\,\mathbf{X} + \mathbf{H_n^H}\,\mathbf{N} + \boldsymbol{\delta}\mathbf{h}^\mathbf{H}\,\mathbf{N} \\ &= \mathbf{H_n^H}\,\mathbf{H_n}\,\mathbf{X} + \mathbf{H_n^H}\,\mathbf{N} + (\mathbf{H_n}\,\mathbf{X} + \mathbf{N})\,\boldsymbol{\delta}\mathbf{h}^\mathbf{H} \end{aligned} \tag{5.45}$$

From equation (5.45), it is quite clear that during the detection of transmitted symbols under imperfect channel condition, channel coefficient error matrix $\boldsymbol{\delta}\mathbf{h}$ acts as an additive noise along with AWGN noise. This will surely disturb the performance of linear decoder for both QO-STBC schemes in terms of BER.

Simulation results for both QO-STBC schemes under equation (5.45) will be given in chapter 6.

5.5. Multi Input Multi Output (MIMO) Extension of GR-QO-STBC and EVD-QO-STBC Schemes

From section 5.2 to 5.4, we discussed about GR-QO-STBC and EVD-QO-STBC schemes for multi input single output communication systems (MISO). In this section, we discuss about the implementation of both QO-STBC schemes over multi input multi output communication systems (MIMO). Usage of MIMO systems has boosted the performance of wireless communication systems as discussed in [47]. There are several advantages of using MIMO systems for communication purpose, such as improvement in bit error rate, improvement in capacity and spectral efficiency without any increase in bandwidth and transmitted power.

MIMO systems are generally categorized into three different classes [44] as given below

1. Beam Forming
2. Spatial Multiplexing
3. Spatial Diversity

In Beam forming, depending on the disparity in surroundings and position of the receiver, beam width and size is varied i.e., smart antenna concept is used in Beam forming technique.

In Spatial multiplexing technique, a group of data symbols is converted into N number of subgroups and these subgroups are transmitted from N different antennas. At receiver side, different transmitted symbols are combined using one of the linear combining techniques [48].

In Spatial diversity, N copies of each of the transmitted symbol are generated (where N is the number of transmitting antennas) and transmitted from each antenna in such a way that the severe effects of fading get neutralized. Such schemes are also known as space-time coding techniques as we discussed in chapter 4.

Mathematically, implementation of GR-QO-STBC and EVD-QO-STBC schemes over MIMO systems is given as

Suppose there are N_R receiver antennas at the receiver side and the received signal at the receiver side can be given as

$$\bar{\mathbf{R}} = \bar{\mathbf{H}}\mathbf{X}+\bar{\mathbf{N}} \tag{5.46}$$

where

$$\bar{\mathbf{R}} = \begin{bmatrix} \bar{\mathbf{r}}_1 \\ \bar{\mathbf{r}}_2 \\ \bar{\mathbf{r}}_3 \\ \cdot \\ \cdot \\ \cdot \\ \overline{\mathbf{r}_{N_R}} \end{bmatrix}, \ \bar{\mathbf{r}}_p = \begin{bmatrix} r_{1p} \\ r_{2p} \\ r_{3p} \\ r_{4p} \end{bmatrix}, \ p = 1, 2, \ldots, N_R$$

r_{ip} represents the signal received at p^{th} antenna at i^{th} time slot and i = 1,2,3,4.

$\bar{\mathbf{H}}$ and $\bar{\mathbf{N}}$ represents the channel and noise matrices respectively and both are given as

$$\bar{\mathbf{H}} = \begin{bmatrix} \mathbf{H}_1 \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{H}_{N_R} \end{bmatrix}, \ p = 1,2,\ldots\ldots., N_R$$

$$\bar{\mathbf{N}} = \begin{bmatrix} \mathbf{N}_1 \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{N}_{N_R} \end{bmatrix}, \ p = 1,2,\ldots\ldots., N_R \qquad (5.47)$$

where $\mathbf{H}_p$ represents the channel matrix between the p^{th} receiver antenna and all the transmit antennas. The channel matrix $\mathbf{H}_p$ for GR-QO-STBC scheme is given in equations (5.20) and (5.25) and in equations (5.35) and (5.38) for EVD-QO-STBC scheme. Similarly, $\mathbf{N}_p$ is a noise matrix between the p^{th} receiver antenna and all the transmit antennas and it consist of complex additive white Gaussian noise coefficients with zero mean and unit variance.

Simulation results for both QO-STBC schemes over MIMO systems are given in chapter 6 by using the equations (5.46) and (5.47).

Chapter 6

SIMULATION RESULTS

In this chapter, we provide the bit error rate (BER) performance of QO-STBC schemes discussed in chapter 5. Performance of each QO-STBC scheme has been evaluated using MATLAB simulations.

Fig. 6.1 represents the simulation results for C-QO-STBC, GR-QO-STBC and EVD-QO-STBC schemes. Simulations have been performed under the condition that the receiver has perfect knowledge of channel state information. Channel used is quasi-static Rayleigh flat fading channel i.e., channel remains identical for four symbol intervals. Modulation method used for the transmitted symbols is 4-PSK (QPSK). It is also assumed that the total transmitted power is divided equally between the transmitting antennas.

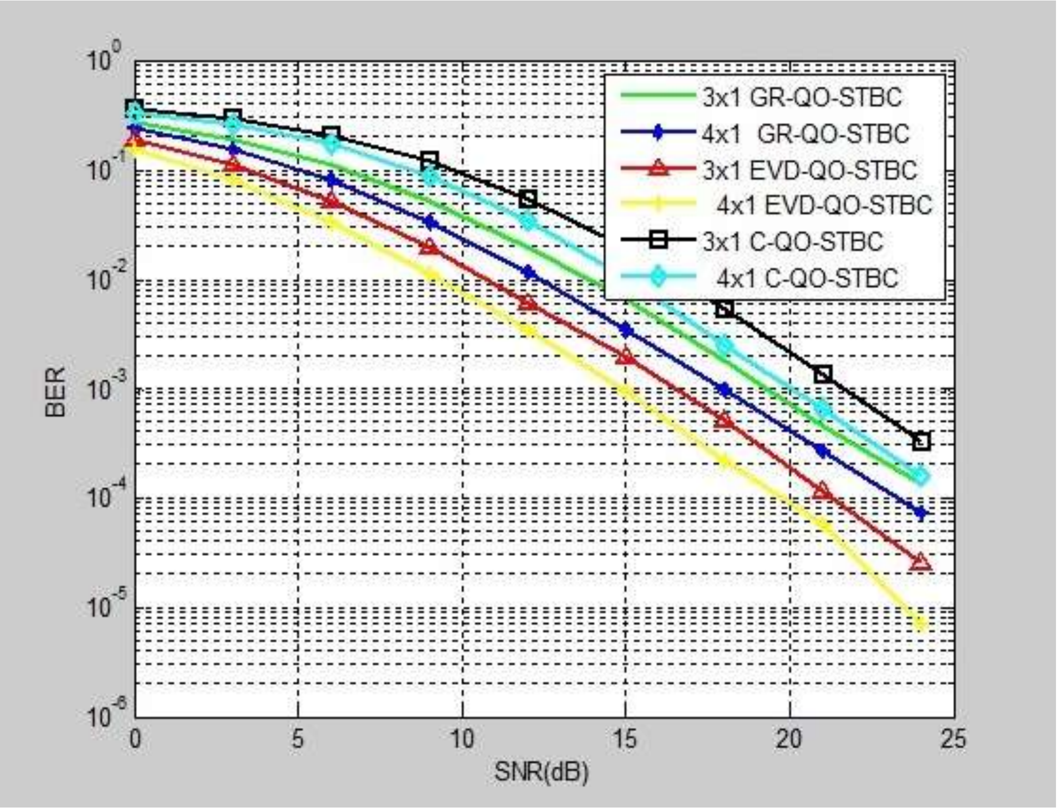

Fig. 6.1. BER performance of GR-QO-STBC and EVD-QO-STBC schemes for three and four transmit antennas under perfect CSI at the receiver.

Simulation results of GR-QO-STBC and EVD-QO-STBC schemes under the condition of imperfect CSI at the receiver side are given in Fig. 6.2. In this case, receiver has imperfect CSI i.e., channel estimator at the receiver side predicts the channel with some estimation errors. Performance of both QO-STBC schemes is analyzed by varying the channel estimation error in dB. Channel under consideration is quasi-static Rayleigh flat fading channel and modulation method used is 4-PSK.

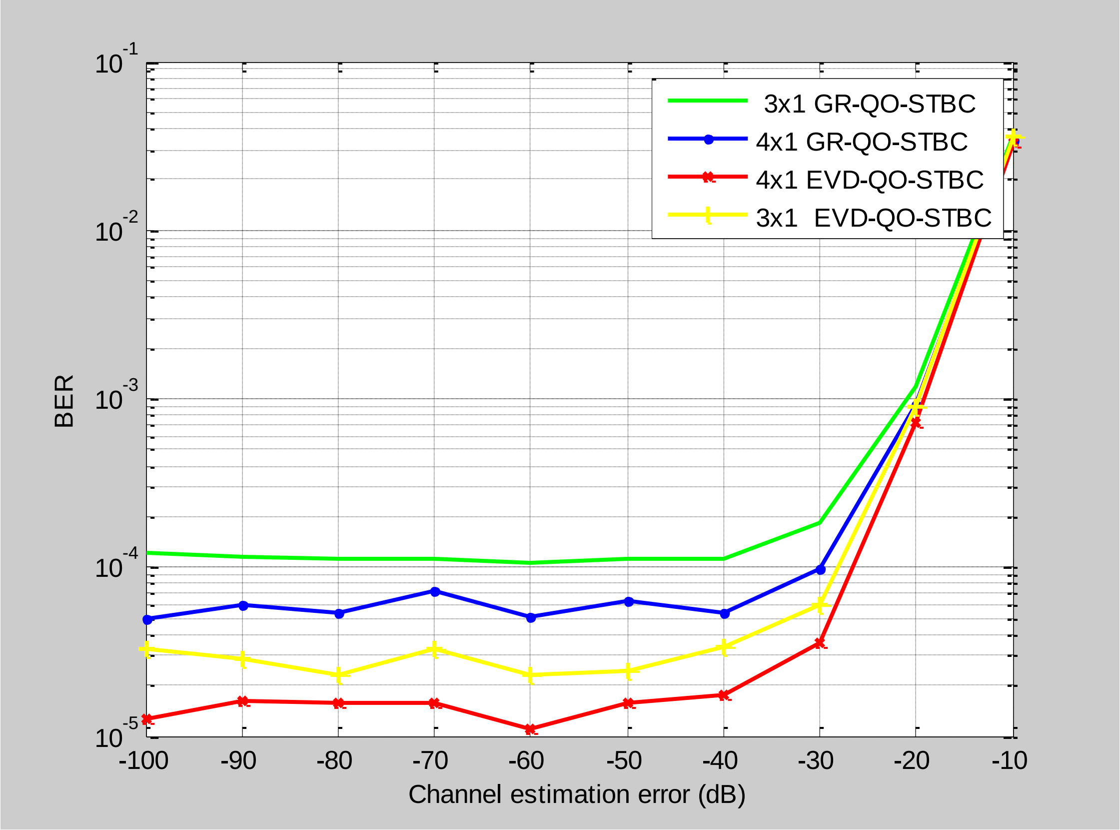

Fig. 6.2. BER performance of GR-QO-STBC and EVD-QO-STBC schemes for three and four transmit antennas under imperfect CSI at the receiver.

Fig. 6.3 represents the simulation results for GR-QO-STBC and EVD-QO-STBC schemes over MIMO systems. In this case, 4×2 and 3×2 MIMO configurations are used for both QO-STBC schemes. Simulations are carried out under the condition of perfect CSI at the receiver side. Channel used simulations is quasi-static Rayleigh flat fading channel along with QPSK modulation method.

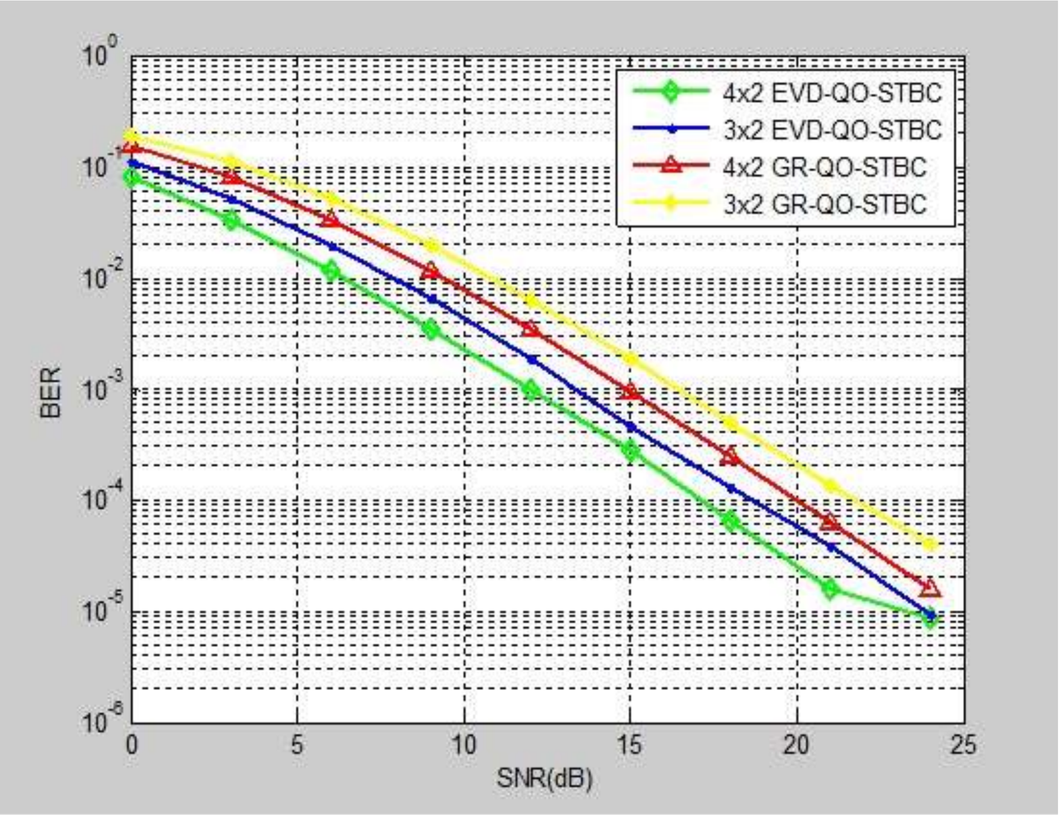

Fig. 6.3. BER performance of GR-QO-STBC and EVD-QO-STBC schemes for MIMO systems.

Chapter 7

CONCLUDING REMARKS AND FUTURE SCOPE

7.1. Concluding Remarks

Three QO-STBC schemes namely C-QO-STBC, GR-QO-STBC and EVD-QO-STBC have been discussed mathematically in this chapter. We evaluated their performance in terms of BER under two different conditions of i.e., (1) Perfect CSI at the receiver side (2) Imperfect CSI at the receiver side. In first case, it is assumed that the receiver has perfect CSI to decode the transmitted symbols. Simulation results in this case proved that EVD-QO-STBC scheme outperforms the other two QO-STBC schemes. For 4×1 systems, EVD-QO-STBC scheme has a diversity gain of approximately 3 dB over GR-QO-STBC scheme and of 6 dB over C-QO-STBC scheme. Even 3×1 EVD-QO-STBC scheme outperforms the 4×1 GR-QO-STBC and C-QO-STBC schemes by some decent margin. Therefore, EVD-QO-STBC scheme not only improves the BER performance, but also reduces the hardware complexity.

In second case, EVD-QO-STBC and GR-QO-STBC schemes have been analyzed for imperfect CSI at the receiver side. After carefully analyzing the simulation results, it is concluded that under the condition of imperfect CSI, EVD-QO-STBC scheme tolerates the channel estimation errors in a better way as compared to GR-QO-STBC scheme i.e., EVD-QO-STBC scheme perform better than GR-QO-STBC scheme for less than -30 dB channel estimation error. However, for more than -30 dB channel estimation error, there is sharp decay in the performance of both QO STBC schemes as shown in the simulation results.

Therefore, it is confirmed that EVD-QO-STBC scheme outpaces the GR-QO-STBC scheme under both aforementioned conditions i.e., with and without perfect CSI at the receiver.

Under MIMO systems, both QO-STBC schemes achieve better performance as compared to MISO systems. This is simply due to increase in their diversity order. Both QO-STBC schemes achieve a diversity gain of 3-4 dB in comparison to MISO systems. In case of MIMO implementation, EVD-QO-STBC scheme again has better BER performance than GR-QO-STBC scheme.

7.2. Future Work

The future work includes the usage of the combination of “constellation rotation and co-ordinate interleaving [36]” with EVD-QO-STBC and GR-QO-STBC schemes.

7.3. Applications

Both QO-STBC schemes – EVD-QO-STBC and GR-QO-STBC can be used in the field of cellular communication with different cellular standards such as EDGE [49], GSM/EDGE [50] and LTE-A [37].

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