Investigation of Various Space Time Coding Scheme

by

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This dissertation is submitted to I.I.U. in partial fulfillment of the requirements for the degree of

MS Electronic Engineering

Department of Electronic Engineering

Faculty of Engineering and Technology

International Islamic University, Islamabad.

2008

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Certificate of Approval

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List of Symbols

ξ	Channel coefficients
η	Noise at Receiver
K	Channel capacity
l	Time slots
γ	Received signal
W	Frame Length
T	Transmit Antenna
R	Receive Antenna
c	Propagation coefficient
y	Received signal vector
s	Transmitted signal vector
C	Channel Matrix
$p(r)$	Probability Density function
λ	Non-singular value of Channel
ρ	Power
χ	Transmitted Signal

Abstract

It is well known that the high data rates and improved link quality has increased over the past few years for the wireless communication systems. Different coding techniques have been introduced as well as the old coding schemes have been enhanced in order to cover this huge demand in the wireless communication systems while keeping in view of limited resources like bandwidth and power. The most efficient techniques is to use the multiple antenna systems which are an efficient means for increasing the performance. In order to achieve maximum gain from the multiple antenna concepts, focus is on to explore the new transmit strategies, which is known as Space-Time Code. These codes use the time and spectral domain as well as the spatial domain.

In this thesis, the performance is investigating for different types of space time coding scheme. These schemes were observed under different constellation scheme (BPSK and QPSK). Further, this performance comparison of different Space Time Coding scheme is based on the Multiple-input multiple output (MIMO) antenna technology. MIMO antenna technology is a latest technique used for the high-speed wireless communications without sacrificing the transmission bandwidth. Simulations for systems with multiple transmit antennas demonstrate the significant performance comparison for different coding scheme at various SNRs.

Acknowledgements

I am grateful to my Almighty Allah, The Kind and Merciful, Who enabled me to complete this work. I owe a debt of gratitude to many people who have helped me with my graduate study and research in diverse ways. Without their generosity and assistance, the completion of this thesis would not have been possible.

I would also like to express my deepest gratitude and appreciation to my supervisor, Dr. Aqdas Naveed Malik, for his excellent guidance and generous support. He allowed me to initiate my graduate studies at International Islamic University, one of the most elite graduate universities in Pakistan. Dr. Aqdas has incredible vision and boundless energy. He is also an endless source of creative ideas. Often times, I have realized how truly fortunate I am to have such an open-minded advisor who allowed me to choose my research subject freely.

My greatest and heartfelt thanks must also go to Professor Dr. T. A. Cheema for his constant encouragement, inspiration, and guidance both in completing this thesis and in my professional development. He led me to the exciting world of wireless communications.

(Ali Raza)

CHAPTER 1

Introduction

1.1 Introduction

Multiple Input Multiple Output (MIMO) systems are currently widely used in the wireless communication system [1], [2] and [3]. Multiple transmitters and receivers antenna are employed for the creation of multiple channels in the MIMO systems. It provides the high spectral efficiencies which increase the data rates without increasing the bandwidth of the wireless communication system. If the channel is known at the receiver end, the capacity of the system will grow linearly with the smaller number of transmit and receive antennas under some conditions. The biggest advantage of MIMO system is achieved low Bit Error Rate (BER) or the data rate.

The Space Time Block Code (STBC) [2] was firstly proposed by Alamouti with the system configuration of two transmit antennas. Based on the Alamouti scheme, later on, the orthogonal design was further extended to the systems with arbitrary number of transmit antennas [4]. The important factor of orthogonal design is its full diversity and low computational complexity Maximum Likelihood (ML) decoding for two transmit antennas. In practical systems, the above mentioned factors make Orthogonal Space Time Block Code (OSTBC) more attractive. There is another space time coding scheme which uses the trellis code named Space Time Trellis Coding (STTC) [5]. STTC achieve both the diversity gain and coding gain. But the only factor of STTC is encoding and decoding complexity which is higher than the OSTBC.

1.2 Contribution

1. Investigation of the different Space Time Coding Scheme which includes Quasi Orthogonal Space Time Block Code (QOSTBC) [6], Quasi Orthogonal Space Time Block Code with optimal rotation of $\frac{\pi}{6}$ (QOSTBC-OR) [7], Space Time Block Code from Cyclic Design (STBC-CD) [8] and Space Time Trellis Code (STTC) [5].
2. The constellation symbols utilized in this study are Binary Phase Shift Key (BPSK) and Quaternary Phase Shift Key (QPSK).
3. Performance comparison were made for the Quasi Orthogonal Space Time Block Code (QOSTBC) [6], Quasi Orthogonal Space Time Block Code with optimal rotation of $\frac{\pi}{6}$ (QOSTBC-OR) [7], Space Time Block Code from Cyclic Design (STBC-CD) [8] and Space Time Trellis Code (STTC) [5]. Constellation symbols utilized in the simulation results are Binary Phase Shift Key (BPSK) and Quaternary Phase Shift Key (QPSK).
4. MIMO communication system is incorporated by employing the system configuration of Three, Four Transmit Antenna's and One Receive Antenna for the simulation result.

1.3 Organization

The outline of the dissertation is as follows:

- **Chapter 2:** In this chapter 2, discussed the wireless communication system along with the vitality and significance of Multiple Antenna Communication System.

- **Chapter 3:** This chapter is devoted to the Space Time Codes (STC), its brief portfolio, terminology and types.
- **Chapter 4:** In this chapter, discussed the Quasi Orthogonal Space Time Block Code (QOSTBC), QOSTBC with Optimal Rotation, Space Time Trellis Code and STBC with the cyclic shift scheme. Pseduo code for the Quasi Orthogonal Space Time Block Code (QOSTBC), QOSTBC with Optimal Rotation, Space Time Trellis Code and STBC with the cyclic shift scheme.
- **Chapter 5:** Simulation results are demonstrated for three, four transmit antenna with one and two receive antenna for the Quasi Orthogonal Space Time Block Code (QOSTBC), QOSTBC with Optimal Rotation, Space Time Trellis Code and STBC with the cyclic shift scheme..
- **Chapter 6:** In this chapter, the thesis is concluded and future extendable dimension regarding the STBC scheme are mentioned and references are listed in the end.

CHAPTER 2

Wireless Communication Systems

2.1 Introduction

Wireless communication system is being a new technology in which different wireless devices and cellular network are incorporated. The goal to evolve the wireless devices and networks is to have a communication medium with anyone from anywhere at anytime for anything. To get this goal, the main problem is that how much of the information can pass through the system, which is the communication channel. This problem is known as the channel capacity for the wireless communication [1], [2]. The frequent use of the wireless communication system and the demand for the capacity of the channel becomes more important, which in turn to be more focus in term of power and complexity of the systems. This means that the capacity of the channel cannot increase by increasing the transmit power of the system. The more frequent use in the communication systems is single antenna system which can be a cellular phone, handheld devices and any thing else. The capacity of the system can be very low due to the factor of the multiple path propagation. So the current focus in the research activity to find ways to make more efficient use of this channel capacity and efficient techniques to increase the capacity. The recent advancement in coding and new robust codes are introduced such as turbo codes and low density parity check codes which make it more feasible to reach almost the Shannon Capacity, the theoretical upper bound for the capacity of the system. The study involve in this chapter is based on the literature survey.

A single antenna systems suffered great drawback of high error rate which is due to one of the factor of multiple path propagation. In an additive white Gaussian noise (AWGN) channel, which is a typical wired channel, the pairwise error probability (PEP), the probability of error of making a decision for the transmitted signal with another one, decreases exponentially with the signal-to-noise ratio (SNR), while keeping in view of other constraints like fading factor. The average PEP for wireless single-antenna systems only decreases linearly with SNR. Therefore, to achieve the same performance, a much longer code or much higher transmit power is needed for single-antenna wireless communication systems.

The single-antenna systems are not attractive approach to meet the needs of future wireless communications due to the above mentioned drawbacks. Therefore, new communication systems superior in capacity and error rate must be introduced and consequently, new communication theories for these systems are of great importance at the present time. Therefore, the new systems employs the digital communication systems using multiple-input-multiple output (MIMO) wireless links, that is, using multiple antennas at the transmitter and the receiver, has emerged that are basis to overcome the drawbacks of single-antenna systems [1], [2] and [9]. This is one of the most significant technical breakthroughs in modern communications. The key feature of a multiple-antenna system is its ability to turn multiple-path propagation, which is traditionally regarded as a disadvantage to wireless communications, into a benefit to the users.

Multiple-antenna systems have much higher Shannon capacity as compared to single-antenna [10]. However, Shannon capacity can only be achieved by codes which have unbounded complexity and delay which does not effect the performance of the wireless communication system. For example, in a system with two transmit antennas, if identical signals are transmitted from both antennas at the same time slot, a PEP that is inversely proportional to SNR is obtained, which is the same as that of single-antenna systems although the coding gain is improved. It is important to develop algorithms keeping in view of the spatial diversity that take advantage of the multiple antennas. Many algorithms and coding scheme design technique with reasonable complexity and performance have been proposed, for example, the diversity techniques and diversity combining methods. The latest technique used to achieve the complexity and performance is space-time coding [1], [2].

In space-time coding, the signal processing at the transmitter is done in the time and spatial dimension. Redundancy is added coherently to both dimensions. By doing this, both the data rate and the performance are improved by many orders of magnitude with no extra cost of spectrum. This is also the main reason that space-time coding attracts much attention from academic researchers and industrial engineers alike.

The idea of space-time coding was first proposed by Tarokh, Seshadri and Calderbank in [9]. They proved that space-time coding achieves a PEP that is inversely proportional to SNR^{TR}, where T is the number of transmit antennas and R is the number of receive antennas. The number MN is called the diversity of the space-time code. Comparing with the PEP of single antenna systems, which is inversely proportional to the SNR, the error rate is reduced dramatically. It is also shown in [9] that by using space-time coding, some coding gain can be obtained. The first practical space-time code is proposed by Alamouti in [2], which works for systems with two transmit antennas. It is also one of the most successful space-time codes because of its great performance and simple decoding.

The results in [11],[12] are based on the assumption that the receiver has full knowledge of the channel, which is not a realistic assumption for systems with fast-changing channels. Hochwald and Marzetta [13] studied the much more practical case where no channel knowledge is available at either the transmitter or the receiver. They first found a capacity-achieving space-time coding structure in [9] and based on this result, they proposed unitary space-time modulation [14]. In [3], they also proved that unitary space-time coding achieves the same diversity, MN, as general space-time coding [15].

The unitary space-time modulation [14] is better tailored for systems with no channel information at both the transmitter and the receiver is proposed by Hochwald and Sweldens and Hughes, which is called differential unitary space-time modulation [14]. Differential unitary space-time modulation can be regarded as an extension of differential phase-shift keying (DPSK), a very successful transmission scheme for single-antenna systems.

The technology of multiple antennas and space-time coding has been improved greatly during the last few years. There are many papers on the design of differential and non-differential unitary space-time codes. There is also much effort in trying to improve the coding gain by combining space-time codes with other error-correcting codes or modulations. Today, this area is still under intensive theoretical study.

2.2 Multiple-Antenna Communication System Model

Consider a wireless communication system with two users. One is the transmitter and the other is the receiver. The transmitter has T transmit antennas and the receiver has R receive antennas as illustrated in Figure 2.1. There exists a wireless channel between each pair of transmit and receive antennas. The channel between the t_{ij} transmit antenna and the r_{ij} receive antenna can be represented by the random propagation coefficient c_{ij}, whose statistics will be discussed later.

To send information to the receiver, at every transmission time, the transmitter feeds signals s_1, s_2, s_3..........s_T to its T antenna respectively. The antennas then send the signals simultaneously to the receiver. Every receive antenna at the receiver obtains a signal that is a

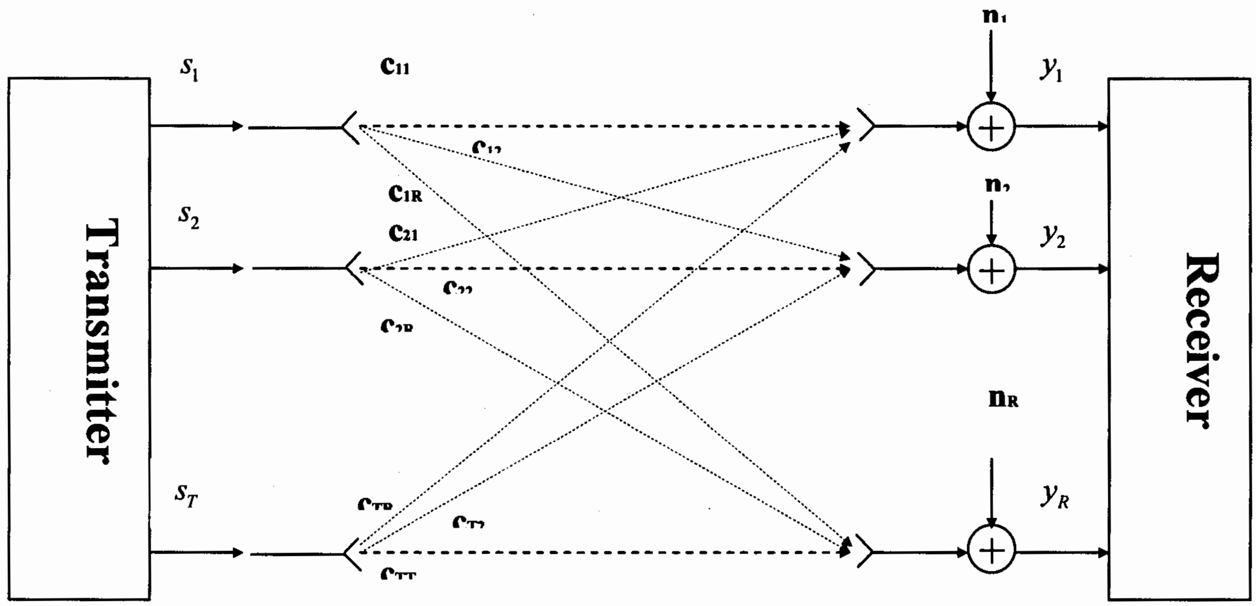

Figure 2.1 Multiple-Antenna Communication System

superposition of the signals from every transmit antenna through the fading coefficient. The received signal is also corrupted by noise. If the noise is denoted at the r_{th} receive antenna by n_r, the received signal at the r_{th} receive antenna is

$$y_r = \sum_{m=1}^{M} h_{mr} s_m + n_r \tag{1}$$

This is true for $r = 1, 2, ...R$. If the vector of the transmitted signal is denoted as $s = [s_1, s_2 ....s_T]$, the vector of the received signal as $y = [y_1, y_2 ......y_T]$, the vector of noise as $n = [n_1, n_2 .....n_T]$ and the channel matrix as

$$C = \begin{bmatrix} c_{11} & \cdots & \cdots & \cdots & c_{1R} \\ c_{21} & \cdots & \cdots & \cdots & c_{1R} \\ \vdots & \cdots & \cdots & \cdots & \vdots \\ \vdots & \cdots & \cdots & \cdots & \vdots \\ c_{T1} & \cdots & \cdots & \cdots & c_{TR} \end{bmatrix} \tag{2}$$

The system equation can be written as

$$y = sC + n \tag{3}$$

The total transmit power is

$$P = ss^{*} = tr\left(s^{*}s\right) \tag{4}$$

2.3 Rayleigh Flat-Fading Channel

There are different factors involve which places fundamental limitations on the performance of wireless communication systems [13]. As the wired channels which are stationary and predictable easily, wireless channels are random and due to the diverse environment are not easily analyzable.

In a wireless communication system environment, the different objects, such as buildings, trees, and houses act as reflectors of electromagnetic waves which in turn cause multi-path effects. Electromagnetic waves travel along different paths of varying lengths and have various amplitudes and phases which is generally caused by due to these reflections. The interaction between these waves causes multiple fading at the receiver location, and the strength of the wave decreases as the distance between the transmitter and the receiver increases. Propagation modeling focuses to predict the mean signal strength for an arbitrary transmitter-receiver separation distance which is known as *large-scale* propagation models. Propagation modeling also focuses the rapid fluctuations of the received signal strength over very short travel distances or short time durations which is called *small scale* or *fading* models.

Small-scale fading is affected by many factors, such as multiple-path propagation, speed of the transmitter and receiver, speed of surrounding objects, and the transmission bandwidth of the signal. In this work, narrowband systems are considered, in which the bandwidth of the transmitted signal is smaller than the channel's *coherence bandwidth*, which is defined as the frequency range over which the channel fading process is correlated. This type of fading is referred to as flat fading or frequency nonselective fading.

The Rayleigh distribution is commonly used to describe the statistical time-varying nature of the received envelope of a flat-fading signal. It is also used to model fading channels in this thesis. For a typical mobile wireless channel in indoor or urban areas, It may be assume that the direct line-of-sight wave is obstructed and the receiver obtains only reflected waves from the surrounding objects. When the number of reflected waves is large, according to central limit theory, two quadrature components of the received signal are uncorrelated Gaussian random processes with mean zero and variance σ^2. As a result, the envelope of the received signal at any time instant has a Rayleigh distribution and its phase is uniform between $-\pi$ and π. The probability density function of the Rayleigh distribution is given by

$$p(r) = \begin{cases} \frac{r}{\sigma^2} e^{\frac{r^2}{2\sigma^2}} & r \geq 0 \\ 0 & r \prec 0 \end{cases} \tag{5}$$

If the fading coefficients in the multiple-antenna system model given in (3) are normalized by

$$\sum_{m=1}^{M} \left| c_{mr}^2 \right| = T, \qquad \text{for } i = 1,2,....R, \tag{6}$$

where $\sigma^2 = \frac{1}{2}$. Therefore, the fading coefficient c_{tr} has a complex Gaussian distribution with zero-mean and unit-variance, or equivalently, the real and imaginary parts of c_{tr} are independent Gaussians with mean zero and variance $\frac{1}{2}$. Note that with (4)

$$E\left|\sum_{m=1}^{M} c_{mr} s_r\right|^2 = \sum_{m=1}^{M} E\left|c_{mr}\right|^2 \left|s_r\right|^2 \tag{7}$$

$$E\left|\sum_{m=1}^{M} c_{mr} s_r\right|^2 = \sum_{m=1}^{M} E|s_r|^2 = P, \tag{8}$$

which indicates that the normalization in (4) makes the received signal power at every receive antenna equals the total transmit power.

2.4 Capacity Results

The main reason to employ the multiple antenna system that it can greatly increase the capacity of the channel. The capacity of multiple-antenna communication systems with Rayleigh fading channels [16] to be consider here under three different scenarios for measuring the channel capacity of multiple-antenna communication system with Rayleigh fading channels: both the transmitter and the receiver know the channel, only the receiver knows the channel, and neither the transmitter nor the receiver knows the channel [13],[14] and [16].

It is obvious that the capacity depends on the transmit power. Therefore, assume that the power constraint on the transmitted signal is

$$E \text{ tr } s^*s \leq P, \text{ or equivalently, E tr } ss^* \leq P \tag{9}$$

In the first scenario, assume that both the transmitter and receiver know the channel matrix C. Note that C is deterministic in this scenario. Consider the singular value decomposition of $C: C = VDU^*$ where V is an T x R unitary matrix, U is an R x R unitary matrix, and D is an T x R diagonal matrix with non-negative diagonal entries. By defining $\tilde{x} =$ Ux, $\tilde{s}$ = sV, and $\tilde{v} = Uv$, the system equation (3) is equivalent to

$$\tilde{x} = D\tilde{s} + \tilde{v} \tag{10}$$

Since v is circularly symmetric complex Gaussian with mean zero and variance I_N, $\tilde{v}$ is also circularly symmetric complex Gaussian with mean zero and variance I_N. Since the rank of C is min {T,R}, at most min {T,R}of its singular values are non-zero. Denote the non-zero singular values of C as $\sqrt{\lambda_i}$. The system equation can be written component-wisely to get

$$\tilde{x}_i = \sqrt{\lambda_i}\,\tilde{s}_i + \tilde{n}_i \qquad for\ 1 \le i \le \min\{T,R\} \tag{11}$$

Therefore, the channel is decoupled into min {T,R} uncorrelated channels, which is equivalent to min {T,R} single-antenna systems. It is proved in [12] that the capacity achieving distribution of $\tilde{s}_i$ is circularly symmetric Gaussian and the capacity for the i^{th} independent channel is $\log(1+\lambda_i P_i)$, where $P_i = E\,\tilde{s}_i\,\tilde{s}_i^*$ is the power consumed in the i^{th} independent channel. Therefore, to maximize the mutual information, $\tilde{s}_i$ should be independent circularly symmetric Gaussian distributed and the transmit power should be allocated to the equivalent independent channels optimally [16]. It is also proved that the power allocation should follow "water-filling" mechanism. The power for the i^{th} sub-channel should be $E\ \tilde{s}_i^*\,\tilde{s}_i = (\mu\text{-}\lambda_i^{-1})^+$, where μ is chosen such that $\sum_{i=1}^{\min\{T,R\}} (\mu - \lambda_i^{-1})^+ = P^3$. The capacity of the system is thus

$$K = \sum_{i=1}^{\min\{T,R\}} \log(\mu\lambda_i) \tag{12}$$

which increases linearly in min {T,R}.

When only the receiver knows the channel, the transmitter cannot perform the "water-filling" adaptive transmission. It is proved in [16] that the channel capacity is given by

$$K = \log\ \det(I_R + (P/T)C^*C) \tag{13}$$

which is achieved when s is circularly symmetric complex Gaussian with mean zero and variance $(P/T)I_T$. When the channel matrix is random according to Rayleigh distribution, the expected capacity is just

$$K = E \log \det(I_N + (P/T)C^*C) \tag{14}$$

where the expectation is over all possible channels.

For a fixed R, by the law of large numbers, $\lim_{T\to\infty} \frac{1}{T} C^*C = I_R$ with probability 1. Thus the capacity behaves, with probability 1 , as $R \log(1+P)$, which grows linearly in R, the number of receive antennas. Similarly, for a fixed T,

$$\lim_{T\to\infty} \frac{1}{T} C^*C = I_R \tag{15}$$

with probability 1. Since $\det(I_R + (P/T)C^*C) = \det(I_T + (P/T)CC^*)$, the capacity behaves, with probability 1, as $T \log(1+\frac{PR}{T})$, which increases almost linearly in T, the number of transmit antennas. Therefore, comparing with the single antenna capacity

$$\log(1+P) \tag{16}$$

the capacity of multiple-antenna systems increases almost linearly in $\min\{T,R\}$. Multiple-antenna systems then give significant capacity improvement than single-antenna systems. The capacity for the case when neither the transmitter nor the receiver knows the channel is still an open problem. Zheng and Tse have some results based on the block-fading channel model [17].

2.5 Diversity

Multiple-antenna systems provide better reliability in transmissions by using diversity techniques without increasing transmit power or sacrificing bandwidth, which is a major advantage of Multiple-antenna systems [18]. The basic idea of diversity is that, if two or more independent samples of a signal are sent and then fade in an uncorrelated manner, the probability that all the samples are simultaneously below a given level is much lower than the probability of any one sample being below that level [19], [20]. Thus, properly combining various samples greatly reduces the severity of fading and improves reliability of transmission.

The system equation for a single-antenna communication system is

$$y = \sqrt{\rho} sc + \eta \tag{17}$$

where c is the Rayleigh flat-fading channel coefficient. ρ is the transmit power. η is the noise at the receiver, which is Gaussian with zero-mean and unit-variance. s satisfies the power constraint $E|s|^2 = 1$. Therefore, the SNR at the receiver is $\rho|c|^2$. Since c is Rayleigh distributed, $|c|^2$ is exponentially distributed with probability density function

$$p(y) = e^{-y}, \quad \mathrm{y} > 0 \tag{18}$$

Thus, the probability that the receive SNR is less than a level ε is,

$$P(\rho|c|^2 < \varepsilon) = P(|c|^2 < \frac{\varepsilon}{\rho}) = \int_0^{\frac{\varepsilon}{\rho}} e^{-y} dy = 1 - e^{-\frac{\varepsilon}{\rho}} \tag{19}$$

When the transmit power is high $(\rho >> 1)$,

$$P(\rho|c|^2 < \varepsilon) \approx \frac{\varepsilon}{\rho} \tag{20}$$

which is inversely proportional to the transmit power. For a multiple-antenna system, with the same transmit power, the system equation is

$$y = \sqrt{\rho} sC + \eta \tag{21}$$

where $E\, ss^* = 1$. Further assume that the elements of s are i.i.d, in which case $E|s_i|^2 = \frac{1}{T}$. Since c_{ij} are independent, the expected SNR at the receiver is

$$\rho EsCC^* s^* = \rho \sum_{i=1}^{T} \sum_{j=1}^{T} \sum_{k=1}^{T} E\ \mathrm{s_i} \overline{s_j} c_{ik} \overline{c_{jk}} = \rho \sum_{i=1}^{T} E|s_i|^2 \sum_{k=1}^{T} |c_{ik}|^2 = \frac{\rho}{T} \sum_{i=1}^{T} \sum_{k=1}^{T} |c_{ik}|^2 \tag{22}$$

The probability that the SNR at the receiver is less than the level ε is then

$$P(\frac{\rho}{T} \sum_{i=1}^{T} \sum_{k=1}^{T} |c_{ik}|^2 < \varepsilon) = P(\sum_{i=1}^{T} \sum_{k=1}^{R} |c_{ik}|^2 < \varepsilon \frac{T}{\rho}) \tag{23}$$

$$< P(|c_{11}|^2 < \frac{ct}{\rho}, \ldots\ldots\ldots, |C_{TR}|^2 < \frac{\varepsilon T}{\rho}) \tag{24}$$

$$= \prod_{i=1,k=1}^{T,R} P(|c|^2 < \frac{\varepsilon T}{\rho}) \ = (1 - e^{-\frac{\varepsilon T}{\rho}})^{TR}. \tag{25}$$

When the transmit power is high $(\rho >> 1)$,

$$P(\frac{\rho}{T} \sum_{i=1}^{T} \sum_{k=1}^{R} |c_{ik}|^2 < \varepsilon) < (\frac{\varepsilon T}{\rho})^{TR} \tag{26}$$

which is inversely proportional to ρ^{TR}. Therefore, multiple-antenna systems have much lower error probability than single-antenna systems at high transmit power [21]. There are a lot of diversity techniques.

Diversity can be categorized to *time diversity, frequency diversity and antenna diversity* (space diversity). Time diversity can be achieved by transmitting identical messages in different time slots, which results in uncorrelated fading signals at the receiver. Frequency diversity can be achieved by using different frequencies to transmit the same message.

Depending on whether multiple antennas are used on the transmitter side or on the receiver side, space diversity can be classified into two categories: receive diversity and transmit diversity [18]. The replicas are properly combined to increase the overall receive SNR and mitigate fading. There are many combining methods, for example, selection combining, switching combining, maximum ratio combining, and equal gain combining.

Transmit diversity is more difficult to implement than receive diversity due to the need for more signal processing at both the transmitter and the receiver [22]. In addition, it is generally not easy for the transmitter to obtain information about the channel, which results in more difficulties in the system design. Transmit diversity in multiple-antenna systems can be exploited by a coding scheme called space-time coding, which is a joint design of error-control coding, modulation, and transmit diversity [23].

CHAPTER 3

Space Time Codes

3.1 Introduction

Space-Time Codes (STC) were introduced by Tarokh et al. from AT&T research labs [1], [3] in 1998 provide transmit diversity for the multiple-antenna fading channel. Multipath fading in multiple antenna wireless systems was mostly deal with by other diversity techniques, such as temporal diversity, frequency diversity and receive antenna diversity, with receive antenna diversity being the most widely applied technique. However, it is hard to efficiently use receive antenna diversity at the remote units because of the need for them to remain relatively simple, inexpensive and small. Therefore, for commercial reasons, multiple antennas are preferred at the base stations, and transmit diversity schemes are growing increasingly popular as they promise high data rate transmission over wireless fading channels in both the uplink and downlink while putting the diversity burden on the base station.

The space-time coding scheme by Tarokh et al. [1], [3], is essentially a joint design of coding, modulation, transmit and receive diversity, and has been shown to be a generalization of other transmit diversity schemes, such as the bandwidth efficient transmit diversity scheme and the delay diversity scheme [24].

There are two main types of STCs, namely space-time block codes (STBC) and space-time trellis codes (STTC). Space-time block codes operate on a block of input symbols, producing a matrix output whose columns represent time and rows represent antennas. In contrast to single-antenna block codes for the AWGN channel, space-time block codes do not generally provide coding gain, unless concatenated with an outer code. Their main feature is the provision of full diversity with a very simple decoding scheme.

On the other hand, space-time trellis codes operate on one input symbol at a time, producing a sequence of vector symbols whose length represents antennas. Like traditional TCM (trellis coded modulation) for a single-antenna channel, space-time trellis codes provide coding gain. Since they also provide full diversity gain, their key advantage over space-time block codes is the provision of coding gain. Their disadvantage is that they are extremely hard to design and generally require high complexity encoders and decoders.

Let start with a model of the multiple antenna system. This is followed by a discussion of Alamouti's two-antenna transmit diversity scheme in relation to maximum ratio combining (MRC), where the outline of the general construction of STBCs which generalized Alamouti's scheme.

3.2 System Model

Consider a mobile communication system where the base station is equipped with n antennas and the remote unit is equipped with m receive antennas (see Figure (3.1)). At each time slot l, signals χ_l^i, i = 1,2,.....t are transmitted simultaneously from the t transmit antennas. The channel is flat-fading and the path gain from transmit antenna i to receive antenna j is denoted by ξ_{ij}. The path gains are modeled as samples of independent complex Gaussian random variables with variance 0.5 per real dimension, i.e., $\xi_{ij} \neq N(0,1)$, as signals received at different antennas experience independent fading.

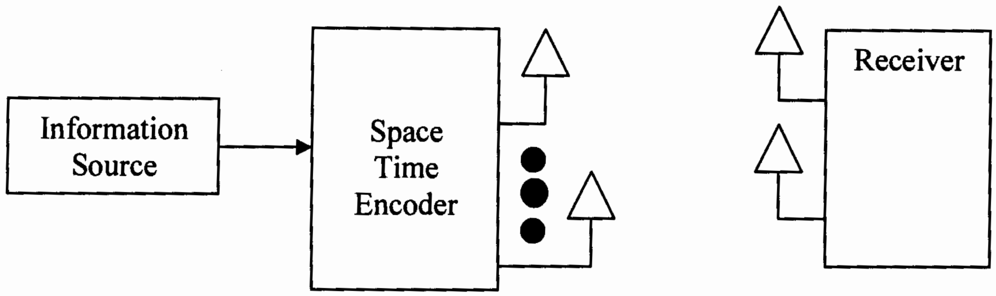

Figure. 3.1 System Block Diagram

Let's consider modeling the path gains in slow Rayleigh fading. For slow fading, it is assumed that the path gains are constant during a frame of length W and vary from one frame to another, i.e., channel is quasi-static.

At time l, the signal γ_l^j, received at antenna j is given by

$$\gamma_l^j = \sum_{i=1}^{n} \xi_{i,j} \chi_l^i + \eta_l^j \tag{27}$$

where the noise samples η_l^j are i.i.d. zero mean complex Gaussian with variance $\sigma^2 = 1/(2E_x/N_0) = 1/(2SNR)$ per dimension. The average energy of the symbols transmitted from each antenna is normalized to one, so that the average power of the received signal at each receive antenna is n.

It is assumed that channel state information is only available at the receiver, who uses it to compute the decision metric

$$\sum_{w=1}^{l} \sum_{j=1}^{t} \left| \gamma_w^j - \sum_{i=1}^{r} \xi_{i,j} \chi_w^i \right|^2 \tag{28}$$

over all codewords $\chi_1^1\chi_1^2.....\chi_1^r\chi_2^1\chi_2^2.....\chi_2^r\chi_w^1\chi_w^2.....\chi_w^r$ and decide in favor of the code word that minimizes the sum.

The signals $\{\chi_w^i\}$, i = 1, 2,….,n, are encoded using a STBC. This scheme is described in detail in the next section.

3.3 Space Time Block Code

3.3.1 Alamouti Scheme

In 1998, Alamouti [1] proposed a simple transmit diversity scheme (see Figure (3.2)), which improves the bit error rate at the receiver side.

3.3.1.1 Two Antenna Transmit Diversity Scheme

Let's start transmitting the two symbols χ_1 and χ_2 from T_{x1} and T_{x2} for the first time slot and for the next time slot, it will transmit the two symbols $-\chi_2^*$ and χ_1^* from T_{x1} and T_{x2} respectively .

In accordance with our system model in section 3.2, let $\xi_1(w)$ denote the path gain from T_{x1} to the receiver; similarly let $\xi_2(w)$ be that from T_{x2} to the receiver. If the fading is assumed to be constant across two consecutive symbols, it can be written as

$$\xi_1(w) = \xi_1(w+W) = \xi_1 = \alpha_1\, e^{j\Theta_1} \tag{29}$$

$$\xi_2(w) = \xi_2(w+W) = \xi_2 = \alpha_2\, e^{j\Theta_2} \tag{30}$$

where T is the symbol period.

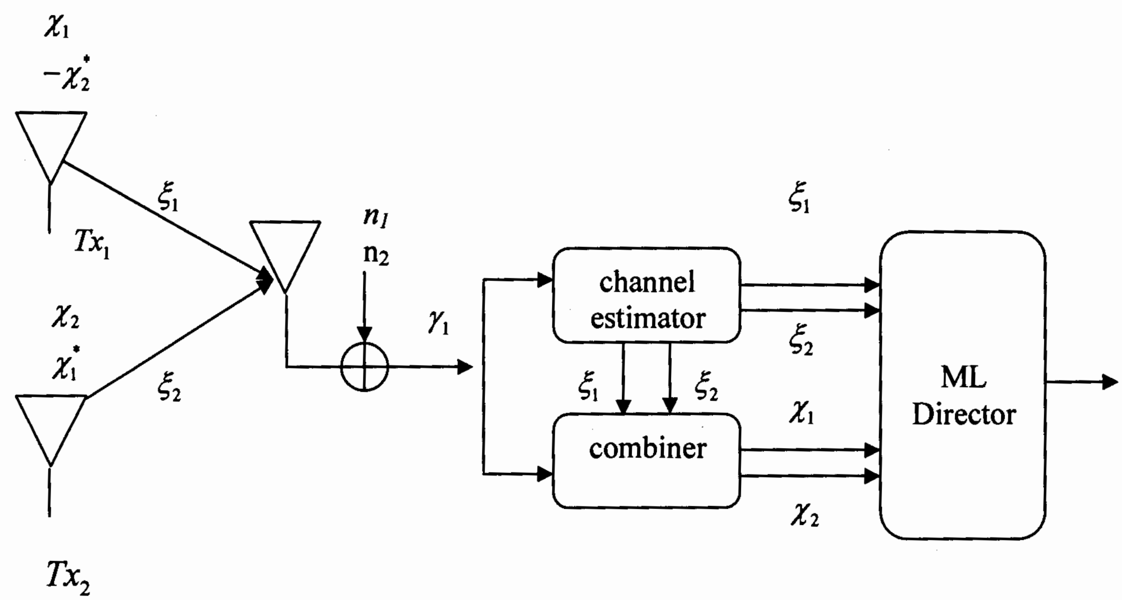

Figure 3.2 Alamouti's Two Antenna Transmit Diversity Scheme

The received signals are

$$\gamma_1 = \gamma(w) = \xi_1 \chi_1 + \xi_2 \chi_2 + \eta_1 \tag{31}$$

$$\gamma_2 = \gamma(w+W) = -\xi_1 \chi_2^* + \xi_2 \chi_1^* + \eta_2, \tag{32}$$

where γ_1 and γ_2 are the received signals at time w and $w+W$. The combiner combines the received signals as follows:

$$\tilde{\chi}_1 = \xi_1^* \gamma_1 + \xi_2 \gamma_2^* = (\alpha_1^2 + \alpha_2^2)\chi_1 + \xi_1^* \eta_1 + \xi_2 \eta_2^* \tag{33}$$

$$\tilde{\chi}_2 = \xi_2^* \gamma_1^* - \xi_1 \gamma_2^* = (\alpha_1^2 + \alpha_2^2)\chi_2 - \xi_1 \eta_2^* + \xi_2^* \eta_1 \tag{34}$$

and sends them to the maximum likelihood detector, which minimizes the following decision metric

$$|\gamma_1 - \xi_1\chi_1 - \xi_2\chi_2|^2 + |\gamma_2 + \xi_1\chi_2^* - \xi_2\chi_1^*|^2 \quad (35)$$

over all possible values of χ_1 and χ_2. Expanding this, and deleting terms that are independent of the codewords, the above minimization reduces to separately minimizing

$$|\gamma_1\xi_1^* + \gamma_2^*\xi_2 - \chi_1|^2 + (\alpha_1^2 + \alpha_2^2)|\chi_1|^2 \quad (36)$$

for detecting χ_1 and

$$|\gamma_1\xi_2^* + \gamma_2^*\xi_1 - \chi_2|^2 + (\alpha_1^2 + \alpha_2^2 - 1)|\chi_2|^2 \quad (37)$$

for decoding χ_2. Equivalently, using the notation $d^2(x, y) = (x - y)(x^* - y^*) = |x - y|^2$,

the decision rule for each combined signal $\tilde{\chi}_j$, j = 1, 2 becomes: Pick χ_i if and only if (iff)

$$(\alpha_1^2 + \alpha_2^2 - 1)|\chi_i|^2 + d^2(\tilde{\chi}_j, \chi_i) \le (\alpha_1^2 + \alpha_2^2 - 1)|\chi_k|^2 + d^2(\tilde{\chi}_j, \chi_k), \quad \forall i \ne k \quad (38)$$

For PSK signals (equal energy constellations), this simplifies to

$$d^2(\tilde{\chi}_j, \chi_i) \le d^2(\tilde{\chi}_j, \chi_k), \quad \forall i \ne k \quad (39)$$

3.3.1.2 Maximum Ratio Combining

In the case of maximum ratio combining (see Figure (3.3)), the resulting received signals are

$$\gamma_1 = \xi_1\chi_0 + \eta_1 \quad (40)$$

$$\gamma_2 = -\xi_2\chi_0 + \eta_2 \quad (41)$$

and the combined signal is

$$\tilde{\chi}_0 = \xi_1^*\gamma_1 + \xi_2^*\gamma_2 \quad (42)$$

$$= (\alpha_1^2 + \alpha_2^2)\chi_0 + \xi_1^*\eta_1 + \xi_2^*\eta_2 \quad (43)$$

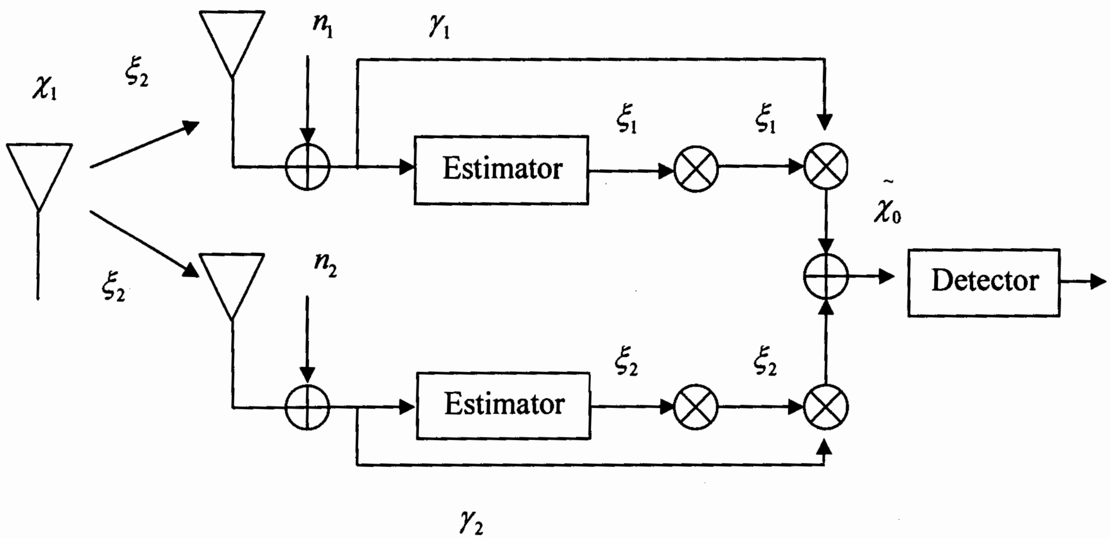

Figure 3.3 Maximum Ratio Combining with 1 Tx and 2 Rx

The maximum likelihood detector decides signal χ_i using exactly the same decision rule in (40), or in (41) for PSK signals.

Note that the MRC signal $\tilde{\chi}_0$ in (42) is equivalent to the resulting combined signals of the transmit diversity scheme in (40), except for a phase difference in the noise components which do not affect the effective SNR. This shows that the diversity order from Alamouti's two-antenna transmit diversity scheme is the same as that of the two-branch MRC.

3.3.1.3 Summary of Alamouti's Scheme

Alamouti [2] further extended this scheme to the case of 2 transmit antennas and r receive antennas, and showed that the scheme provided a diversity order of 2r. Characteristics of this scheme include:

- no feedback from receiver to transmitter is required.

- no bandwidth expansion (as redundancy is applied in space across multiple antennas, not in time or frequency) and low complexity decoders.
- identical performance as MRC if the total radiated power is doubled from that used in MRC, else if transmit power is kept constant, this scheme suffers a 3dB penalty in performance.
- added reliability as scheme includes a soft failure mode, where the transmitted signal may still be received with lower quality even if diversity gain was lost.
- no need for a complete redesign of existing systems to incorporate this diversity scheme.

3.4 General Construction

Tarokh et al. [1], [3] and [9] later generalized Alamouti's transmit diversity scheme to an arbitrary number of transmit antennas, and presented more complex space-time block codes akin to Alamouti's. These codes require no channel state information at the transmitter, achieve maximum-likelihood decoding through linear processing at the receiver, and exhibit maximum diversity. For real signal constellations (such as PAM), they are known to provide the maximum possible transmission rate allowed by the theory of STC. For complex constellations, STBCs can be constructed for any numbers of transmit antennas, and they provide full spatial diversity and half of the maximum possible rate allowed by the theory of STC.

3.4.1 Real Orthogonal Designs

An STBC is defined by a *p x n* transmission matrix **G**, whose entries are linear combinations of $x_1, x_2, ..., x_k$ and their conjugates $x_1^*, x_2^*, ..., x_k^*$, and whose columns are pairwise-orthogonal. In the case when $p = n$ and $\{x_i\}$ are real, G is a linear processing orthogonal design which satisfies the condition that $G^T G = D$, where D is a diagonal matrix with the $(i,i)_{th}$ diagonal element of the form $(l_1^i x_1^2 + l_2^i x_2^2 + ... + l_n^i x_n^2)$, with the coefficients $l_1^i, l_2^i, ..., l_n^i > 0$. Without loss of generality, the first row of G contains entries with positive signs; if not, one can always negate certain columns of G to arrive at a positive first row. Examples include the 2 x 2 and 4 x 4 designs:

$$G_2 = \begin{bmatrix} x_1 & x_2 \\ -x_2 & x_1 \end{bmatrix} \text{ and } G_4 = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & -x_2 \\ -x_4 & -x_3 & x_2 & x_1 \end{bmatrix} \quad (44)$$

3.4.2 Encoding and Decoding

Let's assume that transmission at the baseband employs a signal constellation A with 2b elements. At the first time slot, *nb* bits arrive at the encoder and select constellation signals $c_1, ..., c_n$.. Setting $x_i = c_i$ for $i = 1, 2....n$ in G yields a matrix C whose entries are linear combinations of the c_i and their conjugates. While G contains the indeterminates $x_1, x_2, ..., x_n$, C contains specific constellation symbols (or linear combinations of them), which are transmitted from the *n* antennas as follows:

At time *t*, the entries of row *t* of C are simultaneously transmitted from the *n* antennas, with the i^{th} antenna sending the i^{th} entry of the row. So each row of C gives the symbols sent at a certain time, while each column of C gives the symbols sent by a certain antenna.

The rate of transmission is clearly **b** bits/s/Hz, and the diversity order of the above coding scheme is shown in [5] to be **nm**. The maximum-likelihood decoding scheme is entirely analogous to that of Alamouti's [2] except in more general form: choose c_i among all the constellation symbols c if

$$c_i = \arg\min_{s \in A} \left| \sum_{t=1}^{n} \sum_{j=1}^{m} r_t^j h_{\epsilon_t(i),j}^{*} \Delta_k(i) - s \right|^2 + (-1 + \sum_{k,l} |h_{k,l}|^2) |c|^2 \quad (45)$$

where $\Delta_k(i)$ denotes the sign of x_i in the k^{th} row of G, $\in_k$ denotes the permutation of the k^{th} row of G, and $e_k(p) = q$ means that x_p is up to a sign change the (k, q)th element of G.

In the case when $p < n$, G is a generalized orthogonal design [7] in the variables $x_1, x_2, \ldots\ldots, x_k$ if it satisfies

$$G^T G = (x_1^2, x_2^2, \ldots\ldots, x_k^2) I \qquad (46)$$

Transmission using a generalized orthogonal design is similar to the case when *p = n,* except that now *kb* bits are sent during each *p* transmissions. Since *p* time slots are used to transmit *k* symbols, the rate R of this coding scheme is defined to be *kb/pb = k/p*. The diversity order remains *nm*.

A(R; *n*) is defined to be the minimum number *p* such that there exists a p x n generalized orthogonal design with rate at least **R** for a given **R**, *n*,. If no such orthogonal design exists, then **A(R**;*n*)=INF. A generalized orthogonal design attaining the value of **A(R**;n) is called delay-optimal. The value of **A(R**;n) is the fundamental question of generalized orthogonal design theory. The most interesting part of this question is the computation of **A(**1;n) since the generalized orthogonal designs of full rate are bandwidth-efficient.

3.4.3 Complex Orthogonal Design

Complex orthogonal designs of size n are completely analogous to their real counterparts, except that it now contains entries $\pm x_1, \pm x_2, \ldots\ldots, \pm x_n$, , their conjugates $\pm x_1^*, \pm x_2^*, \ldots\ldots, \pm x_n^*$, or multiplies of these indeterminants by $i = \sqrt{-1}$. It is shown by simple construction in [9] that a complex orthogonal design of size n determines a real orthogonal design of size *2n*, and a corollary of this is that complex orthogonal designs only exist for n = 2 or 4, since their real counterparts only exist for n = 2,4 or 8.

A complex linear processing orthogonal design, **G**, is a complex orthogonal design such $G^T G = D$, where **D** is a diagonal matrix with all diagonal entries linear combinations of $|x_1|^2, \ldots\ldots, |x_n|^2$ with all strictly positive coefficients. Note that complex linear processing orthogonal designs only exist when n = 2. Hence, the STBC proposed by Alamouti [2], which uses the following complex linear orthogonal design:

$$G_2 = \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix} \tag{47}$$

is somewhat unique.

For *generalized complex orthogonal designs*, G_c is a *p x n* matrix whose entries are $o, \pm x_1^*, \pm x_2^*, \ldots\ldots, \pm x_n^*, \pm x_1, \pm x_2, \ldots\ldots, \pm x_n$, or their product with *i*, which satisfies the condition that $G_c^T G_c = D_c$,, where D_c is a diagonal matrix with the (I, i)th diagonal entry of the form $(l_1^i |x_1|^2 + l_2^i |x_2|^2 + \ldots.. + l_n^i |x_n|^2)$, with the coefficients $l_1^i, l_2^i, \ldots., l_n^i > 0$.

As with generalized real orthogonal designs, the existence of such codes is not completely understood. Tarokh et al. [3] constructed examples of rate 1=2 codes and rate 3/4 codes, but it remains an open question whether there exists any other generalized designs in higher dimensions with rate greater than 1/2.

`CHAPTER 4

Investigation of various coding scheme

4.1 Introduction

Various coding schemes of Space Time Codes are introduced in the field of the wireless communication system. These coding schemes are designed based on different structure and the special focus is on designing a coding scheme in such a way that the structure is inter-symbol interference free. Special focus is also made on low computational complexity by using maximum likelihood and Viterbi decoding. Alamouti [2] is the first coding scheme in the space time code which utilize complex orthogonal design and it provides full diversity for two transmit antenna with one receive antenna. Later, Tarokh [1] proved that full rate complex orthogonal code does not exists with more than two transmit antenna. Therefore, the Alamouti Space Time Scheme is the only design which achieve full transmission rate without giving the orthogonality principal.

For achieving the full rate for more than two transmit antenna in the space time codes [6], one must give up the principal of orthogonality. Thus, JafarKhani [6] proposed a quasi orthogonal code which have full rate but the diversity is low for four transmit antennas. In Sharma [4] proposed a quasi orthogonal code by utilizing the constellation rotation for any number of transmit antennas which has improved the performance. Jafarkhani [5] also proposed the coding scheme design by the trellis structure which is Space Time Trellis Code (STTC). These codes are designed in a systematic way that achieve the full diversity and improved coding gain. These codes used the set partitioning technique and a super set of space time block code.

Later Xian [8] proposed a new technique of designing space time block code which uses the cyclic design technique. These codes are cyclic in nature and provide full rate and full diversity.

In this Chapter, analysis are made on various space-time coding scheme and also study the performance of the different scheme and provide the comparison of different coding scheme.

4.2 System Model

Let's start with the system model with four transmit antennas and one receive antennas. The matrix are designed in such a way that the columns represent the transmit antennas and the rows represent the time slot. This means that at each time slot, four symbols are transmitted from four transmit antennas. The transmission rate is defined as Rate R= Total number of constellation symbols/ Frame length = P/L.

4.3 Transmission Matrix

The transmission matrix for the QOSTBC [6], QOSTBC (with Optimal Rotation) [7], STBC (with cyclic design) [8] are as follows:

$$A_4 = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & -x_4^* & x_1^* & x_2^* \\ x_4 & -x_3 & -x_2 & x_1 \end{bmatrix} \qquad (48)$$

The A_4 matrix represents the Quasi Orthogonal Space Time Block Code. The columns represent the transmit antennas while the rows represent the time slots.

$$B_4 = \begin{bmatrix} x_1 & x_2 & x_3 e^{i\pi/6} & x_4 e^{i\pi/6} \\ -x_2^* & x_1^* & -x_4^*(e^{i\pi/6})^* & x_3^*(e^{i\pi/6})^* \\ -x_3^* & -x_4^* & x_1^*(e^{i\pi/6})^* & x_2^*(e^{i\pi/6})^* \\ x_4 & -x_3 & -x_2 e^{i\pi/6} & x_1 e^{i\pi/6} \end{bmatrix} \tag{49}$$

The B_4 matrix represents the Quasi Orthogonal Space Time Block Code with Optimal Rotation (optimal angle is $\frac{\pi}{6}$). The columns represent the transmit antennas while the rows represent the time slots.

$$C_4 = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & -x_4^* & x_1^* & x_2^* \\ x_4 & -x_3 & -x_2 & x_1 \end{bmatrix} \tag{50}$$

The C_4 matrix represents the Space Time Trellis Code. This code is designed on a trellis structure and uses the set partitioning technique. The Viterbi decoded is used for the decoding the symbols. The columns represent the transmit antennas while the rows represent the time slots.

$$D_4 = \begin{bmatrix} x_1 & x_2 & x_3^* & x_4^* \\ x_4 & x_1 & x_2^* & -x_3^* \\ -x_3 & -x_4 & x_1^* & x_2^* \\ -x_2 & x_3 & x_4^* & x_1^* \end{bmatrix} \tag{51}$$

The D_4 matrix represents the Space Time Block Code with Cyclic Design. These codes are based on the cyclic design which means they are cyclic in nature column and row-wise. The columns represent the transmit antennas while the rows represent the time slots.

4.4 Pseudo Code for Quasi Orthogonal Space Time Block Code

1. Initialize the time slot t.
2. Repeat until i is not equal to time slot.
3. Initialize number of samples to be taken.
4. Generate the random channel.
5. Generate the codeword.
6. Set the constellation symbol to be used.
7. Generate the codeword from the constellation symbol randomly.
8. Construct all the possible codeword to accelerate ML decoding.
9. Initialize the SNR value.
10. Repeat until j is not equal to SNR.
11. Calculate the received signal r_1, r_2, r_3 and r_4 by using the Quasi Orthogonal Space Time Block Code.
12. Perform ML Decoding of the received signal to calculate the minimum distance.
13. Increment j and go to 10.
14. Find the minimum distance of the received signal.
15. Calculate the Bit Error Rate after taking the decision based on 13.
16. Increment i and go to 2.
17. Plot 14 BER vs SNR.

4.5 Pseudo Code for Quasi Orthogonal Space Time Block Code with Optimal Rotation

1. Initialize the time slot t.
2. Repeat until i is not equal to time slot.
3. Initialize number of samples to be taken.
4. Generate the random channel.
5. Generate the codeword.
6. Set the constellation symbol to be used.
7. Generate the codeword from the constellation symbol randomly.
8. Construct all the possible codeword to accelerate ML decoding.
9. Initialize the SNR value.
10. Repeat until j is not equal to SNR.
11. Calculate the received signal r_1, r_2, r_3 and r_4 by using the Quasi Orthogonal Space Time Block Code with Optimal Rotation.
12. Perform ML Decoding of the received signal to calculate the minimum distance.
13. Increment j and go to 10.
14. Find the minimum distance of the received signal.
15. Calculate the Bit Error Rate after taking the decision based on 13.
16. Increment i and go to 2.
17. Plot 14 BER vs SNR.

4.6 Pseudo Code for Space Time Trellis Code

1. Initialize the time slot t.
2. Repeat until i is not equal to time slot.
3. Initialize number of samples to be taken.
4. Generate the random channel.
5. Generate the codeword.
6. Set the constellation symbol to be used.
7. Generate the codeword from the constellation symbol randomly.
8. Construct all the possible codeword to accelerate ML decoding.
9. Initialize the SNR value.
10. Repeat until j is not equal to SNR.
11. Calculate the received signal by using the Space Time Trellis Code.
12. Perform ML Decoding of the received signal to calculate the minimum distance.
13. Increment j and go to 10.
14. Find the minimum distance of the received signal.
15. Calculate the Bit Error Rate after taking the decision based on 13.
16. Increment i and go to 2.
17. Plot 14 BER vs SNR.

4.7 Pseudo Code for Space Time Block Code from Cyclic design

1. Initialize the time slot.
2. Repeat until i is not equal to time slot.
3. Initialize number of samples to be taken.
4. Generate the random channel.
5. Generate the codeword.
6. Set the constellation symbol to be used.
7. Generate the codeword from the constellation symbol randomly.
8. Construct all the possible codeword to accelerate ML decoding.
9. Initialize the SNR value.
10. Repeat until j is not equal to SNR.
11. Calculate the received signal r_1, r_2, r_3 and r_4 by using the Space Time Block Code from cyclic design.
12. Perform ML Decoding of the received signal to calculate the minimum distance.
13. Find the minimum distance of the received signal
14. Calculate the Bit Error Rate after taking the decision based on 13.
15. Plot 14 BER vs SNR

CHAPTER 5

Simulation Results

In this chapter, the performance comparison of various coding scheme are simulated. Figure 5.1 and figure 5.2 show the bit error rate versus signal-to-noise ratio curves of the quasi-orthogonal code from equation (48), the quasi-orthogonal code with optimal constellation rotation (optimal angle is $\frac{\pi}{6}$) from equation (49), Space Time Trellis Code from equation (50) and Space Time Block Codes from Cyclic design from equation (51) for a BPSK constellation with three transmit antennas, one and two receive antenna operating at 2 bits/s/Hz. Codes matrices for the below figures are chosen by taking the first three columns of the respective matrix of various space time coding.

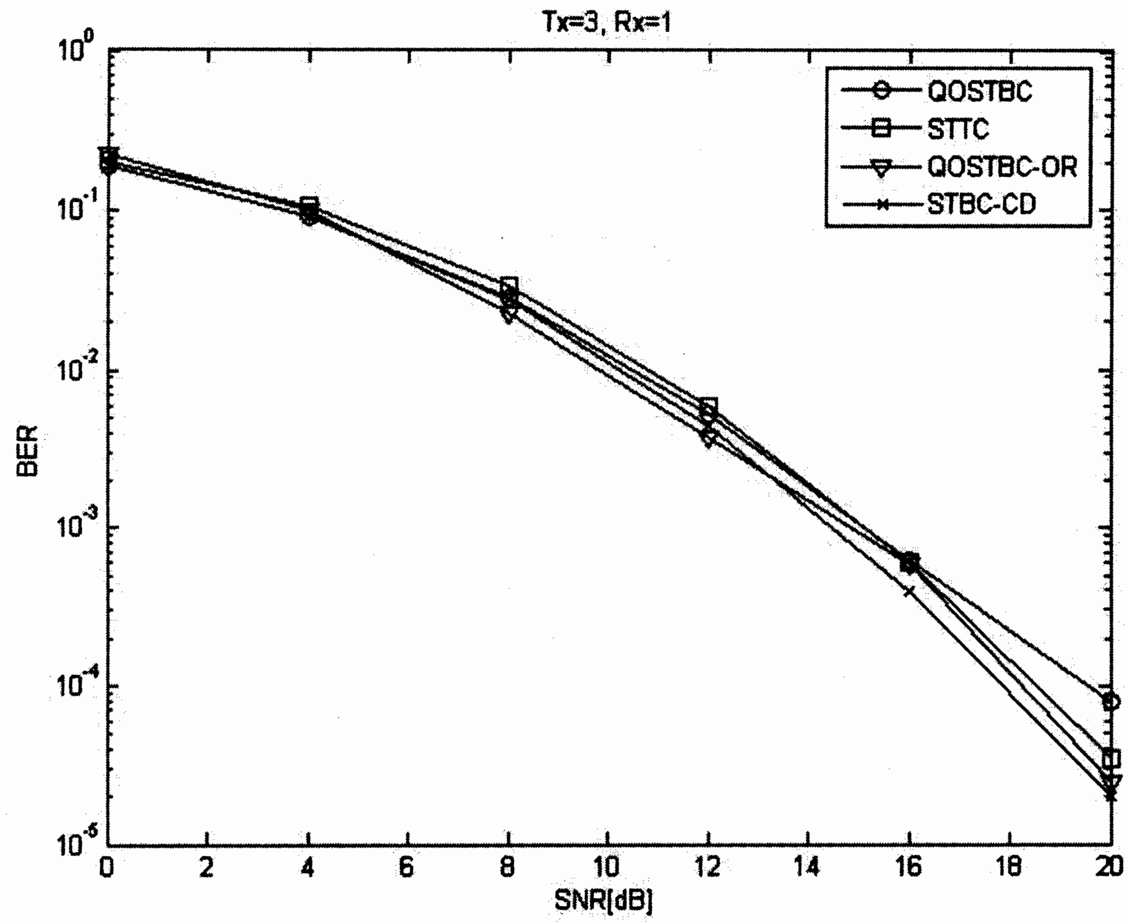

Figure 5.1 Performance comparison of various codes (N=3, M=1, BPSK)

In figure 5.1 and figure 5.2, observation are made that on the lower SNR region, the slopes of SNR versus bit-error-rate curves of the quasi-orthogonal code and the quasi-orthogonal code with optimal constellation rotation are almost the same. Thus, the diversity order is same for both the codes. Partial diversity is achieved in the case of the quasi-orthogonal code without rotation. When employed the receive diversity, space time code from cyclic code always provides better performance than other codes. As quasi-orthogonal codes (without constellation rotation) have less ISI, it performs a little better than the quasi-orthogonal codes (with constellation rotation) in the low SNR region. The cyclic code performs better than the rest of the coding scheme at high SNR values.

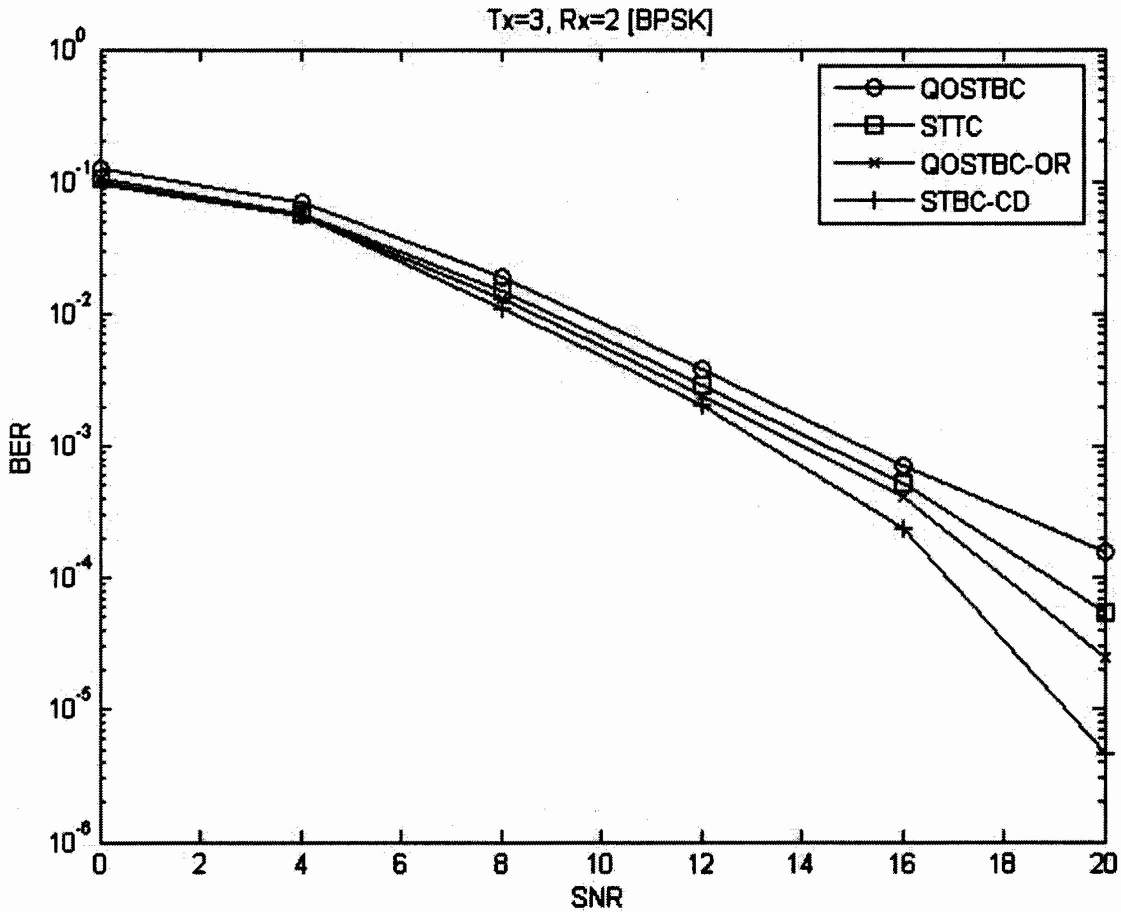

Figure 5.2 Error Performance of various coding scheme (N=3, M=2, BPSK)

Figure 5.3 and figure 5.4 show the error performance curves for the quasi-orthogonal code from equation (48), the quasi-orthogonal code with optimal constellation rotation from equation (49), Space Time Trellis Code from equation (50) and Space Time Block Codes from Cyclic design from equation (51) for a BPSK system with four transmit antennas, one and two receive antenna operating at 2 bits/s/Hz.

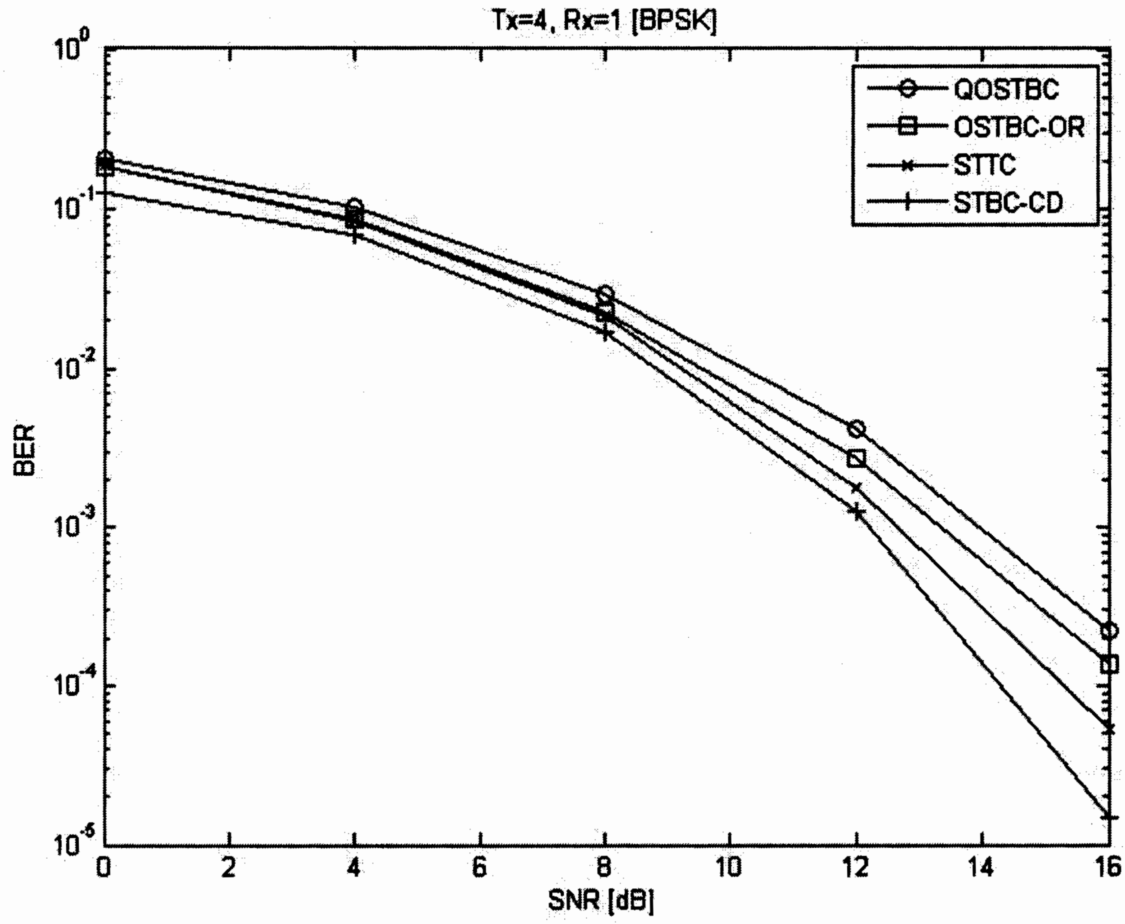

Figure 5.3 Error Performance of Cyclic Code (N=4, M=1, BPSK)

In Figure 5.3 and figure 5.4, observation that the slope of SNR versus bit-error-rate curves of the space time trellis code performs better than the quasi-orthogonal code and the quasi-orthogonal code with optimal constellation rotation at low SNR region. Space time code from cyclic design performs better than the other space time codes in the low SNR region.

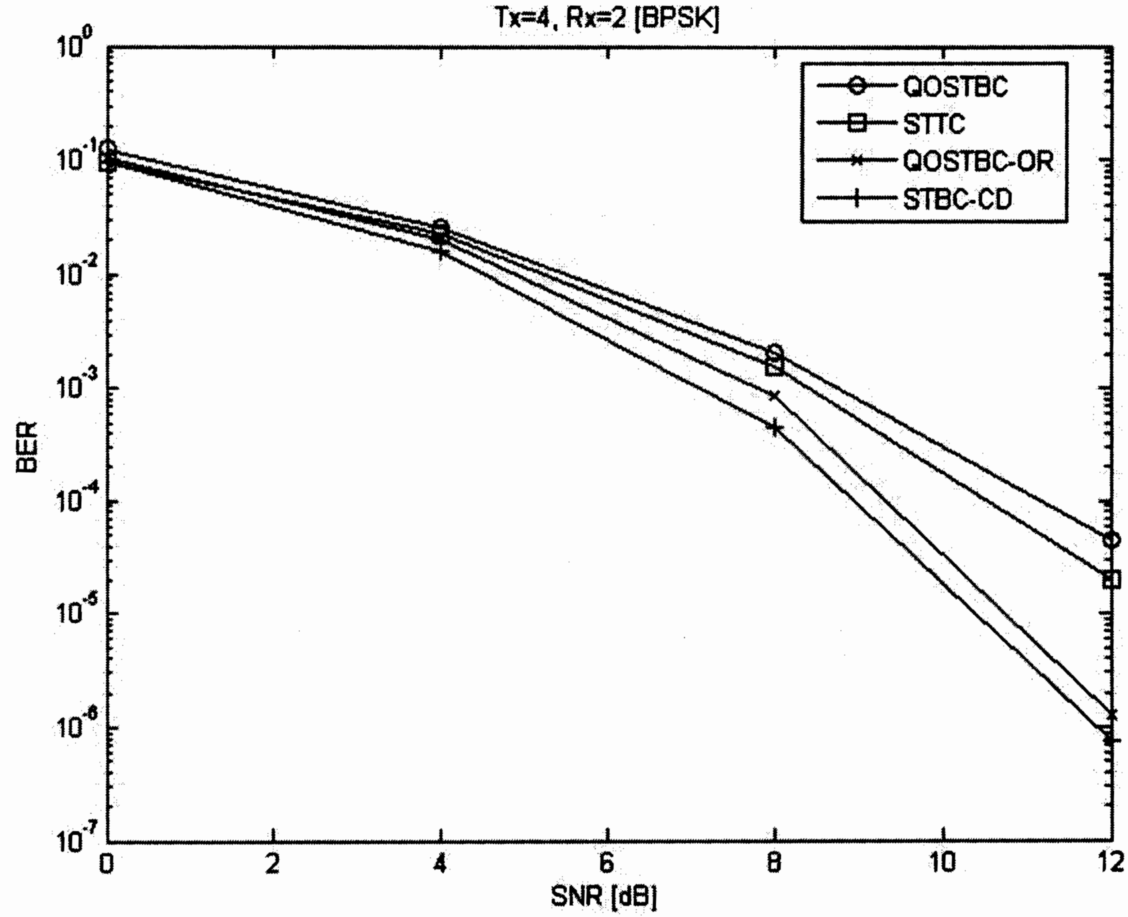

Figure 5.4 Error Performance of Cyclic Code (N=4, M=2, BPSK)

At high SNR values, the cyclic code outperforms the unrotated quasi-orthogonal code, rotated quasi-orthogonal code and space time trellis code. The quasi-orthogonal code without rotation is found to provide only partial diversity but all other codes achieve the same diversity order. The added advantage of space time trellis code is to provide the coding gain. The cyclic code always provides better performance than both of code while achieving the receive diversity.

Figure 5.5 and figure 5.6 show the error performance curves the quasi-orthogonal code from equation (48), the quasi-orthogonal code with optimal constellation rotation (optimal angle is $\frac{\pi}{6}$) from equation (49), Space Time Trellis Code from equation (50) and Space Time Block Codes from Cyclic design from equation (51) for a BPSK system with three transmits antennas, one and two receive antenna operating at 2 bits/s/Hz .

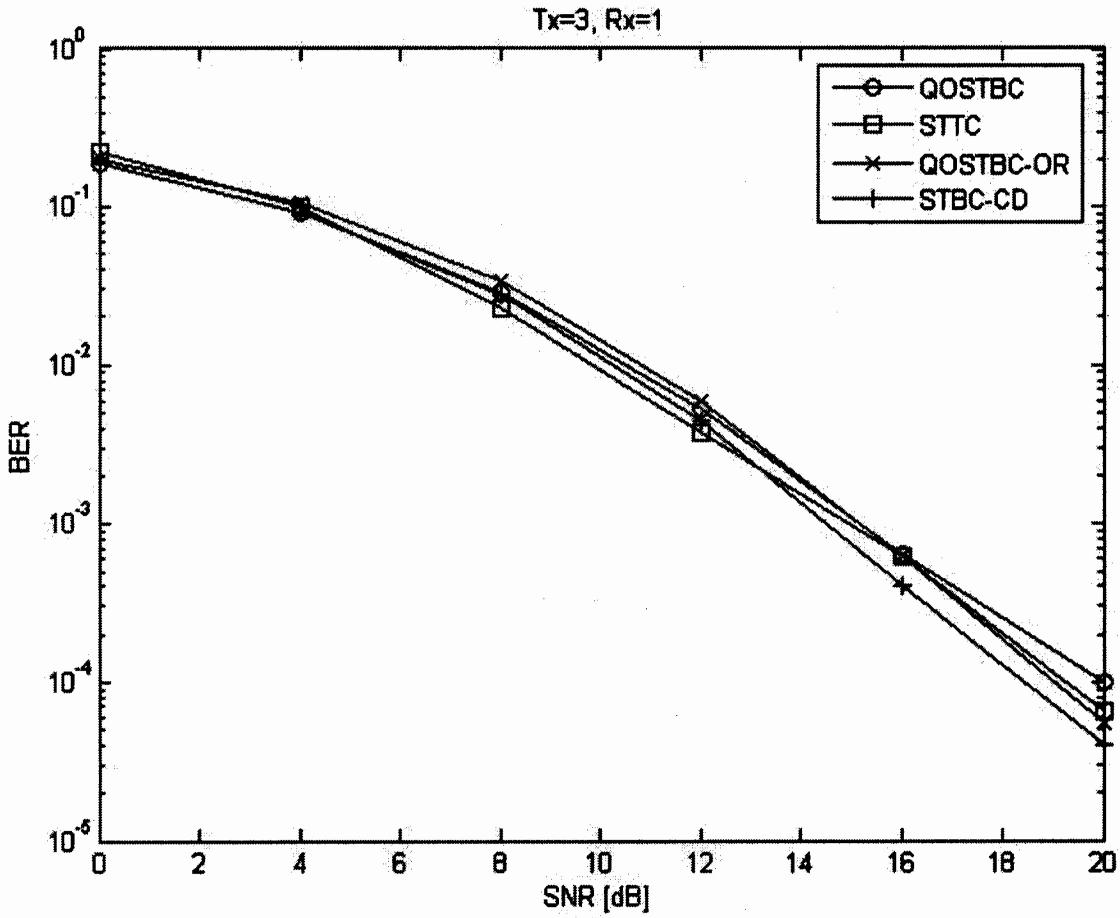

Figure 5.5 Performance comparison of various codes (N=3, M=1, QPSK)

Code matrices for Figure 5.5 and figure 5.6 for the quasi-orthogonal design and the cyclic design are chosen as, respectively, the first three columns of A_4 and the first three columns of D_4. It is observed from figure 5.5 and figure 5.6 that the slopes of SNR versus bit-error-rate curves of the quasi-orthogonal code and the quasi-orthogonal code with optimal constellation rotation are the same at low SNR. Therefore, both codes achieve the same diversity order. The quasi-orthogonal code without rotation is found to provide only partial diversity. The cyclic code always provides better performance than other codes when use receives diversity. In the low SNR region, quasi-orthogonal codes (without constellation rotation) perform slightly better than the quasi-orthogonal codes (with constellation rotation) because quasi-orthogonal codes have less ISI. At high SNR values, the cyclic code outperforms the unrotated quasi-orthogonal code, rotated quasi-orthogonal code and space time trellis code.

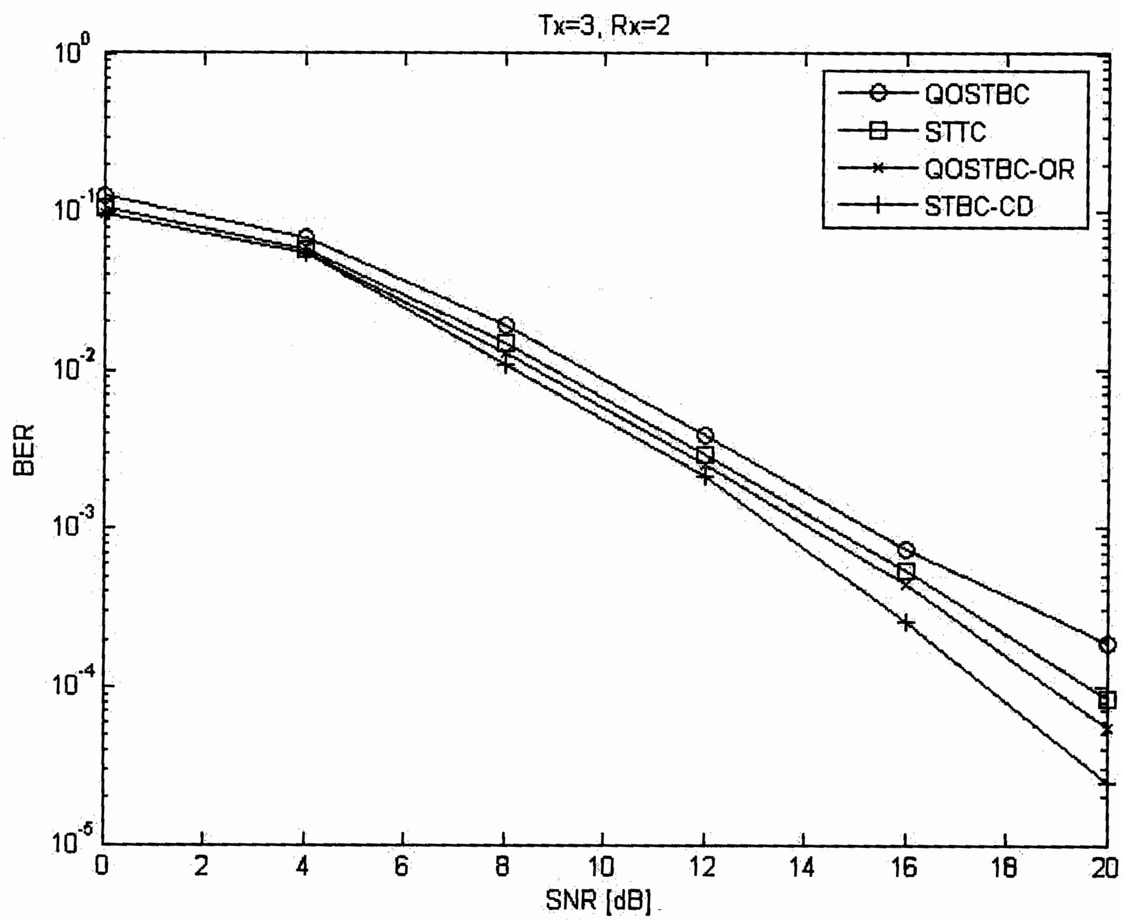

Figure 5.6 Error Performance of various coding scheme (N=3, M=2, QPSK)

Figure 5.7 and figure 5.8 shows the error performance curves of the cyclic code, the quasi-orthogonal code, quasi-orthogonal code with optimal constellation rotation (optimal angle is $\frac{\pi}{6}$, see [8]) and space time trellis code for a QPSK system with four transmits antennas, one and two receive antenna operating at 2 bits/s/Hz.

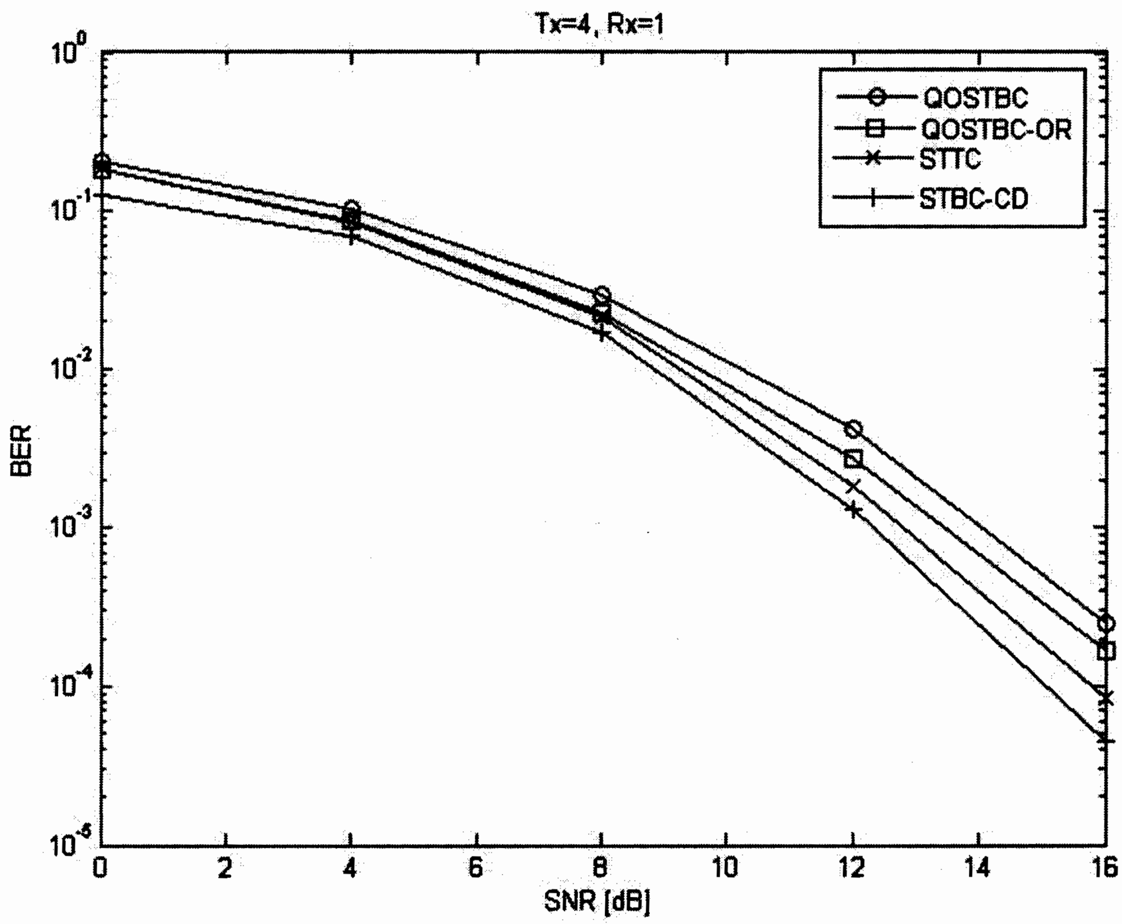

Figure 5.7 Error Performance of Cyclic Code (N=4, M=1, QPSK)

In figure 5.7 and figure 5.8, observation are made that the slope of SNR versus bit-error-rate curves of the cyclic and trellis code performs better than the quasi-orthogonal code and the quasi-orthogonal code with optimal constellation rotation at low SNR region.

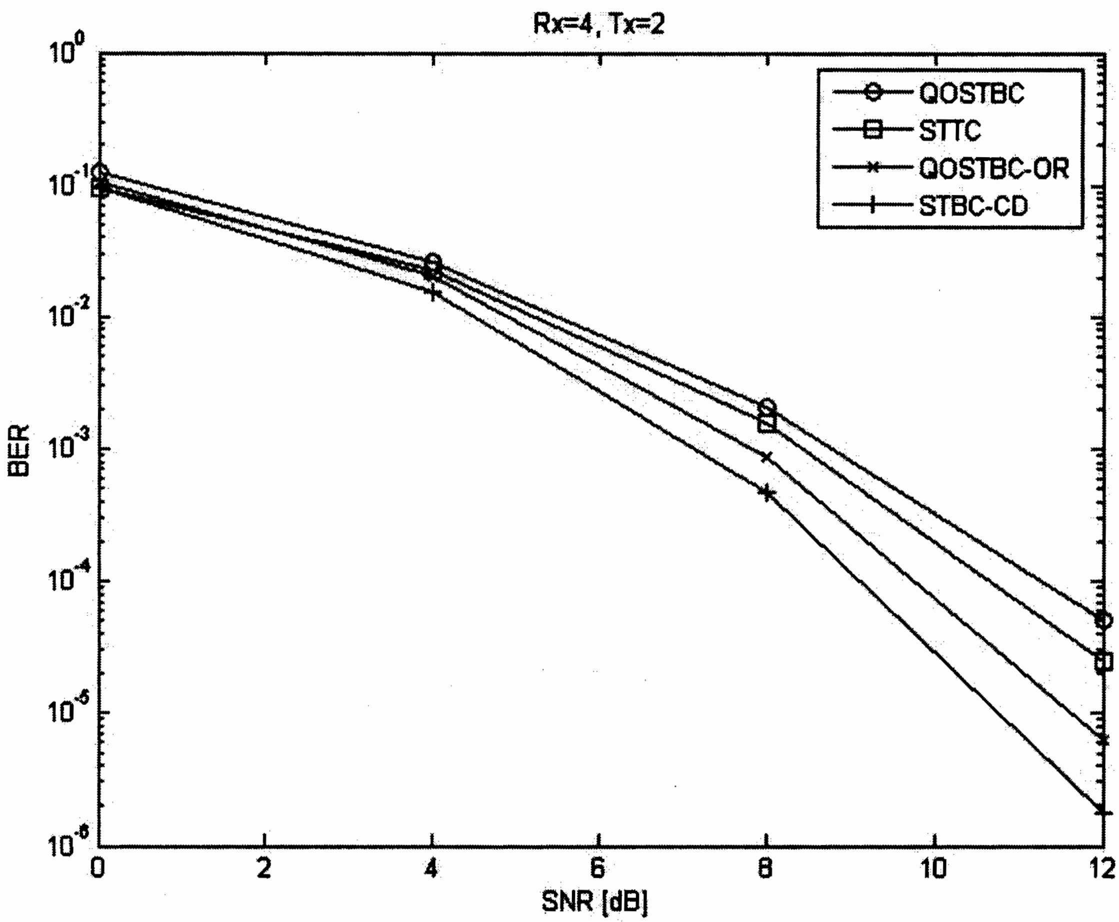

Figure 5.8 Error Performance of Cyclic Code (N=4, M=2, QPSK)

At high SNR values, the cyclic code outperforms the unrotated quasi-orthogonal code and rotated quasi-orthogonal code. Both of these codes achieve the same diversity order but the quasi-orthogonal code without rotation is found to provide only partial diversity. The cyclic code always provides better performance than both of code while achieving the receive diversity.

CHAPTER 6

Conclusions and Future Work

6.1 Conclusions and Future Work

The performance comparison of the Space Time codes by using the different design technique was under observation in this work. Space Time Block Code from cyclic design performs better than the other coding schemes. These comparisons can be further investigated for different channels.

These coding schemes have been compared for BPSK and QPSK constellation with three and four transmit antennas. These codes achieve full rate and full diversity without requiring constellation rotation. Compared with the Quasi-Orthogonal code, the cyclic code has a lower encoding complexity (decoding complexity is the same) and always performs better.

These comparisons could be further investigated to check the performance for any number of arbitrary number of transmit antenna. Further different other constellation scheme can be employed to compare the performance comparison. Blind Channel identification can be utilized to analyze the different result of the various Space Time Coding Schemes. These coding schemes can be further investigate in the beamforming.

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Glossary

2G	*2^{nd} Generation*
3G	*3^{rd} Generation*
AM	*Amplitude Modulation*
AMPS	*A*dvance *M*obile *P*hone *S*ystem
AWGN	*A*dditive *W*hite *G*aussian *N*oise
BER	*B*it *E*rror *R*ate
BPSK	*B*inary *P*hase *S*hift *K*eying
CDMA	*C*ode *D*ivision *M*ultiple *A*ccess
CIR	*C*hannel *I*mpulse *R*esponse
CSI	*C*hannel *S*tate *I*nformation
DS	*D*irect *S*equence
FDMA	*F*requency *D*ivision *M*ultiple *A*ccess
FFH	*F*ast *F*requency *H*opping
FM	*Frequency Modulation*
GA	*G*enetic *A*lgorithm
GSM	*G*lobal *S*ystem of *M*obile
ISI	*I*nter *S*ymbol *I*nterference
ITU	*I*nternational *T*elecommunication *U*nion
MF	*M*atch *F*ilter
MIMO	*Multiple Input Multiple Output*
MMSE	*M*inimum *M*ean *S*quare *E*rror

ML	*Maximum Likelihood*
MUD	Multi User Detection
MRC	Maximum Ratio Combining
MT	Multi Tone
OFDM	Orthogonal Frequency Division Multiplexing
OSTBC	*Orthogonal Space Time Block Code*
PIC	Parallel Interference Canceller
QOSTBC	*Quasi Orthogonal Space Time Block Code*
QPSK	*Quarterany* Phase Shift Keying
SDMA	Space Division Multiple Access
SFH	Slow Frequency Hopping
SIC	Successive Interference Cancellor
SNR	Signal to Noise Ratio
STBC	*Space Time Block Code*
STC	*Space Time Code*
SSS	Spread Spectrum Signal
SUD	Single User Detection
TH	Time Hopping
TDMA	Time Division Multiple Access
TD-SCDMA	Time Duplex-Smart antenna aided *CDMA*