STUDY OF MIMO SYSTEMS WITH LIMITED FEEDBACK

INTERNSHIP PROJECT REPORT

by

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ABSTRACT

Wireless networks have quickly become part of everyday life.However, wireless devices are range and data rate limited. One method is to use Multiple-Input Multiple-Output (MIMO) links. The multiple antennas allow MIMO systems to perform precoding (multi-layer beamforming), diversity coding (space-time coding),and spatial multiplexing. Beamforming consists of transmitting the same signal with different gain and phase over all transmit antennas such that the receiver signal is maximized. Diversity consists of transmitting a single space-time coded stream through all antennas. Spatial multiplexing increases network capacity by splitting a high rate signal into multiple lower rate streams and transmitting them through the different antennas.

Feedback in a communications system can enable the transmitter to exploit channel conditions and avoid interference. In the case of a multiple-input multiple-output channel, feedback can be used to specify a precoding matrix at the transmitter, which activates the strongest channel modes.Codebook indexing design can be employed for low power feedback. In situations where the feedback is severely limited, important issues are how to quantize the information needed at the transmitter and how much improvement in associated performance can be obtained as a function of the amount of feedback available.In this report we can see how the variation occurs in efficiency of a system.

Contents

List of Abbreviation, Symbols, Nomenclatures

α magnitude of the channel transfer function

λ_c wavelength of the carrier frequency

$\tilde{s}$ estimated vector

$h_{i,j}$ channel transfer function from the *j*th transmit antenna and the *i*th receive antenna

N_r number of elements at the receiver

N_t number of antenna elements at the transmitter

s^* complex conjugate of a signal vector

AOA angle of arrival

AOD angle of departure

BER Bit Error Rates

BTS Base Transceiver Station

FDD Frequency-Division Duplex

H channel matrix

HSDPA High Speed Downlink Packet Access

MIMO Multiple Input Multiple Output

MISO Multiple Input Single Output

n noise vector

OSTBC Orthogonal Space Time Block Coding

SIMO Single Input Multiple Output

SISO Single Input Single Output

SNR Signal to Noise Ratio

STBC Space Time Block Codes

TDD Time-Division Duplex

TOA time of arrival

x,s transmitted signal vector

y received signal vector

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Chapter 1

INTRODUCTION

All we look for is high data transfer rate.As a technically and economically feasible method,Multiple Input Multiple Output antenna processing with interference cancellation is now considered as one of the effective technologies to reach the target of HSDPA(High Speed Downlink Packet Access) in 3G systems.

The rapid growth in mobile communications leads to an increasing demand for wideband high data rate communications services.Recent research in information theory has shown that large gains in capacity and reliability of communications over wireless channels could be achieved by exploiting the spatial diversity. One appealing technology is called MIMO (multiple input multiple output), which uses multiple antennas at both transmit and receive sides.

The multiple antennas allow MIMO systems to perform precoding (multi-layer beamforming), diversity coding (space-time coding),and spatial multiplexing. Beamforming consists of transmitting the same signal with different gain and phase over all transmit antennas such that the receiver signal is maximized. Diversity consists of transmitting a single space-time coded stream through all antennas.

Advantages of MIMO systems include:

1. *Beamforming* - A transmitter receiver pair can perform beamforming and direct their main beams at each other,thereby increasing the receiver's received power and consequently the SNR.

2. *Spatial diversity* - A signal can be coded through the transmit antennas, creating redundancy, which reduces the outage probability.

3. *Spatial multiplexing* - A set of streams can be transmitted in parallel, each using a different transmit antenna element. The receiver can then perform the appropriate signal processing to separate the signals.

It is important to note that each antenna element on a MIMO system operates on the same frequency and therefore does not require extra bandwidth.

Space-time block coding (STBC), one of the STC techniques, is used to improve the performance of MIMO systems. It takes advantage of the spatial and temporal diversity as well as coding gain. STBC can provide diversity gain over an uncoded system without sacrificing the bandwidth and increase the effective transmission rate as well as the potential system capacity.

Accurate estimation of channel parameters is critical to a reliable recovery of the transmitted signals. Therefore, an effective channel estimation method plays an important role.

As a consequence of their advantages, MIMO wireless systems have captured the attention of international standard organizations. The use of MIMO has been proposed multiple times for use in the high-speed packet data mode of thirdgeneration cellular systems (3G),as well as the fourthgeneration cellular systems (4G).

Chapter 2

MIMO SYSTEM

Before discussing the system and the channel models,familiarisation with certain terms is necessary.

1. **Array Gain**:Array gain is the average increase in the signal-to-noise ratio (SNR) at the receiver that arises from the coherent combining effect of multiple antennas at the receiver or transmitter or both.If the channel is known to the multiple antenna transmitter,the transmitter will weigh the transmission with weights,depending on the channel coefficients,so that there is coherent combining at the single antenna receiver (MISO case).The array gain in this case is called transmitter array gain.Alternately if we have only one antenna at the transmitter and no knowledge of the channel and a multiple antenna receiver,which has a perfect knowledge of the channel,then the receiver can suitably weight the incoming signals so that they coherently add up at the output (combining),thereby enhancing the signal.This is the SIMO case.This is called receiver array gain.Basically,multiple antenna systems require perfect channel knowledge either at the transmitter or receiver or both to achieve this array gain.

2. **Diversity Gain**:Multipath fading is a significant problem in communications. In a fading channel,signals experience fades (i.e., they fluctuate in their strength). When the signal power drops significantly, the channel is said to be in a fade. This gives rise to high bit error rates (BER) . We resort to diversity to combat fading. This involves providing replicas of the transmitted signal over time, frequency, or space. There are three types of diversity schemes in wireless communications.

   (a) *Temporal diversity*:In this case replicas of the transmitted signal are provided across time by a combination of channel coding and time interleaving strategies. The key requirement here for this form of diversity to be effective is that the channel must provide sufficient variations in time. It is applicable in cases where the coherence time of the channel is small compared with the desired interleaving symbol duration. In such an event, we are assured that the interleaved symbol is independent of the previous symbol. This makes it a completely new replica of the original symbol.

(b) *Frequency diversity*:This type of diversity provides replicas of the original signal in the frequency domain. This is applicable in cases where the coherence bandwidth of the channel is small compared with the bandwidth of the signal. This assures us that different parts of the relevant spectrum will suffer independent fades.

(c) *Spatial diversity*:This is also called antenna diversity and is an effective method for combating multipath fading. In this case, replicas of the same transmitted signal are provided across different antennas of the receiver.This is applicable in cases where the antenna spacing is larger than the coherent distance to ensure independent fades across different antennas.

Basically the effectiveness of any diversity scheme lies in the fact that at the receiver we must provide independent samples of the basic signal that was transmitted.In such an event we are assured that the probability of two or more relevant parts of the signal undergoing deep fades will be very small. The constraints on coherence time, coherence bandwidth, and coherence distance ensure this. The diversity scheme must then optimally combine the received diversified waveforms so as to maximize the resulting signal quality. We can also categorize diversity under the subheading of spatial diversity, based on whether diversity is applied to the transmitter or to the receiver.

(a) *Receive diversity*:Maximum ratio combining is a frequently applied diversity scheme in receivers to improve signal quality. In cell phones it becomes costly and cumbersome to deploy. This is one of the main reasons transmit diversity became popular, since transmit diversity is easier to implement at the base station.

(b) *Transmit diversity*:In this case we introduce controlled redundancies at the transmitter, which can be then exploited by appropriate signal processing techniques at the receiver. Generally this technique requires complete channel information at the transmitter to make this possible. But with the advent of space-time coding schemes like Alamouti's scheme, it became possible to implement transmit diversity without knowledge of the channel.

Therefore, in MIMO we talk a lot about receive antenna diversity or transmit antenna diversity. In receive antenna diversity, the receiver that has multiple antennas receives multiple replicas of the same transmitted signal, assuming that the transmission came from the same source. This holds true for

SIMO channels. If the signal path between each antenna pair fades independently, then when one path is in a fade, it is extremely unlikely that all the other paths are also in deep fade. Therefore, the loss of signal power due to fade in one path is countered by the same signal but received through a different path (route).

2.1 Choosing between Open-Loop and Closed-Loop MIMO Systems

MIMO is a promising technique for achieving the high-speed data rate needed in future wireless data systems. Multiple streams can be transmitted using MIMO, thereby increasing system throughput.
In a traditional wireless system, the receiver and transmitter do not communicate back and forth. The receiver is alone in figuring out the channel information and decoding the streams. This puts a heavy complexity burden on the receiver and prevents the system from fully utilizing channel diversity or capacity. These systems are called open-loop systems.
Most current wireless standards allocate a limited feedback channel between the handset and Base Transceiver Station (BTS). This channel can be used for many purposes, especially for sending vital information about the channel back to the BTS. The information enables simple spatial diversity and multiplexing techniques that increase the system's effective Signal-to-Noise Ratio (SNR) and potentially simplify the receiver architecture. These systems are called closed-loop systems.

2.1.1 Open-Loop Systems

For multiple transmit antennas, the channel becomes more complicated, and there is interference between different transmitted streams. If the transmitter has no channel knowledge, the receiver is alone in exploiting MIMO capacity, which usually means that a complicated algorithm is required.
Spatial Multiplexing is a well-known open-loop MIMO technique widely used in wireless systems.The system can be modelled as given in the next page.

Where , x is the transmitted signal vector, H is the channel matrix, n is the adding noise vector, and y is the received signal vector.

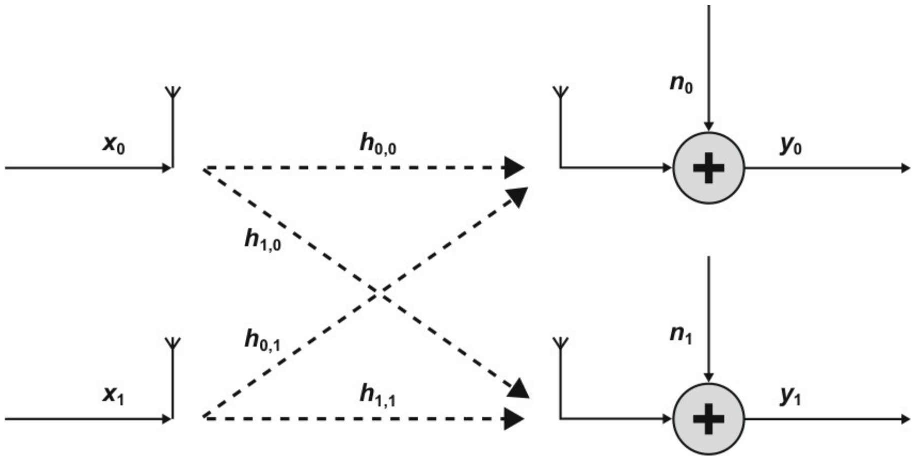

Figure 2.1: Spatial Multiplexing System

Space Time Codes is another widely used open-loop MIMO technique is space-time code. With space-time codes, a single data stream is transmitted from multiple transmit antennas, but the signal is coded to exploit independent fading in multiple antennas to achieve space diversity.

2.1.2 Closed-Loop Systems

Closed-loop MIMO is becoming more important in modern wireless communications. The BTS transmitter utilizes channel information to enable simple spatial diversity or beam-forming techniques that increase the system's effective SNR and potentially simplify the receiver architecture.

2.1.3 Limited Feedback Systems

The main problem is how to obtain channel knowledge at the transmitter. Most current wireless standards allocate a feedback channel to transmit channel knowledge to the BTS. This feedback solution can work in Frequency-Division Duplex (FDD) and Time-Division Duplex (TDD) systems. Because the redundant channel information puts heavy overhead on the system uplink, channel information is usually quantized to reduce the feedback message size. This quantized information feedback is called limited feedback.

the system provides a **code book**, which includes precoding matrices corresponding to possible channels. According to the estimated channel in the handset, the corresponding precoding matrix index is chosen and transmitted back to the BTS.

Another way to obtain channel information is by **uplink sounding**, where the handset transmits a sounding signal in the uplink. The BTS utilizes the channel's reciprocity property to obtain downlink channel information. The advantage of uplink sounding is that it has less delay than a feedback solution and does not require a feedback channel. However, this method has some drawbacks. Uplink sounding is suitable in a TDD system, but in an FDD system, downlink and uplink use different frequency bands whose channel properties may be different.

2.1.4 The Pros and Cons

Among open-loop MIMO techniques, spatial multiplexing pursues maximum multiplexing gain. Although this method can transmit multiple data streams in multiple transmit antennas, it requires a complicated detection algorithm in the receiver. In contrast with spatial multiplexing, Alamouti code provides simple optimal detection and can achieve maximum diversity gain, but it transmits only one data stream in multiple transmit antennas. Choosing spatial multiplexing or Alamouti code depends on the channel condition.

As opposed to open-loop MIMO approaches, closed-loop MIMO techniques utilize channel knowledge to improve SNR or capacity and simplify receiver design. Because there is a delay to receive channel information, designers should be careful when applying closed-loop MIMO in a highly mobile environment. Furthermore, closed-loop MIMO suffers performance loss due to incomplete channel knowledge in limited feedback and uplink sounding.

Each MIMO technique has advantages and disadvantages. When designing a wireless system, designers should choose an appropriate MIMO technique by considering its service type, channel condition, complexity, and delay.

2.2 System Model

MIMO systems are composed of three main elements,namely the transmitter(TX), the channel (H), and the receiver (RX). In this paper, N_t is denoted as the number of antenna elements at the transmitter, and N_r is denoted as the number of elements at the receiver. Figure 1 depicts such MIMO system block diagram.

The channel with N_r outputs and N_t inputs is denoted as a $N_r \times N_t$ matrix:

$$\mathbf{H} = \begin{pmatrix} h_{1,1} & \cdots & h_{1,N_t} \\ \vdots & \ddots & \vdots \\ h_{N_r,1} & \cdots & h_{N_r,N_t} \end{pmatrix} \tag{2.1}$$

where each entry $h_{i,j}$ denotes the attenuation and phase shift (transfer function) between the j^{th} transmitter and the i^{th} receiver.

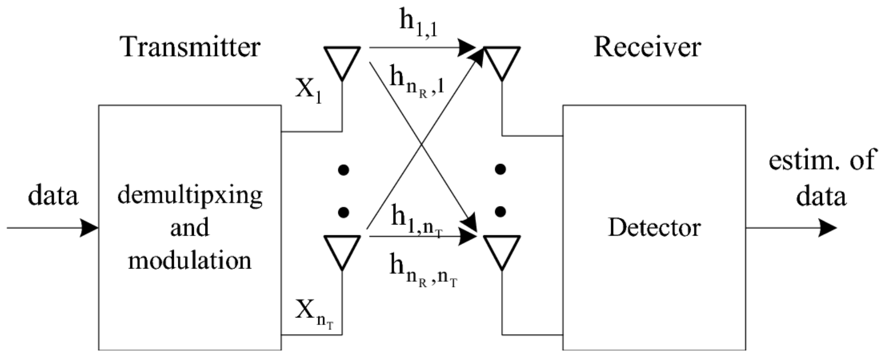

Figure 2.2: MIMO block diagram

MIMO signal is described as:

$$\vec{r} = \mathbf{H}\vec{s} + \vec{n} \tag{2.2}$$

where $\vec{r}$ is the received vector of size $N_r \times 1$, H is the channel matrix of size $N_r \times N_t$, $\vec{s}$ is the transmitted vector of size $N_t \times 1$, and $\vec{n}$ is the noise vector of size $N_r \times 1$. Each noise element is typically modeled as independent identically distributed (i.i.d.) white Gaussian noise,with variance N_t=(2 . SNR). An explanation for this model is as follows. The transmitted signals are mixed in the channel since they use the same carrier frequency. At the receiver side,the received signal is composed of a linear combination of each transmitted signal plus noise. The receiver can solve for the transmitted signals by treating (3) as a system of linear equations. If the channel H is correlated, the system of linear equations will have more unknowns than equations. One reason correlation between signals can occur is due to the spacing between antennas. To prevent correlation due to the spacing, they are typically spaced at least $\lambda_c/2$, where λ_c is the wavelength of the carrier frequency. The second reason correlation can occur is due to lack of multipath components. It is for this reason that rich multipath is desirable in MIMO systems. The multipath effect can be interpreted by each receive antenna being in a different channel.

Since the performance of MIMO systems depends highly on the channel matrix, it is important to model the channel matrix realistically. The following section provides an overview of typical channel models used for computer simulations.

2.3 Channel Model

Channel models for MIMO systems can be either simple or very complex, depending on the environment modeled and the desired accuracy. There are two different techniques for modeling MIMO channels. One method is to calculate the MIMO channel matrix according to a physical representation of the environment. The channel matrix in such a physical model would depend on physical parameters such as the angle of arrival (AOA), angle of departure (AOD), and time of arrival (TOA).As expected, these type of deterministicmodels are highly complex.

Another technique to model MIMO channels, is to model the channel analytically. Such a model treats all channels between each transmit antenna to each receive antenna as SISO channels. This type of model assumes that the channels are independent and identically distributed (i.i.d.). However, depending on the environment modeled, this assumption is rarely true. The reason is that MIMO channels can experience spatial correlation between links. It is possible to generate a MIMO channel with a specific correlation matrix. The channel correlation matrix is usually measured in the field and it is tied to the environment setup such as antenna element patterns, spacing between antennas, and surrounding reflectors.

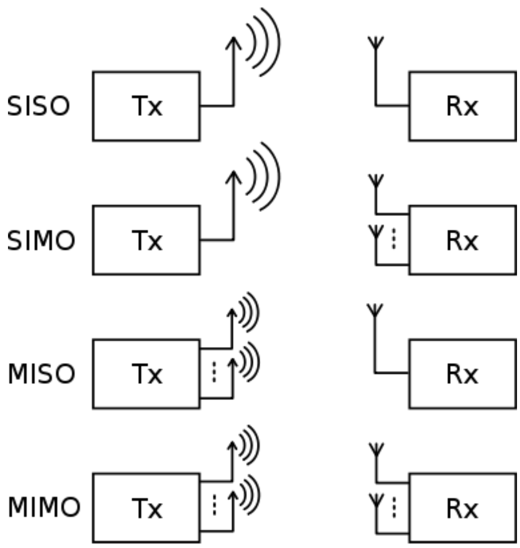

Figure 2.3: Channel models

2.4 Mathematical Analysis of One and Two receivers

During internship I did my analysis for two transmitters and one/two receiver(s) systems.
The Transmission matrix is taken as:

$$T = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix} \tag{2.3}$$

2.4.1 Two Transmitters and One Receiver

$$r_1^{(1)} = r_1(t) = h_1 s_1 + h_2 s_2 + n_1^{(1)} \tag{2.4}$$

$$r_1^{(2)} = r_1(t+T) = -h_1 s_2^* + h_2 s_1^* + n_1^{(2)} \tag{2.5}$$

where r_1 is the received signal at antenna 1, h_j is the channel transfer function from the *j*th transmit antenna,n_1 is a complex random variable representing noise at antenna 1.And $r^{(k)}$ denotes r at time instant k.

2.4.2 Two Transmitters and Two Receiver

$$r_1^{(1)} = h_{1,1}s_1 + h_{1,2}s_2 + n_1^{(1)}$$

$$r_1^{(2)} = -h_{1,1}s_2^* + h_{1,2}s_1^* + n_1^{(2)}$$

$$r_2^{(1)} = h_{2,1}s_1 + h_{2,2}s_2 + n_2^{(1)}$$

$$r_2^{(2)} = -h_{2,1}s_2^* + h_{2,2}s_1^* + n_2^{(2)}$$

2.5 MATLAB Outputs and Analysis

These are the simulation outputs for a MIMO System with feedback.

2.5.1 Two Transmitter and one Receiver System

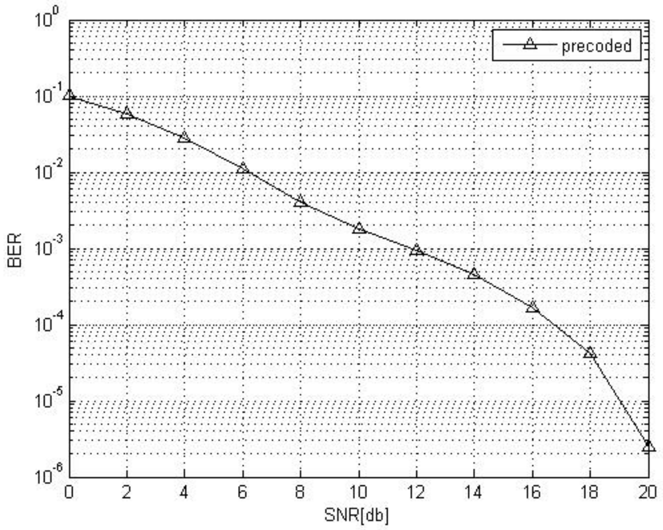

Figure 2.4: two cross one output

The above matlab output shows how bit error rate decreases with increase in the transmission power.

2.5.2 Two Transmitter and two Receiver System

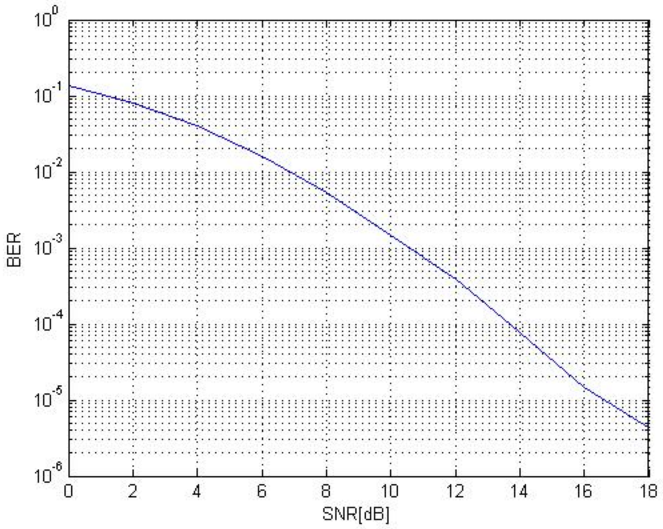

Figure 2.5: two cross two output

We can clearly make out from the above matlab output for Two Transmitter and Two Receiver system that bit error error rate drops faster as compared to the case earlier,in one receiver system.Thus we can decrease the bit error rate by simply increasing the number of antennas on the receiver side.

Chapter 3

Vector Quantization

3.1 Introduction

Vector quantization is a classical quantization technique which allows the modeling of probability density functions by the distribution.It works by dividing a large set of points (vectors) into groups having approximately the same number of points closest to them. Each group is represented by its centroid point.The density matching property of vector quantization is powerful, especially for identifying the density of large and high-dimensioned data. Since data points are represented by the index of their closest centroid, commonly occurring data have low error, and rare data high error.
A vector quantizer maps k-dimensional vectors in the vector space R^k into a finite set of vectors Y = { y_i: i = 1, 2, ..., N}. Each vector y_i is called a code vector or a codeword. and the set of all the codewords is called a codebook. Associated with each codeword, y_i, is a nearest neighbor region called Voronoi region, and it is defined by:

$$V_i = \{x\epsilon R^k : \|x - y_i\| \leq \|x - y_j\|, forallj \neq i\} \tag{3.1}$$

However it might be the case that there are some points in the plane that might have more than one site that is the closest to it. These points do not lie in either Voronoi Region, but simply lie on the boundary of two adjacent regions. All such points form a skeleton of lines that is called the Voronoi Skeleton.

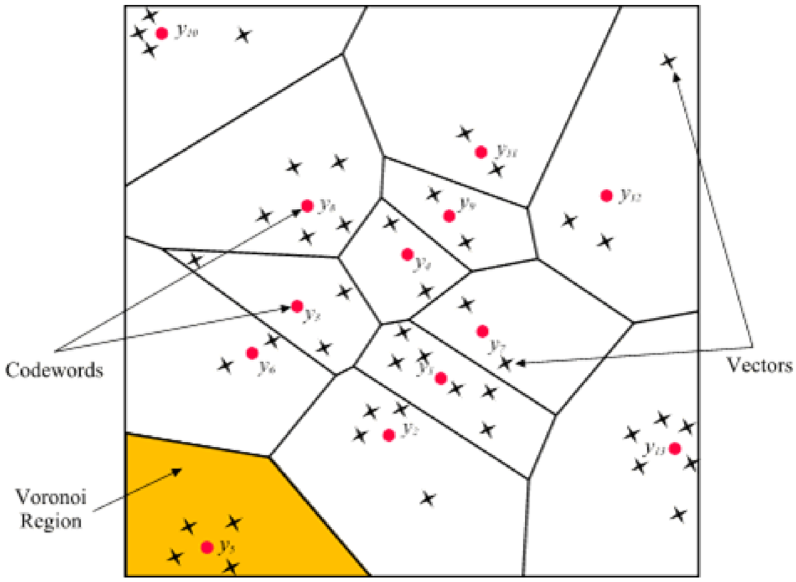

Figure 3.1: Codewords in 2-dimensional space. Input vectors are marked with an x, codewords are marked with red circles, and the Voronoi regions are separated with boundary lines

The infinite number of samples are taken and then quantized in a finite number of vectors,i.e.the codebook is designed and then sent through the channel.

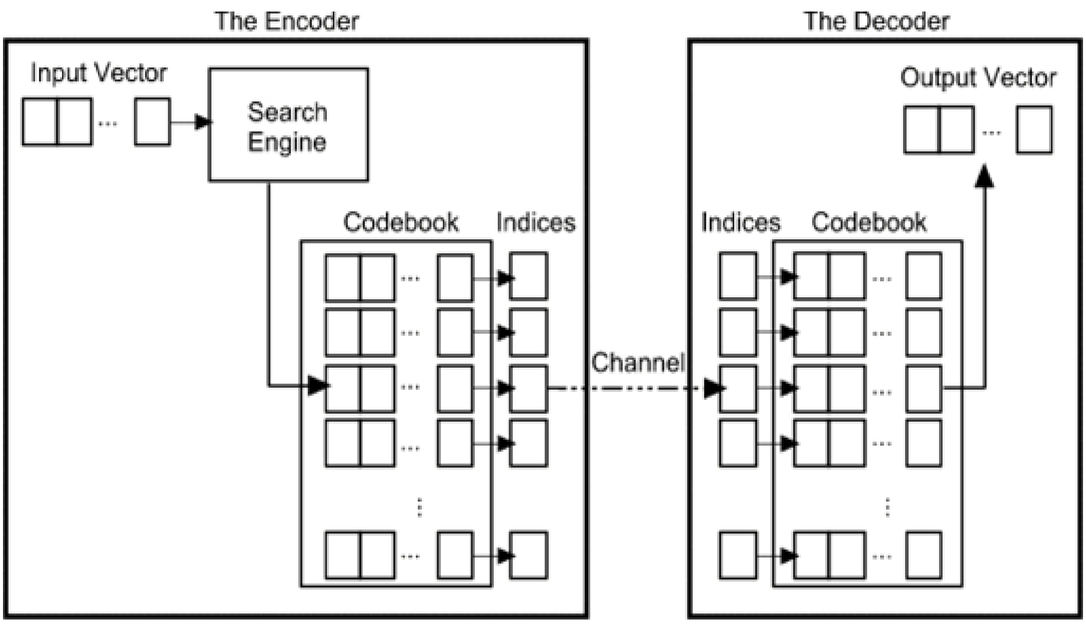

Figure 3.2: Schematic of a Vector Quantizer

Vector quantization lowers the bit rate of the signal being quantized thus making it more bandwidth efficient. But this however contributes to it's implementation complexity (computation and storage).

3.2 Why Design Codebook?

- When information about the channel is available at the transmitter, the performance of OSTBC can be significantly improved by exploiting the array gain. However, providing full knowledge of channel state at the transmitter may not he affordable in many practical cases.
- Unfortunately, transmitters in many wireless systems have no knowledge about current channel conditions. This motivates limited feedback precoding methods such as channel quantization.
- The receiver chooses a matrix from the codebook based on current channel conditions and conveys the optimal codebook matrix to the transmitter over an error-free, zero-delay feedback channel.

Thus depending upon the feedback from the receiver side,the Transmitter can choose the channel for transmission to optimize the transmission power.

Chapter 4

SPACE TIME BLOCK CODING

One of the methodologies for exploiting the capacity in MIMO system consists of using the additional diversity of MIMO systems, namely spatial diversity, to combat channel fading. This can be achieved by transmitting several replicas of the same information through each antenna. By doing this, the probability of loosing the information decreases exponentially. The antennas in a MIMO system are used for supporting a transmission of a SISO system since the targeted rate of is that of a SISO system. The diversity order or diversity gain of a MIMO system is defined as the number of independent receptions of the same signal. A MIMO system with N_t transmit antennas and N_r receive antennas has potentially full diversity (i.e. maximum diversity) gain equal to N_tN_r. The different replicas sent for exploiting diversity are generated by a space-time encoder which encodes a single stream through space using all the transmit antennas and through time by sending each symbol at different times. This form of coding is called Space-Time Coding (STC). Due to their decoding simplicity, the most dominant form of STCs are space-time block codes (STBC).

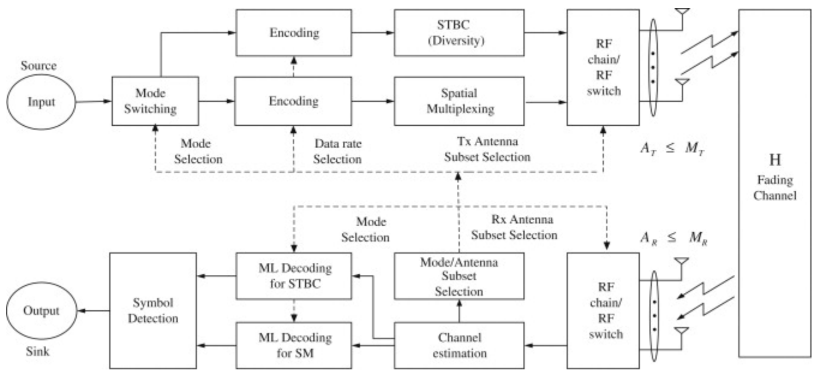

Figure 4.1: Space time block diagram

4.1 Alamouti Scheme

Space Time Block Codes having two transmit antenna configuraion is referred to as **Alamouti scheme**.The Alamouti STBC scheme uses two transmit antennas and N_r receive antennas and can accomplish a maximum diversity order of $2N_r$. Moreover, the Alamouti scheme has full rate (i.e. a rate of 1) since it transmits 2 symbols every 2 time intervals. Next, a description of the Alamouti scheme is provided for both 1 and 2 receive antennas, followed by a general expression for the decoding mechanism for the case of N_r receive antennas.

4.1.1 Description

As mentioned earlier, Alamouti STBC uses two transmit antennas regardless of the number of receive antennas. In this report, the rows of each coding scheme represents a different time instant, while the columns represent the transmitted symbol through each different antenna. In this case, the first and second row represent the transmission at the first and second time instant respectively. At a time *t*,the symbol s_1 and symbol s_2 are transmitted from antenna 1 and antenna 2 respectively. Assuming that each symbol has duration T, then at time *t* + T, the symbols $-s_2^*$ and s_1^*,where $(.)^*$ denotes the complex conjugate, are transmitted from antenna 1 and antenna 2 respectively.

$$T = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix} \tag{4.1}$$

4.1.2 Mathematical analysis for One and Two Receivers

I analysed for Two transmitters and One/Two receiver antenna systems.

For 1 receiver antenna

The reception and decoding of the signal depends on the number of receive antennas available. For the case of one receive antenna, the receive signals are:

$$r_1^{(1)} = r_1(t) = h_{1,1}s_1 + h_{1,2}s_2 + n_1^{(1)} \tag{4.2}$$

$$r_1^{(2)} = r_1(t+T) = -h_{1,1}s_2^* + h_{1,2}s_1^* + n_1^{(2)} \tag{4.3}$$

where r_1 is the received signal at antenna 1, $h_{i,j}$ is the channel transfer function from the *j*th transmit

antenna and the *i*th receive antenna,n_1 is a complex random variable representing noise at antenna 1, and $x^{(k)}$ denotes x at time instant *k* (i.e. at time t + (k - 1)T).
Before the received signals are sent to the decoder, they are combined as follows:

$$\tilde{s}_1 = h_{1,1}^* r_1^{(1)} + h_{1,2} r_1^{*(2)} \tag{4.4}$$

$$\tilde{s}_2 = h_{1,2}^* r_{(1)} + h_{1,1} r_1^{*(2)} \tag{4.5}$$

and substituting (2),(3) in (4),(5) yields:

$$\tilde{s}_1 = (\alpha_{1,1}^2 + \alpha_{1,2}^2) s_1 + h_{1,1}^* n_1^{(1)} + h_{1,2} n_1^{*(2)} \tag{4.6}$$

$$\tilde{s}_2 = (\alpha_{1,1}^2 + \alpha_{1,2}^2) s_2 - h_{1,1} n_1^{*(2)} + h_{1,2}^* n_1^{(1)} \tag{4.7}$$

where $\alpha_{i,j}^2$ is the squared magnitude of the channel transfer function $h_{i,j}$.The calculated $\tilde{s}_1$ and $\tilde{s}_2$ are then sent to a Maximum Likelihood (ML) decoder to estimate the transmitted symbols s_1 and s_2 respectively.

For 2 receiver antenna

For the case of two receiver antennas, the received symbols are:

$$r_1^{(1)} = h_{1,1} s_1 + h_{1,2} s_2 + n_1^{(1)}$$

$$r_1^{(2)} = -h_{1,1} s_2^* + h_{1,2} s_1^* + n_1^{(2)}$$

$$r_2^{(1)} = h_{2,1} s_1 + h_{2,2} s_2 + n_2^{(1)}$$

$$r_2^{(2)} = -h_{2,1} s_2^* + h_{2,2} s_1^* + n_2^{(2)}$$

Before sending these signals to the decoder,they are combined as follows:

$$\tilde{s}_1 = h_{1,1}^* r_1^{(1)} + h_{1,2} r_1^{*(2)} + h_{2,1}^* r_2^{(1)} + h_{2,2} r_2^{*(2)} \tag{4.8}$$

$$\tilde{s}_2 = h_{1,2}^* r_1^{(1)} + h_{1,1} r_1^{*(2)} + h_{2,2}^* r_2^{(1)} + h_{1,1} r_2^{*(2)} \tag{4.9}$$

substituting $r_1^{(1)}$,$r_1^{(2)}$,$r_2^{(1)}$,$r_2^{(2)}$ in equations:(8) and (9),we get:

$$\tilde{s}_1 = (\alpha_{1,1}^2 + \alpha_{1,2}^2 + \alpha_{2,1}^2 + \alpha_{2,2}^2)s_1 + h_{1,1}^* n_1^{(1)} + h_{1,2} n_1^{*(2)} + h_{2,1}^* n_2^{(1)} + h_{2,2} n_2^{*(2)} \tag{4.10}$$

$$\tilde{s}_2 = (\alpha_{1,1}^2 + \alpha_{1,2}^2 + \alpha_{2,1}^2 + \alpha_{2,2}^2)s_2 + h_{1,2}^* n_1^{(1)} - h_{1,1} n_1^{*(2)} + h_{2,2}^* n_2^{(1)} - h_{2,1} r_2^{*(2)} \tag{4.11}$$

4.1.3 Decoding decision for Nr receiving antennas

The Maximum Liklihood decoder decision statistic decodes in favor of s_1 and s_2 over all possible values of s_1 and s_2 such that (12) and (13) are minimized; where ψ is given by (14) for N_t = 2:

$$| \left[\sum_{i=1}^{N_r} (r_i^{(1)} h_{i,1}^* + r_i^{*(2)} h_{i,2}) \right] - s_1 |^2 + \psi |s_1|^2 \tag{4.12}$$

$$| \left[\sum_{i=1}^{N_r} (r_i^{(1)} h_{i,2}^* - r_i^{*(2)} h_{i,1}) \right] - s_2 |^2 + \psi |s_2|^2 \tag{4.13}$$

Where ψ is defined as:

$$\psi = (-1 + \sum_{i=1}^{N_r} \sum_{j=1}^{N_t} |h_{i,j}|^2) \tag{4.14}$$

If having more antennas at the receivers is not a problem, this scheme can be used with 2 transmit antennas and N_r receive antennas while accomplishing a $2N_r$ full diversity.

4.2 Othogonal Space Time Block Codes

The Alamouti scheme discussed above is part of a general class of STBCs known as Orthogonal Space-Time Block Codes (OSTBCs).We can apply the mathematical framework of orthogonal designs to construct both real and complex orthogonal codes that achieve full diversity. However, for the case of complex orthogonal codes, it is unknown if a full rate and full diversity codes exist for N_t > 2.

4.2.1 for 3 transmit antennas

For the case of 3 transmit antennas.Taking examples of block codes for 1/2 and 3/4 coding rate and full diversity $3N_r$.

n_t = 3 with rate 1/2,full diversity is given by:

$$g_3 = \begin{pmatrix} s_1 & s_2 & s_3 \\ -s_2 & s_1 & -s_4 \\ -s_3 & s_4 & s_1 \\ -s_4 & -s_3 & s_2 \\ s_1^* & s_2^* & s_3^* \\ -s_2^* & s_1^* & -s_4^* \\ -s_3^* & s_4^* & s_1^* \\ -s_4^* & -s_3^* & s_2^* \end{pmatrix} \tag{4.15}$$

This code transmits 4 symbols every 8 time intervals,and therefore has rate 1/2.The decision metric to minimize by the decoder for detecting s_1,s_2,s_3,s_4 are given by (19),(20),(21),(22) respectively where

$$\psi = (-1 + 2\sum_{i=1}^{N_r}\sum_{j=1}^{N_t}|h_{i,j}|^2) \tag{4.16}$$

$$|\left[\sum_{i=1}^{N_r}(r_i^{(1)}h_{i,1}^* + r_i^2 h_{i,2}^* + r_i^3 h_{i,3}^* + r_i^{*(5)}h_{i,1} + r_i^{*(6)}h_{i,2} + r_i^{*(7)}h_{i,3})\right] - s_1|^2 + \psi|s_1|^2 \tag{4.17}$$

$$|\left[\sum_{i=1}^{N_r}(r_i^{(1)}h_{i,2}^* - r_i^{(2)}h_{i,1}^* + r_i^{(4)}h_{i,3}^* + r_i^{*(5)}h_{i,2} - r_i^{*(6)}h_{i,1} + r_i^{*(8)}h_{i,3})\right] - s_2|^2 + \psi|s_2|^2 \tag{4.18}$$

$$|\left[\sum_{i=1}^{N_r}(r_i^{(1)}h_{i,3}^* - r_i^{(3)}h_{i,1}^* + r_i^{(4)}h_{i,2}^* + r_i^{*(5)}h_{i,3} - r_i^{*(7)}h_{i,1} - r_i^{*(8)}h_{i,2})\right] - s_3|^2 + \psi|s_3|^2 \tag{4.19}$$

$$|\left[\sum_{i=1}^{N_r}-(r_i^{(2)}h_{i,3}^* + r_i^{(3)}h_{i,2}^* - r_i^{(4)}h_{i,1}^* - r_i^{*(6)}h_{i,3} + r_i^{*(7)}h_{i,2} - r_i^{*(8)}h_{i,1})\right] - s_4|^2 + \psi|s_4|^2 \tag{4.20}$$

n_t **= 3 with rate 3/4:**

$$H_3 = \begin{pmatrix} s_1 & s_2 & \frac{s_3}{\sqrt{2}} \\ -s_2^* & s_1^* & \frac{s_3}{\sqrt{2}} \\ \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} & \frac{-s_1-s_1{}^*+s_2-s_2{}^*}{2} \\ \frac{s_3^*}{\sqrt{2}} & -\frac{s_3^*}{\sqrt{2}} & \frac{s_1-s_1{}^*+s_2+s_2{}^*}{2} \end{pmatrix} \tag{4.21}$$

As can be observed,(23) transmits 3 symbols every 4 time intervals, and therefore has rate 3/4. The decision statistic to minimize for detecting s_1, s_2, and s_3 are given by (24), (25),and (26) respectively

$$|\left[\sum_{i=1}^{N_r}(r_i^{(1)}h_{i,1}^* + r_i^{*(2)}h_{i,2} + \frac{(r_i^{(4)} - r_i^{(3)})h_{i,3}^*}{2} - \frac{(r_i^{(3)} + r_i^{(4)})^* h_{i,3}}{2})\right] - s_1|^2 + \psi|s_1|^2 \tag{4.22}$$

$$|\left[\sum_{i=1}^{N_r}(r_i^{(1)}h_{i,2}^* - r_i^{*(2)}h_{i,1} + \frac{(r_i^{(4)} + r_i^{(3)})h_{i,3}^*}{2} + \frac{(-r_i^{(3)} + r_i^{(4)})^* h_{i,3}}{2})\right] - s_2|^2 + \psi|s_2|^2 \tag{4.23}$$

$$|\left[\sum_{i=1}^{N_r}(\frac{(r_i^{(1)} + r_i^{(2)})h_{i,3}^*}{\sqrt{2}} + \frac{r_i^{*(3)}(h_{i,1} + h_{i,2})}{\sqrt{2}} + \frac{r_i^{*(4)}(h_{i,1} - h_{i,2})}{\sqrt{2}})\right] - s_3|^2 + \psi|s_3|^2 \tag{4.24}$$

4.3 Result and Analysis

The following are the matlab outputs for Space Time Block Codes without feedback.

4.3.1 Two Transmitters and One Receiver

MIMO-STBC has a better performance than just MIMO.Yet the BER has lesser slope as compared to MIMO case.This is because the transmitter does not have the feedback information from the receiver.

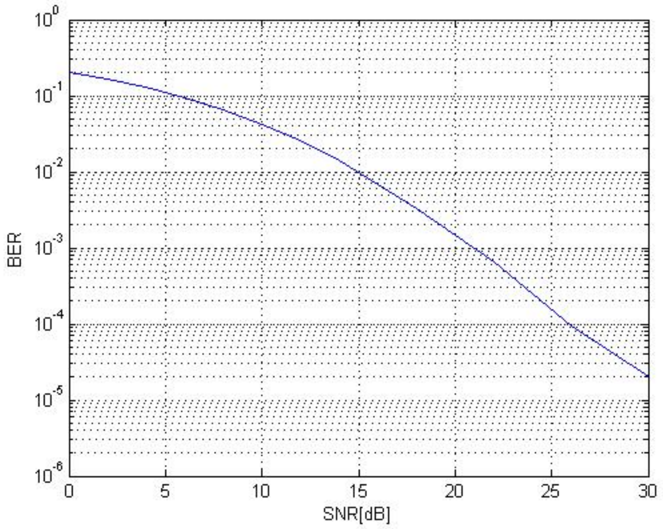

Figure 4.2: two cross one STBC output

4.3.2 Two Transmitters and Two Receivers

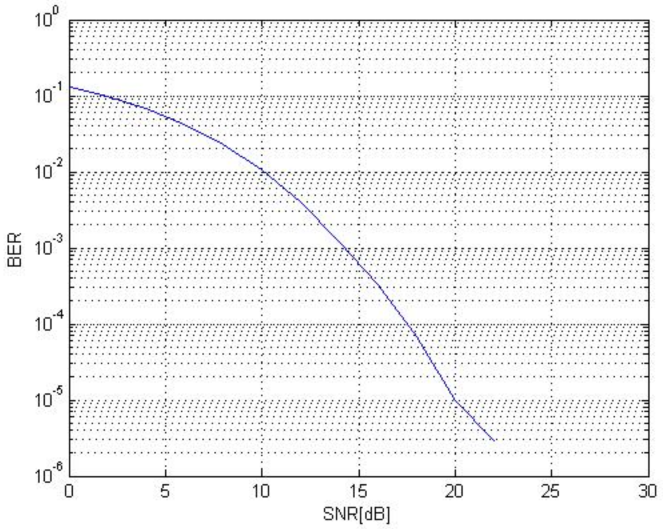

Figure 4.3: two cross two STBC output

The slope increases with increase in the number of receiving antennas.Thus efficiency can be enhanced with lesser transmission power requirement,than it used to be.

If we were to compare the bit error rates for all systems under a single graph.It would appear as under.The plots are for open loop.fig:4.4

As a part of my project,I did try working for Two Transmitter and One Receiver system using Alamouti scheme with feedback.As an output I expected to get a greater sloped waterfall curve.Constant BER is what i have got so far working on it.fig:4.5

Matlab code for this is attached as Appendix A7 in this report.

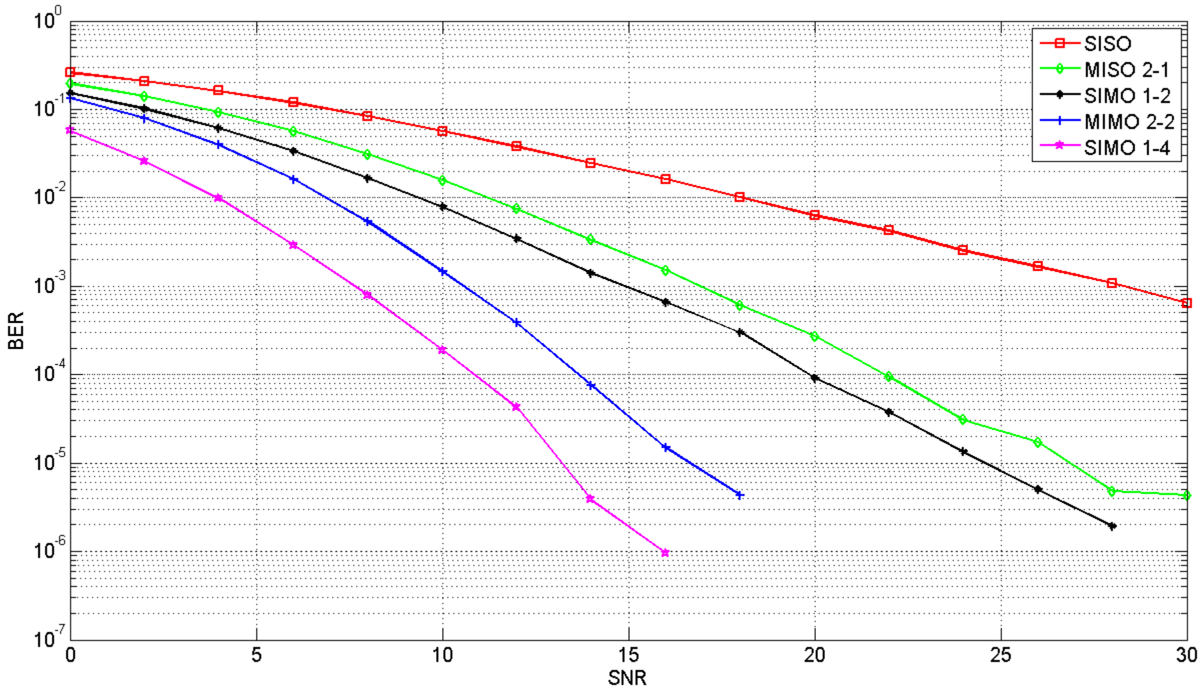

Figure 4.4: Comparision

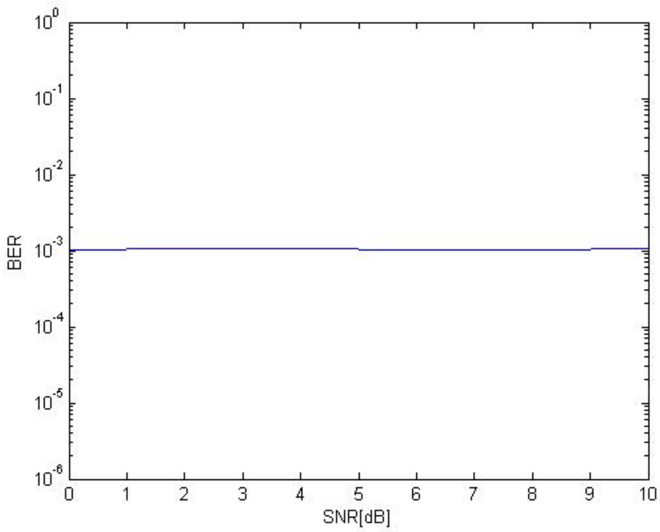

Figure 4.5: STBC two cross one output with feedback(partial)

Chapter 5

CONCLUSION

MIMO systems enhances the data transfer rate; further it prevents a system from falling into *Outage*,even if data in a channel is lost. Moreover providing the Transmitter with the channel information as per the output received at receiving end,transmitting power can be optimized. Thus the closed-loop multiple-input multiple-output systems with feedback channel significantly improve performance of systems.Performance of MIMO systems is enhanced by Space Time Block Coding,which takes the advantages of spatial diversity as well as temporal diversity.

Codebook design is of great use as it helps in data compression.moreover sending entire data over transmission channel would result in loss of data and very high power would be required for transmission.With *Codebook* the *Quantized* data is not sent as it is. The receiver notes the *Index* and transmits the index instead.Lesser bandwidth is required for index transmission.Thus a closed loop is formed.

However,the STBC for closed-loop MIMO systems with 2 transmit antennas is not known so far. In this project,I worked on MIMO systems with feedback comprising One and Two receivers,STBC systems without feedback for both One and Two Receivers and tried working on STBC system with feedback.The theoritical output is different from what I received for STBC with feedback.There could possibly be some discrepancy in the algorithm.

Appendix A1

Matlab code for Two Transmitters and one Receiver MIMO System

```
clear all
n_frame=1000;                   %number of frames
n_packet=100;                   %number of packets
b=2;                            %bit size is two
m=2^b;                          %modulating factor
mod_obj=modem.qammod('m',m,'symbolorder','gray','inputtype','bit');
demod_obj=modem.qamdemod(mod_obj);
%MIMO parameters
t_tx=4;
code_length=64;                   %length of the code
nt=2;                             %two transmitters
nr=1;                             %one receiver
n_pbits=nt*b*n_frame;n_tbits=n_pbits*n_packet;
code_book=codebook_generator;           %codebook generator from sub program
fprintf('===============\n');
fprintf('precoding transmission');
fprintf('n %d x %d MIMO\n %d QAM',nt,nr,m);
fprintf('\n simulation bits : %d',n_tbits);
fprintf('\n=============\n');
SNRdbs = [0:2:30];
sq2=sqrt(2);
for i_SNR=1:length(SNRdbs)
    SNRdb=SNRdbs(i_SNR);
    noise_var=nt*0.5*10^(-SNRdb/10);sigma=sqrt(noise_var);  %noise variance
    rand('seed',1);randn('seed',1);n_ebits=0;
    for i_packet=1:n_packet
        msg_bit=randint(n_pbits,1);

        %%%%%%%transmitter%%%%%%%

        s=modulate(mod_obj,msg_bit);
        scale=modnorm(s,'avpow',1);
        S=reshape(scale*s,nt,1,n_frame);
        tx_symbol=[S(1,1,:) -conj(S(2,1,:));S(2,1,:) conj(S(1,1,:))];

        %%%%%%%%%%%%%%%%%%channel noise%%%%%%%%%%%%%%%%%%%
```

```
        h=(randn(nr,t_tx)+j*randn(nr,t_tx))/sq2;
        for i=1:code_length
            cal(i)=norm(h*code_book(:,:,i),'fro');
        end
        [val,index]=max(cal);
        he=h*code_book(:,:,index);
        norm_h2=norm(he)^2;
        for i=1:n_frame
            rx(:,:,i)=he*tx_symbol(:,:,i)+sigma*(randn(nr,2)+j*randn(nr,2));
        end

        %%%%%%%%%%%%%%%%receiver%%%%%%%%%%%%%%%%%

        for i=1:n_frame
            y(1,i)=(he(1)'*rx(:,1,i)+he(2)*rx(:,2,i)')/norm_h2;  %received at T1
            y(2,i)=(he(2)'*rx(:,1,i)-he(1)*rx(:,2,i)')/norm_h2;  %received at T2
        end
        s_hat=reshape(y/scale,nt*n_frame,1);
        msg_hat=demodulate(demod_obj,s_hat);
        n_ebits=n_ebits+sum(msg_hat~=msg_bit);
    end
    BER(i_SNR)=n_ebits/n_tbits;
end
semilogy(SNRdbs,BER,'-k^','linewidth',1); hold on;grid on;
xlabel('SNR[db]'),ylabel('BER');legend('precoded');
```

Appendix A2

Matlab code for Two Transmitters and one Receiver MIMO System

```
%%%%%two cross two %%%%%%%%%
clear all
n_frame=1000;
n_packet=100;
b=2;
m=2^b;
mod_obj=modem.qammod('m',m,'symbolorder','gray','inputtype','bit');
demod_obj=modem.qamdemod(mod_obj);
%MIMO parameters
t_tx=4;
code_length=64;
nt=2;
nr=2;
n_pbits=nt*b*n_frame;n_tbits=n_pbits*n_packet;
code_book=codebook_generator;
fprintf('===============\n');
fprintf('precoding transmission');
fprintf('n %d x %d MIMO\n %d QAM',nt,nr,m);
fprintf('\n simulation bits : %d',n_tbits);
fprintf('\n=============\n');
SNRdbs = [0:2:10];
sq2=sqrt(2);
for i_SNR=1:length(SNRdbs);
    SNRdb=SNRdbs(i_SNR);
    noise_var=nt*0.5*10^(-SNRdb/10);sigma=sqrt(noise_var);
    rand('seed',1);randn('seed',1);n_ebits=0;
    for i_packet=1:n_packet
        msg_bit=randint(n_pbits,1);

        %%%%%%%transmitter%%%%%%%

        s=modulate(mod_obj,msg_bit);
        scale=modnorm(s,'avpow',1);
        S=reshape(scale*s,nt,1,n_frame);
        tx_symbol=[S(1,1,:) -conj(S(2,1,:));S(2,1,:) conj(S(1,1,:))];
```

```
        %%%%%%%%%%%%%%%%%%%channel noise%%%%%%%%%%%%%%%%%%%

       hr=(randn(nr,t_tx)+j*randn(nr,t_tx))/sq2;
        for i=1:code_length
            cal1(i)=norm(hr*code_book(:,:,i),'fro');
        end
        [val,index]=max(cal1);
        he1=hr*code_book(:,:,index);
        norm_h1=norm(he1)^2;
        for i=1:n_frame
         r1(:,:,i)=he1*tx_symbol(:,:,i)+sigma*(randn(nr,2)+j*randn(nr,2));
        end

        %%%%%%%%%%%%%%%%%receiver%%%%%%%%%%%%%%%%%

        for i=1:n_frame
              y(1,i,:)=((he1(1,1)'*r1(1,1,i)'+he1(1,2)*r1(2,1,i)')+
                        (he1(2,1)'*r1(1,1,i)'+he1(2,2)*r1(2,2,i)'))/norm_h1;   %yT1
              y(2,i,:)=((he1(1,2)'*r1(2,2,i)'-he1(2,1)*r1(1,2,i)')+
              (he1(2,2)'*r1(2,2,i)'-he1(1,2)*r1(2,2,i)'))/norm_h1;   %yT2

        end
        s_hat=reshape(y/scale,nt*n_frame,1);
        msg_hat=demodulate(demod_obj,s_hat);
        n_ebits=n_ebits+sum(msg_hat~=msg_bit);
    end
    BER(i_SNR)=n_ebits/n_tbits;
end
semilogy(SNRdbs,BER,'-k^','linewidth',2); hold on;grid on;
xlabel('SNR[db]'),ylabel('BER');legend('precoded');
```

Appendix A3

Matlab code for the codebook generator sub program

```
function[code_book]=codebook_generator
n_nt=4;n_m=2;n_l=64;
column_index=[1 2];
rotation_vector=[1,7,52,56];
kk=0:n_nt-1;ll=0:n_nt-1;
w=exp(j*2*pi/n_nt*kk.'*ll)/sqrt(n_nt);
w_1=w(:,column_index([1 2]));
theta = diag(exp(j*2*pi/n_l*rotation_vector));
code_book(:,:,1)=w_1;
for i=1:n_l-1,
code_book(:,:,i+1)= theta*code_book(:,:,i);
end
```

Appendix A4

Matlab code for two transmitters and one receiver using Alamouti's scheme(STBC)

```
%%%%%%%%%%%% two cross one STBC %%%%%%%%%%%%%%%
N_frame=130; N_packet=4000;NT=2; NR=1; b=2;
SNRdBs=[0:2:30]; sq_NT=sqrt(NT); sq2=sqrt(2);
for i_SNR=1:length(SNRdBs)
SNRdB=SNRdBs(i_SNR); sigma=sqrt(0.5/(10^(SNRdB/10)));
for i_packet=1:N_packet
msg_symbol=randint(N_frame*b,NT);

%%%%%%%%%%%%%%%%%%%% Transmitter %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tx_bits=msg_symbol.'; tmp=[]; tmp1=[];

for i=1:NT
[tmp1,sym_tab,P]=modulator(tx_bits(i,:),b); tmp=[tmp; tmp1];
end
X=tmp.'; X1=X; X2=[-conj(X(:,2)) conj(X(:,1))];

%%%%%%%%%%%%%%%%%%%%%% noise channel %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for n=1:NT
    hr(n,:,:)=(randn(N_frame,NT)+j*randn(N_frame,NT))/sq2;       %noise
end

h=reshape(hr(n,:,:),N_frame,NT); Habs(:,n)=sum(abs(h).^2,2);

%%%%%%%%%%%%%%%%%%%% receiver %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

r1 = sum(h.*X1,2)/sq_NT+sigma*(randn(N_frame,1)+j*randn(N_frame,1));
                            % received signal + noise matrix for time T1
r2 = sum(h.*X2,2)/sq_NT+sigma*(randn(N_frame,1)+j*randn(N_frame,1));
                             % received signal + noise matrix for time T2

Z1 = r1.*conj(h(:,1)) + conj(r2).*h(:,2);
Z2 = r1.*conj(h(:,2)) - conj(r2).*h(:,1);

%%%%%%%%%%%% estimation and distance minimization %%%%%%%%%%%%%%%%%%%%%%
for m=1:P
```

```
xi = (-1+sum(Habs,2))*abs(sym_tab(m))^2;
e1(:,m) = abs(sum(Z1,2)-sym_tab(m)).^2 + xi;    % estimated signal for T1
e2(:,m) = abs(sum(Z2,2)-sym_tab(m)).^2 + xi;    % estimated signal for T2
end
[y1,i1]=min(e1,[],2); S1d=sym_tab(i1).'; clear e1 %row distance minimization for time T1
[y2,i2]=min(e2,[],2); S2d=sym_tab(i2).'; clear e2 %row distance minimization for time T2
Xd = [S1d S2d];                                          % decoded signal
tmp1=X>0 ; tmp2=Xd>0;
noeb_p(i_packet) = sum(sum(tmp1~=tmp2));% for coded
end % end of FOR loop for i_packet
BER(i_SNR) = sum(noeb_p)/(N_packet*N_frame*b);
end % end of FOR loop for i_SNR
semilogy(SNRdBs,BER), axis([SNRdBs([1 end]) 1e-6 1e0]);
grid on; xlabel('SNR[dB]'); ylabel('BER');
```

Appendix A5

Matlab code for two transmitters and two receivers using Alamouti's scheme(STBC)

```
% two cross two%
clear
clc
N_frame=130;
N_packet=4000;
NT=2;
NR=2;
b=2;
SNRdBs=[0:2:30];
sq_NT=sqrt(NT);
sq2=sqrt(2);
for i_SNR=1:length(SNRdBs)
    SNRdB=SNRdBs(i_SNR);
    sigma=sqrt(0.5/(10^(SNRdB/10)));
    for i_packet=1:N_packet
        msg_symbol=randint(N_frame*b,NT);

        %%%%%%%%%%%%% transmitter side %%%%%%%%%%%%%%%%%%%%%%%%%%%%

        tx_bits=msg_symbol.'; tmp=[]; tmp1=[];
        for i=1:NT
            [tmp1,const,M]=modulator(tx_bits(i,:),b); tmp=[tmp; tmp1];      %
        end
        X=tmp.'; X1=X; X2=[-conj(X(:,2)) conj(X(:,1))];

        %%%%%% noise channel %%%%%%%%%%%%%%%

        for n=1:NT
            n1(n,:,:)=(randn(N_frame,NT)+j*randn(N_frame,NT))/sq2;
        end
        for n=1:NT
            n2(n,:,:)=(randn(N_frame,NT)+j*randn(N_frame,NT))/sq2;
        end
        h1=reshape(n1(n,:,:),N_frame,NT); Habs(:,n)=sum(abs(h1).^2,2);
        h2=reshape(n2(n,:,:),N_frame,NT); Habs1(:,n)=sum(abs(h2).^2,2);
```

```
    %%%%%%%%%%%%%%%%%%%%%% receiver side %%%%%%%%%%%%%%%%%%%%%%

    r11 = sum(h1.*X1,2)/sq_NT+sigma*(randn(N_frame,1)+j*randn(N_frame,1));
                                    % receiver matrix at rx1 at time T1
    r21 = sum(h1.*X2,2)/sq_NT+sigma*(randn(N_frame,1)+j*randn(N_frame,1));
                                    % receiver matrix at rx2 at time T1
    r12 = sum(h2.*X1,2)/sq_NT+sigma*(randn(N_frame,1)+j*randn(N_frame,1));
                                    % receiver matrix at rx1 at time T2
    r22 = sum(h2.*X2,2)/sq_NT+sigma*(randn(N_frame,1)+j*randn(N_frame,1));
                                    % receiver matrix at rx2 at time T2

    Z1 = r11.*conj(h1(:,1)) + conj(r21).*h1(:,2) + r12.*conj(h2(:,1))
          + conj(r22).*h2(:,2);
    Z2 = r11.*conj(h1(:,2)) - conj(r21).*h1(:,1) + r12.*conj(h2(:,2))
         - conj(r22).*h2(:,1);
   %%%%%%%%%%%%%% estimation and distance minimization %%%%%%%%%%%%%
  for m=1:M
   xi = (-1+sum(Habs,2))*abs(const(m))^2;
   e1(:,m) = abs(sum(Z1,2)-const(m)).^2 + xi;% estimated signal for T1
   e2(:,m) = abs(sum(Z2,2)-const(m)).^2 + xi;    % estimated signal for T2
      end
          [y1,i1]=min(e1,[],2); S1d=const(i1).'; clear e1
                             % row distance minimization for time T1
          [y2,i2]=min(e2,[],2); S2d=const(i2).'; clear e2
                             % row distance minimization for time T2
          Xd = [S1d S2d];                                % decoded signal
           tmp1=X>0 ; tmp2=Xd>0;
          noeb_p(i_packet) = sum(sum(tmp1~=tmp2));% for coded
      end % end of FOR loop for i_packet
BER(i_SNR) = sum(noeb_p)/(N_packet*N_frame*b);
   end % end of FOR loop for i_SNR
semilogy(SNRdBs,BER), axis([SNRdBs([1 end]) 1e-6 1e0]);
grid on; xlabel('SNR[dB]'); ylabel('BER');
```

Appendix A6

Matlab code for modulator sub program

```
function [mod_symbols,const,M]=modulator(bitseq,b)
N_bits=length(bitseq);sq10=sqrt(10);
if b==1 % BPSK modulation
   const=exp(1j*[0 -pi]);const=sym_table([1 0]+1);
    inp=bitseq; mod_symbols=sym_table(inp+1); M=2;
elseif b==2 % QPSK modulation
   const=exp(1j*pi/4*[3 1 0 2]);
   const=const([0 1 3 2]+1);
    inp=reshape(bitseq,b,N_bits/b);
    mod_symbols=const([2 1]*inp+1);
    M=4;
elseif b==3 % generates 8-PSK symbols
   const=exp(1j*pi/4*[0:7]);
   const=sym_table([0 1 3 2 6 7 5 4]+1);
    inp=reshape(bitseq,b,N_bits/b);
    mod_symbols=sym_table([4 2 1]*inp+1); M=8;
elseif b==4 % 16-QAM modulation
    m=0;
    for k=-3:2:3 % Power normalization
        for l=-3:2:3
            m=m+1;
           const(m)=(k+1j*l)/sq10;
        end
    end
   const=sym_table([0 1 3 2 4 5 7 6 12 13 15 14 8 9 11 10]+1);
    inp=reshape(bitseq,b,N_bits/b);
    mod_symbols=sym_table([8 4 2 1]*inp+1); M=16; %16-ary symbol sequence
else
    error('Unimplemented modulation');
end
```

Appendix A7

Matlab code for STBC two cross one system with feedback.The code is not fully correct and is still being worked upon.

```
clear all
P=4;
N_frame=1000;
N_packet=100;
b=2;
m=2^b;
mod_obj=modem.qammod('m',m,'symbolorder','gray','inputtype','bit');
%MIMO parameters
t_tx=4;
code_length=64;
NT=2;
NR=1;
n_pbits=NT*b*N_frame;n_tbits=n_pbits*N_packet;
code_book=codebook_generator;
fprintf('===============\n');
fprintf('transmission with feedback');
fprintf('n %d x %d STBC\n %d QPSK',NT,NR,m);
fprintf('\n simulation bits : %d',n_tbits);
fprintf('\n=============\n');
SNRdbs = [0:2:10];
sq2=sqrt(2);
for i_SNR=1:length(SNRdbs)
    SNRdb=SNRdbs(i_SNR);
    noise_var=NT*0.5*10^(-SNRdb/10);sigma=sqrt(noise_var);
    rand('seed',1);randn('seed',1);n_ebits=0;
    for i_packet=1:N_packet
        msg_bit=randint(n_pbits,1);


        %%%%%%transmitter%%%%%%

        s=modulate(mod_obj,msg_bit);
        scale=modnorm(s,'avpow',1);
        S=reshape(scale*s,NT,1,N_frame);
```

```
        const=exp(1j*pi/4*[3 1 0 2]);
        const=const([0 1 3 2]+1);
        for i=1:1000;
        s1=[S(1,1,i);S(2,1,i)];
        s2=[-conj(S(2,1,i));conj(S(1,1,i))];
        tx_symbol=[s1 s2];
        %%%%%%%%%%%%%%%%%%%channel noise%%%%%%%%%%%%%%%%%%%%
         h=(randn(NR,t_tx)+j*randn(NR,t_tx))/sq2;
        for i=1:code_length
            cal(i)=norm(h*code_book(:,:,i),'fro');
        end
        [val,index]=max(cal);
        he=h*code_book(:,:,index);
        hr=reshape(he,NT,NR); Habs=sum(abs(hr).^2,2);

%%%%%%%%%%%%%%%%%%%% receiver %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

r1 = sum(hr.*s1,2)/sqrt(2)+sigma*(randn(NT,1)+j*randn(NT,1));
                              % received signal + noise matrix for time T1
r2 = sum(hr.*s2,2)/sqrt(2)+sigma*(randn(NT,1)+j*randn(NT,1));
                              % received signal + noise matrix for time T2

Z1 = r1.*conj(hr(1,1)) + conj(r2).*hr(2,1);
Z2 = r1.*conj(hr(2,1)) - conj(r2).*hr(1,1);
        end
%%%%%%%%%%%%% estimation and distance minimization %%%%%%%%%%%%%%%%%%%%%%%%
for m=1:P
xi = (-1+sum(Habs,2))*abs(const(m))^2;
e1(:,m) = abs(sum(Z1,2)-const(m)).^2 + xi;    % estimated signal for T1
e2(:,m) = abs(sum(Z2,2)-const(m)).^2 + xi;    % estimated signal for T2
end
[y1,i1]=min(e1,[],2); S1d=const(i1).'; clear e1
                                  % row distance minimization for time T1
[y2,i2]=min(e2,[],2); S2d=const(i2).'; clear e2
                                   % row distance minimization for time T2
Xd = [S1d S2d];% decoded signal
tmp1=tx_symbol>0 ; tmp2=Xd>0;
noeb_p(i_packet) = sum(sum(tmp1~=tmp2));% for coded
end % end of FOR loop for i_packet
BER(i_SNR) = sum(noeb_p)/(N_packet*N_frame*b);
end % end of FOR loop for i_SNR
semilogy(SNRdbs,BER), axis([SNRdbs([1 end]) 1e-6 1e0]);
 xlabel('SNR[dB]'); ylabel('BER');
```

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