PERFORMANCE ANALYSIS OF SPACE – TIME BLOCK CODED MULTIPLE ANTENNA SYSTEMS

by

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ABSTRACT

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Multiple input and multiple output(MIMO) communications are seen as key technology to achieve high data rates for next generation of air interfaces like Wifi, WiMAX, and 3GPP-LTE, because of the spatial dimension complementing time (TDM), frequency (FDM), and code (CDM) multiple access technologies. MIMO technology has many captivating characteristics such as, it offers significant increases in data throughput and link range without additional bandwidth or transmit power. It achieves this by higher spectral efficiency (more bits per second per hertz of bandwidth) and diversity (reduced fading). Because of these properties, MIMO is a current theme of international wireless research.

Diversity Coding techniques are used when there is no channel knowledge at the transmitter. In diversity methods a single stream is transmitted, but the signal is coded using techniques called space-time coding. The signal is emitted from each of the transmit antennas using certain principles of full or near orthogonal coding. Diversity exploits the independent fading in the

multiple antenna links to enhance signal diversity. Considering the evolving nature and wide applications of this technology, it is important to analyze the system performance for different scenarios employing space-time coding, channel coding, interleaving and puncturing.

In this thesis, we mainly target the analysis of the bit error rate (BER) performance of the MIMO system with space-time block coding. We have implemented five different configurations of the MIMO system namely, two transmit and one receive antenna, two transmit and two receive antennas, three transmit and one receive antenna, four transmit and one receive antenna and finally four transmit and four receive antenna. We have analyzed the improvement in the performance of the MIMO system over an un-coded system using Rayleigh flat fading channel. Furthermore, we have evaluated the performance of the MIMO system by additionally including channel coding techniques namely convolutional coding and turbo coding which observed that the turbo code provides better reliability than the convolutional codes. Finally, performance analysis is carried out for various interleaving and puncturing schemes in the different MIMO configuration communication systems.

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CHAPTER 1

INTRODUCTION

Wireless communication systems have evolved enormously and the ever increasing demand for wireless services is driving the wireless market to grow explosively. The goal of achieving reliable communication, higher capacity, flexible data rate and wide variety of applications under the constraint of available resources like bandwidth and power along the co-existence with the current wireless devices is a challenging task. This is where MIMO communications comes into picture. Multiple input multiple output communications offers high data throughput and link range. MIMO systems are implemented using space-time codes (STC). The goal of the space-time coding is to achieve maximum diversity, maximum coding gain and the highest possible throughput. Space-time block coding is STC technique which can be considered as a modulation scheme for multiple transmit antennas that provide full diversity and very low complexity encoding and decoding. MIMO exploits the diversity capability to achieve its goal i.e. in the presence of random fading caused by multipath propagation the SNR is significantly improved by combining the output of de-correlated antenna elements. Also antenna arrays can be used to increase the capacity of wireless links.

Multi-antenna techniques are seen as key technology to achieve the required data rates for the next generation of the air interfaces Wifi, WiMAX and 3GPP-LTE because of the spatial dimension complementing time (TDM), frequency (FDM), and code (CDM) multiple access technologies. Some of the practical applications of MIMO are

- WLAN – Wifi 802.11n

- Mesh Networks
- WMAN – WiMAX 802.16e
- 4G
- RFID
- Digital Home

High Throughput Wifi - 802.11n uses the space dimension (MIMO) to boost data rates up to 600 Mbps through multiple antennas and signal processing. Target applications include: large files backup, HD streams, online interactive gaming, home entertainment, etc. MIMO in Ad-Hoc Network is a collection of wireless mobile nodes that self-configure to form a network (data rate + range). Here, no fixed infrastructure is required, any two nodes can communicate with each other and high capacity link are useful for scalability and multimedia services. Mobile-WiMAX 802.16e provides up to 4-6 mbps per user for a few km by using multiple antenna systems exploiting the spatial diversity, spatial multiplexing capability MIMO. MIMO is also used in RFID for increasing read reliability using space diversity and increasing read range and read throughput.

1.1 Scope and organization of the thesis

Considering that MIMO is a rapidly evolving technology and due to the number of benefits it offers to wireless communication, it is important to analyze the performance of the MIMO communication system. The thesis explores the fundamentals of the MIMO technology and emphasizes on the physical layer design and the performance analysis of the system.

The thesis is organized into five main sections. Chapter 2, “Multiple antennas wireless communication systems” introduces the concepts related to MIMO wireless communication and discusses the modeling of the system. It also gives insights into space-time coding, channel coding, puncturing and interleaving. Chapter 3,”Space – time block coding” is devoted to understanding of implementing the MIMO system using STBC. It introduces us to design criteria of space-time block codes and the pioneering work of Alamouti who proposed the Alamouti code. It also gives an idea of the encoding and the decoding technique that is used in STBC. The chapter 4, “Channel coding” presents us with concepts, practical applications and advantages of channel coding. Furthermore, it also deals with two major channel coding techniques namely convolutional coding and turbo coding. Chapter 5, “Design and analysis” contains information regarding the designing of the system that was used in the thesis and provides analysis of the simulated MIMO system. The performance of the MIMO system is analyzed using space-time block coded system, channel coding techniques like convolutional codes and turbo codes, channel burst error combating technique like interleaving and finally puncturing to provide variable data rates. The simulation results are included in this chapter.

The chapter 6, “Conclusions and future work” summarizes the analyzed results explained in the previous chapters and discusses about future work for this thesis.

CHAPTER 2

MULTIPLE ANTENNAS WIRELESS COMMUNICATION SYSTEMS

2.1 Introduction

The ability to communicate with people on the move has evolved remarkably since Guglielmo Marconi first demonstrated radio's ability to provide continuous contact with ships sailing the English Channel. That was in 1897, and since then new wireless communications methods and services have been enthusiastically adopted by people throughout the world.

Wireless communications is a rapidly growing segment of the communications industry, with the potential to provide high-speed high-quality information exchange between portable devices located anywhere in the world. Potential applications enabled by this technology include multimedia Internet-enabled cell phones, smart homes and appliances, automated highway systems, video teleconferencing and distance learning, and autonomous sensor networks, to name just a few. However, supporting these applications using wireless communication poses significant technical challenges such as limited availability of the radio frequency spectrum, complex space - time varying environment, increasing demand for high data rate, higher network capacity and better quality of service [3].

Wireless communication is highly challenging due to the complex, time varying propagation medium. If we consider a wireless link with one transmitter and one receiver, the transmitted signal that is launched into wireless environment arrives at the receiver along a number of diverse paths, referred to as multipath. These paths occur from scattering and rejection of radiated energy from objects (buildings, trees ...) and each path has a different and time-varying delay, angle of arrival, and signal amplitude. As a consequence, the received signal can vary as a function of frequency, time and space. These variations are referred to as fading and cause deterioration of the system quality. Furthermore, wireless channels suffer of cochannel interference (CCI) from other cells that share the same frequency channel, leading to

distortion of the desired signal and also low system performance. Therefore, wireless systems must be designed to mitigate fading and interference to guarantee a reliable communication.

A successful method to improve reliable communication over a wireless link is to use multiple antennas. The key points that argue the above statement are:

- Interference reduction

  Cochannel interference contributes to the overall noise of the system and deteriorates the performance. By using multiple antennas it is possible to suppress interfering signals which leads to an improvement of system capacity.

- Diversity gain

  An effective method to combat fading is diversity. Diversity techniques are classified into time, frequency and space diversity. Space or antenna diversity has been popular in wireless microwave communications and can be classified into two categories: receive diversity and transmit diversity [1] , depending on whether multiple antennas are used for reception or transmission.

  - Receive Diversity

    It can be used in channels with multiple antennas at the receive side. The receive signals are assumed to fade independently and are combined at the receiver so that the resulting signal shows significantly reduced fading. Receive diversity is characterized by the number of independent fading branches and it is at most equal to the number of receive antennas.

- Transmit Diversity

  Transmit diversity is applicable to channels with multiple transmit antennas and it is at most equal to the number of the transmit antennas, especially if the transmit antennas are placed sufficiently apart from each other. Information is processed at the transmitter and then spread across the multiple antennas. Transmit diversity has become an active research area [2].

The principle of diversity is to provide the receiver with multiple versions of the same transmitted signal. Each of these versions are affected by independent fading conditions, the probability that all branches are in fade at the same time reduces dramatically. In case of multiple antennas at both link ends, utilization of diversity requires a combination of receive and transmit diversity explained above. The diversity order is bounded by the product of the number of transmit and receive antennas, if the channel between each transmit-receive antenna pair fades independently. As fading can occur in frequency, time and space diversity techniques can be exploited in each of these domains [3]. In this thesis we have exploited the space – time domain.

2.2 Modeling the MIMO System

2.2.1 System Model

Consider a point-to-point MIMO system with n_t transmit and n_r receive antennas. The block diagram is given in Fig. 2.1.

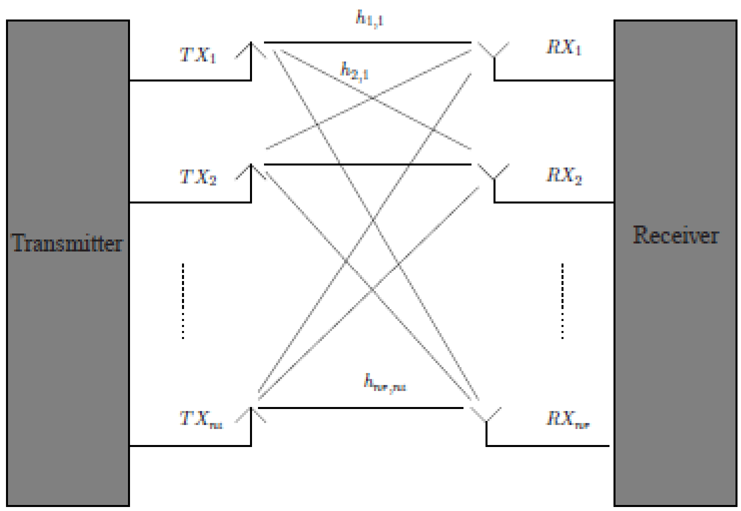

Figure 2.1 MIMO model with n_t transmit and n_r receive antennas.

Let $h_{i,j}$ be a complex number corresponding to the channel gain between transmit antenna j and receive antenna i. If at a certain time instant the complex signals $\{s_1, s_2, \cdot \cdot \cdot, s_{nt}\}$ are transmitted via n_t transmit antennas, the received signal at antenna i can be expressed as:

$$y_t = \sum_{j=1}^{n_t} h_{i,j}\ s_j + n_i$$

where n_i is a noise term. Combining all receive signals in a vector y, the above equation can be easily expressed in matrix form

$$y = Hs + n.$$

y is the $n_r \times 1$ receive symbol vector, H is the $n_r \times n_t$ MIMO channel transfer matrix given as follows,

$$H = \begin{bmatrix} h_{1,1} & \cdots & h_{1,n_t} \\ \vdots & \ddots & \vdots \\ h_{n_r,1} & \cdots & h_{n_r,n_t} \end{bmatrix}$$

s is the $n_t \times 1$ transmit symbol vector and n is the $n_r \times 1$ additive noise vector. Note that the system model implicitly assumes a flat fading MIMO channel, i.e., channel coefficients are constant during the transmission of several symbols. Flat fading, or frequency non-selective fading, applies by definition to systems where the bandwidth of the transmitted signal is much smaller than the coherence bandwidth of the channel. All the frequency components of the transmitted signal undergo the same attenuation and phase shift propagation through the channel.

2.2.2 Channel Model

In wireless communication system, signals arrive at a receiver via various propagation mechanisms. A highly complex transmission channel exists due to multiple scattered paths with different time-varying time delays, directions of departure and arrival, phases and attenuations. Except for the line-of-sight, all these mechanisms imply the interaction of the propagating wave with one or more arbitrary obstacles (buildings, trees, cars, human beings, etc.). Figure 2.2 illustrates this multipath propagation concept. The line-of-sight path experiences free-space loss only. Reflection occurs when a propagating wave hits against a

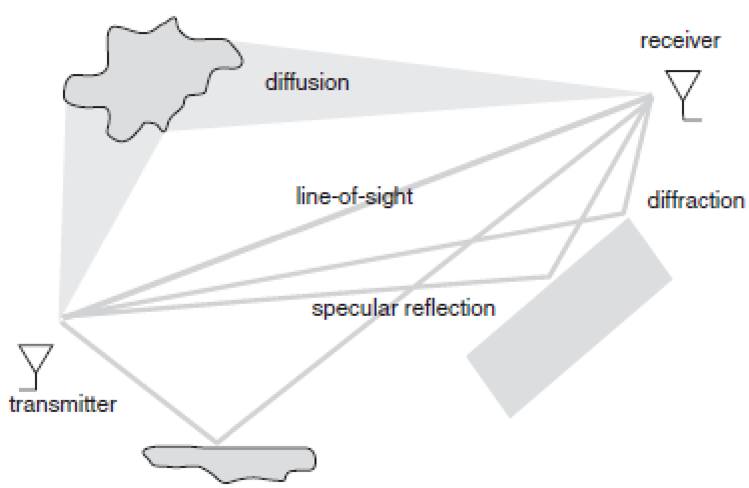

Figure 2.2 A multipath scenario [3]

plane surface whose dimensions are very large compared to the wavelength. Diffraction occurs when the path between the transmitter and the receiver is obstructed. Due to the obstruction there is partial absorption of energy. Finally, diffusion is caused by interactions of the wave with objects the dimensions of which are on the order of the wavelength.

The propagation channel between a transmitter located at p_t and a receiver located in the three-dimensional space at p_r for n_s paths can therefore be expressed

$$h(p_t, p_r, \tau, \Omega_t, \Omega_r) = \sum_{k=0}^{n_{s-1}} h_k (p_t, p_r, \tau, \Omega_t, \Omega_r)$$

where τ, Ω_t and Ω_r represent the delay, the direction of departure and the direction of arrival, respectively.

2.2.2.1 Rayleigh fading

Fading describes the variation of the local channel h(t) due to the varying phases and amplitudes of scatterers. When the independent scatterers n_s is large and all scattered contributions are non-coherent (not LOS) and of approximately equal energy, then by the central limit theorem h(t) is a complex Gaussian variable with zero mean and
independent quadrature components. The distribution of |h(t)| = s(t) is given by the Rayleigh probability density function as shown below [3].

$$p_s(s) = \frac{s}{\sigma_s^2} \exp(- \frac{s^2}{2\, \sigma_s^2})$$

where $2\sigma_s^2$ is the average power of s(t). In our thesis we consider a Rayleigh flat fading channel.

2.3 Space – Time coding

To transmit information over a wireless link, different transmission and reception strategies can be applied. The knowledge of the instantaneous MIMO channel parameters at the transmitter side determines which strategy can be used. If the channel state information is not available at the transmitter space-time coding (STC) can be used for transmission. If the channel state information is available at the transmitter, beamforming can be used to transmit a single data stream over the wireless link. In this way, spectral efficiency and robustness of the system can be improved.

The choice of the transmission model depends on three entities important for wireless link design, namely bit rate, system complexity and reliability. A space-time coding has low complexity and promises high diversity, but the bit rate is moderate. In our thesis, we adopt the space-time coding approach. In the first part of the thesis, we will analyze space-time coding transmission without any channel knowledge at the transmitter side and in the second part of the thesis, we will analyze space-time coding transmissions with channel coding. We will propose some low complexity puncturing and interleaving schemes which provide variable data rates and improve the overall system quality without increasing the system complexity substantially.

Mostly a lot of signal processing is performed at the receiver. The receiver has to regain the transmitted symbols from the mixed received symbols. There are several methods to do this, to name a few:

- Maximum Likelihood (ML) Receiver

  ML achieves the best system performance (maximum diversity and lowest bit error rate can be obtained), but needs the most complex detection algorithm. The ML receiver calculates all possible noiseless receive signals by transforming all possible transmit signals by the known MIMO channel transfer matrix. Then it searches for that signal calculated in advance, which minimizes the Euclidean distance to the actually received signal. The undisturbed transmit signal that leads to this minimum distance is considered as the most likely transmit signal.

- Linear Receivers

  Zero Forcing (ZF) receivers and Minimum Mean Square Error (MMSE) receivers belong to the group of linear receivers. The ZF receiver completely nulls out the influence of the interference signals coming from other transmit antennas and detects every data stream separately. At the output of the receiver, the overall response function is equal to one for the symbol being detected and an overall zero response for other symbols [4]. The disadvantage of this receiver is that due to canceling the influence of the signals from other transmit antennas, the noise may be strongly increased and thus the performance may degrade. Due to the separate decision of every data stream, the complexity of this algorithm is much lower than in case of an ML receiver. The MMSE receiver compromises between noise enhancement and signal interference and minimizes the mean squared error between the transmitted symbol and the detected symbol. Thus the results of the MMSE equalization are the transmitted data streams plus some residual interference and noise. After MMSE equalization each data stream is separately detected (quantized) in the same way as in the ZF case.

- Bell Labs Layered Space-Time (BLAST) nulling and canceling

  These receivers implement an ordering, nulling and canceling algorithm. In principle, all received symbols are equalized according to the ZF approach (Nulling) and afterwards the symbol with the highest SNR is detected by a grid decision. The detected symbol is assumed to be correct and its influence on the received symbol vector is subtracted (Canceling). The performance of these nulling and canceling receivers lies in between the performance of linear receivers (ZF and MMSE) and ML receivers. In this thesis, the

ML receiver and the ZF receiver for Space – Tine coded transmissions will be discussed.

2.4 Channel coding

Channel coding protects digital data from errors by introducing redundancies in the transmitted data. Due to the redundant bits introduced the bandwidth requirement is increased but provides good BER performance at low SNR. There are three basic types of error correction codes namely block codes, convolutional codes and turbo codes. In our thesis we mainly focus on convolutional codes and turbo codes.

- Convolutional codes

  In convolutional coding continuous sequence of data bits are mapped to continuous sequence of encoder bits. Figure2.3 shows a block diagram of convolutional encoder. A convolutional code is obtained by passing raw information bits through a finite state shift registers. If k bits of data are given as an input to the encoder, the number of output bits for each k bit sequence is n bits. The code rate is given by the following equation,

$$R_c = k/n$$

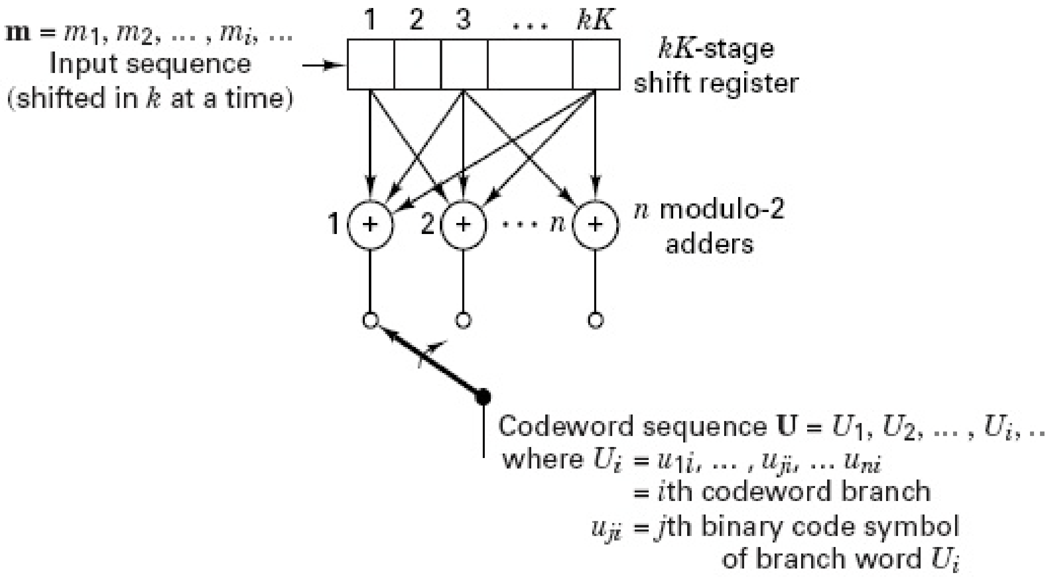

Figure 2.3 Block diagram of a convolutional encoder

2.5 Interleaving

From the previous sections it is evident that channel coding helps improve the performance of the system by error correction. However, these error correction codes are not very efficient in combating burst of errors, i.e. a group of consecutive or connected erroneous code symbols. Interleaving is a scheme that helps reduce the effect of burst errors and improve the signal quality. It’s a process to rearrange code symbols so as to spread bursts of errors over multiple code words that can be corrected by error correction codes. By converting burst of errors into random like errors, interleaving thus becomes an effective means to combat error bursts. Fig 2.4 illustrates the interleaving scheme.

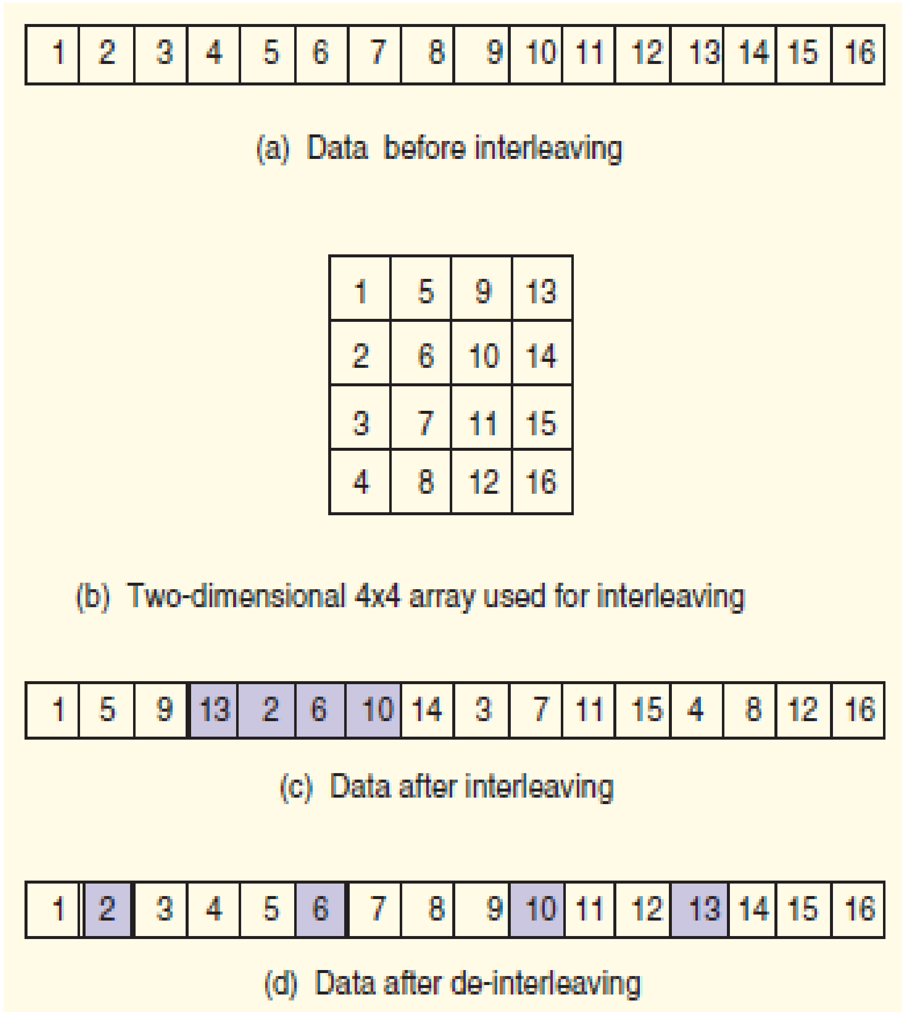

Figure 2.4 1-D Block interleaving scheme

Consider a code in which each code-word contains four code symbols. Furthermore, the code possesses the random error correction capability. For better understanding, if we assume the one-random-error-correction capability is that, if there is any single code symbol error that has occurred in one code-word, then it can be corrected. Suppose there are 16 symbols, which correspond to four code-words. That is, code symbols from 1 to 4 form a code-word, from 5 to 8 another codeword, and so on. One of the 1-D interleaving procedures, known as block interleaving, first creates a 4×4 2-D array, called block interleaver as shown in Figure

2.2.(a). The 16 code symbols are read into the 2-D array column-by-column (or row-by-row) manner. The interleaved code symbols are obtained by writing the code symbols out of the 2-D array in a row-by-row (or column-by- column) fashion. This process has been depicted in Figure 2.4 (a), (b), and (c). Now take a look at how this interleaving technique can correct error bursts. Assume a burst of error occurred, involving four consecutive symbols as shown in Figure 2.4 (c). After de-interleaving as shown in Figure 2.4 (d), the error burst is effectively spread among four code-words, resulting in only one code symbol in error for each of the four code-words. With the one-random-error-correction capability, it is obvious that no decoding error will result from the presence of such an error burst. This simple example demonstrates the effectiveness interleaving technique in combating bursts of errors, i.e., how the interleaving spreads code symbols over multiple codewords so as to convert a burst of errors occurred with the interleaved array into random-like errors in the deinterleaved array. In other words, the pair of interleaving and de-interleaving can equivalently convert a bursty channel into a random-like channel. This in turn makes it possible for random error correction codes to correct burst errors. In our thesis we use different interleaving schemes to analyze the system performance.

2.6 Puncturing

In wireless communication, puncturing is the technique which helps convert a low rate code to high rate code without any additional hardware requirement. In this method bits are deleted from the encoder output in such a way that the decoder can insert these deleted bits at the destination. With puncturing the same decoder can be used regardless of how many bits have been punctured, thus puncturing considerably increases the flexibility of the system without significantly increasing its complexity. Also, if the puncturing pattern is selected carefully, it can improve the overall bandwidth of the system.

In a lot of practical applications, high rate channel coded bits are required. The implementation of the decoder for such high rate channel codes is very complex and expensive. The computational complexity inherent in the implementation of the decoder of a high-rate channel code can be avoided by designing high-rate code from a low-rate code in which some of the coded bits are deleted from transmission. The deletion of selected coded bits at the output of a channel encoder is called puncturing. Thus, one can generate high-rate channel codes by puncturing rate 1/n codes with the result that the decoder maintains the low complexity of the rate 1/n code. The puncturing process may be described as periodically deleting selected bits from the output of the encoder, thus, creating a periodical time varying code. The need for puncturing arises in other applications as well. In speech or image compression some bits may be more significant than others, thus requiring a higher level of protection. Such unequal error protection can be achieved by puncturing.

CHAPTER 3

SPACE – TIME BLOCK CODING

Space-Time Codes (STCs) have been implemented in cellular communications as well as in wireless local area networks. Space time coding is performed in both spatial and temporal domain introducing redundancy between signals transmitted from various antennas at various time periods. It can achieve transmit diversity and coding gain over wireless systems without sacrificing bandwidth. The space-time coding focuses on improving the system performance by employing extra transmit antennas.

Furthermore, two different space-time coding methods, namely space-time trellis codes (STTCs) and space-time block codes (STBCs) have been proposed. Space-time trellis codes has been introduced in [5] as a coding technique that promises full diversity and substantial coding gain. STBCs have been proposed by the pioneering work of Alamouti [6]. The Alamouti code promises full diversity and full data rate in case of two transmit antennas. The key feature of this scheme is the orthogonality between the signal vectors transmitted over the two transmit antennas. Later this scheme was generalized to an arbitrary number of transmit antennas by applying the theory of orthogonal design. The generalized schemes are referred to as space-time block codes [7]. Nevertheless, for more than two transmit antennas no complex valued space-time block codes with full diversity and full data rate exist. Thus, many different code design methods have been proposed providing either full diversity or full data rate [7].

The designs of space-time code amounts to finding transmit matrices that satisfy certain optimal design criteria. The rank and determinant design criteria for space-time codes aims at maximizing the diversity gain and coding gain at high SNRs. The following section gives a brief overview of the rank and determinant criteria for space-time codes.

3.1 Rank and Determinant Design Criteria

Let us consider two different codewords C^1 and C^2. C^1 is as specified below.

$$C^1 = \begin{bmatrix} C_{1,1}^1 & \cdots & C_{1,N}^1 \\ \vdots & \ddots & \vdots \\ C_{T,1}^1 & \cdots & C_{T,N}^1 \end{bmatrix}$$

C^2 is as specified below.

$$C^2 = \begin{bmatrix} C_{1,1}^2 & \cdots & C_{1,N}^2 \\ \vdots & \ddots & \vdots \\ C_{T,1}^2 & \cdots & C_{T,N}^2 \end{bmatrix}$$

Where the $C^1$and C^2 belong to C which is the collection of the signals that are transmitted from N transmit antenna during T time slots.

The rank criterion suggests that for any two codewords C^i not equal to C^j, the error matrix

$$D(C^i, C^j) = C^i - C^j$$

has to be full rank for all i not equal to j in order to obtain full diversity[4].

The determinant criterion says that the minimum determinant of

$$A(C^i, C^j) = D(C^i, C^j)H\ D(C^i, C^j)$$

among all i not equal to j has to be large to obtain high coding gains[4].

3.2 Space-Time Block Codes

Space-time block code aims at achieving maximum diversity which is the product of total number of transmitters and the total number of receivers in the wireless system. Furthermore, it also aims at obtaining maximum coding gain and highest possible throughput. Space-time block code can be considered as a modulation scheme for multiple transmit antennas [4].

3.2.1 Alamouti Code

The Alamouti code is the first Space-time block code that provides full diversity and full data rate for two transmit antennas [6]. A block diagram of the Alamouti space-time encoder is shown in Figure. 3.1 Raw data are first modulated using BPSK modulation scheme.

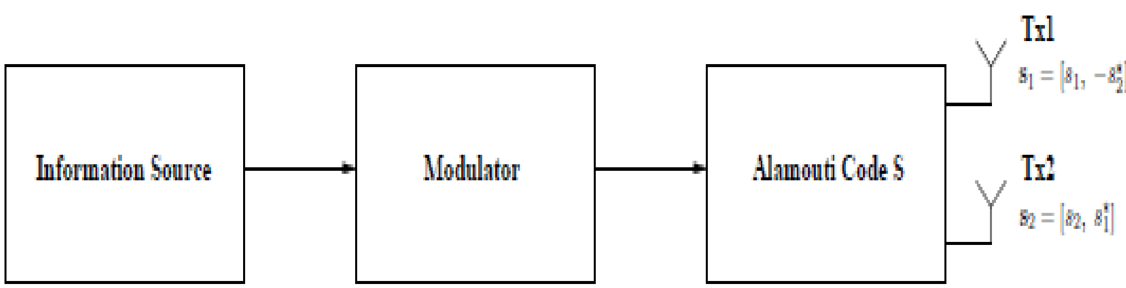

Figure 3.1 Block diagram of Alamouti Space-time encoder

The encoder takes the block of two modulated symbols s_1 and s_2 in each encoding operation and hands it to the transmit antennas according to the code matrix S as shown below.

$$S = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}$$

The first row represents the first symbol time and the second row the second symbol time. During the first transmission, the symbols s_1 and s_2 are transmitted simultaneously from antenna one and antenna two respectively. In the second transmission period, the symbol $-s^*_2$ is transmitted from antenna one and the symbol s^*_1 from transmit antenna two.

It is clear that the encoding is performed in both time (two transmission periods) and space domain (two transmit antennas). The two rows and columns of S are orthogonal to each other:

$$SS^H = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} s_1^* & -s_2 \\ s_2^* & s_1 \end{bmatrix}$$

$$= \begin{bmatrix} |s_1|^2 + |s_2|^2 & 0 \\ 0 & |s_1|^2 + |s_2|^2 \end{bmatrix}$$

$$= (|s_1|^2 + |s_2|^2)\ \mathrm{I}_2$$

where I_2 is a identity matrix of size (2 × 2). This property enables the receiver to detect s_1 and s_2 by a simple linear signal processing operation.

Looking at the receiver side, only one receive antenna is considered. The channel at time t may be modeled by a complex multiplicative distortion $h_1(t)$ for transmit antenna one and $h_2(t)$ for transmit antenna two. We assume that the fading is constant across two consecutive transmit periods. The received signals at the time t(first symbol time) and t + T(second symbol time) can then be expressed as

$$r_1 = s_1h_1 + s_2h_2 + n_1$$

$$r_2 = -s^*_2h_1 + s^*_1 h_2 + n_2$$

where, r_1 and r_2 are the received signals at time t and t + T and n_1 and n_2 are receiver noise and interference for transmitter one and two respectively. This can be also be written as:

$$r = Sh + n$$

where $h = [h_1, h_2]T$ is the complex channel vector and n is the noise vector at the receiver.

3.2.2 Channel Matrix of the Alamouti Code

Conjugating the signal received signal r_2, the received signal can be written equivalently as

$$r_1 = h_1 s_1 + h_2\ s_2 + ň_1$$

$$r_2 = -\ h_1{*}\ s_2 + h_2{*}\ s_1 + ň_2$$

Thus the above equation can be written as

$$\begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} \tilde{n}_1 \\ \tilde{n}_2 \end{bmatrix}$$

or in short notation

$$y = Hs + n$$

H is the equivalent MIMO channel matrix of the Alamouti Space-time block coding scheme. It is given by:

$$H = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}$$

In MIMO channel matrix of the Alamouti Space-time block coding scheme, the rows and columns of the channel matrix are orthogonal:

$$HH^H = H^H\ H = (|h_1|^2 + |h_2|^2)\ I_2 = |h|^2\ I_2$$

where I_2 is the (2 × 2) identity matrix and h^2 is the power gain of the equivalent MIMO channel with

$$h^2 = |h_1|^2 + |h_2|^2$$

Due to this orthogonality the receiver of the Alamouti scheme decouples the 2x1 channel into two virtually independent channels each with channel gain h^2. It is obvious that the MIMO channel matrix depends on the structure of the code and the channel coefficients. The concept of the MIMO channel matrix simplifies the analysis of the STBC transmission scheme. The existence of an MIMO channel matrix is one of the important characteristics of STBCs and is frequently used in this thesis.

3.2.3 Signal Combining and Maximum Likelihood Decoding of the Alamouti Code

Assuming that all the signals in the modulation constellation are equi-probable, a maximum likelihood (ML) detector decides for that pair of signals $(\hat{s}_1, \hat{s}_2)$ from the signal modulation constellation that minimizes the decision metric

$$d^2(r_1, h_1 s_1 + h_2 s_2) + d^2(r_2, -h_1 s_2^* + h_2 s_1^*) = |r_1 - h_1 s_1 - h_2 s_2|^2 + |r_2 + h_1 s_2^* - h_2 s_1^*|^2$$

where,

$$d(x1, x2) = |x1 - x2|$$

On the other hand, a linear receiver combines the received signals r_1 and r_2 as follows,

$$\tilde{s}_1 = h_1^* r_1 + h_2 r_2^* = (|h_1|^2 + |h_2|^2)\, s_1 + h_1^* n_1 + h_2 n_2^*$$

$$\tilde{s}_2 = h_2^* r_1 - h_1 r_2^* = (|h_1|^2 + |h_2|^2)\, s_2 - h_1 n_2^* + h_2^* n_1$$

Hence $\tilde{s}_1$ and $\tilde{s}_2$ are two decisions statistics constructed by combining the received signals with coefficients derived from the channel state information. These noisy signals are sent to ML detectors and thus the ML decoding rule mentioned above can be separated into two independent decoding rules for s1 and s2 as follows.

For detecting s_1,

$$\hat{S}_1 = \arg\min_{\hat{S}1\,\epsilon\,S} d^2(\check{s}_1, s_1)$$

and for detecting s_2,

$$\hat{S}_2 = \arg\min_{\hat{S}2\,\epsilon\,S} d^2(\check{s}_2, s_2)$$

The Alamouti transmission scheme is a simple transmit diversity scheme which improves the signal quality at the receiver using a simple signal processing algorithm at the transmitter. The diversity order obtained is equal to that one applying maximal ratio combining (MRC) with one antenna at the transmitter and two antennas at the receiver where the resulting signals at the receiver are:

$$r_1 = h_1 s_1 + n_1$$

$$r_2 = h_2 s_1 + n_2$$

and the combined signal is,

$$\check{s}1 = h_1^* r_1 + h_2 r_2^*$$

$$= (|h_1|^2 + |h_2|^2) s_1 + h_1^* n_1 + h_2 n_2^*$$

The resulting combined signals are equivalent to those obtained from a two-branch MRC as shown in the above equations. Therefore, the resulting diversity order obtained by the Alamouti scheme with one receiver is equal to that of a two-branch MRC at the receiver.

3.2.4 Orthogonal Space-Time Block Codes

The original work of Alamouti has been the basis to create OSTBCs for more than two transmit antennas. Firstly, V.Tarokh studied the error performance associated with unitary signal matrices [7] and there were many more research papers in this area like [8].

Orthogonal STBCs are an important subclass of linear STBCs that guarantee that the ML detection of different symbols $\{s_n\}$ is decoupled and at the same time the transmission scheme achieves a diversity order equal to $n_t n_r$ (product of number of transmit antennas and number of receive antennas). The main disadvantage of OSTBCs is the fact that, for more than two transmit antennas and complex-valued signals, OSTBCs only exist for code rates smaller than one symbol per time slot. We will have a brief explanation on orthogonal design and various properties of OSTBCs. There exist real orthogonal and complex orthogonal designs. We will discuss complex orthogonal designs here.

An OSTBC is a linear space-time block code S that has the following property:

$$S^H S = \sum_{n=1}^{N} |S_n|^2 I$$

The i-th row of S represents the symbols transmitted simultaneously through nt transmit antennas at time i and the j-th column of S corresponds to the symbols transmitted from the j-th transmit antenna in N transmission periods. The rows of the transmission matrix S are orthogonal to each other. The orthogonality enables us to achieve full transmit diversity and at the same time, it allows the receiver to decouple the signals transmitted from different antennas and consequently, it allows a simple ML decoding.

3.2.4.1 Examples of OSTBCs

For n_t = 2 transmit antennas, Alamouti code is the most popular OSTBC. We will have a look at OSTBC matrices for n_t = 3 and n_t = 4 antennas.

Below is the OSTBC with a rate of 1/2 for n_t = 3

$$\mathbf{S}_3 = \begin{bmatrix} s_1 & s_2 & s_3 \\ -s_2 & s_1 & -s_4 \\ -s_3 & s_4 & s_1 \\ -s_4 & -s_3 & s_2 \\ s_1^* & s_2^* & s_3^* \\ -s_2^* & s_1^* & -s_4^* \\ -s_3^* & s_4^* & s_1^* \\ -s_4^* & -s_3^* & s_2^* \end{bmatrix}$$

Here, 4 symbols are taken at a time and transmitted via three transmit antennas at eight time slots. Thus the rate is ½.

And following is the OSTBC for n_t = 4

$$\mathbf{S}_4 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix}$$

In the OSTBC for four transmit antennas, four symbols are transmitted using four transmit antennas in eight time slots and hence the rate = ½.

Following is the OSTBC with a rate of 3/4 for $n_t = 3$

$$\mathbf{S}'_3 = \begin{bmatrix} s_1 & s_2 & \frac{s_3}{\sqrt{2}} \\ -s_2^* & s_1^* & \frac{s_3}{\sqrt{2}} \\ \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} & \frac{(-s_1 - s_1^* + s_2 - s_2^*)}{2} \\ \frac{s_3^*}{\sqrt{2}} & -\frac{s_3^*}{\sqrt{2}} & \frac{(s_2 + s_2^* + s_1 - s_1^*)}{2} \end{bmatrix}$$

Below is the OSTBC with a rate of 3/4 for $n_t = 4$

$$\mathbf{S}'_4 = \begin{bmatrix} s_1 & s_2 & \frac{s_3}{\sqrt{2}} & \frac{s_3}{\sqrt{2}} \\ -s_2^* & s_1^* & \frac{s_3}{\sqrt{2}} & -\frac{s_3}{\sqrt{2}} \\ \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} & \frac{(-s_1 - s_1^* + s_2 - s_2^*)}{2} & \frac{(-s_2 - s_2^* + s_1 - s_1^*)}{2} \\ \frac{s_3^*}{\sqrt{2}} & -\frac{s_3^*}{\sqrt{2}} & \frac{(s_2 + s_2^* + s_1 - s_1^*)}{2} & -\frac{(s_1 + s_1^* + s_2 - s_2^*)}{2} \end{bmatrix}$$

CHAPTER 4

CHANNEL CODING

A communication channel provides the connection between the transmitter and he receiver. The channel can be a pair of wires, optic fiber cables or free space. A common problem in signal transmission through any channel is additive noise. Thermal noise is the noise that is generated internally by components such as resistors and solid state devices used to implement the communication system. Other factor that affects the signal during transmission is the interference that is caused externally to the system by other users of the channel. All these have adverse effect on the signal that is being transmitted resulting in degradation of the signal quality.

Channel coding is a technique that is used to overcome the effects of noise and interference in the transmission of the signal through the channel. The channel encoder in a communication system converts its input into an alternate sequence of codewords which possesses redundancy whose role is to provide immunity from the various channel impairments. The ratio of the number of bits that enter the channel encoder to the number that depart from it is called the code rate, denoted by R, with $0 < R < 1$. The channel decoder is to recover the original data from the noisy/distorted sequence of codewords.

Channel coding or error control coding can also ease the design process of a digital transmission system in multiple ways such as the following:

- The transmission power requirement of a digital transmission scheme can be reduced by the use of an error control code. This aspect is exploited in the design of most of the modern wireless digital communication systems such as a cellular mobile communication system.
- The size of a transmitting or receiving antenna can be reduced by the use of an error control codec while maintaining the same level of end-to-end performance.
- Access of more users to same radio frequency in a multi-access communication system can be ensured by the use of error control technique [example: cellular CDMA].
- Jamming margin in a spread spectrum communication system can be effectively increased by using suitable error control technique. Increased jamming margin allows signal transmission to a desired receiver in battlefield and elsewhere even if the enemy tries to drown the signal by transmitting high power in-band noise.

Application of an error correction code and a judicious choice of the code parameters are guided by several conflicting factors. Some of these factors are described in brief below:

- Nature of communication channel

  Effects of many physical communication channel manifest in random and isolated errors while some channels cause bursty errors. The modulation technique employed for transmission of information, sensitivity level of a receiver (in dBm), rate of information transmission are some other issues.
- Available channel bandwidth

  As mentioned, use of an error-control scheme involves addition of controlled redundancy to original message. This redundancy in transmitted massage calls for larger bandwidth than what would be required for an uncoded system. This undesirable fact is tolerable because of the obtainable gains or advantages of coded communication system over an uncoded one for a specified overall system performance in terms of BER or cost.

- Hardware complexity cost and delay

  Some error correction codes of larger block length asymptotically satisfy the requirements of high rate as well as good error correcting capability but the hardware complexity, volume, cost and decoding delay of such decoders may be enormous. For a system designer, the choice of block length is somewhat limited.

- The coding gain

  Error correction codes of different code rates and block sizes offer different coding gains in $\frac{E_b}{N_0}$ over an uncoded system. At the first level, the coding gain is defined as:

  [($\frac{E_b}{N_0}$ in dB needed by a uncoded system to achieve a specified BER of 10^{-x}) –($\frac{E_b}{N_0}$ in dB needed by an FEC coded system to achieve the same BER of 10^{-x})].

4.1 Convolutional Coding

Convolutional codes are commonly described using two parameters: the code rate and the constraint length. The code rate, k/n, is expressed as a ratio of the number of bits into the convolutional encoder (k) to the number of channel symbols output by the convolutional encoder (n) in a given encoder cycle. The constraint length parameter, K, denotes the "length" of the convolutional encoder, i.e. how many k-bit stages are available to feed the combinatorial logic that produces the output symbols. Closely related to K is the parameter m, which indicates how many encoder cycles an input bit is retained and used for encoding after it first appears at the input to the convolutional encoder. The m parameter can be thought of as the memory length of the encoder.

Convolutional codes are widely used as channel coding technique in practical communication systems for error correction. The encoded bits depend on the current k input bits and a few past input bits. The main decoding strategy for convolutional codes is based on the widely used Viterbi algorithm. As a result of the wide acceptance of convolutional codes, there have been several approaches to modify and extend this basic coding scheme. Turbo code is one such example. In turbo coding, redundancy is added by parallel concatenated convolutional encoders. We will discuss more about turbo codes in the next section.

4.1.1 Convolutional Encoder

A simple convolutional encoder is shown in Figure.4.1. The information bits are fed in small groups of k-bits at a time to a shift register. The output encoded bits are obtained by modulo-2 addition of the input information bits and the contents of the shift registers which are a few previous information bits.

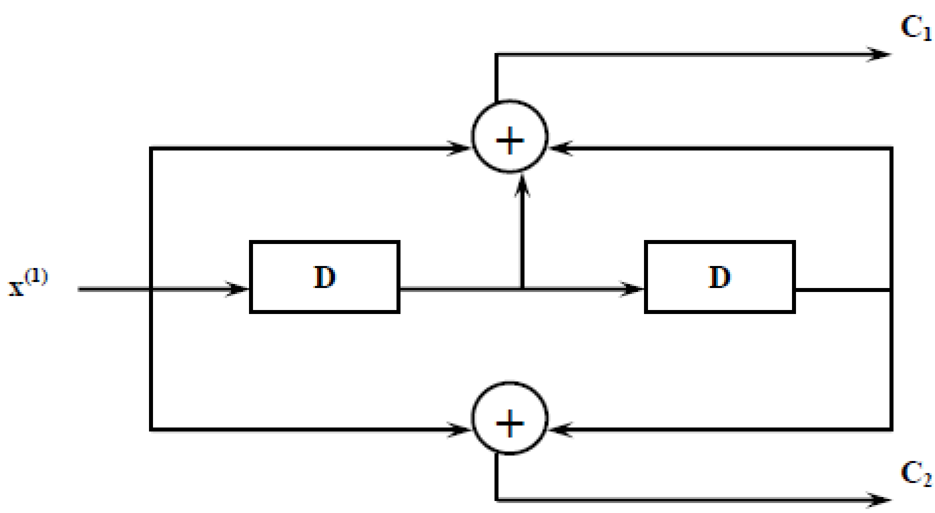

Figure 4.1 Block of a convolutional encoder with k = 1, n = 2 and r = ½

If the encoder generates a group of ‘n’ encoded bits per group of ‘k’ information bits, the code rate R is commonly defined as R = k/n. In Figure.4.1, k = 1 and n = 2. The number, K of elements in the shift register which decides for how many codewords one information bit will affect the encoder output, is known as the constraint length of the code. For the present example, K = 3.

The operation of a convolutional encoder can be explained in several but equivalent ways such as, by

- State diagram representation
- Tree diagram representation
- Trellis diagram representation

4.1.1.1 State Diagram Representation

A convolutional encoder may be defined as a finite state machine. Contents of the rightmost (K-1) shift register stages define the states of the encoder. The number of states is given by $2^{k(K-1)}$. Hence, the encoder in Figure. 4.1 has four states. The transition of an encoder from one state to another, as caused by input bits, is shown in the state diagram. Figure. 4.2 shows the state diagram of the encoder in Figure. 4.1.

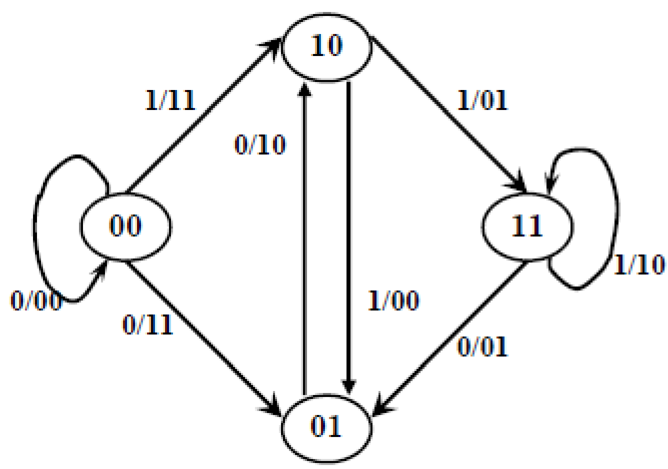

Figure 4.2 State diagram representation of the encoder in Figure 4.1

A new input bit causes a transition from one state to another. The path information between the states, denoted as b/c_1c_2, represents input information bit ‘b’ and the corresponding output bits (c_1c_2).

4.1.1.2 Tree Diagram Representation

The tree diagram representation shows all possible information and encoded sequences for the convolutional encoder. Figure. 4.3 shows the tree diagram for the encoder in Figure. 4.1. The encoded bits are labeled on the branches of the tree. Given an input sequence, the encoded sequence can be directly read from the tree. As an example, an input sequence (1011) results in the encoded sequence (11, 10, 00, 01).

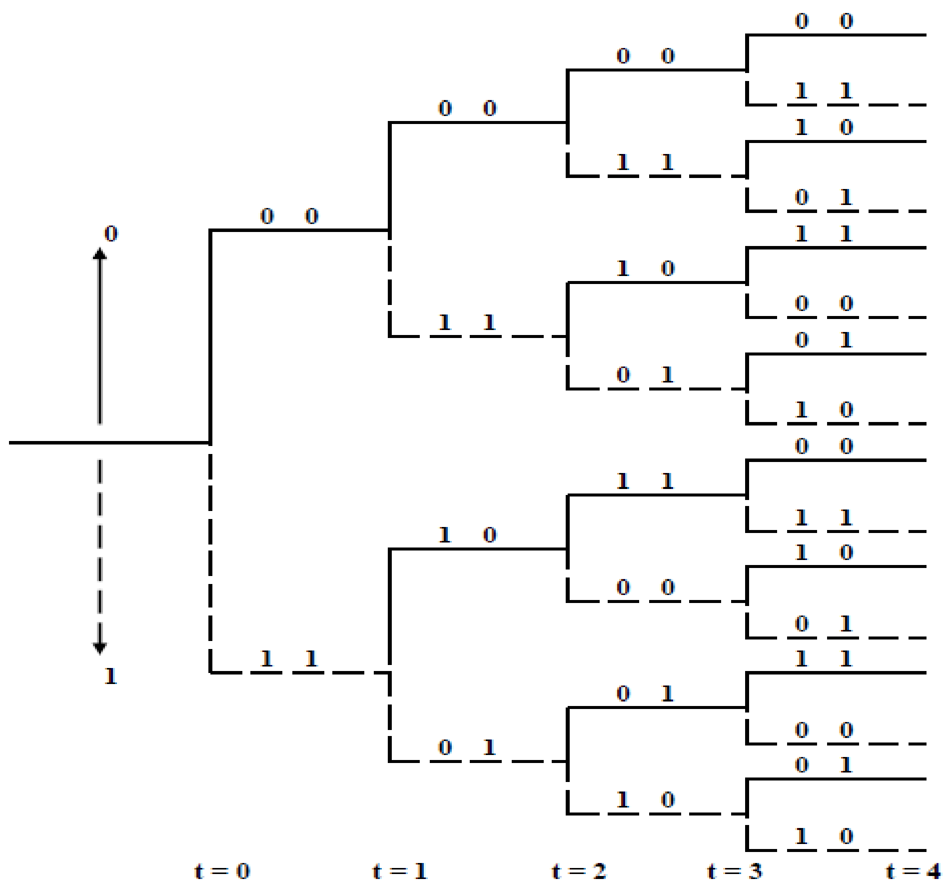

Figure 4.3 Tree diagram representation of the encoder in Figure 4.1

4.1.1.3 Trellis Diagram Representation

The trellis diagram of a convolutional code is obtained from its state diagram. All state transitions at each time step are explicitly shown in the diagram to retain the time dimension, as is present in the corresponding tree diagram. Usually, supporting descriptions on state transitions, corresponding input and output bits etc. are labeled in the trellis diagram. It is interesting to note that the trellis diagram, which describes the operation of the encoder, is very convenient for describing the behavior of the corresponding decoder, especially when the famous ‘Viterbi Algorithm (VA)’ is followed. Figure 6.35.4 shows the trellis diagram for the encoder in Figure 4.1.

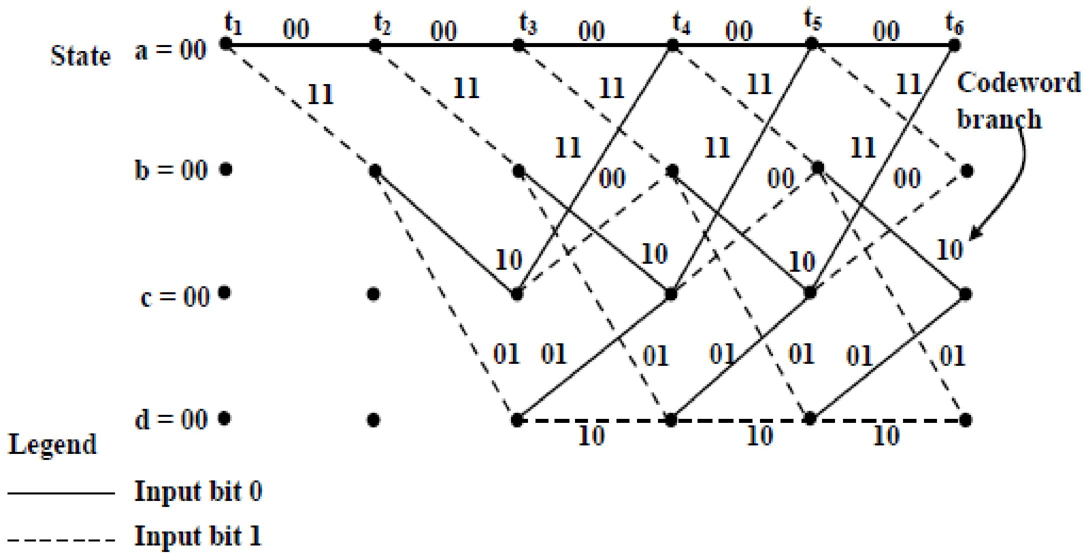

Figure 4.4 Trellis diagram for the encoder in Figure 4.1

4.1.2 Viterbi Decoding

Viterbi decoding can be done using hard decision or soft decision decoding. Hard-decision and soft-decision decoding are based on the type of quantization used on the received bits. Hard-decision decoding uses 1-bit quantization on the received samples. Soft-decision decoding uses multi-bit quantization (e.g. 3 bits/sample) on the received sample values.

4.1.2.1 Hard-Decision Viterbi Algorithm

The Viterbi Algorithm (VA) finds a maximum likelihood (ML) estimate of a transmitted code sequence c from the corresponding received sequence r by maximizing the probability p(r|c) that sequence r is received conditioned on the estimated code sequence c. Sequence c must be a valid coded sequence.

The Viterbi algorithm utilizes the trellis diagram to compute the path metrics. The channel is assumed to be memory less, i.e. the noise sample affecting a received bit is independent from the noise sample affecting the other bits. The decoding operation starts from state '00', i.e. with the assumption that the initial state of the encoder is '00'. With receipt of one noisy codeword, the decoding operation progresses by one step deeper into the trellis diagram. The branches, associated with a state of the trellis tell us about the corresponding codewords that the encoder may generate starting from this state. Hence, upon receipt of a codeword, it is possible to note the 'branch metric' of each branch by determining the Hamming distance of the received codeword from the valid codeword associated with that branch. Path metric of all branches, associated with all the states are calculated similarly.

Now, at each depth of the trellis, each state also carries some 'accumulated path metric', which is the addition of metrics of all branches that construct the 'most likely path' to that state. As an example, the trellis diagram of the encoder shown in Figure. 4.1, has four states and each state has two incoming and two outgoing branches. At any depth of the trellis, each state can be reached through two paths from the previous stage and as per the VA, the path with lower accumulated path metric is chosen. In the process, the 'accumulated path metric' is updated by adding the metric of the incoming branch with the 'accumulated path metric' of the state from where the branch originated. No decision about a received codeword is taken from such operations and the decoding decision is deliberately delayed to reduce the possibility of erroneous decision. The trellis diagram for the viterbi decoder is shown in figure 4.5.

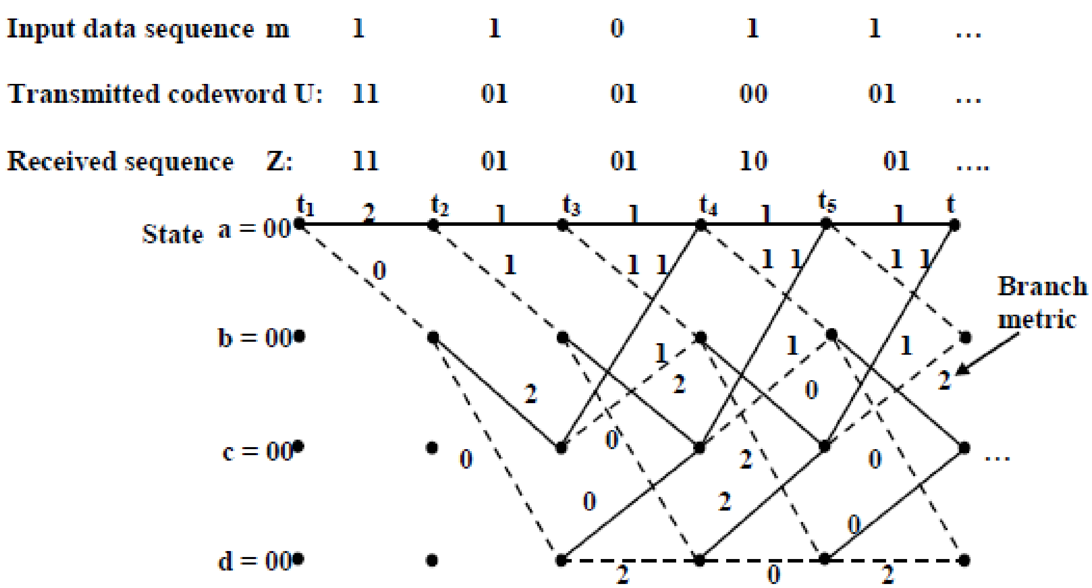

Figure 4.5 Trellis diagram for the viterbi decoder corresponding to the encoder in Figure 4.1

The basic operations which are carried out as per the hard-decision Viterbi Algorithm after receiving one codeword are summarized below:

- All the branch metrics of all the states are determined.
- Accumulated metrics of all the paths (two in our example code) leading to a state are calculated taking into consideration the ‘accumulated path metrics’ of the states from where the most recent branches emerged.
- Only one of the paths, entering into a state, which has minimum ‘accumulated path metric’ is chosen as the ‘survivor path’ for the state (or, equivalently ‘node’).
- So, at the end of this process, each state has one ‘survivor path’. The ‘history’ of a survivor path is also maintained by the node appropriately (e.g. by storing the

codewords or the information bits which are associated with the branches making the path).

- The above mentioned four steps are repeated and decoding decision is delayed till sufficient number of codewords has been received. The decision strategy is simple. Upon receiving sufficient number of codewords and carrying out the above mentioned steps, we compare the 'accumulated path metrics' of all the states (four in our example) and chose the state with minimum overall 'accumulated path metric' as the 'winning node' for the first codeword. Then we trace back the history of the path associated with this winning node to identify the codeword tagged to the first branch of the path and declare this codeword as the most likely transmitted first codeword.

The above procedure is repeated for each received codeword hereafter. Thus, the decision for a codeword is delayed but once the decision process starts, we decide once for every received codeword.

4.1.2.2 Soft-Decision Viterbi Algorithm

In soft-decision decoding, the demodulator does not assign a '0' or a '1' to each received bit but uses multi-bit quantized values. The soft-decision Viterbi algorithm is very similar to its hard-decision algorithm except that squared Euclidean distance is used in the branch metrics instead of simpler Hamming distance. However, the performance of a soft-decision VA is much more impressive compared to hard decision decoding.

4.2 Turbo Coding

Turbo codes represent a class of parallel concatenation of two convolutional codes. The parallel-concatenated codes have several advantages over the serial concatenated ones. The parallel decoder facilitates the idea of feedback in decoding to improve the performance of the system. There are some differences between conventional convolutional code and turbo codes. Several parameters affect the performance of turbo codes such as:

- Component decoding algorithms
- Number of decoding iterations
- Generator polynomials and constraint lengths of the component encoders
- Interleaver type

4.2.1 Turbo encoding

The term turbo coding refers to a forward error correction (or channel coding) scheme introduced in 1993 by Berrou and Glavieux [9]. A turbo code is constructed from relatively simple convolutional codes by forming a parallel concatenation of two or more such codes. To increase the effects of coding diversity, the sequence to be encoded (also called information or systematic sequence) is block-interleaved before it is encoded. The output of a turbo code consists of outputs of each convolutional encoder as well as the original sequence; hence, the overall code is systematic (that is, the information sequence appears at the output)

A turbo encoder is sometimes built using two identical convolutional codes of special type, such as, recursive systematic (RSC) type with parallel concatenation. An individual encoder is termed a component encoder. An interleaver separates the two component encoders. The interleaver is a device that permutes the data sequence in some predetermined manner.

Figure. 4.6 shows the block diagram of a turbo encoder using two identical encoders. The first encoder outputs the systematic V0 and recursive convolutional V1 sequences while the second encoder discards its systematic sequence and only outputs the recursive convolutional V2 sequence. There are several types of interleavers such as,

- Block interleaver
- Diagonal interleaver

- Odd-even block interleaver
- Pseudo-random interleaver
- Convolutional interleaver
- Helical interleaver
- Uniform interleaver
- Cyclic shift interleaver
- Code matched interleaver.

Depending on the number of input bits to a component encoder it may be binary or m-binary encoder. Encoders are also categorized as systematic or non-systematic. If the component encoders are not identical then it is called an asymmetric turbo code. The block diagram of a basic turbo encoding structure is shown in figure 4.6 and a specific example is shown in figure 4.7

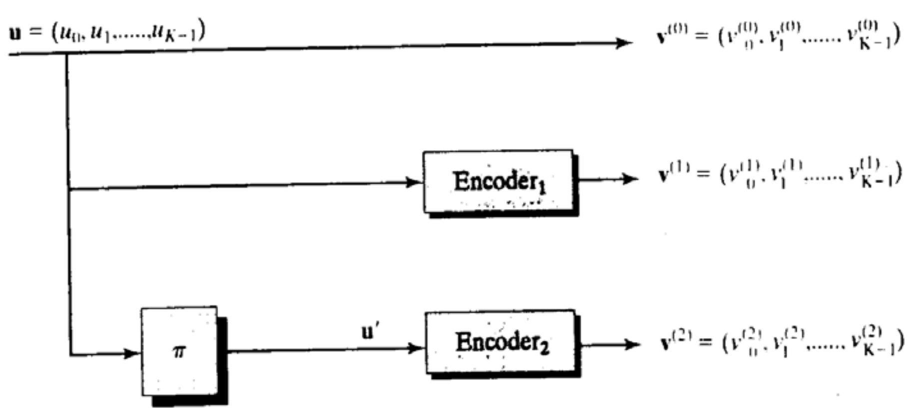

Figure 4.6 Block diagram of a turbo encoder

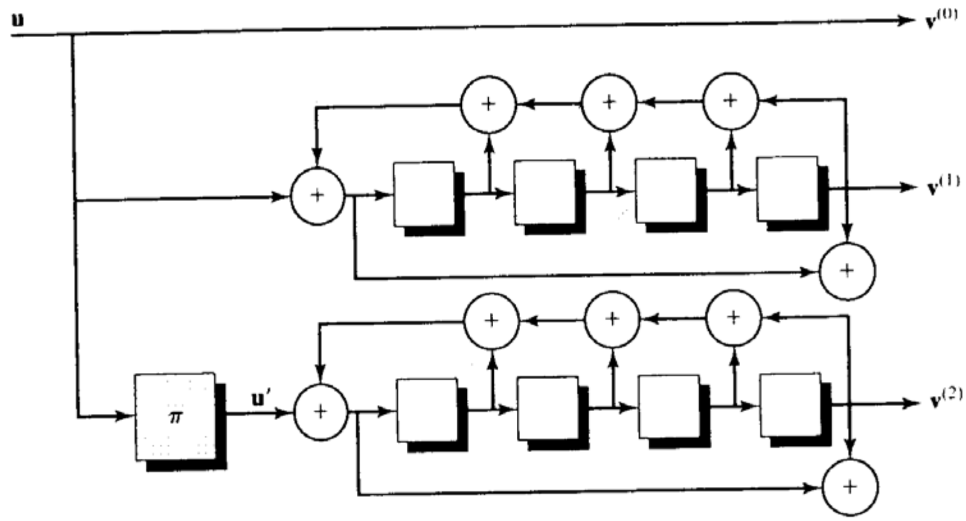

Figure 4.7 Schematic of a specific turbo encoder

The basic system consists of an input sequence, two systematic feedback convolutional encoders and an interleaver, denoted by π. Let us assume that the input sequence contains K* information bits plus v termination bits to return the first encoder to all zero state $S_0 = 0$, where v is the length of the first encoder. The information sequence is of length K = K* + v and is represented by a vector.

$$u = (u_0, u_1, \ldots, u_{K-1})$$

As the encoding is systematic, the first transmitted sequence is u, i.e.

$$u = v^{(0)} = (v_0^{(0)}, v_1^{(0)}, \ldots, v_{K-1}^{(0)})$$

The first encoder generates the parity sequence

$$v^{(1)} = (v_0^{(1)}, v_1^{(1)}, \ldots, v_{K-1}^{(1)})$$

The interleaver permutes the K bits of information block so that the second encoder receives a permuted information sequence u' different from the first one. The parity sequence generated by the second encoder is represented as

$$v^{(2)} = (v_0^{(2)}, v_1^{(2)}, \ldots, v_{K-1}^{(2)})$$

and the final transmitted sequence is

$$v = (v_0^{(0)} v_0^{(1)} v_0^{(2)}, v_1^{(0)} v_1^{(1)} v_1^{(2)}, . . . , v_{K-1}^{(0)} v_{K-1}^{(1)} v_{K-1}^{(2)})$$

so that the overall code has a length N = 3K and Rate = K* / N = (K – v)/3K ≈ 1/3 for large K. The information sequence u along with the first parity sequence $v^{(1)}$ is referred to as the first constituent code and the permuted information sequence u' along with the second parity sequence $v^{(2)}$ is referred to as the second constituent code. In figure 4.7 both the codes are generated by the systematic encoder whose generator matrix is given by

$$G (D) = [1 (1 + D4) / (1 + D + D2 + D3 + D4)]$$

Below are few points related to the operation of turbo coding:

- Performance close to Shannon limit can be achieved when K is very large (thousand bits).
- Using short constraint length constituent codes (typically v = 4 or less), maximum performance can be achieved at moderate BER's down to about 10^{-5}
- The constituent codes are generated by the same encoder.
- Recursive constituent codes generated by systematic feedback encoders, give much better performance than non-recursive constituent codes, i.e. forward encoders
- Bits can be punctured from parity sequences to produce higher code rates. Also, bits can be punctured from the information sequence to produce partially systematic or nonsystematic turbo codes
- Lower rate codes can be also produced by additional constituent codes and interleavers, which is called multiple turbo code
- The best interleavers reorder the bits in a pseudorandom manner. Conventional block interleavers do not perform well in turbo codes

- The interleaver is an integral part of the overall encoder, and hence the state complexity of the turbo codes is extremely large, making trellis based ML or MAP decoding impossible
- As the MAP decoder uses a forward-backward algorithm, the information is arranged in blocks. Thus the first constituent encoder is terminated by v bits to get it to a zero state. Because the interleaver reorders the input sequence, the second encoder will not normally return to the zero state.
- Block codes can also be used as constituent codes in turbo encoders
- Decoding can be stopped, and a final decoding estimate declared, after some fixed number of iterations or based on a stopping criterion.

4.2.2 Turbo decoding

The basic structure of an iterative turbo decoder is shown in figure 4.8. (We assume here a rate R = 1 / 3 parallel concatenated code without puncturing). It employs two SISO decoders using the MAP algorithm. At every time unit, three output values are received from the channel, one for the information bit $u_l = v_l^{(0)}$ denoted by $r_1^{(0)}$ and two for the parity bits $v_l^{(1)}$ and $v_l^{(2)}$, denoted by $r_l^{(1)}$ and $r_l^{(2)}$ and the 3K dimensional vector is denoted by

$$r = (r_0^{(0)} r_0^{(1)} r_0^{(2)}, r_1^{(0)} r_1^{(1)} r_1^{(2)}, \ldots , r_{K-1}^{(0)} r_{K-1}^{(1)} r_{K-1}^{(2)})$$

Let each transmitted bit be represented using the mapping 0 --> -1 and 1 → +1. Then for an AWGN channel with unquantized (soft) outputs, we define the log-likelihood ratio (L-value) L ($v_l^{(0)} \mid v_l^{(1)}$) = L (ul | rl(0)) (before decoding) of transmitted information bit ul given the received value rl(0) as

$$L (ul \mid rl(0)) = \ln [P(ul = +1 \mid rl(0)) / P(ul = -1 \mid rl(0))]$$

$$= \ln \{ [P(rl(0 \mid ul = +1) P(ul = +1)] / [P(rl(0 \mid ul = -1) P(ul = -1)]\}$$

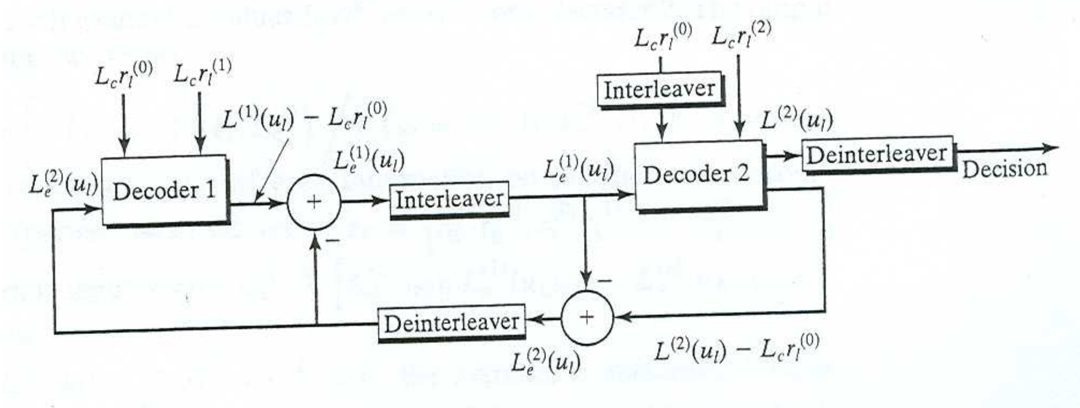

Figure 4.8 Basic structure of an iterative turbo decoder

L (ul | rl(0)) = ln [P(rl(0) | ul = +1) / P(rl(0) | ul = -1)] + ln P(ul = +1) / P(ul = -1)

L (ul | rl(0)) = ln [e-(Es/N0) (rl(0) - 1)2 / e-(Es/N0) (rl(0) + 1)2] + ln P(ul = +1) / P(ul = -1)

where Es/N0 is the channel SNR, and ul and rl(0) have both been normalized by a factor of $\sqrt{\text{Es}}$.

This equation simplifies to

L (ul | rl(0)) = -Es/N0 [(rl(0) - 1)2 – (rl(0) + 1)2] + ln P(ul = +1) / P(ul = -1)

L (ul | rl(0)) = 4 [Es/N0] rl(0) + ln P(ul = +1) / P(ul = -1)

L (ul | rl(0)) = Lc rl(0) + La (ul)

where, Lc = 4 [Es/N0] is the channel reliability factor and La (ul) is the priori L-value of the bit ul. In the caseof transmitted parity bit vl(j), given the received value rl(j), j = 1, 2, the L-value is given by

L(vl | rl(j)) = Lc rl(j) + La (vl(j)) = Lc rl(j) , j = 1, 2,

and

La (vl(j)) = ln P(ul = +1) / P(ul = -1) = 0, j = 1, 2,

The received soft channel L-values Lc rl(j) for ul and Lc rl(1) for vl(1) enter decoder 1, and the received soft channel L-values Lc rl(0) for ul and the received soft channel L-values Lc rl(2) for vl(2) enter decoder 2. The output of decoder 1 contains two terms:

L1 (ul) = ln [P(ul = +1 / r1, La(1)) / P(ul = -1 / r1, La(1))]

CHAPTER 5

DESIGN AND ANALYSIS

5.1 Performance Analysis of MIMO System

The transmitter, channel model and receiver are simulated using MATLAB version R2009a and the results are presented in the following sub-sections. The block diagram of the communication system that was simulated is as shown in figure 5.1.

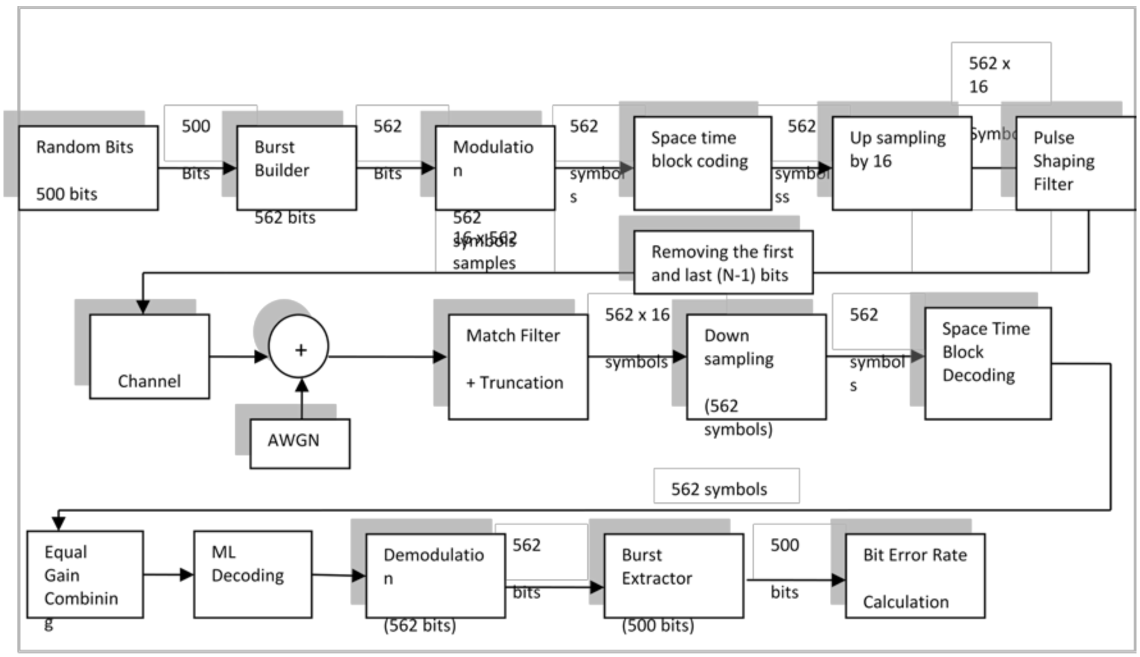

Figure 5.1 Block diagram of the communication system

The description of few blocks in the system is mentioned below:

- Burst Builder: In the Burst builder additional bits are added to the information bits. These are the Guard bits and the unique word. For synchronization and channel estimation we add 50 unique word bits. At the output we obtain 562 bits.
- Modulation: In this Project we have used BPSK where each bit is mapped as shown below.

  1 -> +1

  0 -> -1
- Up sampling: Suppose we have two bits (+1 and -1), then in the real world the transition between the two bits is quite difficult. So to make a smoother transition we use the Up-sampling and Pulse Shaping filter. Basically, in Up-sampling we append fifteen zeroes between any two symbols. Hence, at the output we obtain 562*16 numbers of symbols.
- Pulse shaping Filter: When there is a transition between the two bits we insert only zeroes between the two bits then it is useless as we cannot represent this. This is the reason why we use the Pulse Shaping Filter. It is also called as Interpolation Filter. Here we use linear interpolation for representing the signal. In our project we have used the Raised Cosine Filter to implement the Pulse shaping Filter. The roll off factor for the Raised Cosine Filter is 0.3. Suppose the length of the Raised Cosine Filter is N then the output of the Pulse shaping Filter is [562*16 + (N-1)] symbols. But in the real world we require only 562*16 symbols so we remove (N-1) symbols manually. We remove the starting [(N-1)/2] symbols and the last [(N-1)/2] symbols.
- Matched Filter: Matched Filter is the same as the Pulse Shaping filter at the transmitting end. Here we do the filtering to remove most of the noise and make the best effort to obtain the pure signal. The roll-off factor for square root raised cosine filter is 0.35. Here again the length of the matched filter is N. So at the output we get [562x16 + (N-1)]. We then remove the (N-1) bits manually as done previously.

- Down-sampling: The output of the Matched filter (562x16 symbols) is then given to down sampler. As in the system, at the transmitter end we have up sampled the burst of 562 symbols we should perform down-sampling to remove the zeroes inserted between the symbols. Thus at the output we obtained 562 symbols.
- Equal Gain Combining: The next block is equal gain combining block. Receiver diversity is a form of space diversity, where there are multiple antennas at the receiver. The presence of receiver diversity poses an interesting problem - how do we use effectively the information from all the antennas to demodulate the data. Equal gain combining is one solution to the problem. Equal-gain combining is similar to maximal-ratio combining except that the weights are all set to unity. The possibility of achieving an acceptable output SNR from a number of unacceptable inputs is still retained. The performance is marginally inferior to maximal ratio combining.
- Burst Extractor: In the Burst Extractor block we remove the appended bits that we had added to the information bits at the transmitting end. The output of the Burst Extractor gives us 500 bits i.e. we remove the 12 Guard bits and the 50 unique word bits to obtain the 500 information bits.
- BER Calculator: We compare the generated payload at the transmitter and the received burst at the output of the burst extractor and calculate the BER. In our thesis we are applying Monte Carlo Simulation technique by running this simulation 10000 times. Finally we plot the graph of E_b/N_o(energy per bit to noise power spectral density ratio)vs. the Bit Error Rate (BER).

5.1.1 Performance Analysis of 2x1 MIMO

The system shown in figure 5.1 is simulated and the performance of the system with 2 transmit antennas and 1 receive antenna(2x1 MIMO) is analyzed. Here Alamouti scheme is used for space-time block coding. The Alamouti scheme is as shown below

$$S = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}$$

And the channel matrix is given by

$$\mathrm{H} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}$$

As shown in chapter 3, due to the orthogonality property of the channel matrix, we can employ simple signal combining and ML decoding to estimate the transmitted signal. Comparison is drawn between the performance of the system with and without space-time block coding. Additionally, the performance of the system is analyzed when Rayleigh fading channel, channel coding, puncturing and interleaving is introduced. The system employs convolutional coding and viterbi decoding & turbo coding and MAP decoding discussed in detail in chapter 4.

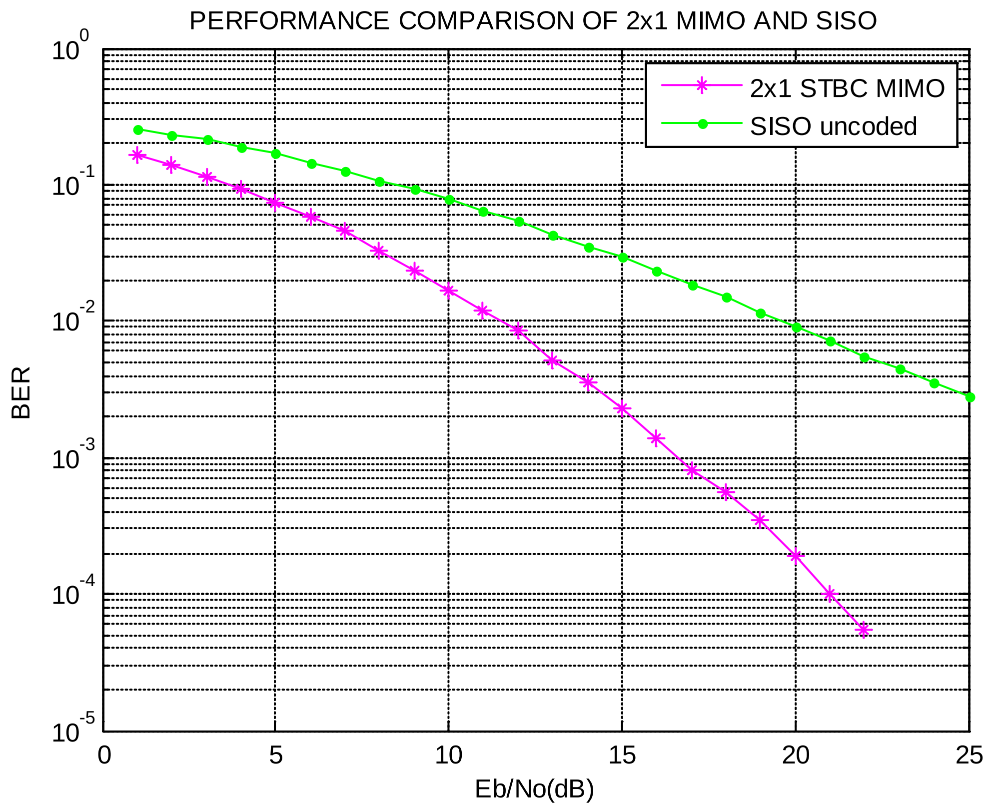

Figure 5.2 Performance of 2x1 STB coded vs. SISO uncoded

Figure 5.2 shows the performance of the simulated system for 2x1 space-time coded MIMO versus the SISO which is un-coded. Here the channel is considered to be Rayleigh flat fading channel. The performance of the system when employing 2x1 MIMO is improved as compared to un-coded SISO, as the increase in the transmit antenna introduces diversity gain of the order 2.

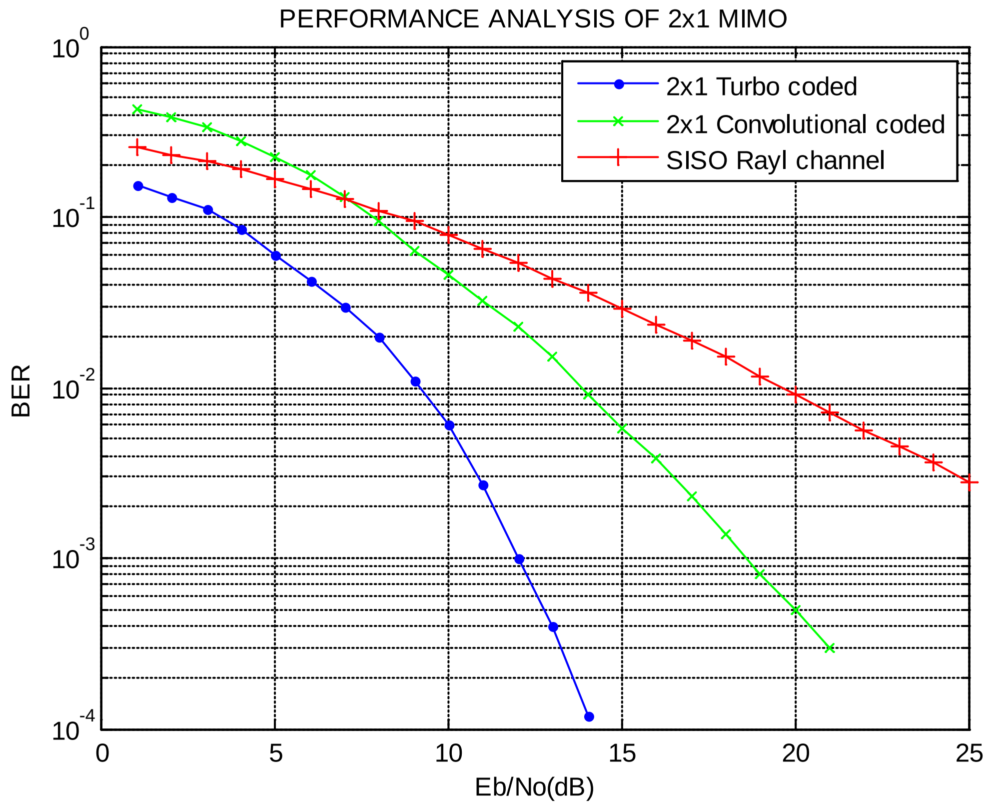

Figure 5.3 Performance analysis of 2x1 MIMO with Rayleigh channel and employing channel coding

Figure 5.3 shows the graph obtained for 2x1 MIMO when a Rayleigh channel is used. The graph verifies that the system performance degrades due to the affect of multipath that is introduced by the Rayleigh fading channel. Also, seen in the graph is the performance of the system when convolutional encoder and viterbi decoder & turbo encoder and decoder respectively are used to combat noise and interference.

The information bits are convolutional encoded using rate ½ encoder with constraint length equal to 7 and the code generator matrix specified as [133 171]. The encoded bits are interleaved using an interleaver with size 10x5.

The turbo encoder consists parallel concatenation of two identical recursive systematic convolutional codes. Here since two component codes are used the rate of the mother code is 1/3.

Hence for better comparison between the performance of the convolutional code and turbo code we have punctured the turbo coded bits using the puncturing pattern [1 1 1 0 0 1]. Thus, the rate obtained after puncturing is ½. Also we have used the same interleaving scheme mentioned earlier for turbo coded system as well.

It is very evident from the graphs that turbo encoding out performs convolutional coding scheme. We see a gain of 6.5dB at BER equal to 10^{-3}. This is because the encoder is a systematic encoder and the structure of the turbo code is such that it produces code which has random-like property. Also, the decoder uses soft-output values and iterative decoding in estimating the transmitted signal.

5.1.1.1 Performance comparison of puncturing schemes

Here we simulated the system with convolutional coding and punctured the channel coded bits to obtain variable code rate. The mother code rate = ½. The puncturing scheme used to obtain code rate = 2/3 is [1 1 0 1] i.e. every third bit out of 4 bits block is punctured and the new code rate can be calculated as shown,

$$\text{new code rate} = \frac{1}{2 * \frac{3}{4}}$$

$$= \frac{2}{3}$$

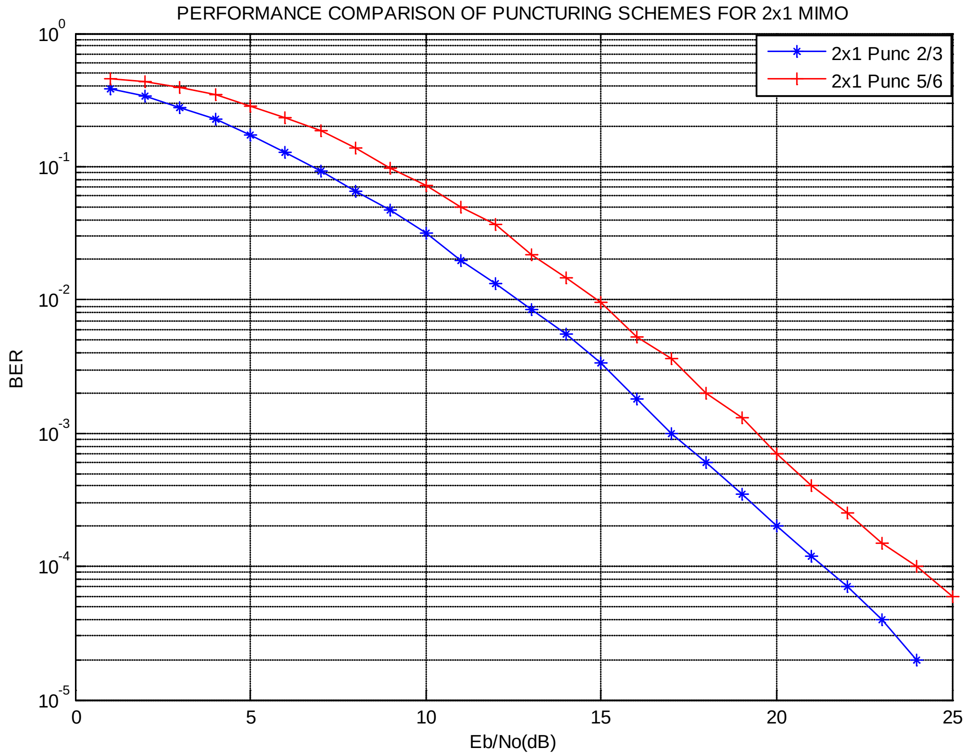

Figure 5.4 Performance comparison of puncturing schemes using 2x1 MIMO and the scheme used to get code rate = 5/6 is [1 0 1 0 1 1 1 0 1 0] i.e.,

$$\text{new code rate} = \frac{1}{2*\frac{6}{10}} = \frac{5}{6}$$

As we see in figure 5.4, the punctured code with rate = 2/3 outperforms the punctured code with rate = 5/6. This is because, for the same number of bits, more information is transmitted in the case of puncturing scheme with rate = 2/3 than with rate = 5/6. This also verifies that by employing different puncturing techniques, we can obtain different coding rate without any change in the design of the system. The encoder and the decoder can remain the same and we can still obtain different coding rates.

5.1.1.2 Performance comparison of interleaving schemes

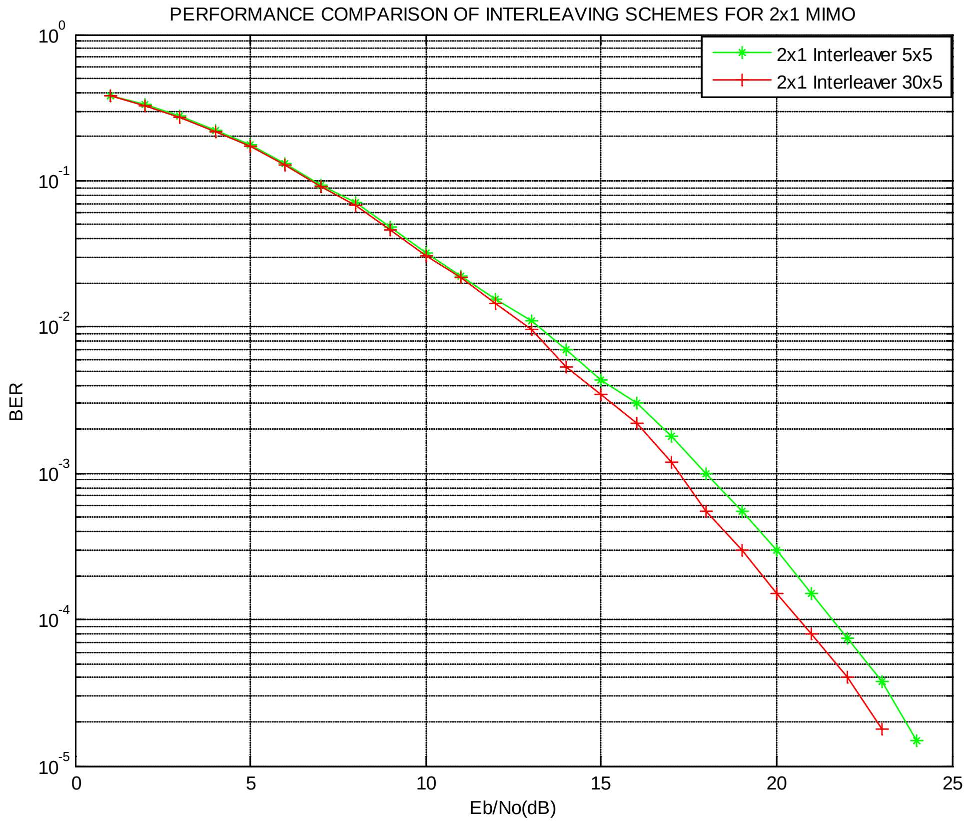

Figure 5.5 Performance comparison of interleaving schemes using 2x1 MIMO

Figure 5.5 depicts the performance of two interleaving schemes. The performance of the system varies depending on the interleaving degree. In the first scheme we use 5x5 block interleaver, were information is entered into a 5x5 block row-wise and the output column-wise.In the second scheme we use a 30x5 block. The figure 5.5 demonstrates that the 30x5 interleaving scheme is better than the 5x5 scheme. Consecutive bits in a codeword are separated by 30 bits in 30x5 scheme. However, in 5x5 interleaving scheme the separation is only 5 bits. Hence if there is a burst error affecting more than 5 consecutive bits, then more than 1 bit in the code-word will be affected having an adverse effect on the BER.

5.1.2 Performance Analysis of 2x2 MIMO

In this technique, 2 symbols are transmitted using two transmitting antennas at one symbol time period and their conjugates at another time period as specified by Alamouti code mentioned in the earlier sections.

$$H = \begin{bmatrix} h11 & h12 \\ h21 & h22 \end{bmatrix}$$

$$R_1^{(1)} = S_1h_{11} + S_2h_{12} + n_{11}$$

$$R_2^{(1)} = S_1h_{21} + S_2h_{22} + n_{12}$$

$$R_1^{(2)} = S_1^* h_{12} - S_2^* h_{11} + n_{21}$$

$$R_2^{(2)} = S_1^* h_{22} - S_2^* h_{21} + n_{22}$$

Here, $R_1(1)$ and $R_1(2)$ are the received symbols during Ts1 and Ts2 respectively at reciever1 and similarly for reciever2, $R_2(1)$ and $R_2(2)$ are the received symbols during Ts1 and Ts2. Then, hermitian of the channel matrix is multiplied with the received symbols to estimate the transmitted symbols according to

$$H^H . H = | h_{11} |^2 + | h_{12} |^2 + | h_{21} |^2 + | h_{22} |^2$$

Furthermore, the decoded symbols are combined using equal gain combining.

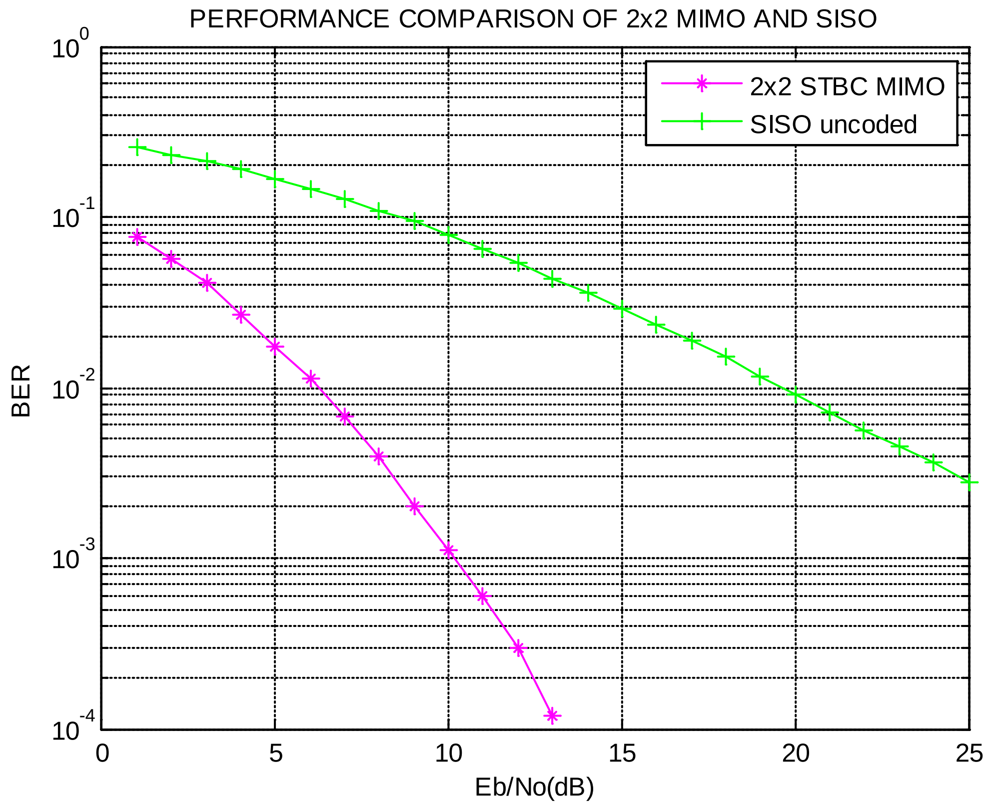

Figure 5.6 Performance of 2x2 STB coded vs. SISO uncoded

From the above figure it is observed that the performance employing 2x2 MIMO using space-time block coding is superior to a system without any space-time coding. This is due to the fact that in 2x2 MIMO, there is both transmit and receive diversity. This diversity gain is of the order of 4. There is a gain of nearly 19dB at 10^{-3} over the SISO system.

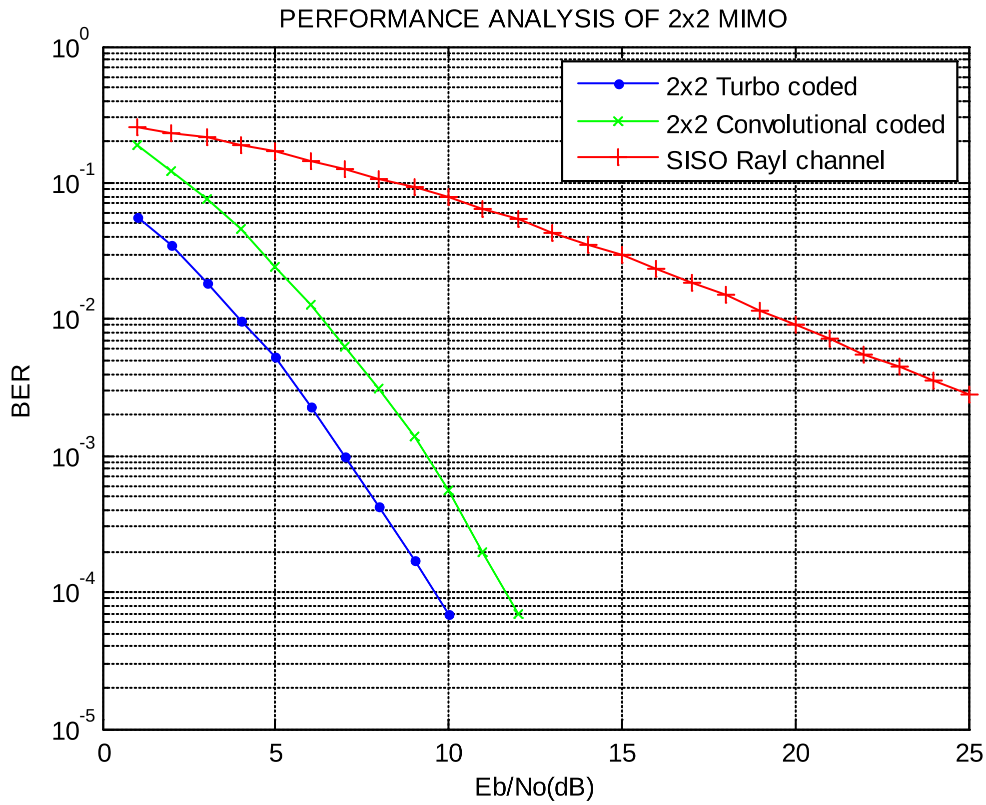

Figure 5.7 Performance analysis of 2x2 MIMO with Rayleigh channel and employing channel coding

The figure 5.7 illustrates the performance of the 2x2 MIMO system with space-time block coding. There is a gain of of 2.5dB when the system uses turbo to convolutional code. Also seen is that there is a gain of nearly 20dB at 10^{-3} when convolutional code and 2x2 MIMO is used as compared to the SISO system.

5.1.2.1 Performance comparison of puncturing schemes

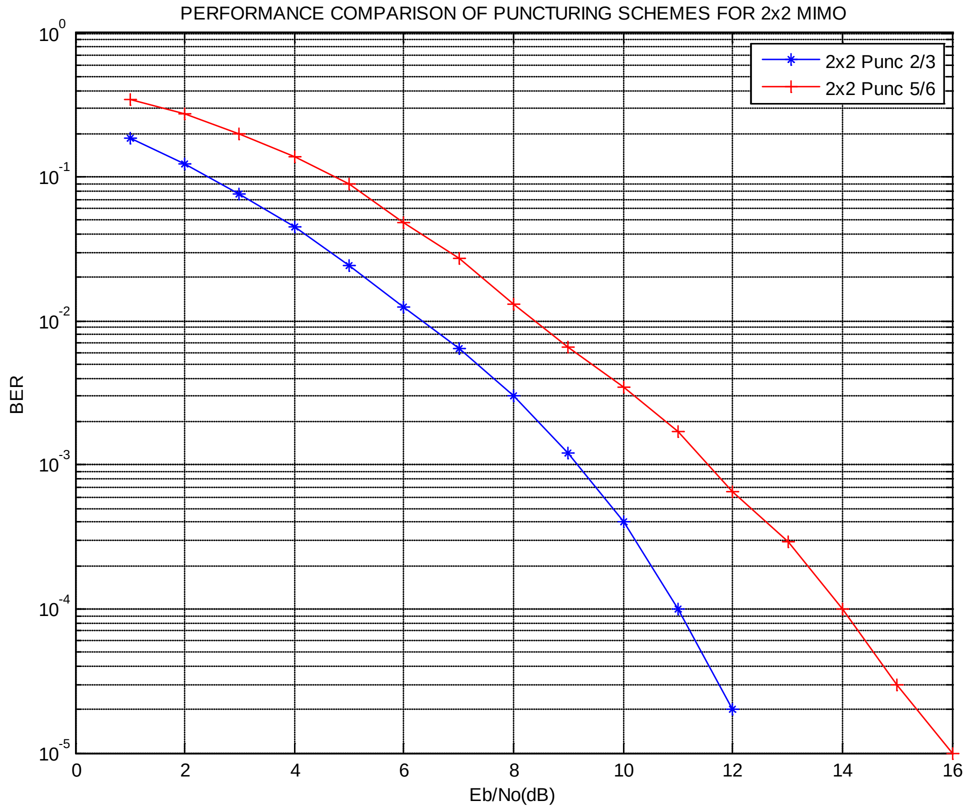

Figure 5.8 Performance comparison of puncturing schemes using 2x2 MIMO

From the above figure it is evident that there is a 3dB gain at 10^{-3} when puncturing is used to get a code rate of 2/3 as against the one that is used to get a code rate of 5/6. This verifies that as the coding rate decreases, BER also decreases increasing the performance of the system.

5.1.2.2 Performance comparison of interleaving schemes

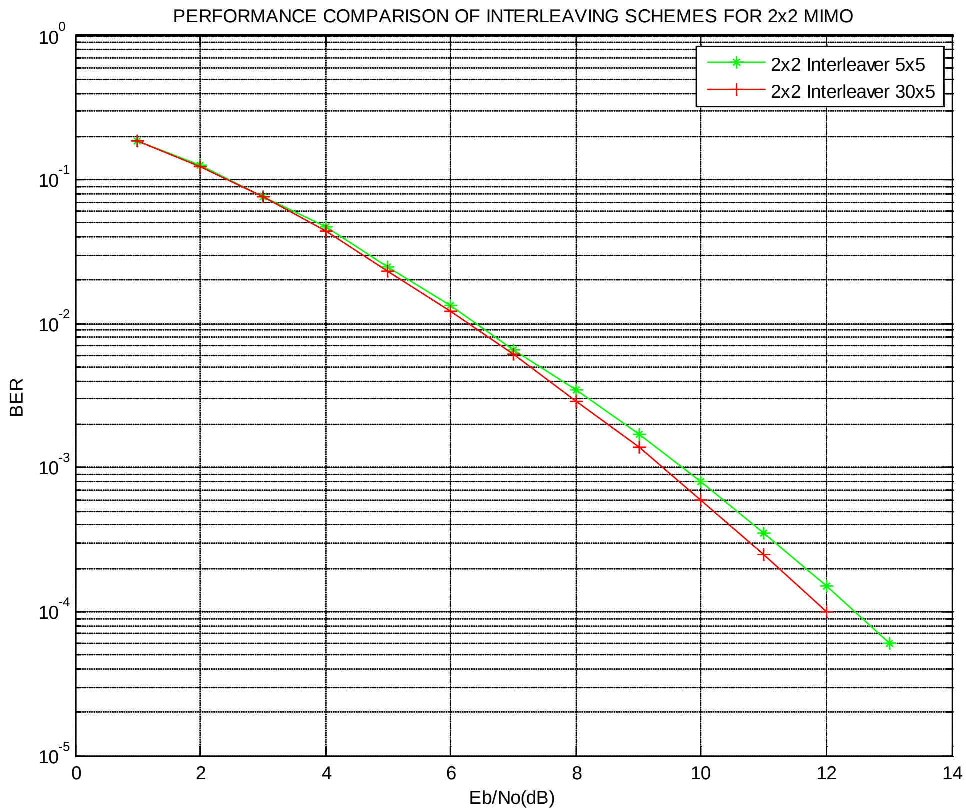

Figure 5.9 Performance comparison of interleaving schemes using 2x2 MIMO

In the case of 2x2 MIMO using the interleaving schemes, the graph confirms that the performance of the system depends on the interleaver degree. Furthermore, it also verifies that increased interleaver degree reduces the BER. As shown in the figure 5.9, graph obtained using interleaver of degree 30 has a better performance compared to the graph obtained for interleaver of degree 5.

5.1.3 Performance Analysis of 3x1 MIMO

The 3x1 system is implemented using the non-orthogonal space-time MIMO. The MIMO is coded according to the design given below

$$S_c = \begin{bmatrix} s_1 & s_2 & -s_3 \\ -s_2^* & s_1^* & -s_4^* \\ s_3 & s_4 & s_1 \\ -s_4^* & s_3^* & s_2^* \end{bmatrix}$$

The channel matrix is given by

$$H_c = \begin{bmatrix} H_1 & H_2 \\ -H_2 & H_1 \end{bmatrix} = \begin{bmatrix} h_1 & h_2 & -h_3 & 0 \\ h_2^* & -h_1^* & 0 & -h_3^* \\ h_3 & 0 & h_1 & h_2 \\ 0 & h_3^* & h_2^* & -h_1^* \end{bmatrix}$$

The above channel matrix is formed by combining

$$H_1 = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}$$

and

$$H_2 = \begin{bmatrix} -h_3 & 0 \\ 0 & -h_3^* \end{bmatrix}$$

using Hadamard transform.

The received signal can be represented by the following equation

$$Y = H_c S + N_c$$

The reconstructed signal is obtained by applying the matched filter H_c^H to the received vector as follows

$$Y = H_c^H H_c S + H_c^H N_c$$

After applying the matched filter, ML decoding is used to obtain the transmitted bits. Here we notice that four symbols are transmitted in 4 symbol time resulting in a rate equal to 1.

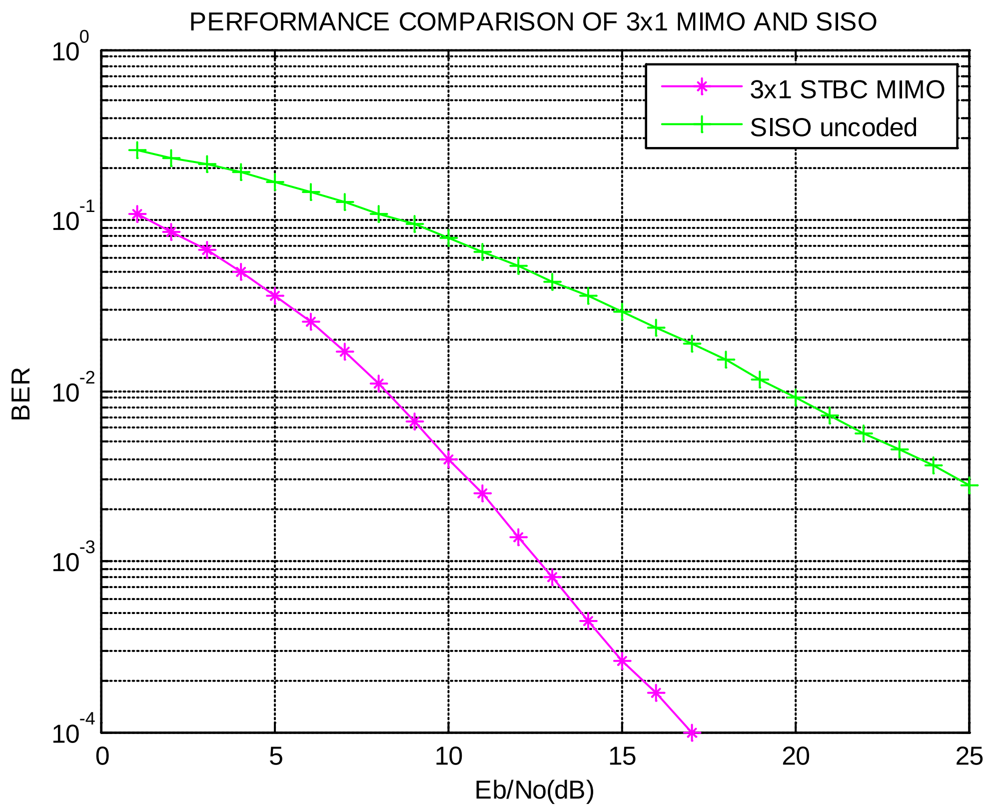

Figure 5.10 Performance of 3x1 STB coded vs. SISO uncoded

As seen in the graph shown by figure 5.10, it is confirmed again that a system with space-time coding performs better than an uncoded system. Using 3x1 MIMO we obtain a gain of about 12dB over the uncoded system.

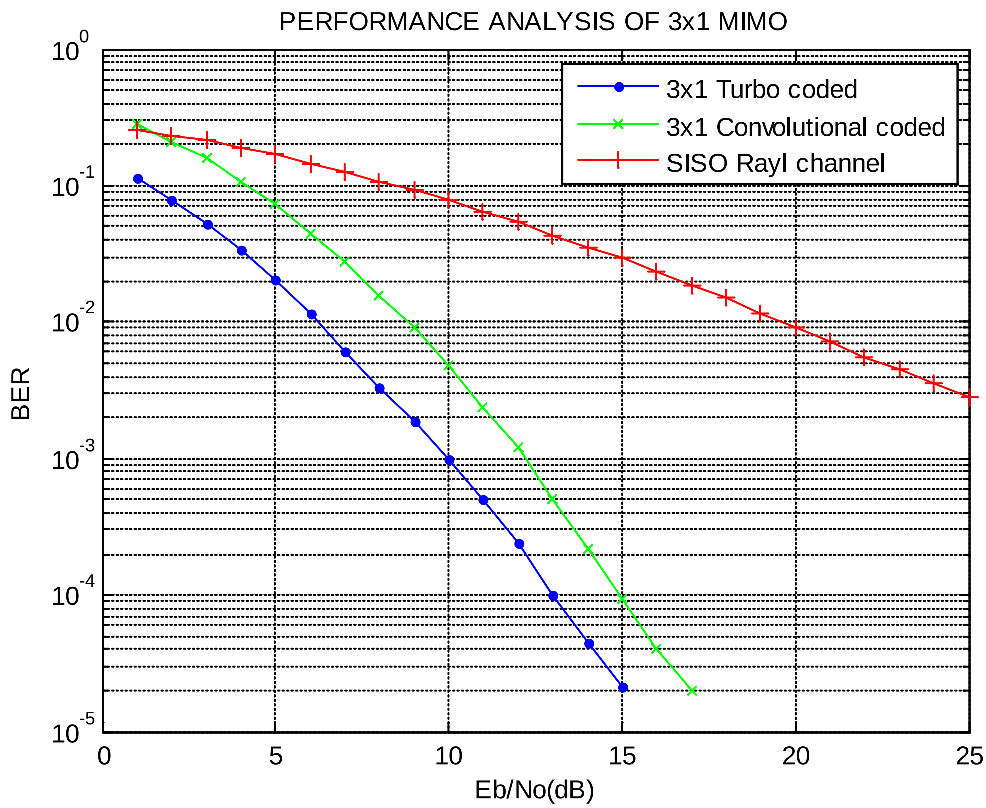

Figure 5.11 Performance analysis of 3x1 MIMO with Rayleigh channel and employing channel coding

In figure 5.11 we see that 3x1 MIMO with convolutional coding has achieved a gain of about 16 db at 10^{-3} over an un-coded system. Also a gain of 19 dB is obtained when turbo code is used due to the fact that turbo decoding is an iterative decoding technique.

5.1.3.1 Performance comparison of puncturing schemes

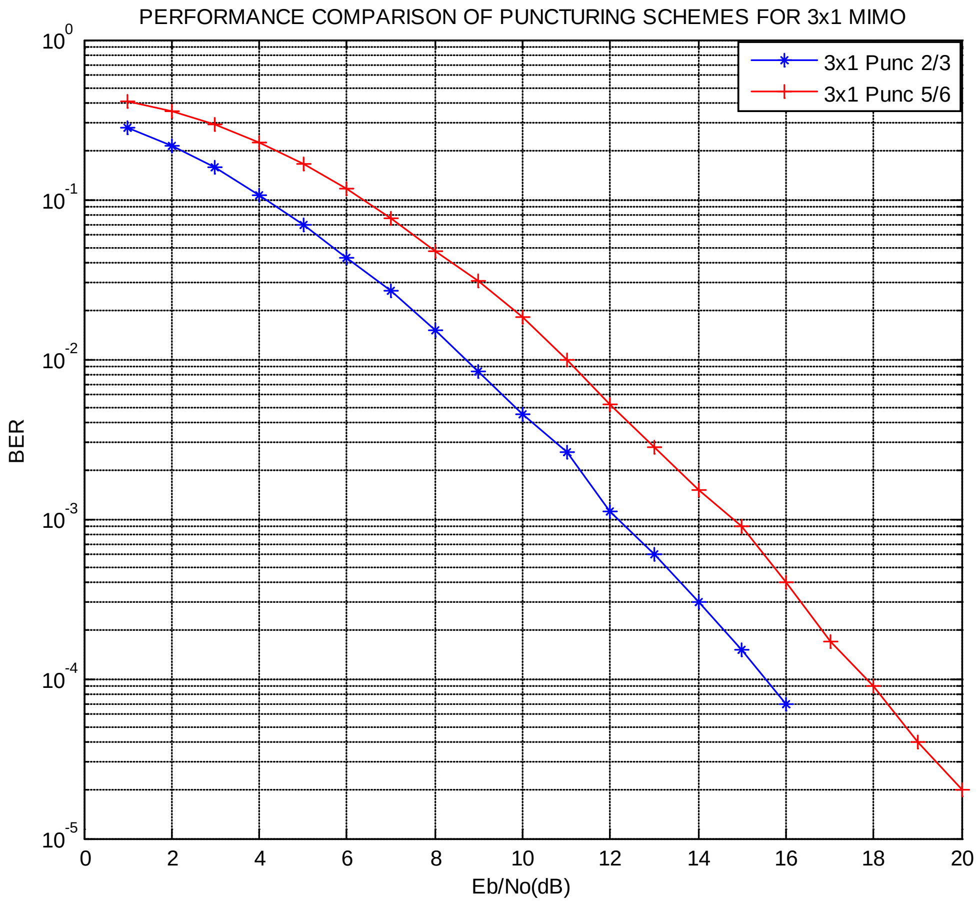

Figure 5.12 Performance comparison of puncturing schemes using 3x1 MIMO

In figure 5.12 we see a gain of 3dB at 10^{-3} when puncturing is employed to generate 2/3 rate code as compared to the scheme that is used to generate rate 5/6. Also, we see the general decrease in the BER in both the graphs due to the fact that there is a diversity of order 3 introduced by the transmit antennas.

5.1.3.2 Performance comparison of interleaving schemes

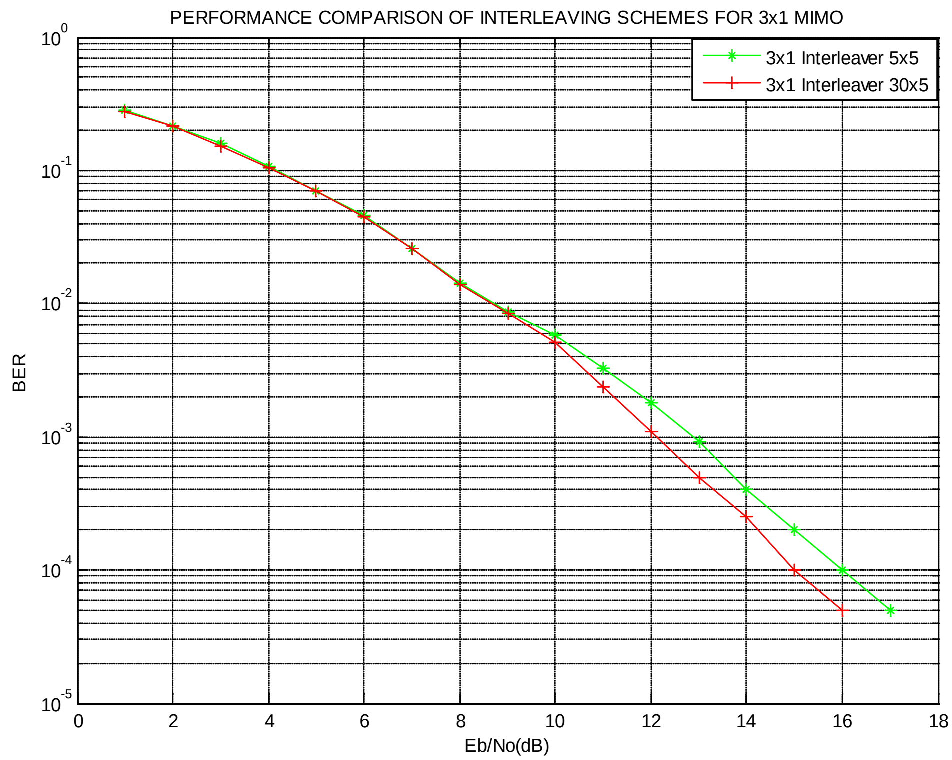

Figure 5.13 Performance comparison of interleaving schemes using 3x1 MIMO

Figure 5.13 shows that the performance of the interleaver scheme with degree 30 becomes pronounced as compared to the interleaver scheme with degree 5 as the energy per bit to noise power spectral density increases.

5.1.4 Performance Analysis of 4x1 MIMO

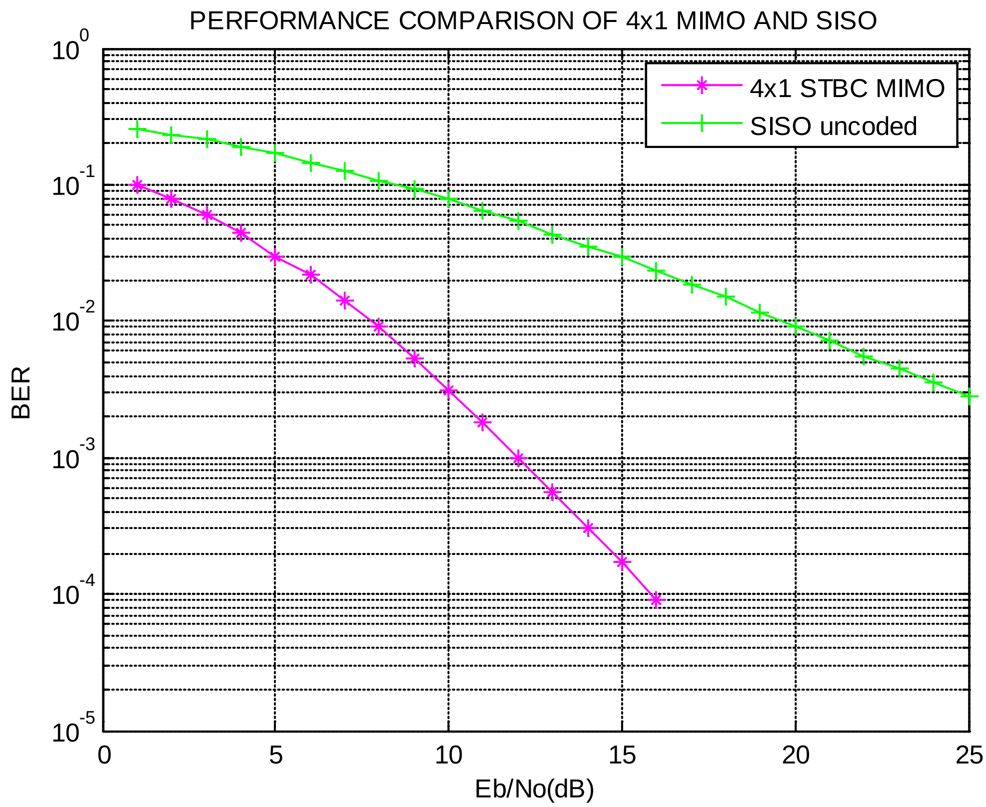

Figure 5.14 Performance of 4x1 STB coded vs. SISO uncoded

From figure 5.14, we observe that buy employing 4x1 non orthogonal MIMO we get a gain of 16 dB at 10^{-3} over the SISO system. However, If we observe closely this gain is actually less than the gain attained by 2x2 MIMO. The reason being, we use Alamouti code to implement 2x2 MIMO which is perfectly orthogonal. Furthermore, we use non orthogonal STBC design for 4x1 MIMO. Hence because of the non orthogonality, we see a slight degradation in the gain.

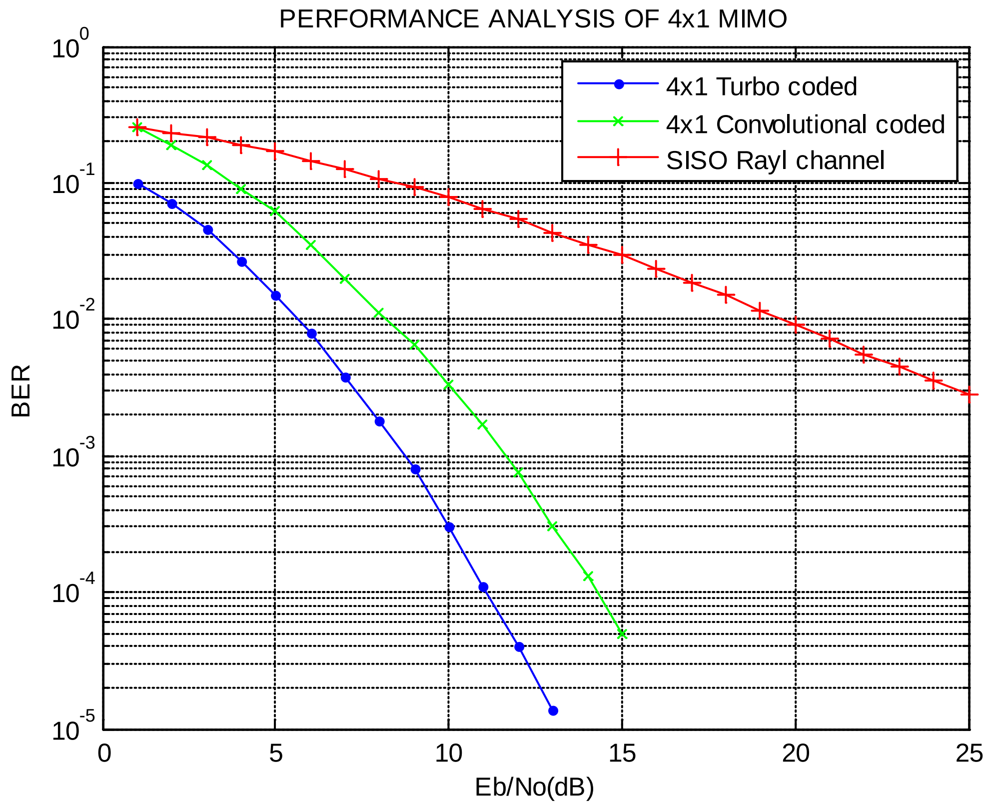

Figure 5.15 Performance analysis of 4x1 MIMO with Rayleigh channel and employing channel coding

From the above figure it is verified that as the diversity order increases, there is a reduction in the signal degradation. Furthermore, we see an improvement in the performance when convolutional code and turbo code are used.

5.1.4.1 Performance comparison of puncturing schemes

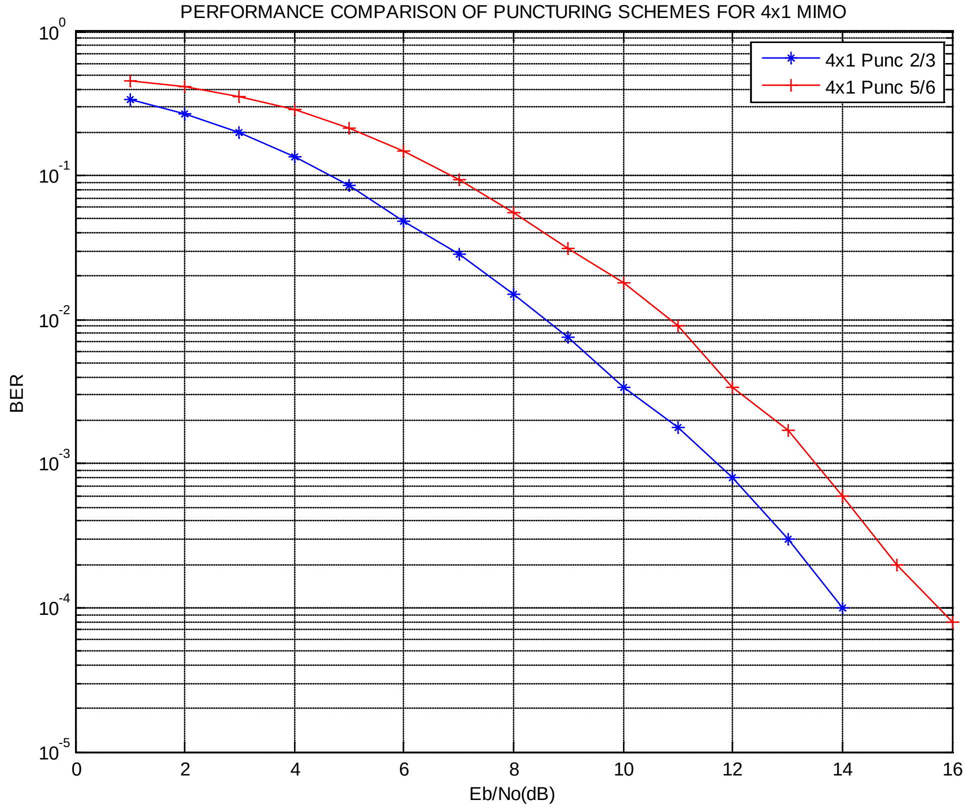

Figure 5.16 Performance comparison of puncturing schemes using 4x1 MIMO

In figure 5.16 it can be observed that there is a gain of 3dB at 10^{-4} when every third bit of four bits are punctured as compared to puncturing every 2 bits out of 6. The reason for this behavior is that more information is transmitted when the code rate = 2/3 as compared to when the code rate = 5/6.

5.1.4.2 Performance comparison of interleaving schemes

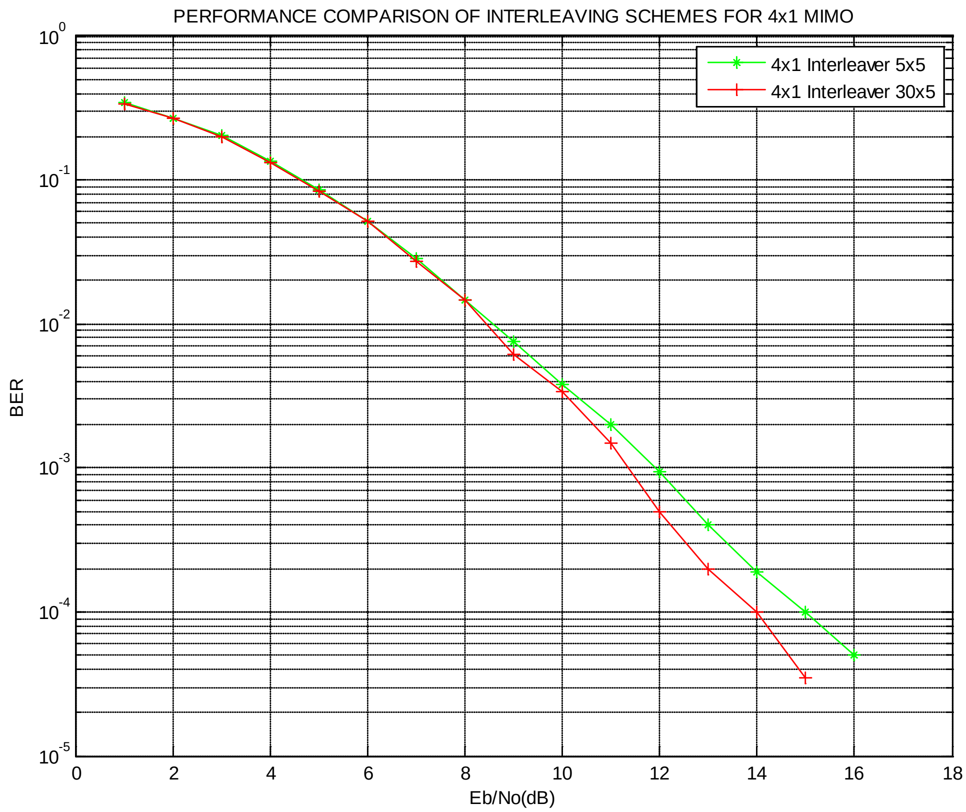

Figure 5.17 Performance comparison of interleaving schemes using 4x1 MIMO

As the degree of interleaving increases the BER reduces, as the bits in a codeword are less affected by bursty errors. This is verified in the figure 5.17. The system with interleaver degree equal to 30 outperforms the one with interleaver degree equal to 5.

5.1.5 Performance Analysis of 4x4 MIMO

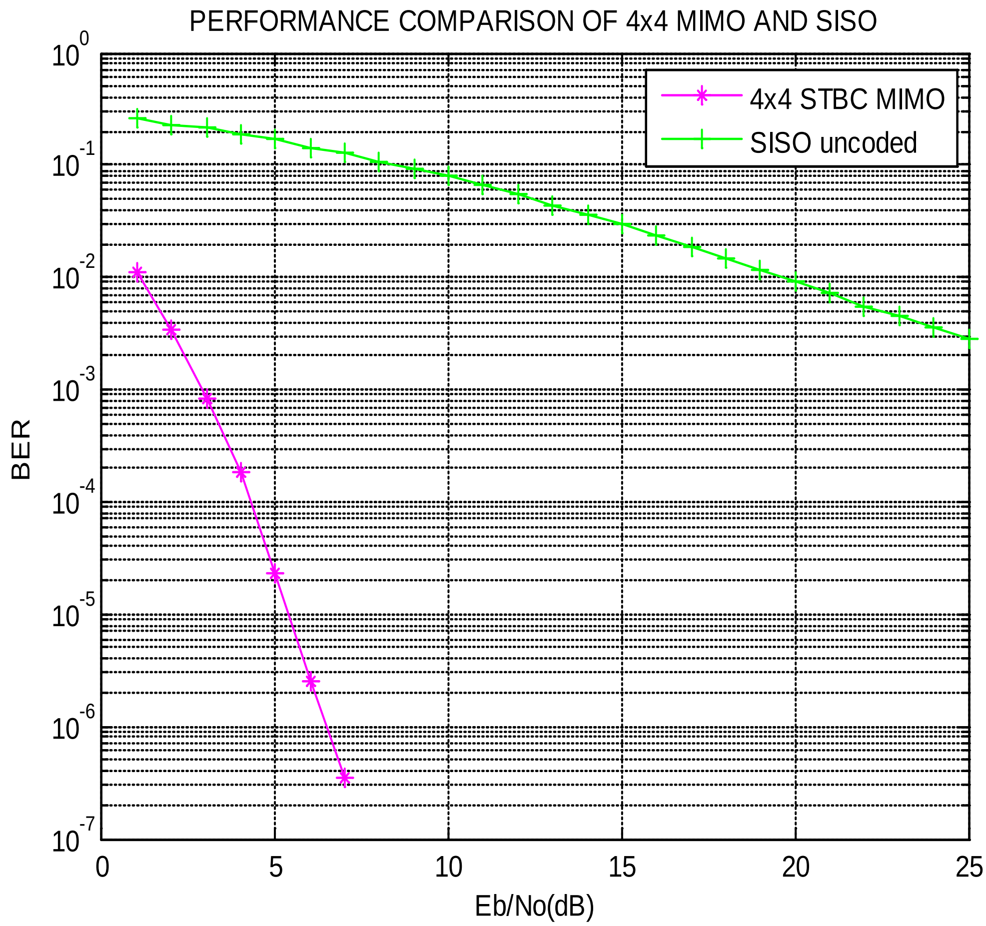

Figure 5.18 Performance of 4x4 STB coded vs. SISO uncoded

We see in figure 5.18 that by employing 4 antennas at the transmit side and 4 at receive side we can obtain a gain of 23 dB at 10^{-3} BER compared to a single transmit and receive antenna. This is a huge incentive considering the fact that the system is only STBC coded.

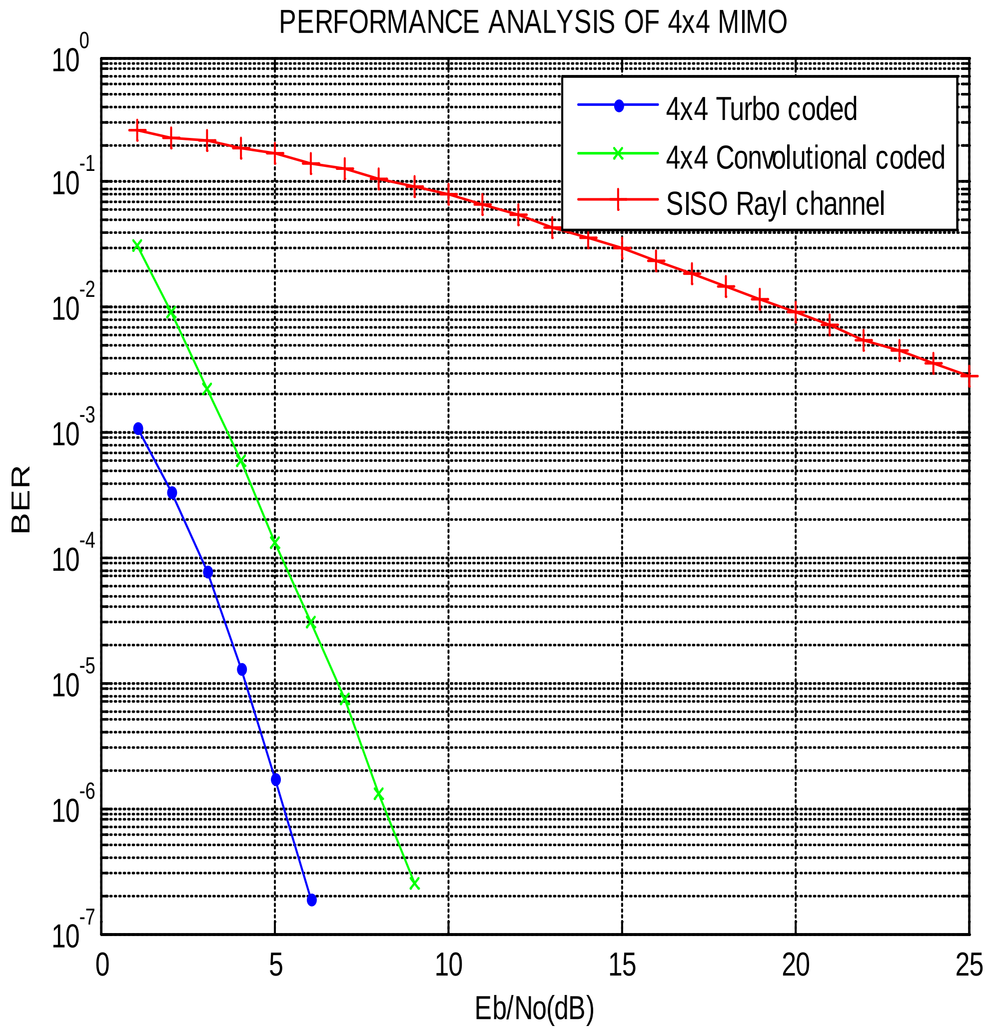

Figure 5.19 Performance analysis of 4x4 MIMO with Rayleigh channel and employing channel coding

In real world one of the common channels is rayleigh channel and the analysis of 4x4 MIMO becomes imminent. We see in figure 5.19 that the system has a gain of more than 23dB at 10^{-4}. The reason behind this is that we get a diversity of order 16 in this system. We also notice that the performance of the turbo code in rayleigh channel is better than the performance STBC in static channel. As mentioned in the chapter 4, turbo coding uses previous decoded values to evaluate future values. In a 4x4 MIMO system the error is very much reduced due to diversity.

Due to this, there is less error propagation during the turbo decoding giving a good signal quality.

5.1.5.1 Performance comparison of puncturing schemes

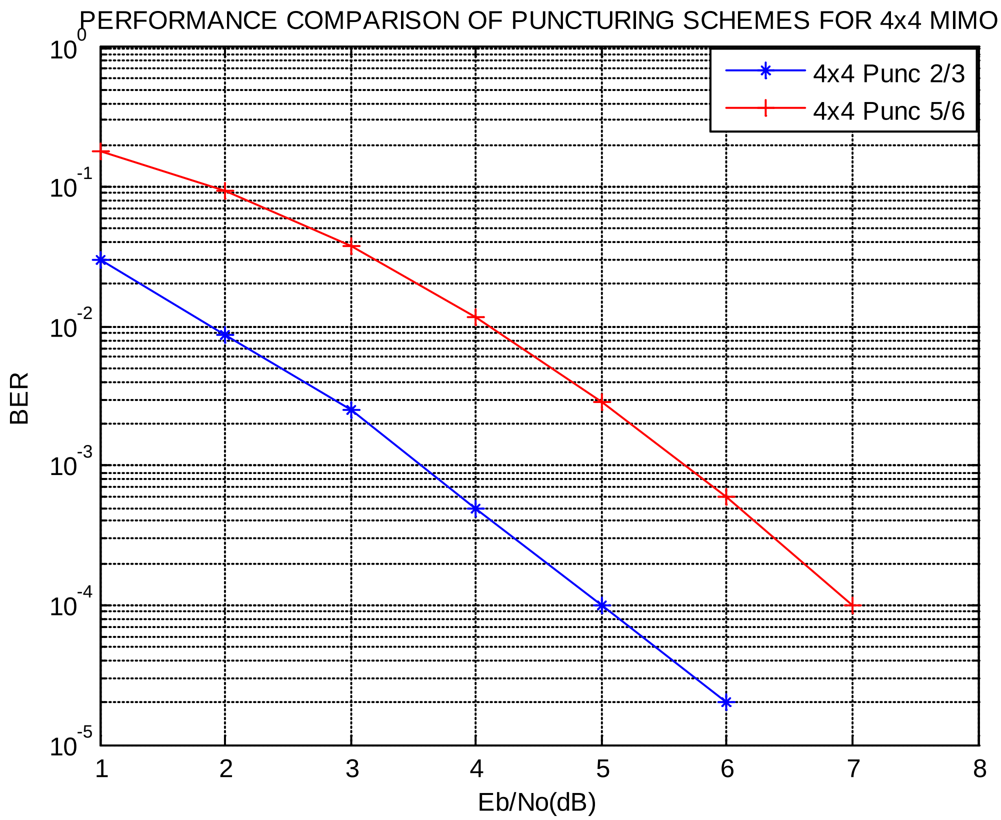

Figure 5.20 Performance comparison of puncturing schemes using 4x4 MIMO

Once again we see in figure 5.20 that as the code rate reduces, the BER also reduces.

5.1.5.2 Performance comparison of interleaving schemes

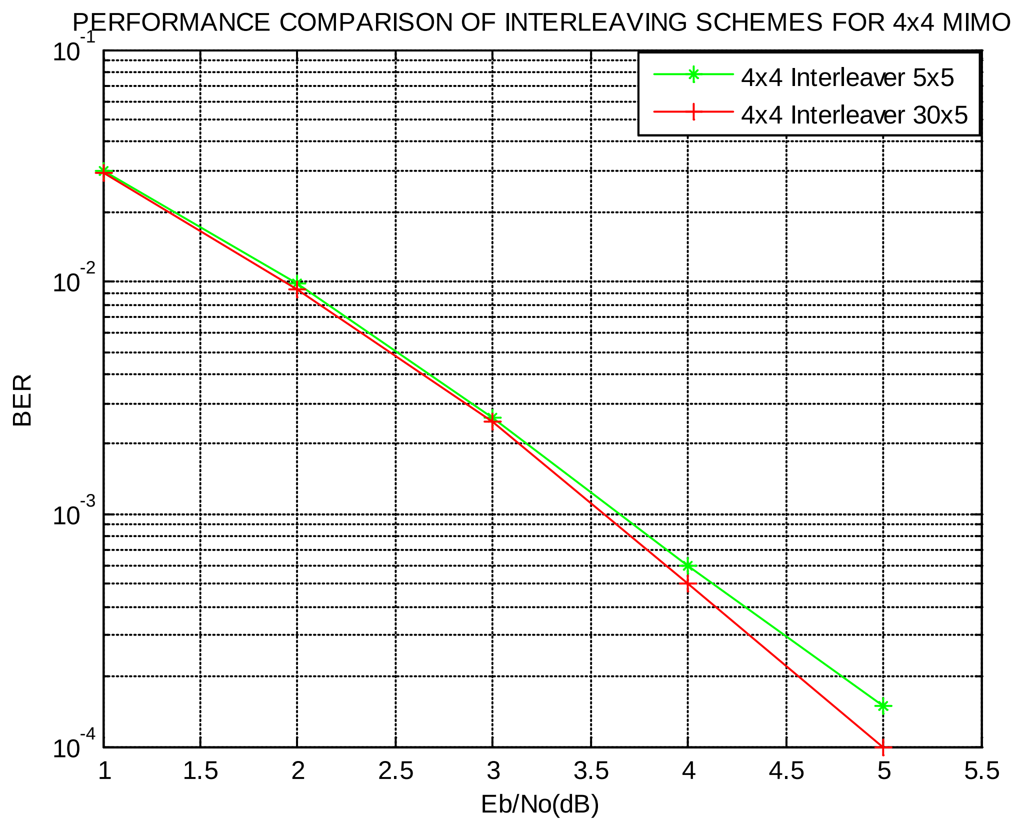

Figure 5.21 Performance comparison of interleaving schemes using 4x4 MIMO

In figure 5.21 we see that the performance of the 4x4 MIMO system with interleaver of degree 5 has a worse performance as compared to the system with interleaver degree 30.

5.1.6 Performance Comparison of 2x1, 2x2, 3x1, 4x1 and 4x4 MIMO

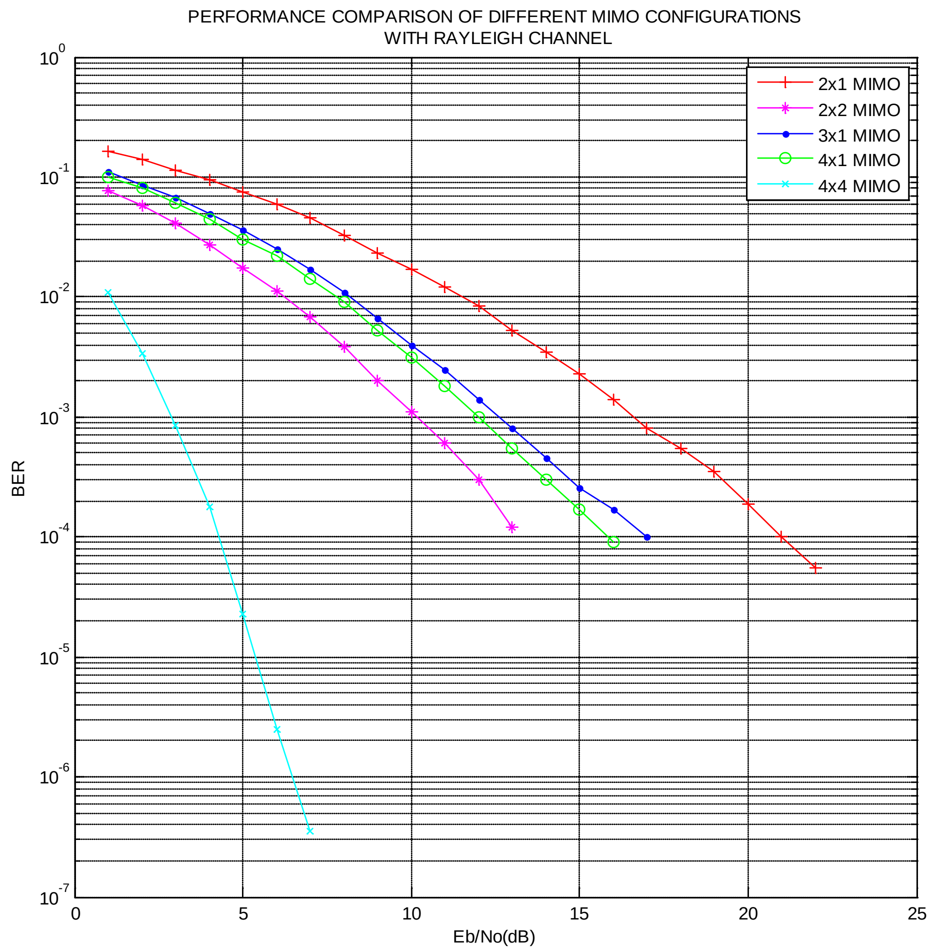

Figure 5.22 Performance comparison of 2x1, 2x2, 3x1, 4x1 and 4x4 MIMO in static channel

From figure 5.22 we get a good idea about the influence of diversity on BER in a wireless communication system. The performance of the system is the best when employing 4x4 as the diversity is of the order 16, 2x2 system with diversity 4, next is the system with 4x1 with diversity order = 4, closely followed by 3x1 with diversity order = 3 and lastly the 2x1 system with diversity order = 2. We might notice that although the system with 2x2 and 4x1 have the same diversity order, 2x2 MIMO outperforms 4x1. This is because we use a non orthogonal 4x1

STBC design to implement 4x1 MIMO. Also, 4x1 MIMO outperforms 3x1 MIMO as we use non orthogonal STBC design for 3x1 MIMO as well. However, 3x1 MIMO has a better performance than 2x1 MIMO because of the higher diversity in the system.

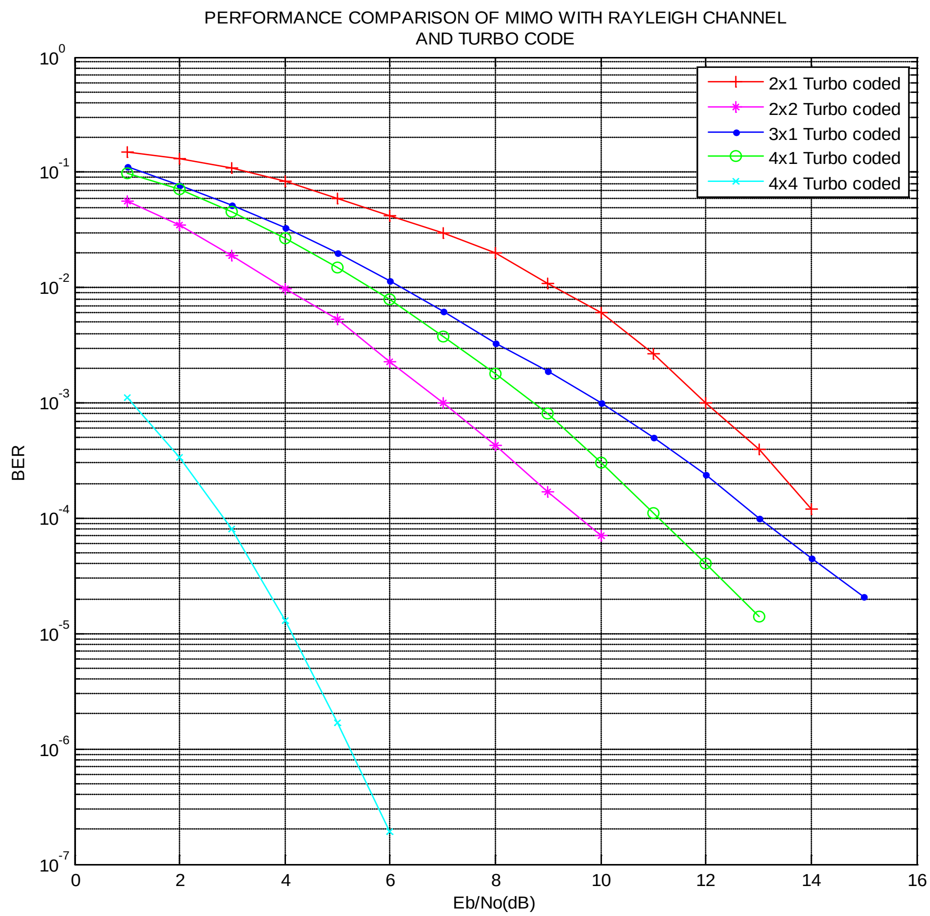

Figure 5.23 Performance comparison of 2x1, 2x2, 3x1, 4x1 and 4x4 MIMO using rayleigh channel and turbo coding

We notice in figure 5.23 that in STBC turbo coded system due to the different diversity introduced by the different transmit and receive antenna configurations the BER varies according to the diversity order. We also observe 2x2 outperforms 4x1 MIMO verifying that due to the non orthogonal design although we get rate = 1 STBC the performance is not as good when compared to published results employing orthogonal STBC design.

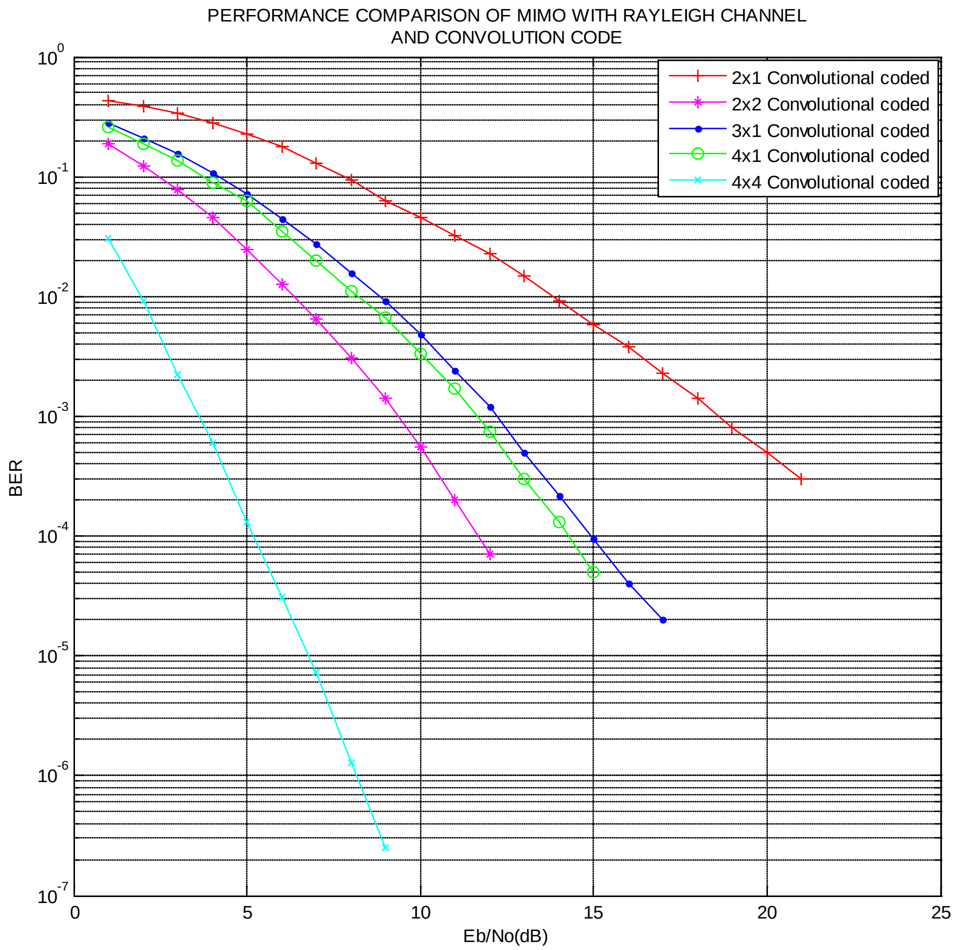

Figure 5.24 Performance comparison of 2x1, 2x2, 3x1, 4x1 and 4x4 MIMO using rayleigh channel and convolutional coding

In figure 5.24 we see the same result as seen in the previous graph but only see higher BER due to the fact that we have used convolutional coding for channel coding. From the previous graph we can note that turbo code outperforms the convolutional code.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Considering that MIMO is a rapidly evolving technology being targeted for the use in various communication applications for the reliable communication, variable data rate, increased data throughput and higher capacity, the performance analysis of the MIMO system is an important issue. In the work presented in this thesis, we have tried to achieve the performance curves for various practical cases.

We implemented five different configurations of the full rate MIMO system namely , two transmit and one receive antenna, two transmit and two receive antennas, three transmit and one receive antenna, four transmit and one receive antenna and finally four transmit and four receive antenna. We used perfectly orthogonal Alamouti code to implement two transmit and one/two receive MIMO system. On the other hand, we used non-orthogonal STBC design for three transmit and one receive & four transmit and one/four receive so as to obtain full rate. We must emphasize the fact that full rate perfectly orthogonal design exists only in the case of two transmit and one/two receive antennas. We observed that the performance of the implemented MIMO system not only depends on the diversity order but also on the space-time code design. The system with four transmit and four receive antennas performed the best as the diversity was of the order 16, followed by two transmit and two receive with diversity of order 4. However, four transmit and one receive performance was worse as compared to two transmit and two receive because we used a non orthogonal STBC design for the system. Three transmit and one receive antenna with diversity order of 3 performed worse than four transmit and one receive but outperformed two transmit and one receive antenna with diversity of 2. This simulation was carried out in Rayleigh fading channel conditions.

Additionally, we simulated and analyzed the performance of the system with channel coding. Specifically we implemented convolutional encoding and viterbi decoding & turbo encoding and MAP decoding. The performance of the system improved drastically when turbo encoding and decoding was introduced, almost close to static channel behavior. Also, turbo coding outperformed convolutional encoding. The reason for this being, turbo encoder introduces more redundant information as compared to the convolutional encoder and also the fact that turbo encoders are systematic encoders adds to the better performance of turbo codes. We must also emphasize fact that turbo encoders employ iterative decoding to decode bits. This greatly enhances the performance of the turbo codes. However, it comes with a disadvantage that due to the iterative decoding the complexity is high as compared to convolutional code and if there is any round off errors introduced by the computer while iterative decoding, this error gets accumulated with other errors from previous decoding iterations. This error may grow as the number of iterations increases and manifests in the decoded information as decoding error. Nonetheless, this is error is magnified for low BER as compared to high BER. Although turbo codes outperform convolutional code in bit error rate, we must note that convolutional coding is very simple and hence less complex as compared turbo coding.

Furthermore, we analyzed the system by employing puncturing to the system to obtain different code rate. Specifically we simulated a system with code rate = 2/3 and code rate = 5/6. We observed that, the performance of the system improved as the code rate reduced conversely, as the code rate is increased the BER also increased. We must note that to obtain 2/3 code rate from mother of ½ we punctured one bit of every block of 4 bits and on the other hand to obtain a code rate of 5/6 we punctured 2 bits out of every block of 6 bits. This brings out the fact that there is more data transmitted about a code in code rate = 2/3 as compared to rate = 5/6. This point validates the BER performance curves that we have obtained in our simulation.

Besides, implementing all the above communication components we also implemented and analyzed the effect of interleaving in MIMO system. We simulated 5x5 block interleaver with interleaving degree of 5 and 30x5 block interleaver with interleaving degree of 30. We observed that as the interleaving degree increases the BER decreases. Hence, the system with interleaving degree of 30 outperformed the system with interleaving degree of 5 provided the systems are identical. The reason for this behavior is that, with interleaving degree of 30, the consecutive bits of a code-word are separated by 30 bits and if there is any burst errors the chance of more than 1 bit in a code-word getting affected is very less likely. Whereas in interleaving degree of 5, bits of a codeword are separated only by a distance of 5 and hence the chance of more than one bit in a code-word to be affected by burst errors is more likely. This validates the performance of the interleaving schemes we obtained in our simulation.

6.2 Future Work

The analysis carried out in our thesis was performed in a Rayleigh fading channel and non line of sight channel model. It remains to be seen what would be the effect in the case of line of sight channel model. The analysis can be carried out for in outdoor environment as well.

The work presented in the thesis can be extended by employing maximal ratio combiner (MRC) at the receiver as MRC technique is widely used and has a better performance as compared to equal gain combining. The work on turbo code can be extended by analyzing the performance of the turbo code using various other decoding algorithms. Turbo decoder can be implemented using Log-MAP, Max Log-MAP and SAVO decoders. Detailed analysis of the various algorithms and how they can be implemented can be included. The different algorithms can be compared and the performance can be analyzed.

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