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Performance Analysis of Space Time Trellis Code on Rayleigh, Rician and Nakagami Fading Channel

by

Khem Nath Khatiwada

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APPROVAL PAGE

The undersigned certify that they have read and recommended to the Department of Electronics and Computer Engineering for acceptance, a thesis entitled **"Performance Analysis of Space Time Trellis Code on Rayleigh, Rician and Nakagami Fading Channel"**, submitted by **Khem Nath Khatiwada** in partial fulfillment of the requirement for the award of the degree of **"Master of Science in Information and Communication Engineering"**.

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DEPARTMENTAL ACCEPTANCE

The thesis entitled **“Performance Analysis of Space Time Trellis Code on Rayleigh, Rician and Nakagami Fading Channel”**, submitted by **Khem Nath Khatiwada** in partial fulfillment of the requirement for the award of the degree of “**Master of Science in Information and Communication Engineering”** has been accepted as a bonafide record of work independently carried out by him in the department.

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ABSTRACT

Space-time codes merge coding gain with diversity gain and maintain orthogonality between the antennas. Coding works as a promising technique in the reliable digital data communication. STTC provides coding gain as well as diversity gain which gives the additional SNR advantage due to coding gain. This thesis analyzes the STTC over Rayleigh, Rician and Nakagami fading channel along with its implementation. STTC has been used for encoding and vitebri decoder for decoding. The design of 2-PSK for the SISO and use of 2 transmit antennas at transmitting side and use of receive antenna at receiving side up to 4 has been presented for 4, 8, 16 and 32 state. The result shows a significant improvement in performance of STTC with increasing number of states, number of transmit and receive antennas. It makes the data reliable and secured, along with increased throughput between the transmitter and receiver. It has been concluded that STTC over MIMO channel has improved error performance in terms of SNR with Nakagami fading channel.

Key Words: STTC, Vitebri Decoder, MIMO, Nakagami Fading channel.

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List of Abbreviations

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
dB	Decibel
FEC	Forward Error Correction
FFC	Feed Forward Convolutional code
MISO	Multiple Input Single Outputs
MIMO	Multiple Input Multiple Output
SIMO	Single Input Multiple Output
MSB	Most Significant Bit
PDF	Probability Density Function
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
SNR	Signal to Noise Ratio
STBC	Space Time Block Code
STC	Space Time Code
STTC	Space Time Trellis Code
SER	Symbol error rate

CHAPTER ONE: INTRODUCTION

1.1 Overview of MIMO

Wireless communication has been a part of life from its invention. Antennas on transmitter and receiver side are used in wireless communication system for transmission of radio waves. Multiple-Input-Multiple-Output (MIMO) systems are most emerging research areas of wireless communications. MIMO channel has a significant capacity gain, transmit power gain, transmission reliability and bandwidth over Signal Input Single Output (SISO) channel. This provides a fundamental limit on data through in MIMO systems. The spatial diversity obtained from transmit and receive antennas can be combined with channel coding. This combined process leads to space time coding in a coded system [1].

Diversity is a method of conveying information through multiple independent instantiations of random fades. Out of many forms of diversity, this research mainly focuses on time and space diversity through multiple independent transmits and receives antennas. In fact a diversity gain results from multiple paths between transmitter and receiver, and coding gain results from how symbols are correlated across transmit antennas [2]. Diversity gain performance improvement can be achieved from a system by using multiple antennas at both transmitter and receiver. Similarly coding of symbols across space and time can be employed to yield coding gain. Performance of space-time codes is usually illustrated by plotting the SER versus SNR on a logarithmic scale. Figure 1.1 illustrates the effect of each code metric on the SER curve.

Diversity gain affects the asymptotic slope of the SER versus SNR graph - greater the diversity, the faster the SER drops with SNR. Coding gain affects the horizontal shift of the graph - greater the coding gain, the greater the shift to the left.

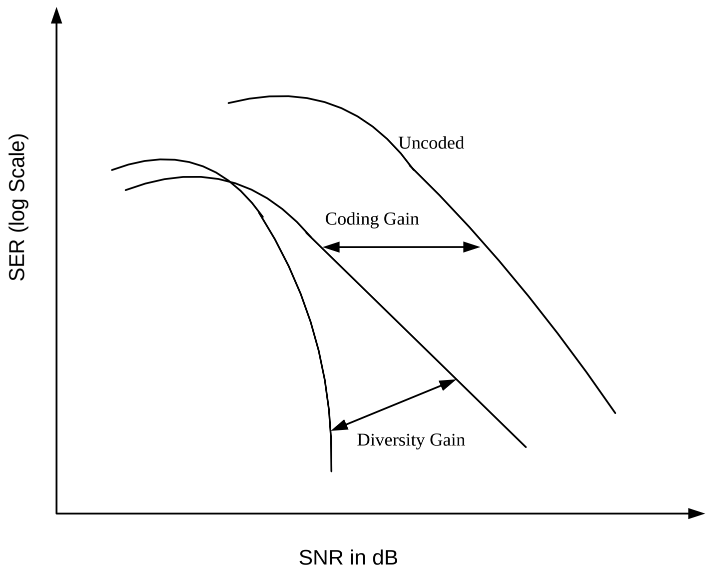


Figure 1-1: Curve of Coding Gain and Diversity Gain

Space-Time Codes (STC) were practiced independently by Tarokh et al. and Alamouti as a means of providing transmit diversity for multiple-antenna fading channels. There are two different types of STC. First one is Space-Time Trellis Codes (STTC) and the second one is Space-Time Block Codes (STBC). Decoding STTC is a complicated task, to reduce decoding complexity, Alamouti discovered a remarkable scheme using STBC for transmitting using two transmit antennas [3]. This is appealing in terms of both simplicity and performance. Tarokh et al. used this scheme for an arbitrary number of transmitter antennas, leading to concept of STBC, in which the codes are orthogonal to each other [4]. STBC have a fast decoding algorithm. STBC can be classified into real orthogonal design and complex orthogonal design. The real orthogonal design deals with real constellations such as PAM while complex design deals with complex constellations such as Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM). Tarokh et al. proposed systematic constructions of real orthogonal designs for any number of transmit antennas with full rate where there exist several different types of space-time block codes obtained from complex orthogonal designs [5],[6]. One of the key features the STBC obtained from orthogonal designs is that by performing linear processing at receiver, data symbols can be recovered. This feature is attractive for mobile and portable communication systems. On the other hand looking at diversity gain obtained from STTC is equal to diversity gain from STBC for same numbers of transmit and receive antennas. STTC can provide coding gain, where a STBC cannot. This additional coding gain is obtained at the cost of increased decoding complexity at receiver because a Viterbi or trellis based decoder has to be employed. The complexity of decoder increases with number of states in trellis and number of transmit antennas [6]. Boleskei et al. considered the effect of receive and transmit correlation in MIMO systems on error performance of STC [7]. They showed that the resulting maximum diversity order was given by the ranks of receive and transmit correlation matrices.

1.2 Historical Background

Spatial diversity was often limited to systems that switched between two antennas or combined signals to provide best signal. Also various forms of beam switching were implemented, to optimize the tradeoff between the diversity gains and complex gains the search went for the design of antenna modes (SISO, SIMO, MISO, MIMO) according to the need of user [8].

New approaches to MIMO technology, which considers configuration where multiple antennas are co-located at transmitter to improve link throughput effectively. Bell Labs were the first lab to demonstrate a laboratory prototype of Spatial Multiplexing (SM) , where the spatial multiplexing is a principle technology to improve the performance of MIMO systems. In commercial arena, Lospan wireless Inc. developed first commercial system that used MIMO-OFDMA technology Lospan technology supported both diversity coding and spatial multiplexing [9].

The researchers have explored the use of multiple-element arrays at the transmitter and the receiver end to meet the high demand for higher bit rates in wireless local-area networks. The study shows that in a single-user, point-to-point links, using multiple element arrays at both the ends increases the capacity significantly over single-antenna systems [10]. The analytical evaluation of the capacity distribution of the MIMO Rayleigh fading channels in concise closed form with an arbitrary correlation among the transmitting and the receiving antennas is performed by Marco Chiani [11]. A MIMO-OFDM prototype has been developed in the framework of a Nortel Networks system concept for 3G evolution systems and next-generation WAN networks.

1.3 Motivation

Signal sent from transmitter does not follow one path before it reaches to destination in wireless channels. Objects present in the environment causes it to traverse many different paths by means of physical effects such as reflection and refraction. Thus, multiple versions of the transmitted signal reach the receiver. The observed signal at the receiver is a sum of all these multiple signals, and it is typically different from the originally transmitted one. Furthermore, in real applications, relative positioning of transmitter-receiver pairs and overall state of objects between them may vary frequently in time, causing a change in multiple paths that signals follow. As a result, it is not rare that signal observed by receiver is not sufficient enough to be able to extract the actual signal. This factor, known as “multipath fading” or simply as “fading”, is fundamental problem in wireless communication.

More and more people are using modern communication services, thus increasing the need for more capacity in transmissions. Since bandwidth is a limited resource, the strongly increased demand in high transmission capacity has to be satisfied by a better use of existing frequency bands and channel conditions. One of recent technical breakthroughs, which will be able to provide the necessary data rates, is the use of MIMO system. Coding provide additional gain in the system which also helps to increase the SNR of the system, this can be achieved by using STTC.

1.4 Problem Statement

Performance of STTC over Rayleigh fading channel, Rician fading channel and Nakagami fading channel under different states and different diversity orders are analyzed in thesis. STTC have attraction over other codes because it have both diversity and coding gain. Coding phenomenon over different channel is an important issue for analysis. STTC coding over the three fading channel scenario is made here for different diversity order. In this work the number of transmit antennas are varied from 1 to 2 and receive antennas are varied from 1 to 4 for all Rayleigh, Rician and Nakagami fading channel. Taking these three channels almost all the scenarios of communication performances can be observed. The STTC was first initiated by Tarokh et.al [20] and later extended by Sujeet singh et. al [21]. The verification of this thesis is carried out with Matlab simulation and result is compared with the reference paper [21].

Fading causes the decrease in reliability of communication between different users. MIMO technology which uses multiple receive and transmit antennas has been used to offset this reliability issue. Transmit diversity over the multipath fading channel can be used. Use of MIMO technology increases the capacity compared to SISO. Use of coding and diversity can increase the system performance by a huge margin. The STTC coding is used to solve this reliability issues as it provides both coding and diversity gain. Tarokh described the coding technique in his work. He gave the theory that the coding technique is applicable for different channels. Later the coding technique which considered Rayleigh fading channel with only the BPSK modulation scheme [21]. In extension to his work this research covers both Rayleigh fading, Rician fading and Nakagami fading channel scenario along with increasing the number of transmitting and receiving antennas for different states. Also the thesis covers the DBPSK modulation scheme which has great advantage of having non-coherent detection over the BPSK modulation. After the simulations the final output was compared with in different states and different diversity order and can be verified that the STTC coding has a better performance.

1.5 Objectives

The overall objective of this research work is

a) Comparison and analysis of MIMO system with SISO system on the basis of Capacity.

b) Performance analysis of Space Time Trellis Code over the Rayleigh, Rician and Nakagami fading channel.

1.6 Organization of the Thesis

Chapter 1 presents general introduction of the thesis topic including brief review of challenges, solutions and most recent research in STBC and STTC. It also provides the information about the motivation of research. In chapter 2, literature review of MIMO, diversity, coding along with the advantages of MIMO compared to SISO is presented. Theoretical back ground for thesis described on Chapter 3.In Chapter 4 describes the methodology used for the research work. In Chapter 5 simulation result and their analysis are described. Conclusion and future recommendations is provided in Chapter 6.

CHAPTER TWO: LITERATURE REVIEW

To transmit high data rate in the order of several Megabits per second (Mbps) is important to future wireless communications. In recent years, antenna systems which employ multiple antennas at both the base station and mobile station, operating in space-time, have been proposed and demonstrated to significantly increase system performance as well as capacity. The merit of using multiple antennas or space diversity is that no bandwidth expansion or increase in transmitted power is required for capacity and performance improvements. A new approach to improve the performance for multiple-input-multiple-output systems for transmission from one base station to many mobile station in both frequency flat and selective fading channels is described [16]. Due to the insufficient spectral resources available, wireless communication technologies that can provide broadband bandwidth-efficient communications are in strong demand. Based on recent studies, it has been shown that through the application of multiple-input multiple-output (MIMO) systems it can provide remarkable information capacity gains in wireless communications [23]. If the fading between pairs of transmit and receive antennas is independently Rayleigh distributed, it is well known that in the high transmit power region the average capacity increases linearly with the minimum number of transmit and receive antennas, even if the transmitter has no knowledge of the channel.

Recent studies indicate that antenna arrays hold great promise for bandwidth-efficient high speed wireless communications. Maximal exploitation of antenna arrays in wireless communication necessitates accurate yet tractable modeling of the MIMO channel coupling the transmitter and receiver [24]. A major benefit of MIMO wireless communication system is the ability to perform well in scenarios traditionally viewed as poor-such as richly scattering environments. Consequently, many emerging wireless technologies, ranging from 802.11n to WiMAX to 4G cellular incorporate some form of MIMO [25]. MIMO system is characterized by multiple antennas at the transmitter and transmitted power supply being upgraded or wider bandwidth required [22]. MIMO system is using the special diversity at both the transmitter and receiver. They have been shown to present a significant increase in capacity over single-input single-output (SISO) systems because of the constituent parallel sub-channels existing within the MIMO channel [18].

Space time code (STC) scheme was proposed by Alamouti for transmit diversity on the downlink. In the IEEE 802.16e 2005 specifications, this scheme is referred to as Matrix A. Originally, Alamouti's transmit diversity was proposed to avoid the use of receive diversity and keep the subscriber stations simple [26]. Space-time coding techniques has attracted great interests in the research of multiple-input-multiple-output (MIMO) wireless communication systems. Some well-known space-time codes (STC) are space-time block codes (STBC), and space-time trellis codes (STTC), which are designed for frequency-flat fading wireless channels and have been shown to be able to exploit the potential spatial diversity of MIMO systems. For frequency-selective fading channels, it has been shown that the above mentioned space-time coding schemes can still achieve the designed spatial diversity but fail to gain any frequency diversity [26]. Space-time (ST) coding has been proved effective in combating fading and enhancing data rates.

Exploiting the presence of spatial diversity offered by multiple transmit and/or receive antennas, ST coding relies on simultaneously coding across space and time to achieve the maximum diversity gain without necessarily consume additional bandwidth and powers. In ST coding, however, the maximum achievable diversity advantage is equal to the product of the number of transmit and receive antennas, no additional diversity inherent, in the mobile wireless channel, for example, multipath diversity in frequency selective channels or Doppler diversity in time- selective systems has been exploited. It is constrained by the size and cost a system can afford [27]. Space-time trellis codes have been introduced to provide improved error performance for wireless systems using multiple transmit antennas [28]. Space-time coding, which purposely adds redundancy along both temporal and spatial dimensions to achieve both diversity and coding gains, has attracted a lot of attentions in recent years.

The design of effective space-time codes has been an active research area, and various approaches to the design and analysis of space-time codes have been proposed [29]. STC is a new technology of space-time signal processing for wireless communication system. Transmitting through multiple elements, it obtains high data rates by exploiting the spatial dimension and efficiently suppressing the interference. STC techniques, such as the block coding scheme, or the trellis coding scheme, are known to be simple and practical ways to increase the spectral efficiency in wireless communications [29]. In space-time coding, also the multiple antennas are employed at the transmitter. This intelligent coding of symbols across space and time can be done to reap the advantages due to coding and diversity. The coding in space is obtained by using multiple antennas at the transmitter and receiver [30]. Thus the use of STTC in MIMO system is a recent trend. The performance analysis of MIMO with different number of transmit and receive antennas is a good topic to analyze. This report will cast more light on these topics in the coming chapters.

Research on MIMO system was started by mid to late 1990s. MIMO systems are expansions of antenna at the transmitter and at the receiver. The main reason for the attraction towards MIMO system was increase in the capacity in wireless communication system substantially without increasing the transmission power and bandwidth.

Various research and performance analysis on MIMO system has been done at IOE, Pulchowk Campus T.U Nepal. Study of MIMO system and simulation was done by A. Khanal on "Study and Simulation of MIMO". The work of Mr. Khanal was focused on study and simulation of MIMO system [31].

The thesis done by Rajeev Prajapati was focused on changing the modulation schemes according to the varying fading channel conditions. It has been presented that adaptive modulation is better than fixed modulation at higher or varying SNR. With the increase in SNR the time taken to transmit is almost similar to 16 QAM instead of delays involved, still the adaptive modulation is more better than fixed modulation scheme in all channel conditions [32].

Space time trellis code technique with different channel fading channels is new concept and has the better gain than the other above discussed research works.

CHAPTER THREE: THEORETICAL BACKGROUND

3.1 MIMO System

The use of multiple antennas at the transmitter and the receiver in wireless system, popularly known as Multiple Input Multiple Output (MIMO) system. It has rapidly gained popularity on over the past decade. As the name suggests it uses multiple antenna at the both transmitter and receiver to improve communication link performance. MIMO uses multiple antennas at transmitter to send multiple parallel signals and use multiple antennas at the receiver. The idea is to combine the signals at the receiver antenna such that the quality or the data rate of the communication for each MIMO users will be improved.

During the transmission fading can be degrade the performance of wireless communication systems significantly. Multiple-input-multiple output (MIMO) antenna systems can improve the performance by providing diversity and/ or multiplexing gains.

3.2 MIMO System Channel Capacity

The capacity of the channel is defined as the maximum possible mutual information between the input (x) and output (y). The maximization is over the probability distribution of the input $f_x(x)$ i.e.

$$c = \max_{f_x(x)}[I(X;Y)] = [h(Y)] - h(Y/X) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.1)$$

Where $I(X;Y)$ represents the mutual information between X and Y equation (3.1) states that the mutual information is maximized with respect to all possible transmitter statistical distributions $f_x(x)$ Mutual information is a measure of the amount of information that one random variable contains about another variable. That can also be written as after the equal sign in equation (3.1),Where $h(Y)$ is the entropy of the output Y, and $h(Y/X)$ represents the conditional entropy between the random variables X and Y. The entropy of a random variable can be described as a measure of the amount of information required on average to describe the random variable. It can also described as a measure of the uncertainty of the random variable[1],[18],[24].

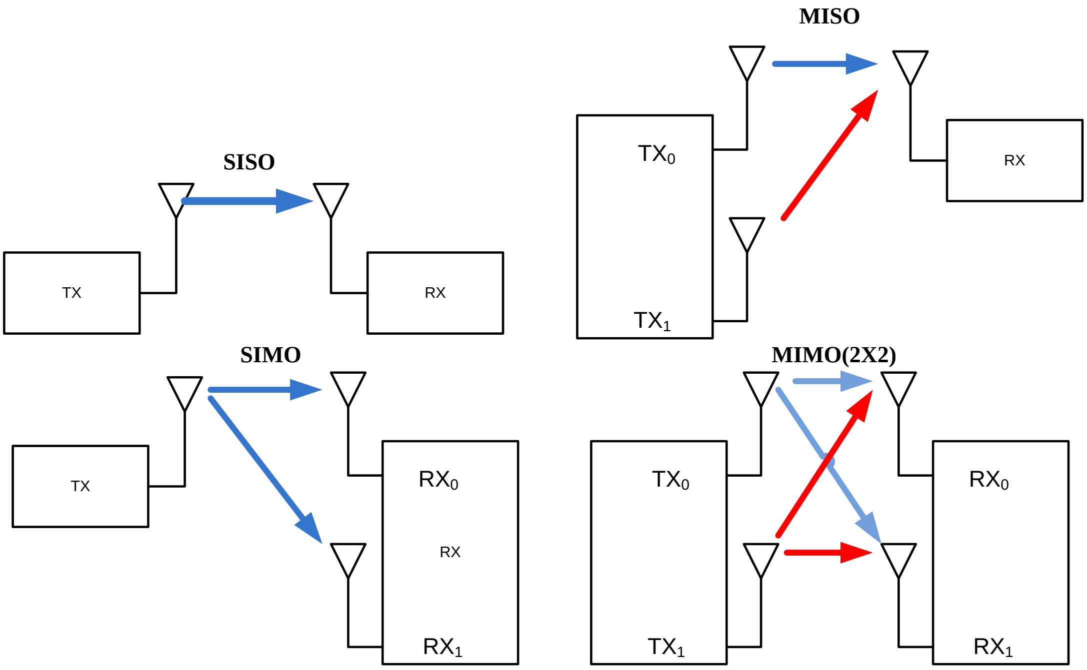


Figure 3-1: Introduction to different types of input and output

Considering a SISO system with additive white Gaussian noise (AWGN) channel, $y = Hx + N$ where where x is the $(N\ X\ 1)$ transmit vector, **y** is the $M\ X\ 1$ receive vector, **H** is the $N\ X\ M$ channel matrix, and **N** is the $(N\ X\ 1)$ additive white Gaussian noise (AWGN) vector at a given instant in time. It is also assumed that the channel is memory less, i.e., for each use of the channel an independent realization of **H** is drawn.

A general entry of the channel matrix is denoted by $\{h_{i,j}\}$. This represents the complex gain of the channel between the $i\ th$ transmitter and the $j\ th$ receiver. With a MIMO system consisting of N transmit antennas and M receive antennas, the channel matrix is written as

$$H = \begin{pmatrix} h_{1,1} & \cdots & h_{1,N} \\ h_{2,1} & & h_{2,N} \\ \vdots & \ddots & \vdots \\ h_{M,1} & \cdots & h_{M,N} \end{pmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Where, $h_{i,j} = \alpha + j\beta$

$$= \sqrt{\alpha^2 + \beta^2}.\, e^{-j\arctan(\frac{\beta}{\alpha})}$$

$$= \left| h_{i,j} \right|.\, e^{j\Phi_{i,j}} \quad \ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.3)}$$

In a Rician scattering environment with no line-of-sight (LOS), the channel gains $\left| h_{i,j} \right|$ are usually Rayleigh distributed. If α and β are independent and normal distributed random variables, then $\left| h_{i,j} \right|$ is a Rayleigh distributed random variable. The ergodic (mean) capacity of a random channel with N=M = 1 and an average transmit power constraint P_T can be expressed as

$$c = E_H \left\{ \max_{p(x):p\leq P_T} I(X;Y) \right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.4)}$$

Where P is the average power of a single channel code-word transmitted over the channel and E_H denotes the expectation over all channel realizations. Compared to the definition the capacity of the channel is now defined as the maximum of the mutual information between the input and the output over all statistical distributions on the input that satisfy the power constraint. If each channel symbol at the transmitter is denoted by s, the average power constraint can be expressed as $P = E[\left| S \right|^2] \leq P_T$ the ergodic (mean) capacity of a SISO system (N=M = 1) with a random complex channel gain $h_{1,1}$ is given by

$$c = E_H \left\{ log_2 \left(1 + \rho. \left| h_{1,1} \right|^2 \right) \right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.5)}$$

where ρ is the average signal-to-noise (SNR) ratio at the receiver branch. If $h_{1,1}$ is Rayleigh, $\left| h_{1,1} \right|^2$ follows a chi-squared distribution with two degrees of freedom. Now the above equation is written as

$$c = E_H\{\log_2(1 + \rho. X_2^2)\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \text{(3.6)}$$

Where X_2^2 is the chi-square distributed random variable with two degrees of freedom. The capacity of a random MIMO channel with power constraint P_T can be expressed as

$$c = E_H \left\{ \max_{p(x):n(\Phi)\leq P_T} I(X;Y) \right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \text{(3.7)}$$

where $\Phi = E\{xx^{\dagger}\}^{2}$ is the covariance matrix of the transmit signal vector **x**. The total transmit power is limited to P_T irrespective of the number of transmit antennas. Now the relationship between mutual information and entropy can be given as

$$
\begin{aligned}
[\mathrm{I}(\mathrm{X};\mathrm{Y})] &= \mathrm{h}(\mathrm{y}) - \mathrm{h}(\mathrm{y} \mid \mathrm{x}) \\
&= \mathrm{h}(\mathrm{y}) - \mathrm{h}(\mathrm{Hx} + \mathrm{n}|\mathrm{x}) \\
&= \mathrm{h}(\mathrm{y}) - \mathrm{h}(\mathrm{n} \mid \mathrm{x}) \\
&= \mathrm{h}(\mathrm{y}) - \mathrm{h}(\mathrm{n}) \quad \ldots\ldots\ldots\ldots (3.8)
\end{aligned}
$$

Here the term $\mathrm{h}(.)$ in this case denotes the differential entropy of a continuous random variable. It is assumed that the transmit vector **x** and the noise vector n are independent. Equation (3.8) is maximized when **y** is Gaussian, since the normal distribution maximizes the entropy for a given variance [23]. The differential entropy of a real Gaussian vector $y \in R^n$ with zero mean and covariance matrix K is equal to $\frac{1}{2}\log_2((2\pi e)^{n} \det \mathrm{K})$ for the complex Gaussian vector $y \in C^n$, the differential entropy is less than or equal to $\log_2 \det(\pi e\, \mathrm{K})$ with equality if and only if **y** is a circularly symmetric complex Gaussian with $\mathrm{E}\{\mathrm{yy}^{\dagger}\} = \mathrm{K}$ as defined in [25]. The covariance matrix of the received complex vector ***y*** is given by

$$
\begin{aligned}
E\{yy^{\dagger}\} &= E\{(Hx+n)(Hx+n)^{\dagger}\} \\
&= E\{Hxx^{\dagger}H^{\dagger}\} + E\{nn^{\dagger}\} \\
&= H\Phi H^{\dagger} + K^{n} \\
&= K^{d} + K^{n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.9)
\end{aligned}
$$

Here the superscript d and n denotes respectively the desired part and the noise part .

The maximum mutual information of a random MIMO channel is expressed by the expression

$$
\begin{aligned}
I &= h(y) - h(n) \\
&= log_2[det(\pi e(K^{d} + K^{n}))] - log_2[det(\pi e K^{n})] \\
&= log_2[det(K^{d} + K^{n})] - log_2[det(K^{n})] \\
&= log_2[det((K^{d} + K^{n})(K^{n})^{-1}] \\
&= log_2[det(K^{d}(K^{n})^{-1} + I_N)] \\
&= log_2[det(H\Phi H^{\dagger}(K^{n})^{-1} + I_N)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.10)
\end{aligned}
$$

When the channel is unknown i.e. the transmitter has no knowledge about the channel, it is optimal to use a uniform power distribution [3]. Now the transmit covariance matrix is then given

$$\Phi = \frac{P_T}{N} I_N \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.11)$$

Let us assume that there is an uncorrelated noise in each receiver branch described by covariance matrix $K^n = \sigma^2 I_N$ The ergodic (mean) capacity for a complex AWGN MIMO channel can then be expressed as in [1],[25],[26].

$$c = E_H \left\{ log_2 \left[det \left(I_N + \frac{P_T}{\sigma^2 N} HH^\dagger \right) \right] \right\} \ldots\ldots\ldots\ldots\ldots\ldots.. (3.12)$$

This equation can be expressed as

$$\mathrm{c} = E_H \left\{ log_2 \left[det(I_N + \frac{\rho}{N} HH^\dagger) \right] \right\} \ldots\ldots\ldots\ldots\ldots\ldots.\ldots.. (3.13)$$

Where $\frac{P_T}{\sigma^2}$ is the average signal-to-noise (SNR) ratio at each receiver branch. By the law of large numbers, the term $\frac{1}{N} HH^\dagger \rightarrow I_N$ as N gets large and M is fixed. Thus the capacity in the limit of large N is

$$c = E_H \{ N. log_2 (1 + \rho) \} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots.\ldots.. (3.14)$$

The detail analysis of MIMO channel capacity given in [1],[23],[24] is possible by diagonalizing the product matrix $HH^\dagger$ either by Eigen value decomposition or singular value decomposition.

Capacity of MIMO channel for a number of transmitter increasing from 1 to 4 and also the number of receiver increasing from 1 to 4 (see Figure 5.1 : Plots showing how the channel capacity increases as the number of antennas increases at both transmitter and receiver side). Here the capacity increases as the number of antennas goes on increasing on both transmitting and receiving side. MIMO system helps to improve the spectral efficiency and link reliability. During simulation the same energy level is transmitted to all the transmitter in case of MIMO. The chart below also shows how the capacity increases as N transmitting and M receiving antennas are employed at transmitter and receiver respectively.

Table 3-1: Channel capacity with the number of antennas at the transmitter and receiver side

System Type	Channel Capacity
SISO	C= B $\log_2$ (1+SNR)
SIMO	C= B $\log_2$ (1+MxSNR)
MISO	C= B $\log_2$ (1+NxSNR)
MIMO	C= B $\log_2$ (1+NxMxSNR)
MIMO with separate channel	C= N B $\log_2$ (1+$\frac{M}{N}$xSNR)

3.3 Fading Channels

In cellular mobile radio environment, surrounding objects such as house, trees or buildings act as reflectors of radio waves. These obstacles produce reflected waves with attenuated amplitude and phases. If modulated signals are transmitted, multiple reflected waves of transmitted waves arrive at receiving antenna from different antennas with the different propagation delay, which are called multipath waves. Due to different arrival angles and times, multipath waves at receiver site have different phases. When they are collected by receiver antenna at any point in space, they are combined either in constructive or destructive way, depending on random phase. The collection of these multipath components forms a spatially varying standing wave field.

The receiver receives signals which vary widely in amplitude and phase. If considered that the receiving unit is stationary, amplitude variations in received signals are due to movements of surrounding objects. The received signal is called the signal fading. It is caused by the time variant multipath characteristics of channel. The research includes the Doppler shift that rise between the relative motion between the transmitter and receiver, however it does not include the multipath fading scenario. If the object moves with the speed of v(m/s), with f transmission carrier frequency in Hertz and c being the velocity of light, the Doppler's shift (in hertz) is calculated as

$$\mathrm{f_d} = \frac{\mathrm{v} * \mathrm{f}}{\mathrm{c}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.15)$$

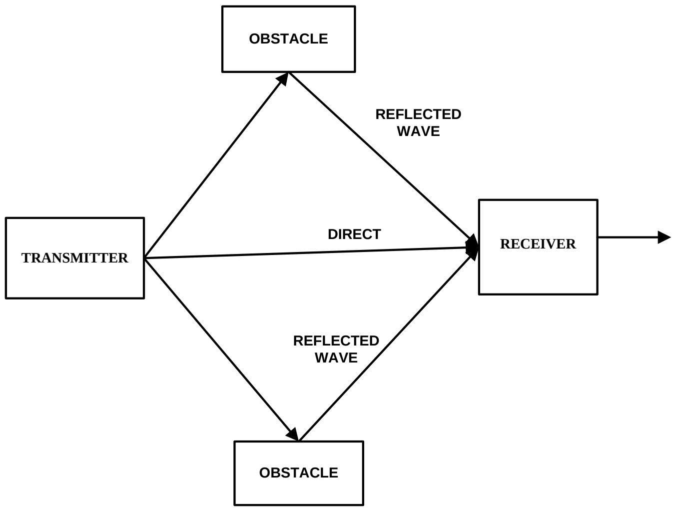


Figure 3-2: Fading Channel Configuration

3.3.1 Rayleigh Fading Channel

Rayleigh fading is caused by multipath reflection of transmitted wave signal. The mobile receiver can receive a large number of reflected, scattered, and dispersed waveform. It can lead to destructive as well as constructive interference to produce a standing wave. This type of channel where only multipath components are received is referred to as a Rayleigh fading channel.

In mobile radio channels, the Rayleigh distribution is commonly used to describe the statically time varying nature of the received envelope of a flat fading signal, or the envelope of an individual multipath component. The Rayleigh distribution has a probability density function (pdf) given by

$$p(r) = \begin{cases} \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right), & 0 \le r \le \infty \\ 0 & (r < 0) \end{cases} \quad \dots\dots\dots\dots\dots\dots\dots\dots..(3.16)$$

Where σ is the rms value of the received voltage signal before envelope detection and σ^2 is the time-average power of the received signal before envelope detection.

According to the central limit theorem, two quadrature components of received signals are uncorrelated zero-mean Gaussian random processes. As a result, envelope of received signal at any instant under goes a Rayleigh probability distribution and its phase obeys a uniform distribution between $-\pi$ to π. Assuming that average signal power is unity, normalized pdf is written as $\mathcal{P}(\alpha) = 2\alpha e^{-\alpha^2}, \forall\ \alpha \geq 0$.

Rayleigh fading can be either fast fading , block or slow fading depending on time variation of channel as well as data rate. In fast fading channel, channel fading coefficients change at beginning of each symbol interval and remain fixed during one symbol interval. If channel fading coefficients are constant during fixed number of symbol interval which is generally shorter than total transmission duration, the channel is referred as block fading. And if channel fading coefficients are constants during a frame and change from one frame to another, the channel is referred as slow fading.

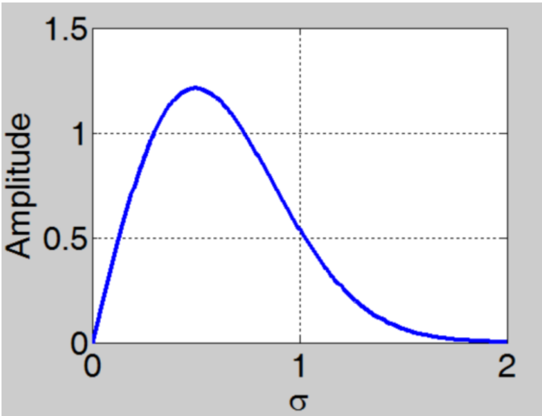


Figure 3-3: PDF Curve of Rayleigh Fading Channel

3.3.2 Rician Fading Channel

Rician Fading is similar to the Rayleigh fading. There is a dominant component present in the Rician fading channel along with the multipath component. When there is a dominant stationary (non-fading) signal component present, such as a line-of-sight propagation path, the small-scale fading envelope distribution is Rician. In such a situation, random multipath components arriving at different angles are superimposed on a stationary dominant signal. At the output of an envelope detector, this has the effect of adding a dc component to the random multipath. As the dominating signal becomes weaker, the composite signal resembles a noise signal which has an envelope that is Rayleigh. Thus, the Rician distribution degenerates to a

Rayleigh distribution when the dominant component fades away. The Rician distribution is given by

$$p(r) = \begin{cases} \frac{r}{\sigma^2} \exp - \frac{(r^2 + A^2)}{2\sigma^2} I_0 \left(\frac{Ar}{\sigma^2}\right), & A \geq 0, r \geq 0 \\ 0 & (r < 0) \end{cases} \quad \ldots \ldots (3.17)$$

The parameter A denotes the peak amplitude of the dominant signal and $I_0$is the modifies Bessel function of the first kind and zero-order. The Rician distribution is often described in terms of a parameter K which is defined as the ratio between the deterministic signal power and the variance of the multipath. It is given by $K=A^2/(2\sigma^2)$. The parameter K is known as the Rician factor and completely specifies the Rician distribution. As $A \to 0, K \to \infty$, and as the dominant path decreases in amplitude, the Rician distribution degenerates to a Rayleigh distribution [27].

In narrowband system, transmitted signals usually occupy bandwidth smaller than channel coherence bandwidth, which is defined as frequency range over which signal fading process is correlated i.e. transmitted signals are subject to same fading attenuation. This type of fading is referred as flat fading.

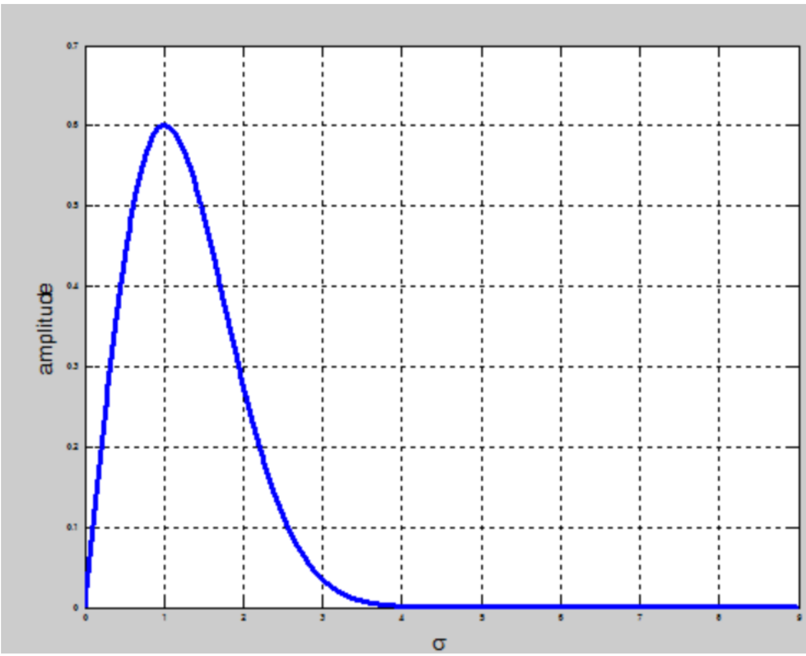


Figure 3-4: PDF Curve of Rician Fading Channel

3.3.3 Nakagami Fading Channel

The Nakagami fading model was initially proposed because it matched empirical results for short wave ionospheric propagation. Nakagami fading occurs for multipath scattering with relatively large delay-time spreads, with different clusters of reflected waves specially in urban environment. Nakagami fading occurs for multipath scattering with relatively large delay-time spreads, with different clusters of reflected waves. This is particularly relevant to model interference from multiple sources in a cellular system. It describes the amplitude of received signal after maximum ratio diversity combining. It is a probability distribution related to the gamma distribution. It has two parameters: a shape parameter m and a second parameter controlling spread, Ω .

After *k*-branch maximum ratio combining (MRC) with Rayleigh-fading signals, the resulting signal is Nakagami with $m = k$. MRC combining of *m*-Nakagami fading signals in *k* branches gives a Nakagami signal with shape factor *mk.*

Since the Nakagami-m random process is defined as an envelope of the sum of 2m independent Gauss random processes, the Nakagami-m distribution is described by the pdf [13],[18]

$$p(r) = \frac{2m^m}{\Gamma(m)\Omega^{\mathrm{m}}} r^{2m-1} \ \exp\left(-\frac{m}{\Omega} r^2\right) \quad r > 0, m \geq 0.5 \ldots\ldots\ldots\ldots (3.18)$$

where r is the received signal level, Γ(.) is the gamma function.

The parameters m and Ω are $$m = \frac{E^2[r]}{Var[r^2]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.19)$$

and $$\Omega = E[r^2] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.20)$$

An alternative way of fitting the distribution is to re-parameterize Ω and m as $\sigma = \Omega/\mathrm{m}$ and m. Then, by taking the derivative of log likelihood with respect to each of the new parameters, the following equations are obtained and these can be solved using the Newton-Raphson method as :

$$\Gamma(m) = \frac{r^{2m}}{\sigma^m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.21)$$

and $$\sigma = \frac{r^2}{m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.22)$$

In the case where the parameter of fading depth is m=1, the Nakagami-m distribution is reduced to the familiar Rayleigh distribution , while the case m=0.5 corresponds to the unilateral Gauss distribution. The case $m \to \infty$ describes the channel without fading. With certain restrictions the Nakagami-m distribution can approximate the Rice distribution [18]. In an analytical sense, the Nakagami-m channel model is simpler than Rice's, in which the Bessel function is used, so that using the above approximation calculation of statistical characteristics is significantly simplified. We choose to analyze the Nakagami-m channel model for reasons of generality, and because the other models can be described by the Nakagami-m distribution by an appropriate choice of relevant parameters [13].

3.4 Diversity

Due to fading the channel may suffer from sudden decline in power, which may be due to the destructive addition of multipath signals in the propagation media or interferences from the other users. Due to which the effective signal-to-noise ratio (SNR) at the receiver can go through deep fades and be dropped dramatically and at the receiver point the reliable recovery of the transmitted signal is impossible.

The main concept of diversity is to provide different replicas of the transmitted signal to the receiver. If these different replicas fade independently, it will be probably less to go on deep fade of all copies of transmitted signals. Therefore, the receiver can reliably decode the transmitted signal using these signals. This can be done, for example, by picking the signal with the highest SNR or by combining the multiple received signals. To define diversity quantitatively, we use the relationship between the received SNR expressed in terms of γ, and the probability of error P_e, the diversity gain is given by

$$G_d = -\lim_{\gamma \to \infty} \frac{\log(P_e)}{\log(\gamma)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (3.23)$$

Therefore the diversity is defined as the slope of error probability curve in terms of the received SNR in a log-log scale. On concept of using diversity one should be careful in using lowest possible consumption of the power, bandwidth, decoding complexity and other Resources along with the highest reduction in the probability of error [2],[22],[25].

Similarly Coding gain is an approximate measure of the advantage provided by a coded system over an un-coded one having the same diversity gain [5]. The use of coding adds redundancy to information by mapping information sequences to longer (when expressed as a binary vector) code sequences or code words. Then the distance (in a predefined sense) of two code words is larger than the distance of the information sequences to which they correspond. This reduces the probability of confusing different information pieces, which is the reward of adding redundancy.

3.4.1 Diversity Types

The goal of diversity is to send two or more copies of the signal through independent fades. The replica of the transmitted signal can be sent through different means i.e. it can be transmitted in a different time slot, a different frequency, a different polarization, or a different antenna. On our work we mainly focus on time and space diversity.

3.4.1.1 Time Diversity

The fading characteristics of a wireless communication channel can be viewed as a function of time. Intuitively, information symbols transmitted with a small time difference will undergo similar amounts of fades. In other words, as two signals are transmitted further apart in time, the fades acting on them tend to behave more independently from one another. Two signals are assumed to undergo dependent fades if they are transmitted within a time period shorter than the coherence time, (on board sense coherence time can be defined as the time duration over which the state of a channel remains predictable) otherwise they are assumed to experience independent fades [27].

Time diversity (also called temporal diversity) combats fading by making proper use of coding and interleaving. Information is encoded using an error-correcting code, each codeword is divided into L parts and consecutive parts are transmitted inside different coherence periods. Let us consider that $X = \{x_1, x_2, \dots \dots x_n\}$ be codeword and x_i, x_j are the two parts of transmitted signal at times t_i, t_j respectively, then the difference $|x_i - x_j|$ should be greater than T_c, coherence time of the channel. Then, the definition of coherence time implies that all parts of x undergo independent fades. Even if some of them get lost due to presence of deep fade, others may suffice to correctly recover the original information. The simplest realization of a time diversity scheme occurs when one uses the repetition code as the error-correcting code. In this case, each codeword consists of L repeated copies of an information symbol [25],[27].

Although it increases the reliability of data transmission significantly, time diversity is easily seen to have major drawbacks. First of all, its data rate is low: it takes L symbol times to transmit one symbol. In addition, due to the necessity of spreading a codeword over different coherence periods, decoding at the receiver cannot start without a certain amount of delay. This means further that employing solely time diversity is not a good option when the channel fading varies too slowly with time. All these drawbacks motivate the use of space diversity together with time diversity.

3.4.1.2 Space Diversity

Time diversity makes use of this fact that receivers in real applications are mobile objects so the same information is sent over independently fading paths. It is known that sufficiently separated antennas cause multi paths which fade more or less independently. This resource is referred to as space diversity (or spatial diversity) and is a special case of the more general antenna diversity. Space diversity is called transmit diversity if multiple transmit antennas are used and receive diversity if multiple receive antennas are used. In our work we promptly discuss on the schemes employing transmit diversity, and receive diversity for calculating the capacity of MIMO channel and discuss on the receive diversity while evaluating the performance of Space Time Trellis codes [25].

A simple scheme which combines both the time diversity and the space diversity can be as done for the better purpose. Suppose we want to transmit a symbol x, also we encode x with an error correcting code. Since we have $X = \{x_1, x_2, \dots \dots x_n\}$. Now we use L different transmit antennas to transmit x. At symbol time t=i, x_i is transmitted by transmit antenna i and the other antennas are silent. If the error correcting code is the repetition code, then this scheme amounts to transmitting the same information symbol through L transmit antennas over L symbol times. This scheme is better suited in cases where there is a strict delay requirement [25].

3.4.2 Frequency Diversity

Frequency diversity implements the simultaneous use of different frequencies for the transmission of signals. This diversity scheme provides replicas of original signal in a frequency domain. Frequency diversity is used to tackle the channel uncertainties like multipath fading. It means that different replicas of signal are transmitted over different frequency bands. To make the channel independent, frequency bands are separated by more than a coherence bandwidth of the channel [25].

3.4.1.3 Angle Diversity

Angle diversity is a special case of space diversity in which a number of directional receiving antennas are used to receive message signal simultaneously. In the receiver, the received signals are the scattered waves coming from all directions which are uncorrelated [8],[25].

3.5 Space Time Coding

Today Space-time coding has received considerable attention in academic and industrial circles because of mainly three reasons: First, it improves the downlink performance without the need for multiple receive antennas at the terminals. For example, for WCDMA, STC techniques [28] to result in substantial capacity gains due to the resulting smoother fading which in turn, makes power control more effective and reduces the transmitted power, and secondly it can be elegantly combined with channel coding, as shown in [29], realizing a coding gain in addition to the spatial diversity gain. And thirdly it does not require CSI at the transmitter, i.e. operates in open-loop mode, thus eliminating the need for an expensive and, in case of rapid channel fading, unreliable reverse link. Mainly there are two types of coding, Space time Block codes(STBC) and Space Time Trellis Codes (STTC).

3.5.1 Space Time Block Codes (STBC)

Space-time block coding is a simple yet ingenious transmit diversity technique in MIMO technology. Space time block coding follows the theory of orthogonal design and is used to obtain full diversity with low decoding complexity. Encoding of data is done by using space time block codes and these encoded data is converted into n streams such that these streams are transmitted simultaneously through n transmit antennas. Each receiving antenna gets the signals which are the linear superposition of the n transmitted signals along with the noise. Decoupling of the signals from different transmit antennas is done to achieve maximum likelihood decoding instead of using joint detection. Orthogonal structure of space time block code is used to obtain maximum likelihood decoding algorithm and the processing at the receiver is completely linear processing. The symbols are arranged in a such a way that, at the receiver, ML decoding can be performed individually on each symbol independent of the other symbols. The data symbols, effectively, are 'orthogonal' to each other. Space time block coding with multiple transmit antennas can provide remarkable performance without the requirement of extra processing. Most remarkably, Space time block coding method implements simple encoding and decoding technique [8],[25],[29].

3.5.2 Space-Time Trellis Code

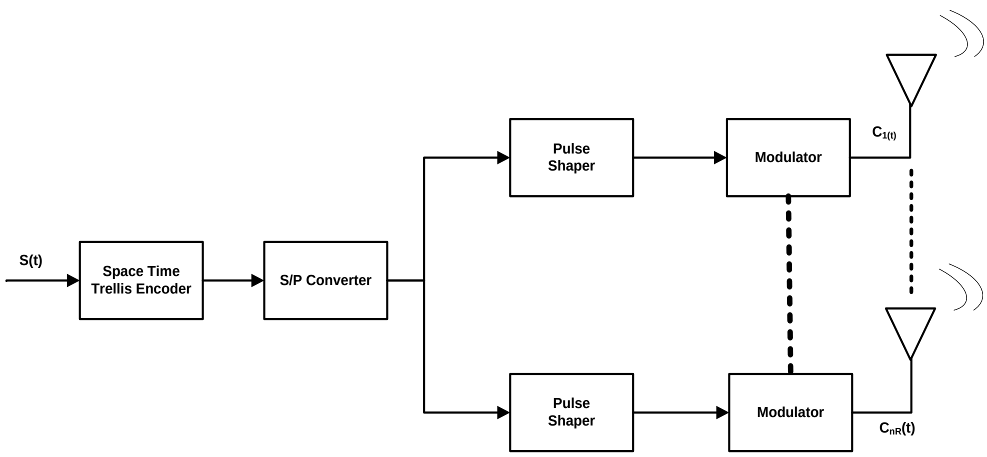
Space-time trellis codes (STTC) provide both diversity gain and coding gain. In this chapter a brief description of a STTC based wireless system is explained.

3.5.3 System Model of STTC Based Wireless System

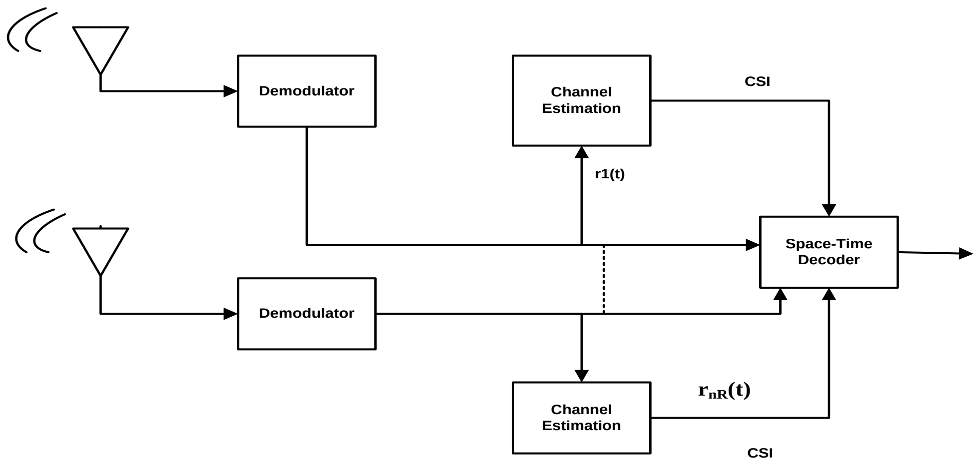
A typical STTC based wireless system has an encoder, pulse shaper, modulator and multiple transmit antennas at the transmitter, and the receiver has one or more receive antennas, demodulator, channel estimator and STTC decoder. We consider a mobile communication system with n_T transmit antennas and n_R receive antennas as shown in Figure 3.5 (a) and (b). The space-time trellis encoder encodes the data $S(t)$ coming from the information source and the encoded data is divided into n streams of data $c_t^1, c_t^2, c_t^3, \dots\dots\dots c_t^{n_T}$. Each of these streams of data passes through a pulse shaper before being modulated. The output of modulator i at time slot t is the signal C_t^i , this signal is transmitted through the antenna i . Here $1 \le i \le n_T$. The transmitted symbols have energy E. We assume that the n_T signals are transmitted simultaneously from the antennas. The signals have transmission period *T*. In the receiver, each antenna receives a superposition of n_T transmitted signals corrupted by noise and multipath fading. Let the complex channel coefficient between transmit antenna i and receive antenna *j* have a value of $h_{i,j}(t)$ at time $\boldsymbol{t}$ where $1 \le i \le n_R$.

The received signal at antenna $j, j = 1,2,3, \ldots\ldots, n_R,$ G.L. Stuber [30] is then

$r_T = \sqrt{E_S} \sum_{i=1}^{n} h_{i,j}(t) C_t^i(t) + \eta_t^j$ where η_t^j is additive white Gaussian noise (AWGN) at receive antenna j, which has zero mean and power spectral density N_o and $h_{i,j}(t)$ is the channel coefficient between transmit and receive antennas. We define the spectral efficiency as the number of information bits transmitted per time slot, here in this case let m bits/sec/Hz. The rate of the code is defined as the number of information bits over the total number of bits transmitted per interval. For assuming the M-array signal constellation, for each m information bits , $n_T x m$ bits are transmitted . Therefore the rate of code can be expressed as $\frac{m}{n_T x m}$



(a)



(b)

Figure 3-5: Block diagram of Space Time Trellis (a)Encoder (b) Decoder

3.6 Encoder

The source coded data have to be channel coded for a reliable transmission. For this purpose, some extra bits are added in the source coded data. It is called a channel encoder or channel coder. Encoders are used at the transmitter part of the wireless system. The purpose of Forward Error Correction (FEC) is to improve capacity of channel by adding some carefully designed redundant information to data being transmitted through channel. The process of adding this redundant information is known as channel coding. Block coding and Convolutional coding are two major forms of channel coding.

3.6.1 Block Codes

Block codes have a property of linearity. The sum of any two codeword is also a codeword. Block codes process the codes on block by block basis, treating each block of information independently from others. In other words block coding is a memory less operation in the sense that code words are independent from others. They can be used to either detect or correct errors. Block codes accept a block of k information bits and produce a block of n coded bits. By predetermined rules, n-k redundant bits are added to the k information bits to form the n coded bits. Commonly, these codes are referred to as (n,k) block codes. Some of the commonly used block codes are Hamming codes, Golay codes, BCH codes, and Reed Solomon codes (uses non binary symbols).

3.6.2 Convolutional Codes

The main idea behind a convolutional code is to make every codeword symbol be the weighted sum of the various input symbols coming from the source encoder. Convolutional codes were first mentioned by Elias in 1955. They can be seen as an attempt to generate random codes that were successfully used by Shannon later. Forward error correction technique is also known as convolutional coding with Viterbi decoding. These codes are primarily used for real time error correction. Convolutional codes operate on serial data, one or a few bits at a time. Block codes operate on relatively large (typically, up to a couple of hundred bytes) message blocks.

Convolutional encoding and decoding is a FEC technique that is particularly suited to a channel in which transmitted signal is corrupted mainly by AWGN. Space time trellis encoder has convolutional codes and are usually described using two parameters: code rate and constraint length. The code rate, k/n, is expressed as a ratio of the number of bits into the convolution encoder (k) to the number of channel symbols output by convolutional encoder (n) in a given encoder cycle. The constraint length parameter, K, denotes "length" of convolutional encoder, i.e. how many k-bit stages are available to feed combinatorial logic that produces output symbols. Closely related to K is parameter m, which indicates how many encoder cycles an input bit is retained and used for encoding after it first appears at input to convolutional encoder. The m parameter is memory length of the encoder [1],[4],[23].

3.6.3 Generator polynomial

The generator polynomial can be explained as the mathematical description of convolutional encoder where each polynomial forming the generator polynomial should be at most K degree. It specifies the connections between shift registers and modulo-two adders. The two generator polynomials are g1(x) = 1 + x2 and g2(x) = 1+x+ x2 which gives g1(x) = (101) and g2(x) = (111). The convolutional codes can be categorized into two parts as recursive and non-recursive. Recursive codes are always systematic where as the non recursive codes are non-systematic. The pattern used to generate the coded output value can be expressed as the binary strings called Generator Polynomial. The table below gives the generator polynomial g1 and g2 for different constrain length.

Table 3-2:Generator polynomial for different constraint length

Constraint length	**g_1**	**g_2**
3	101	111
4	1101	1110
5	11010	11101
6	110101	111011
7	110101	110101
8	110111	1110011
9	110111	111001101

3.6.4 Convolutionally Encoding the Data

Convolutionally encoding data is accomplished by using a shift register and associated combinatorial logic that performs modulo-two addition. A shift register is merely a chain of flip-flops wherein output of nth flip-flop is tied to input of the (n+1)th flip-flop. Every time active edge of clock occurs, input to flip-flop is clocked through to output. The data are shifted over one stage. The two basic components of the convolutional encoder (flip-flops and modulo-two adders) gives convolutional encoder. The picture of a convolutional encoder for a rate 1/2, K = 3, m = 2 is presented below in Figure 3-6.

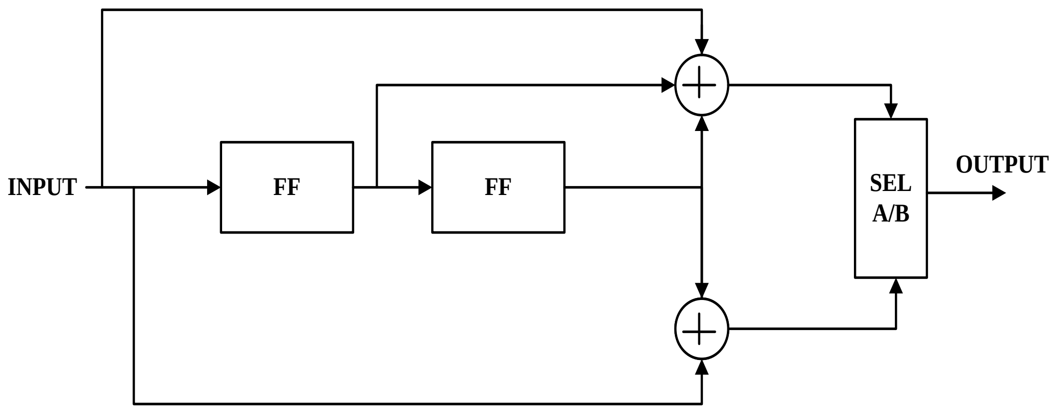


Figure 3-6: Convolutional Encoder

Data bits are provided at a rate of k bits per second. Channel symbols are output at a rate of n = 2k symbols per second. The encoder cycle starts when an input clock edge occurs. When input clock edge occurs, output of left-hand flip-flop is clocked into right-hand flip-flop, previous input bit is clocked into left-hand flip-flop, and a new input bit becomes available. Then outputs of upper and lower modulo-two adders become stable. The output selector (SEL A/B block) cycles through two states, in first state it selects and outputs output of upper modulo-two adder and in second state, it selects and outputs output of lower modulo-two adder. The encoder shown above encodes K = [3, (7, 5)] convolutional code. The octal numbers 7 and 5 represent the code generator polynomials, which when read in binary (111_2 and 101_2) correspond to shift register connections to upper and lower modulo-two adders, respectively. This code has been determined to be the “best” code for rate 1/2, K = 3. [1],[4],[18].

3.7 Modulation

The modulation process the base band signals is used to modify some parameters of the high frequency carrier signal which is achieved by varying any one of the parameter such as amplitude frequency or phase of the carrier which is sinusoid of high frequency in proportion to the base band signal.

The constellation points are usually positioned with the uniform angular spacing in PSK. This spacing gives the maximum phase-separation between the adjacent points and the best immunity to corruption. They are positioned in circle so that they can all be transmitted with the same energy. Two common examples are BPSK- which uses two phases and QPSK- which uses four phases, although any number of phases may be used. Since data to be conveyed are usually binary, the PSK scheme is usually designed with the number of constellation points being a power of 2. To compensate the fading response in the channel an approach may be involved in the channel called the differential modulator or one step equalizer that helps to compensate for the frequency flat fading channel.

3.7.1 Differential Binary Phase Shift Keying (DBPSK)

BPSK uses the phase of the carrier to carry information, the non-coherent approach cannot be applied to demodulate BPSK signals. This difficult can be partially circumvented by modified version of BPSK called Differential Binary Phase Shift

Keying (DBPSK). With DBPSK, it is possible to demodulate the received signal without knowing the absolute phase, but just relative phases. A phase change of across adjacent symbol intervals represents the bit value '1' while no phase change across the adjacent symbol intervals represents '0'.

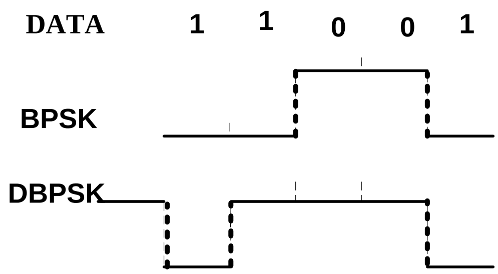


Figure 3-7: DBPSK Signal

3.8 Noise

The sensitivity of communications systems is limited by noise. The broadest definition of noise is "everything except the desired signal". The noise remained mysterious until H. Nyquist, J.B. Johnson and W. Schottky published a series of papers that explained where the noise comes from and how much of it to expect. Some of the noise they identified are described below.

3.8.1 Thermal Noise

Johnson was the first to report careful measurements of noise in resistors, and his colleague Nyquist explained them as a consequence of Brownian motion: thermally agitated charge carriers in a conductor constitute a randomly varying current that gives rise to a random voltage. In honor of the fellows, thermal noise is often called Johnson noise or, less frequently , Nyquist noise. The available noise power is given by the following equation

$$P_{NA} = kT\Delta f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.24)$$

Where k is Boltzmann's constant, T is temperature in Kelvin scale, and Δf is the noise bandwidth in hertz. The above expression shows that a spectral density is independent of frequency.

3.8.2 Shot Noise

Shot noise was first described and explained by Schottky in 1918. It is therefore occasionally known as Schottky noise in recognition of his achievement. The fundamental basis for shot noise is the granular nature of the electronic charge, but how this granularity translates into noise is perhaps not as straightforward as one might think. The expression for rms shot noise current is given by the following expression.

$$\overline{i_n^2} = 2qI_{DC}\Delta f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.25)$$

where $\overline{i_n^2}$ is the rms noise current,q is the electronic charge, $I_{DC}$is the DC current in amperes, and Δf is again the noise bandwidth.

3.8.3 Flicker Noise

Flicker noise is also known as pink or 1/f noise. No universal mechanism for flicker noise has been identified, yet it is ubiquitous. Phenomenon that have no obvious connection, such as cell membrane potentials, the earth's rotation rate, galactic radiation noise, and transistor noise all have fluctuations with a 1/f character. Because of the lack of unifying theory, mathematical expressions for 1/f noise invariably contain various empirical parameters as can be seen in the following equation:

$$\overline{N^2} = \frac{k}{f^n}\Delta f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.26)$$

where $\overline{N}$ is the rms noise, K is an empirical parameter that is device-specific, and n is an exponent that is usually close to unity.

3.8.4 Popcorn Noise

Popcorn noise is less understood than flicker noise. It might be due to the metal ion contamination. Some device fabricated with the same process might exhibit a huge popcorn noise while some other device fabricated at the same time might show very less or no popcorn noise at all. It is difficult to model a popcorn noise. One way of modeling popcorn noise is as given below

$$\overline{N} = \frac{k}{1 + \left(\frac{f}{f_c}\right)^2}\Delta f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.27)$$

Here K is an empirical, device-and fabrication-dependent constant, and f_c is a corner frequency below which popcorn noise density flattens out. Popcorn noise is also known as burst noise, bistable noise, and random telegraph signals, RTS.

3.9 Demodulator

As Phase Shift Keying (PSK) offers the advantages over the Amplitude Shift Keying (ASK), and Frequency Shift Keying (FSK), also the demodulation of these signals are simple too. The method of demodulation is an important factor in determining the selection of modulation scheme. Generally there are two types of demodulation which are distinguished by the need to provide knowledge of the phase of the carrier. Demodulation scheme requiring the carrier phase are termed coherent. Those that do not need phase are non-coherent. Non-coherent modulation is expansive and performs poorly. Coherent modulation requires more complex circuitry, but has better performance.

3.9.1 DBPSK Demodulator

The demodulation of DBPSK is simple. It is a non-coherent modulation scheme using the non-coherent detection since there is no need for demodulator to have the copy of reference signal. To demodulate the DBPSK signal, it is noticed that the value of current bits depends on the value of the previous bits. Since the signals are orthogonal to each other, the non-coherent schemes can be employed here and the decision is made based on the difference of two signals. For the demodulation process, there is a band-pass filter which reduces noise power but preserves the phase of the signal. The final output is passed to the LPF to obtain the required signal.

3.10 Decoder

Decoder receives the corrupted transmitted data and tries to match with the codeword for correct matching. Viterbi decoder is one of the main decoder used to decode convolutionally transmitted data bits. Viterbi decoding was developed by Andrew J. Viterbi in 1967. Since then, other researchers have expanded on his work by finding good Convolutional codes, exploring performance limits of technique, and varying decoder design parameters to optimize implementation of technique in hardware and software. The Viterbi decoding algorithm is also used in decoding trellis coded modulation. Viterbi decoder is most commonly used to resolve convolution codes. This is essential for the purpose of secure transmission of data and its corresponding retrieval during reception. Viterbi decoders also have the property of compressing the number of bits of the data input to half. As a result redundancy in the codes is also reduced. Hence Viterbi decoding is more effective and efficient.

Viterbi decoding is one of two types of decoding algorithms used with convolutional encoding, other type being sequential decoding. Sequential decoding has advantage that it can perform very well with long constraint length convolutional codes, but it has variable decoding time. Viterbi decoding has advantage that it has a fixed decoding time. It is well suited to hardware decoder implementation. But its computational requirements grow exponentially as a function of constraint length. So it is usually limited in practice to constraint lengths of K = 9 or less. The advantage of using the Viterbi decoder are self correction of codes, minimization of transmission energy and minimization of bandwidth.

Convolutional coding with Viterbi decoding has been predominant FEC technique used in space communications, particularly in geostationary satellite communication networks, such as VSAT (very small aperture terminal) networks. The most common variant used in VSAT networks is rate 1/2 convolutional coding using a code with a constraint length K = 7. With this code, transmit binary or quaternary phase-shift-keyed (BPSK or QPSK) signals is at least 5 dB less power [4],[18],[22].

3.10.1 Viterbi Decoder

A Viterbi decoder uses Viterbi algorithm for decoding a bit streams that has been encoded using convolutional code. It is one of the most often used for decoding convolutional codes with constraint lengths $k \leq 10$.

Viterbi decoder decodes the message using the maximum likelihood decoder. The method of maximum likelihood corresponds to many well-known estimation methods in statistics. It is generally related with normal Gaussian distribution with some unknown mean and variance. Maximum-likelihood estimation provides estimation for the model's parameters, which gives a unified approach to estimation [18,31].

The Viterbi algorithm makes the use of the trellis diagram and it follows the path followed by the maximum likelihood path in the trellis diagram. Once the encoded message bits are received at the receiver, the decoder analyzes the path that is most likely of the four paths from any of the four possible states (in case of four states). It discards the path with less likely path. This is determined with the help of the hamming distance between the received word and all the possible code word that could be calculated. The trellis diagram is explained in Appendix B with an example. The working of Viterbi decoder is explained using its block diagram below.

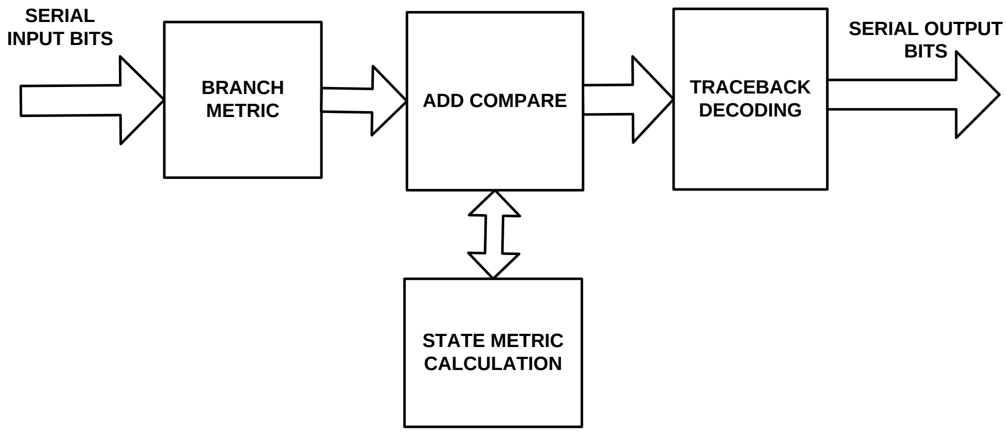


Figure 3-8: Flow Diagram of Viterbi Decoder

The Figure 3.8 shows the basic block diagram used for general decoding used in STTC with the Viterbi decoder. The Branch Metric Calculation (BMC) calculates the hamming distance with all the possible code word as soon as the encoded message bits are available at the input of the decoder. Add-Compare and Select block selects the most likely path and it saves the metric associated with that path in the State Metric Calculation Register. The state metric for the particular state is equal to the sum of the previous value with the new computed value by the BMC block. After receiving the bits for sometimes, the trace back decoding block starts to trace-back through the trellis associated to produce the output serial bits i.e. when the trellis diagram is finished, the trace-back module will search the ML path from the final state which is state 0 to the beginning state which is state 0. Each time, the trace-back block just left shifts one bit of the binary state number and add one bit from the survivor path metric to compute the previous state. By doing this, the most likelihood path is found.

3.11 Performance

Performance of system is evaluated by comparing two data before transmission and data received by receiver. BER is defined as the rate at which errors occur in a transmission system. BER is the ratio of error bits received to the total bits sent.

3.11.1 Bit Error Rate

A Bit Error Rate (BER) is defined as the rate at which errors occur in a transmission system. This can be directly translated into the number of errors that occur in a string of a stated number of bits.

A transmission might have a BER of 10^{-4} which means that for receiving of every 10000 data, one erroneous data is received. Frame error rate is defined as the number or error occurred in each frame which is received after transmission. The number of bits in the frame may be user defined.

In a noisy channel, the BER is often expressed as a function of the normalized carrier-to-noise ratio measure denoted $\frac{E_b}{N_0}$, (energy per bit to noise power spectral density ratio), or Es/N0 (energy per modulation symbol to noise spectral density). For example, in the case of QPSK modulation and AWGN channel, the BER as function of the $\frac{E_b}{N_0}$, is expressed as

$$BER = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.28)$$

BER is used in a digital communication system as a measure of the performance of the system. In optical communication, BER(dB) vs. Received Power(dBm) is usually used; while in wireless communication, BER(dB) vs. SNR(dB) is used. Measuring the bit error ratio helps to choose the appropriate forward error correction codes. Since most such codes correct only bit-flips, but not bit-insertions or bit-deletions, the Hamming distance metric is the appropriate way to measure the number of bit errors, other FEC codes also continuously measure the current BER.

Let m_1 be the number of message bits sent. The transmitted message bits are corrupted by Gaussian distributed noise. If the received bits contains m_2 number of errors, then BER is calculated by the following formula.

$$BER = \frac{m_2}{m_1} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(3.29)}$$

To show the performance of a digital system, BER is plotted against SNR of the system. High value of SNR in the channel leads to less number of error bits and low value of SNR corresponds to higher value of error bits at the receiver.

called Monte Carlo Method that let the possible outcomes of the decision and assess the impact of risk, allowing the better decision making under uncertainty.

The simulation is run for ten times in a loop. The result is averaged to get a refined BER plot against different SNR values. This way of running the simulation in a loop to obtain an average refined plot is known as Monte Carlo Simulation. By using Monte Carlo Simulation in the code, one can get a better picture of the BER plot. Hence this thesis makes use of Monte Carlo Simulation. Use of Monte Carlo Simulation in the code has an adverse effect in the computation time of the code result. It usually takes up to six hours to run and get the result in the plot obtained in this work. The loop value can be increased to more than ten to get even better BER plot. However, it was realized that the loop value of 10 was more than enough to get good enough BER plot.

In practice, BER is expressed as an error per 10^4 or 10^5 message bits transmitted. Thus 10^{-4} BER means $1/10^4$ measure. It means for every 10^4 message bits transmitted, due to channel corruption, we can expect one error per ten thousands message bits transmitted. For a noise tolerant system, we thus expect a system with very low BER, in the range of 10^{-7} in digital communication and 10^{-9} or even less in a satellite communication for a reliable communication.

CHAPTER FOUR: METHODOLOGY

The system design approach and methodology used in this research work is fully described in this chapter. The block diagram of STTC is presented. Each components of STTC block are then explained afterwards. These block diagrams are implemented in MATLAB.

4.1 Description of Research Design

The block diagram of research work is shown in figure. It shows STTC in block diagrammatic form. The description of each block component is explained next.

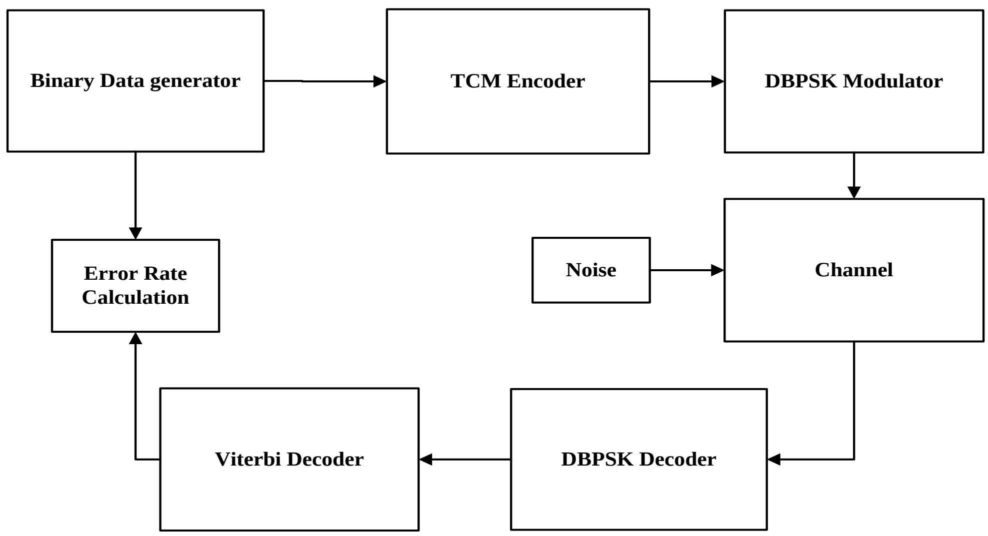


Figure 4-1: General Block diagram of STTC

4.1.1 Data generator

The source or the data generator generates the data required for simulation. The data generator may generate the binary, octal, decimal or hexadecimal data according to need. The random data generator generates the data in random fashion whereas the sequential data generator generates the data in some fixed order with the given probability sequence of all numbers. Here the binary data generator generates the random binary data with equal probability of being 1 and 0. The binary data were created as they were easy to analyze, and they match to the real digital communication world.

4.1.2 Trellis coded Modulation (TCM) Encoder

The generated data bits are encoded using trellis coded modulation. The trellis coded modulation is depicted in schematic form in Figure 4.2. The input is the output bits at the end of the generated data block. The encoder states helps to encode the data and output data bits are formed. For maintaining the same information rate it is required to send each information bit with two coded bits. The coded bits can be transmitted by using the 2-PSK constellation points.

Trellis coded Modulation (TCM)

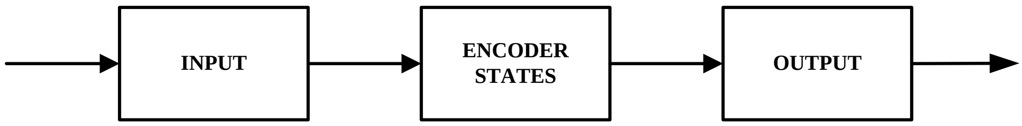


Figure 4-2: General Structure of Trellis Encoder

The parameters used in the thesis for using convolution encoder is listed below:-

Table 4-1: Parameters of Convolution Encoder

Parameters	Value
Input data types	Binary data
Code rate	1/2
Constrain length	3,4,5,6

4.1.3 DBPSK Modulator/ Demodulator

In DBPSK modulator the encoded data has to be modulated before it passes from the channel. Modulation alters a transmittable signal to a information in a message signal, however the message signal is restricted to a finite set. To minimize the fading response in the flat fading channel there is great advantage of using the differential modulation schemes, and using the DBPSK modulation is simpler which modulates the data making the phase difference of 180 degree. For DBPSK if the input bit is 0 or 1, the first modulated symbol is $\exp(j\theta)$ or $-\exp(j\theta)$ respectively and if the successive input bit is 0 or 1 then the modulated symbol is the previous modulated symbol multiplied by exp(jθ) or - exp(jθ) respectively.

Once the data bits are received at the receiver, they have to be extracted, demodulated and regenerated. The demodulator used in this case is DBPSK demodulator as DBPSK modulator was used in the transmitter side of the communication system.

4.1.4 Channel

The transmitted bits has to reach to the receiver. The medium through which these bits reach the receiver is known as channel. The channel can be anything ranging from dedicated guided channel of coaxial cable to atmospheric wireless environment. The channel that will be dealt in this work are Rayleigh fading channel, Rician fading channel, Nakagami fading channel as described in chapter 3. These channels covers both the line of connection and non line of connection between the transmitter and receiver. The parameters use in these channels are tabulated below.

Table 4-2: Parameters of Rayleigh Fading Channel

Parameter	**Values**
Propagation Conditions	Flat Rayleigh fading
Input sample period	1
Maximum Doppler Shift	100Hz
Path Delays	0 sec
Normalize Path Gains	1 dB
Store History	0(no history)
Path Gains	(-0.9458+1.6126j)dB
Reset Before Filtering	1

Table 4-3:Parameters of Rician Fading Channel

Propagation Conditions	**Flat Rician Fading**
Input sample period	1
Maximum Doppler Shift	100Hz
K-Factor	1
Normalize Path Gains	1 dB
Store History	0(no history)
Path Gains	(-0.9458+1.6126j)dB
Reset Before Filtering	1

Table 4.4: Parameters of Nakagami Fading Channel

Propagation Conditions	**Flat Nakagami Fading**
Input sample period	1
Maximum Doppler Shift	100Hz
K-Factor	1
Path Delays	0 sec
Normalize Path Gains	1 dB
Store History	0(no history)
Path Gains	(-0.9458+1.6126j)dB
Reset Before Filtering	1
Shape parameter(m)	0.5
controlling spread(Ω)	1

4.1.5 Noise

AWGN is modeled in this thesis. The randomly generated AWGN is added in the sample points after the modulation is performed in the randomly generated data sample points. The mean value of the noise is 0 where as the variance is 1.

4.1.7 Viterbi Decoder

The demodulated bits at the receiver have to be decoded by a decoder. Viterbi decoder being an efficient decoding technique, is used in this work for decoding purpose. Viterbi decoder is mainly used to decode convolutionally encoded data bits.

Viterbi decoder uses Viterbi algorithm to decode the received demodulated data bits. It uses maximum likelihood decoding technique and decoded information is received with hard decision method since the input is binary data. The parameters used in the thesis using the Viterbi decoder are listed below.

Table 4-5:Parameters of Viterbi Decoder

Parameters	**Value**
Code rate	1/2
Constrain length	3,4,5,6
Decoding type	Maximum likelihood decoding technique
Decision type	hard decision
Operation mode type	Truncation
trace back length	5

4.17.1 Error Rate Calculation

The decoded bits from the Viterbi decoder are compared with the originally generated random data bits. The difference gives the number of errors encountered by the receiver. Bit error rate defines how good the communication receiver is. It is usually defined as 1 in 1 million or 1 in 10 million. It means there is 1 error after encoding and decoding of 1 million data bits.

4.2 Procedure Used in Research Design

Methodology and procedure used to design the STTC block is described in this section. First the methodology is explained. Then the research design used for Rayleigh,Rician and Nakagami fading channel are explained in sections 4.2.2,4.2.3 and 4.2.3.

4.2.1 Simulation System

The methodology of the work is represented in block diagrammatic form in Figure 4.3. The transmitter model channel and the receiver model is implemented in Matlab. It models the encoder, DBPSK modulator, different channels, demodulator and decoder described in the previous section. Basic components used for the simulations are implemented in this block schematic. Firstly the transmitting section is implemented, then the Rayleigh, Rician and Nakagami channel are implemented here. The Rayleigh channel is implemented first separately. Then the Rician, Nakagami channel fading is implemented next then the receiver model is implemented in Matlab. In this section, the demodulator and decoder are implemented. Bit Error Rate performance is calculated by comparing the output of the decoder with the input to the data generator used in the transmitter. The BER calculator calculates the total number of bits flipped at the receiver comparing to the individual bits transmitted by the transmitter.

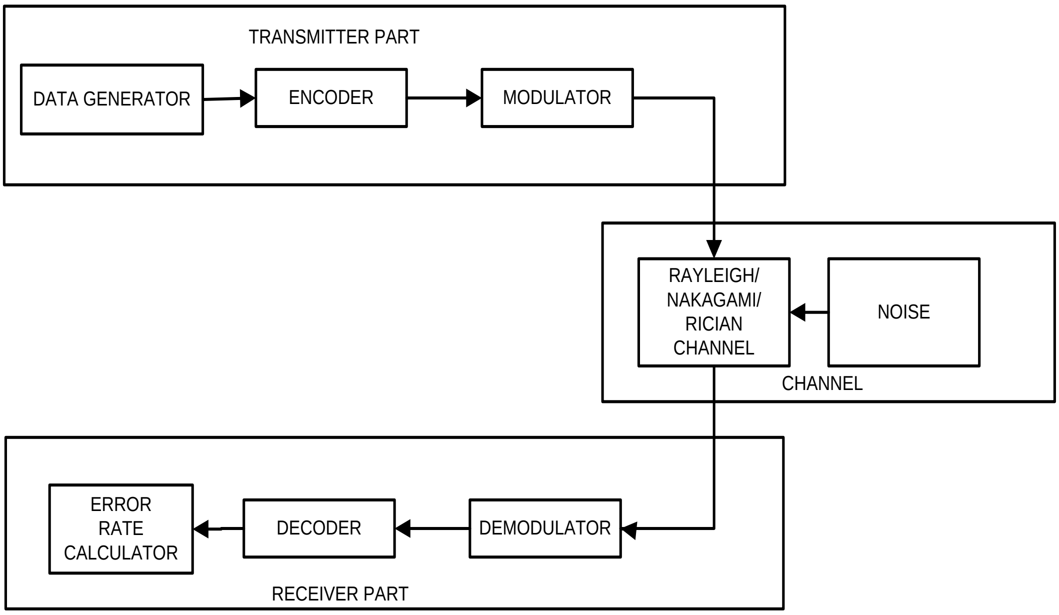


Figure 4-3: Block Diagram Representation of BER Calculation Using STTC

4.2.2 Fading Channels

The flow chart for Rayleigh fading channel, Rician channel and Nakagami channel is depicted in Fig 4.4. The complete process for finding performance of the system for different states are shown. Data were generated, then the trellis structure, channel, modulation and demodulation were defined for different states. Afterwards the encoder encodes the message, modulator modulates and pass it to the channel. The channel mixes the noise. The receiver receives noisy message and pass to the demodulator. Here the demodulator demodulates it and the decoder decodes the demodulated data. Comparator compares the demodulated data with the transmitted data.

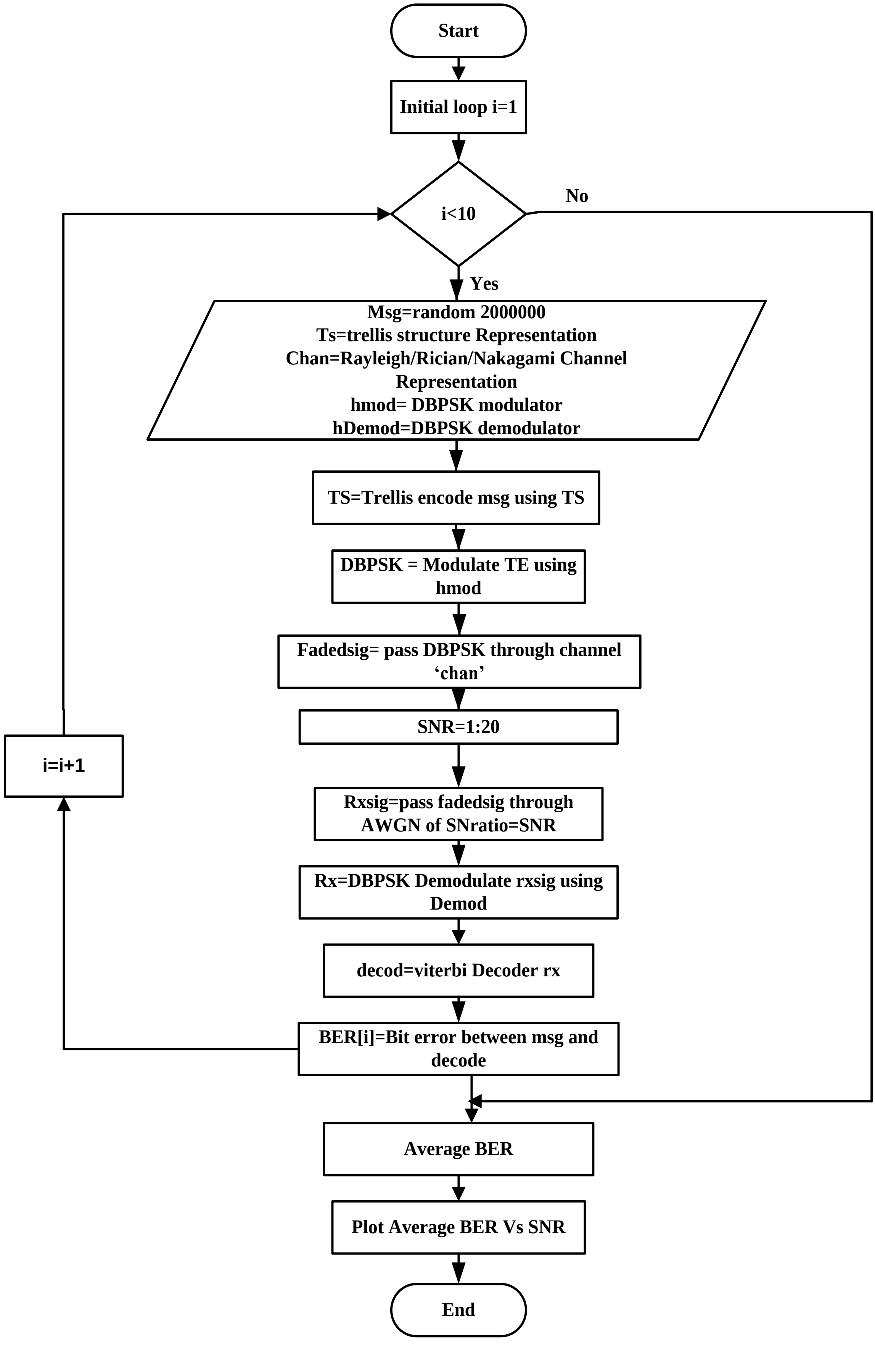


Figure 4-4: Flow Chart for Rayleigh/ Rician/ Nakagami Fading Channel

Simulation parameters

To find the BER, simulation used the following parameters

Table 4-6 : Simulation Parameters

Simulation Parameters	Values
Random data	2000000
Encoder	Convolution Encoder
Number of states	4,8,16,32
Modulation type	DBPSK
Number of Transmitter	1,2
Channel	Rayleigh,Rician,Nakagami channels
Noise Type	Additive White Gaussian Noise
Demodulation type	DBPSK
Channel State information	perfect CSI at receiver
Decoder	Veterbi decoder
Number of Receivers	1,2,3,4

Considering the simulation parameters the random data were generated up to 2000000 to meet the Monte Carlo simulation criteria required for the performance analysis. Also this data gives the BER of 10^{-6} which are used in today's communication world. For the coding and decoding of STTC convolutional encoder and Veterbi decoder are used as they work on the trellis form with reference to Almouti [20] and Sujeet et al [21]. BPSK modulation has a problem, that it needs to have coherent detection at the receiver, so DBPSK modulation is used here for the non-coherent detection purpose. The Rayleigh, Rician and Nakagami channels were considered here as it cover both the line of sight and non line of sight connection between the transmitter and receiver. The number of states up to 32 optimizes STTC performance. The number of transmitting antenna were up to 2 and receiving antenna up to 4 as they achieve the MIMO diversity order. The order of diversity can be increased, however here this thesis covers only up to 4, which can similar for the higher order too. AWGN noise was chosen as this noise adds linearly to the channel and easier for the analysis purpose.

4.3 Algorithm of the system flow

Algorithm of the system flow is described as:

a. Binary source generator acts as the source for the generation of binary data. Random binary message of 200000 bits is generated by using the random function rand.
b. The Simulation parameters are defined in Input specification the specifications are Dimension of generator matrix, generator matrix, modulation parameter, number of states, number of receive antennas and number of transmit antennas.
c. The modulation order is chosen to be 4, i.e. QPSK modulation is chosen.
d. STTC Encoder encodes the message using trellis encoder. Trellis state is defined, here we define different states such as 4, 8, 16 and 32. For this we define a function as: poly2trellis; poly2trellis Convert convolutional code polynomial to trellis description.
e. The modulated data is passed through the channel; the channel we use here are of two types a) Rayleigh fading channel and b) Rician fading channel c)Nakagami fading channel.

   The simplest fading channel from the standpoint of analytical characterization is the Rayleigh channel, whose instantaneous SNR per bit PDF is given by $p_{\gamma}(\gamma) = \frac{1}{\gamma}\exp\left(\frac{\gamma}{\bar{\gamma}}\right)$ $\gamma \geq 0$. Where $\bar{\gamma}$ is the average SNR per bit. And the similar pdf expression is obtained for the Rician fading channel and Nakagami fading channel.
f. Additive white Gaussian noise is considered in the channel. The noise is independent Gaussian random variables with zero mean and the same power spectral density of $\frac{N_0}{2}$.
g. The corrupted signal is passed to the demodulator.
h. We assume that perfect channel state information (CSI) is available at the receiver.
i. DBPSK demodulation is done by using DBPSK demodulator.
j. Than we passed to the decoder, the decoder we use here is Viterbi decoder. For space-time codes the Viterbi decoder is modified from the conventional decoder so that the branch metric is computed from the complex inputs and

the Channel State Information. The Viterbi decoder is then used to calculate the path through the trellis diagram with the lowest accumulated metric. ‘vitdec’ Convolutionally decode binary data using the Viterbi algorithm.

DECODED=vitdec(CODE,TRELLIS,TBLEN,OPMODE,DECTYPE) decodes the vector CODE using the Viterbi algorithm. Here CODE is assumed to be the output of a convolutional encoder specified by the MATLAB structure TRELLIS. OPMODE denotes the operation mode of the decoder. Here for using of opmode we have many options, here we use the ‘trunc’. ‘trunc’ means The encoder is assumed to have started at the all-zeros state and the decoder traces back from the state with the best metric. DECTYPE denotes how the bits are represented in CODE, for using the decoder type we have the options like the hard decoding, soft decoding or unquant decoding, since our input is of binary values so we use the hard decoder. The MATLAB function takes the hard decoder for any binary input values. For each symbol in CODE consists of log_2(TRELLIS. numOutputSymbols) symbols

k. After the encoding and decoding is done we have the set of both uncoded and decoded data. After obtaining these uncoded and the decoded values we compare them to check the performance of the space time trellis codes for different conditions. We calculate the parameter Bit error rate which helps in deciding the performance results of STTC.

l. The value of SNR is taken from 0 to 20 in the interval of 2 for some case and 0 to 30 in the interval of 5 in the other cases.

m. The BER versus SNR is plotted in the semi-logy graph, for different SNR values between 0 to 20 in the interval of 2 each.

CHAPTER FIVE: RESULT AND ANALYSIS

The performance of STTC over Rayleigh fading, Rician fading channel and Nakagami fading channel are based on computer simulations. Simulation is performed using Matlab 2013a. Evaluation of the system is carried out for 2-PSK constellations. The states considered is 4, 8, 16 and 32 states. The transmitter antennas are supposed to be 1 and 2, whereas the number of receiver antennas are assumed to be 1 to 4. The initial part of the thesis discusses on the channel capacity of system. The second part shows the results for Rayleigh, Rician and Nakagami fading channel.

5.1 MIMO Channel Capacity

The SNR values are varied from 2 to 20 in steps of 2 to calculate the channel capacity for different types of the system.

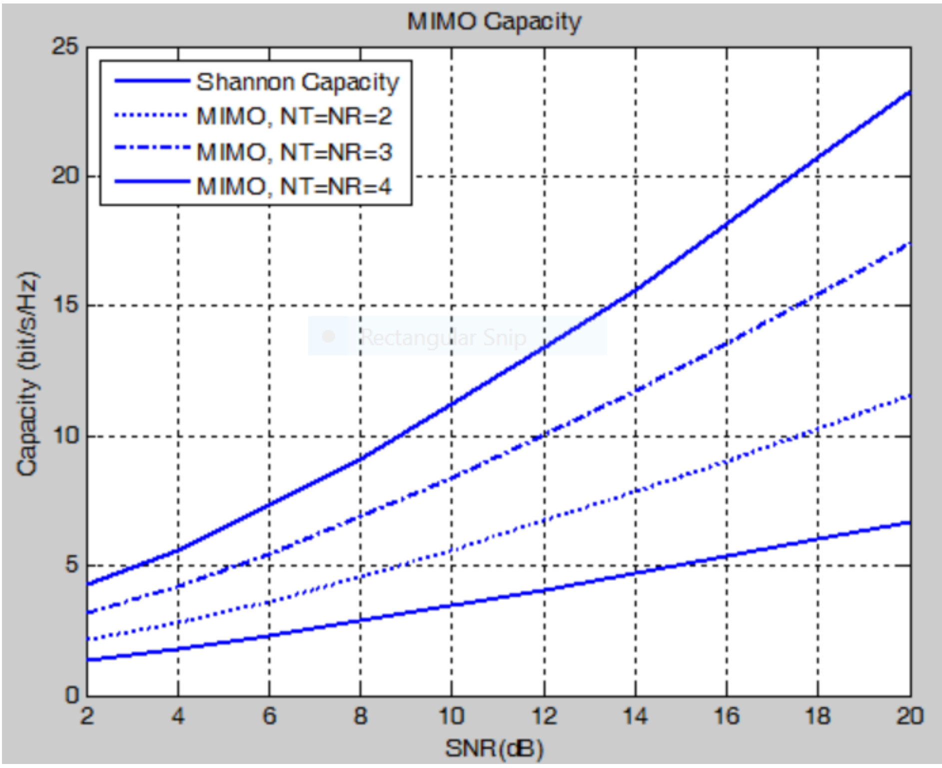


Figure 5-1: Plots Showing the Channel Capacity and SNR

The capacity of channel increases as the value of SNR increases. Lower most line has lowest capacity compared to other as observed in Figure 5-1. Although the capacity increases as the value of SNR increases (here from 2 to 20), it is least compared to

MIMO system which has 2x2, 3x3 or 4x4 antennas. SNR value 18dB corresponds to the capacity of 6bit/Sec/Hz for SISO, but for the same SNR value, the capacity for[2x2],[3x3] and [4x4] antennas are 10.5, 15.5 and 21 respectively. It can be analyzed that for the fixed SNR the capacity of system increases as the number of antennas increases. From this it can be concluded that any system can increase its channel capacity by increasing the number of antennas at both transmitter and receiver side.

The capacity of the system increases as the number of transmitting and receiving antenna increases but this increment is limited to some value. Along with the number of antenna, the spacing between the antenna, the frequency used in the system, surrounding environment and other factors also play vital role in analyzing the performance of any system. The power in the antennas is considered to have equally distributed. The ergodic capacity when the channel is known to the transmitter is always higher then when it is unknown. This advantage reduces at high SNRs. Outage capacity is the capacity that is guaranteed with a certain level of reliability. Asymptotically the capacity in spatially white MIMO channel becomes deterministic and increases linearly with $NT=NR=M$ for a fixed SNR. Also for every 3-dB increase in SNR, we get M bit/s/Hz increase in capacity for a MIMO channel, compared with 1 bit/s/Hz in a SISO channel. The capacity curves substantiate this conclusion.

5.2 STTC Performance Over Rayleigh Fading Channel

When a single antenna is used at both transmitter and receiver. The figure shows that at the bit error rate of 10^{-3}, the gain in SNR value is about 5dB while moving from 4 states to 8 states. Similarly for the same BER the gain is 2dB from 8 to 16 states and about 1.5dB gain while moving from 16 to 32 states. This shows that there is a drastic improvement in gain if we move from 4 to 32 states. The change in the gain while moving from one to next state is not uniform. In general, the coding advantage of the above codes can be improved by constructing encoders with more number of states.

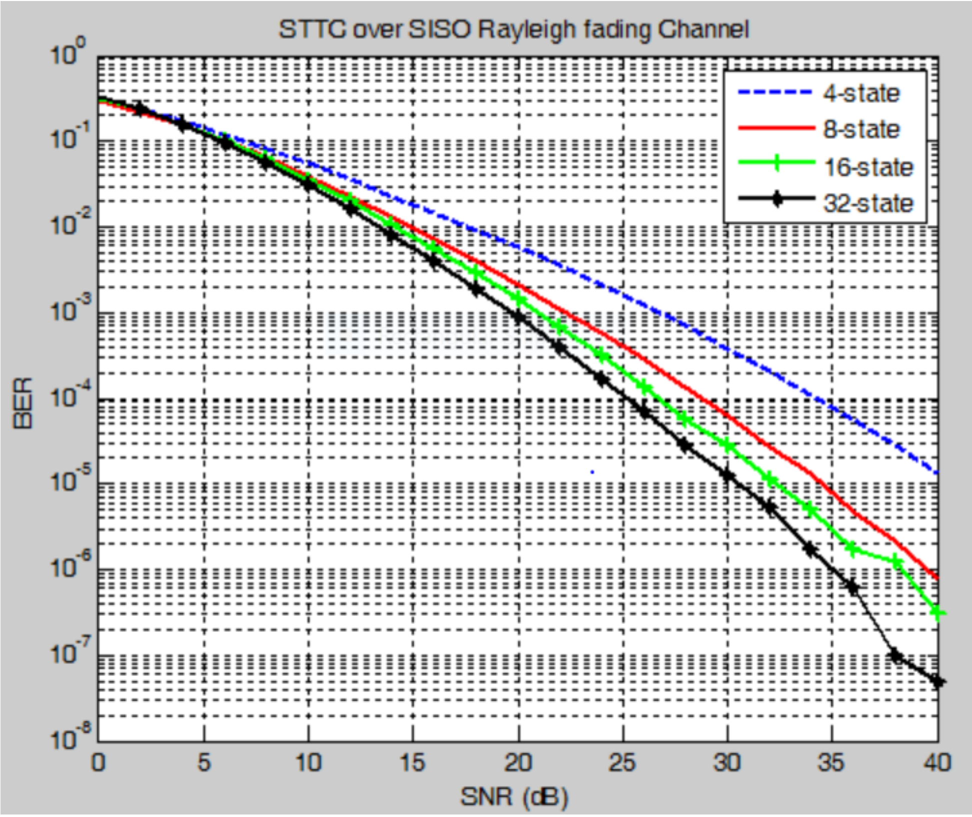


Figure 5-2: Performance of 2-PSK With One Transmit and One Receive Antenna

System performance get improved while moving from 4 states to 32 states. For being a single receive antenna, a complete analysis of distance spectrum is needed to claim a coding gain advantage. The performance is almost identical to SISO except that it has two transmitting antenna at the transmitter and perform transmit diversity advantage. Due to this advantage, BER is lower than that of SISO. Here at the SNR value of 15 dB the performance improvement in BER is from $10^{-2.5}$ to $10^{-1.9}$. Similarly the BER of $10^{-2.5}$ is achieved at the SNR value of 20 dB for 4 states and 16 dB for 32 states , so for the BER there is gain of about 4 dB when moving from 4 to 32 states for the same number of transmit and receive antennas.

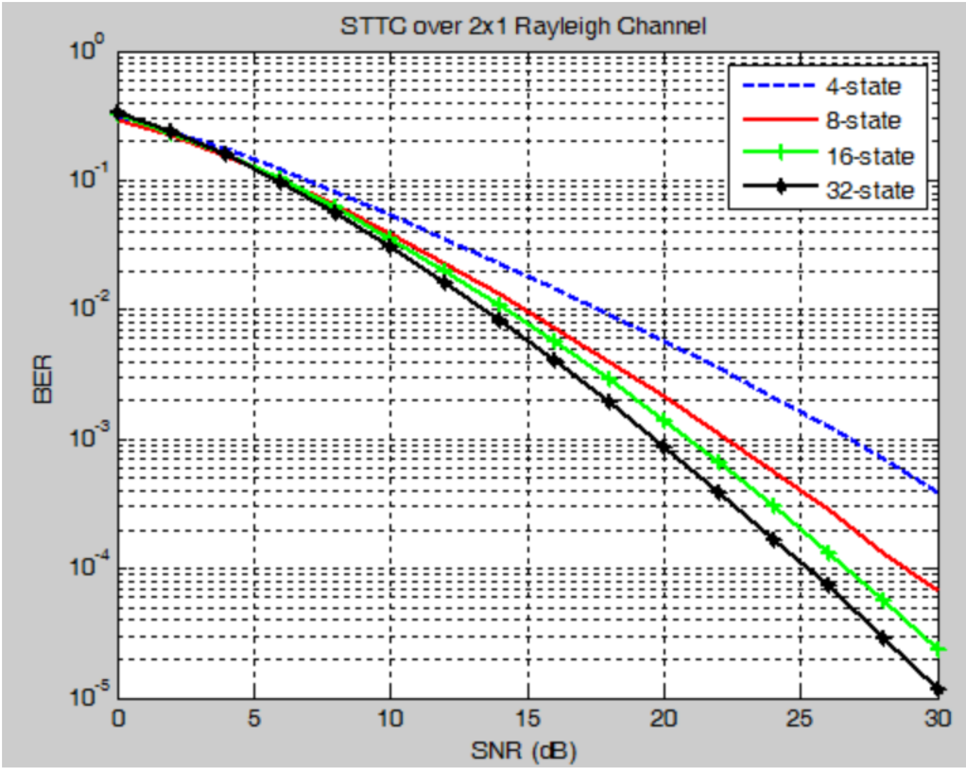


Figure 5-3: Performance of 2-PSK with one transmit and one receive antenna

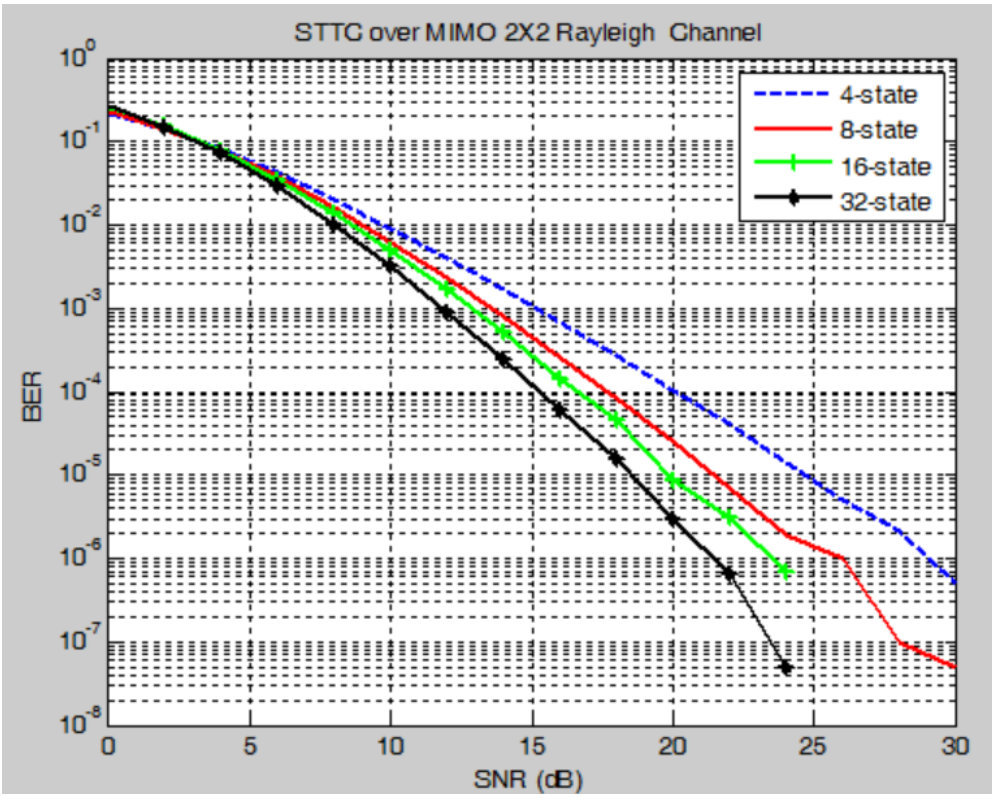


Figure 5-4: Performance of 2-PSK with two transmit and two receive antenna

The performance of STTC over Rayleigh fading channel using two transmit and two receive antennas. The performance of the system increases whenever the number of states gets increased from 4 states to 32 states. Similarly there is increased in diversity gain than observed on Figure 5-3 by two. BER is better pronounced in this case. If we look at BER of 10^{-6}, there is 4dB gain improvement when moving from 4 to 8 states. Similar improvement is seen for increasing the states. As can be seen, increasing the number of states on higher level improves the performance. This improvement is more pronounced at higher SNRs. The effect of receive diversity in providing a coding advantage of almost 7 dB by using two receive antennas instead of one is observed in Figure 5-4

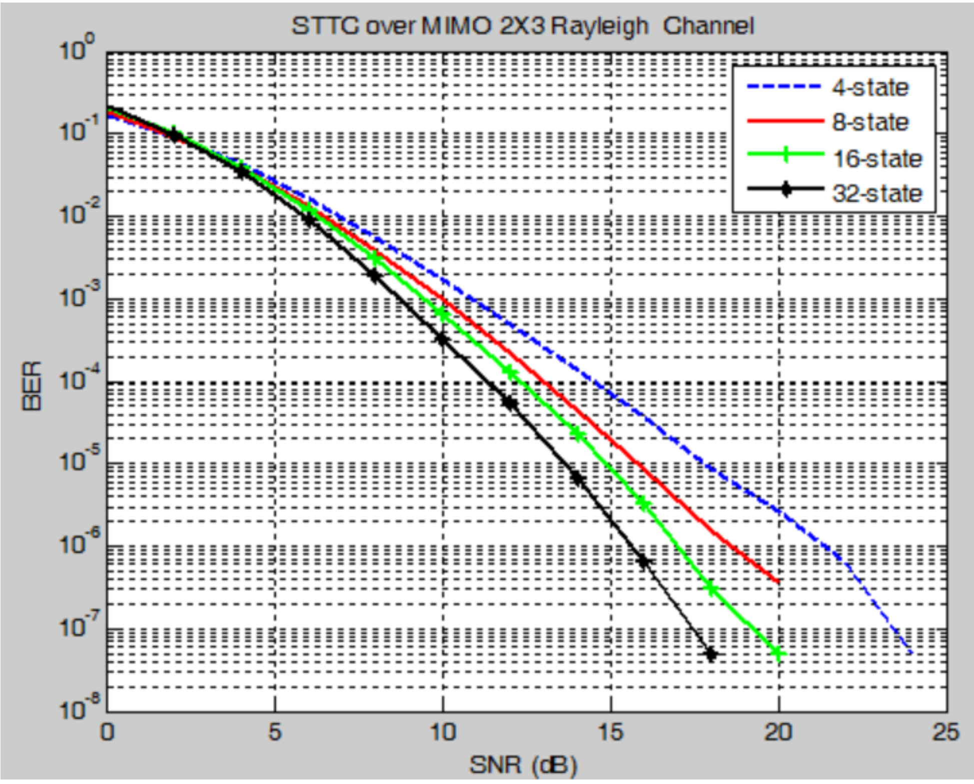


Figure 5-5: Performance of 2-PSK with two transmit and three receive antenna

Performance of STTC over Rayleigh fading channel using two transmit and three receive antennas. Performance of the system increases whenever the number of states gets increased from 4 states to 32 states. Similarly there is increased in diversity gain when compared to Figure 5-2, Figure 5-3 or Figure 5-4. BER is better than the earlier cases. If we focus on BER of 10^{-6}, the SNR value is 22dB for 4 states, 18dB for 8 states 17 dB for 16 states and 16 dB for 32 states. These data are acceptable values for data and voice. There is gain in SNR value for same BER while increasing the states from 4 to 32. This gain is comparatively more than the earlier ones. Performance improvement is non linear when the number of states goes on increasing.

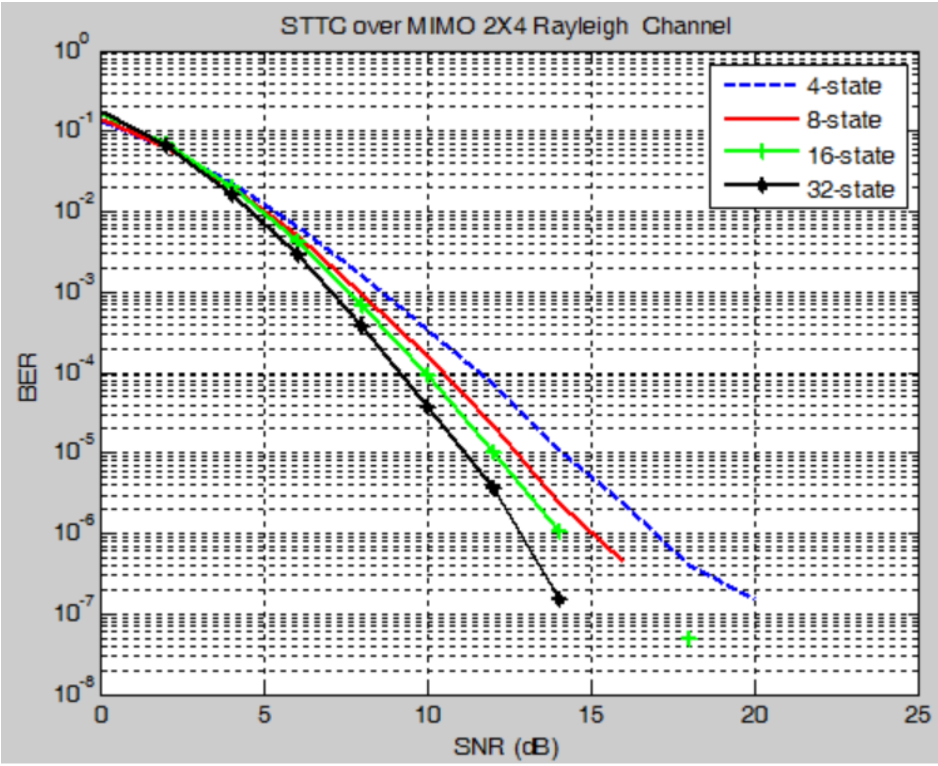


Figure 5-6: Performance of 2-PSK with two transmit and Four receive antenna

Performance of STTC over Rayleigh fading channel using two transmit and four receive antenna for 2-PSK. The figure shows that the output performance is better than the cases depicted in Figure 5-2, Figure 5-3, Figure 5-4 and Figure 5-5. This happens because it has the highest diversity gain. BER improves from $10^{-3.5}$ to $10^{-4.5}$ when increasing from 4 states to 32 states at SNR value of 10dB. Similarly at BER of 10^{-5} ,there is about 5dB gain in SNR value when the number of states increases from 4 to 32 states. From the comparative analysis of above figures, it can be concluded that the performance of the system goes on increasing whenever the number of states goes on increasing. Similarly there is improvement in the performance with the increment of number of receiving antennas.

5.2.1 Summary of STTC performance over Rayleigh fading Channel

Performance in independent Rayleigh fading channels for 4, 8, 16, and 32 states with one transmit antenna and one receive antenna and two transmit antennas and 1, 2, 3 and 4 receive antennas for 2-PSK respectively. In every figure, it can be seen that the performance improves as the number of states increases. It can also be seen that the coding gain between 4 state and 8 state codes is larger than the others. When multiple receiver antennas are used than a significant improvement is achieved for all of the codes. This improvement is due to diversity gain. Bandwidth efficiency of the 4-PSK codes is 2 bits/s/Hz. In the case of Rayleigh fading channels, it can be seen that as the number of states increases from 4 to 32 keeping the number of transmitting and receiving antennas constant, the performance of the system improves. Also when the number of receiver antennas increases, it is found that system performance improves. The plots in the Figure 5-3, Figure 5-4, Figure 5-5 and Figure 5-6 (i.e. MIMO plots) are better than the plots of Figure 5-2 (SISO plot). Also the plots are being better if proceeded from Figure 5-3 to Figure 5-6 (plots within MIMO system). Along with the coding gain, the diversity order of antennas goes on increasing from 2 (i.e. 2 x 1= 2; in Figure 5.3) to 8 (i.e. 2 x 4 = 8; in the Figure 5.6).

5.3 STTC Performance Over Rician Fading Channel

The performance of STTC over Rician channel for different constrain length is presented below. First the number of transmitter antennas are assumed to be 1. The number of the receiver antennas are also assumed to be 1. Then the number of transmitter antennas is increased to 2. The number of the receiver antenna is still 1- The number of the receiver antenna is then increased to 2, 3, and then 4 at the end.

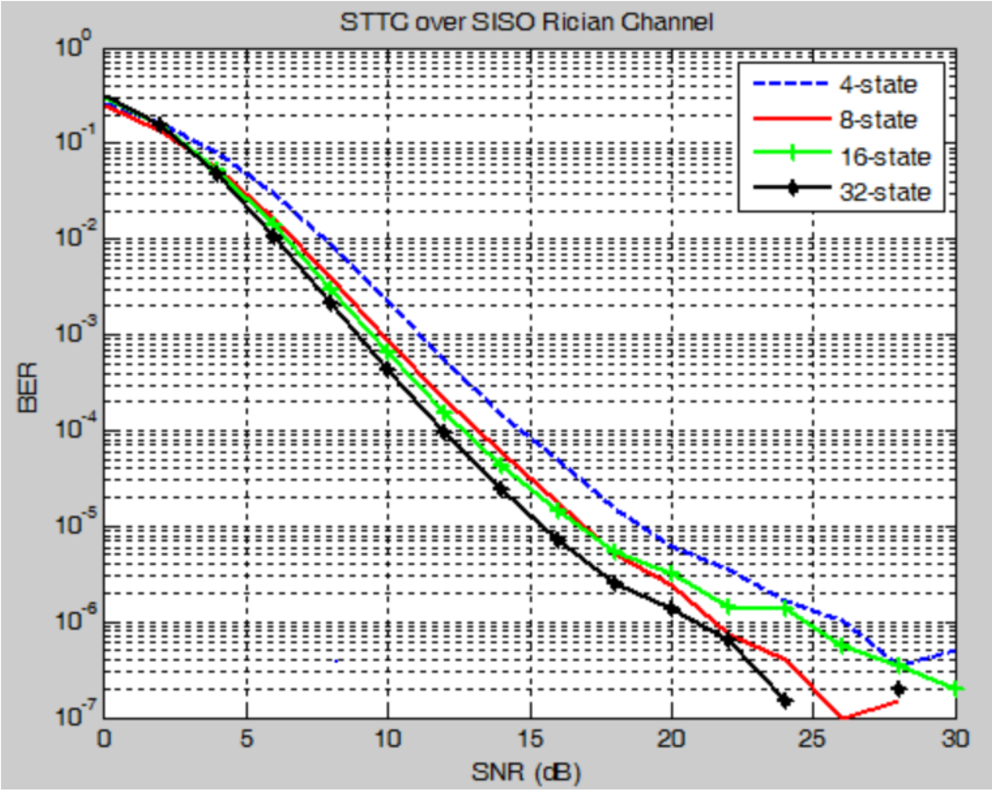


Figure 5-7: Performance of 2-PSK with one transmit and one receive antenna

The system perform on different states on the Rician fading channel. This is the case when a single antenna is used at both transmitter and receiver. The figure depicts that for a bit error rate of 10^{-6}, the gain in SNR value is about 6dB while moving from 4 states to 32 states. This shows that there is an improvement in gain if we move from 4 to 32 states. It can be seen that as the number of states in the trellis increases, the coding gain increases and so does the performance. In general, the coding advantage of the above codes can be improved by constructing encoders with more number of states.

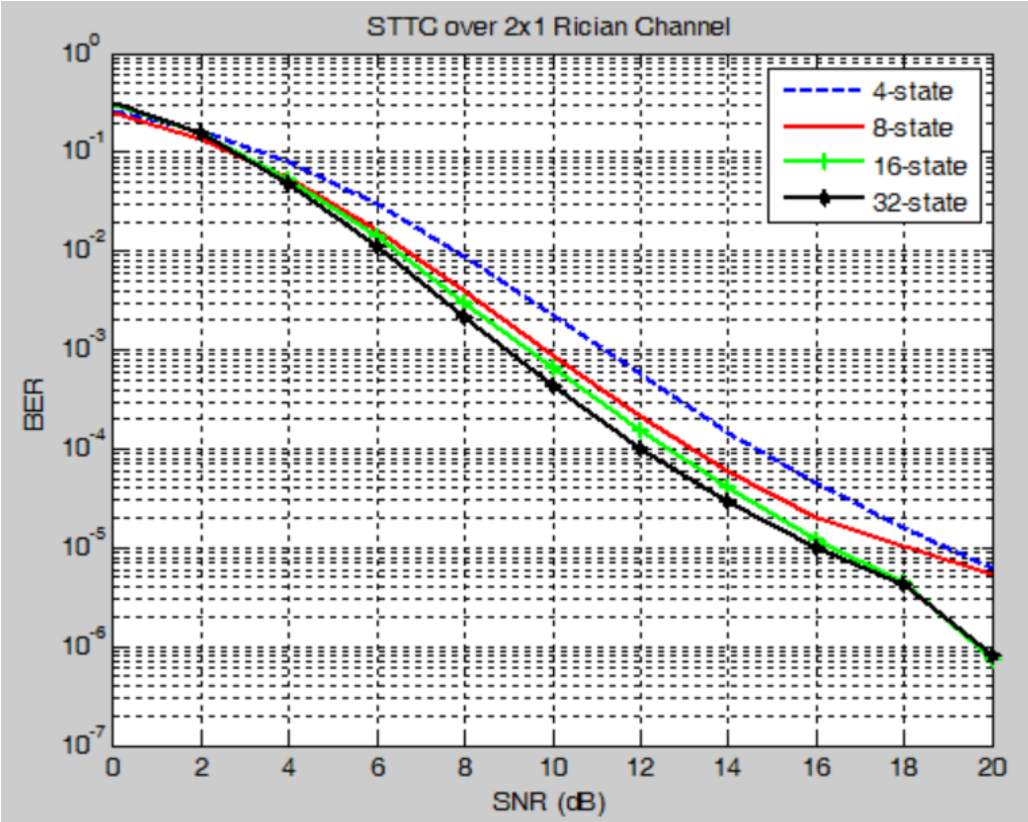


Figure 5-8: Performance of 2-PSK with two transmit and one receive antenna

System perform while using the two antennas at transmitter and a single at the receiver for 2-PSK STTC is shown in figure 5-8. System performance improves while moving from 4 states to 32 states. For being a single receive antenna, a complete analysis of distance spectrum is needed to claim a coding gain advantage. The performance is almost identical to SISO except that it has two transmitting antenna at the transmitter and perform the transmit diversity advantage too. Due to this advantage the BER is lower than the SISO. When the BER is 10^{-5} , then there is gain of 4dB while moving from 4 states to 32 states. This happens due to coding in STTC. Comparing between the earlier figure 5-7 case of SISO and this MISO at the SNR value of 16 dB the BER improvement in this case is $10^{-4.2}$ to $10^{-4.5}$, this shows the capacity increases in this MISO compared to SISO case.

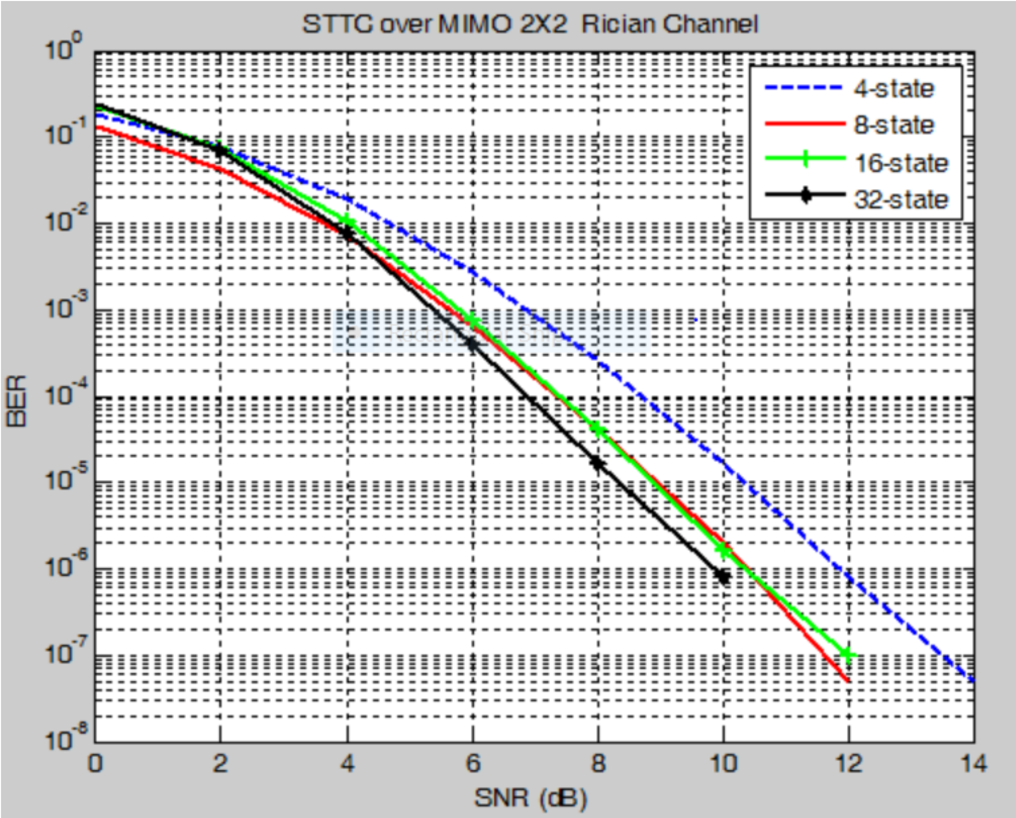


Figure 5-9: Performance of 2-PSK with two transmit and two receive antenna

MIMO system with two transmit and two receive antennas using 2- PSK in STTC is depicted in figure 5-9. As above the figure 5-9 shows, the performance of the system improves whenever the number of states increases from 4 states to 32 states. Similarly there is increased in diversity gain than in Figure 5-8 by two. So BER is better here than the earlier figure 5-8. At BER of 10^{-6} , there is 2dB gain improvement when moving from 4 to 8 states. Similar improvement is seen for increasing the states . As can be seen, increasing the number of states on higher level improves the performance. This improvement is more pronounced at higher SNR. We can also see the effect of receive diversity in this figure providing a coding advantage by using two receive antennas instead of one.

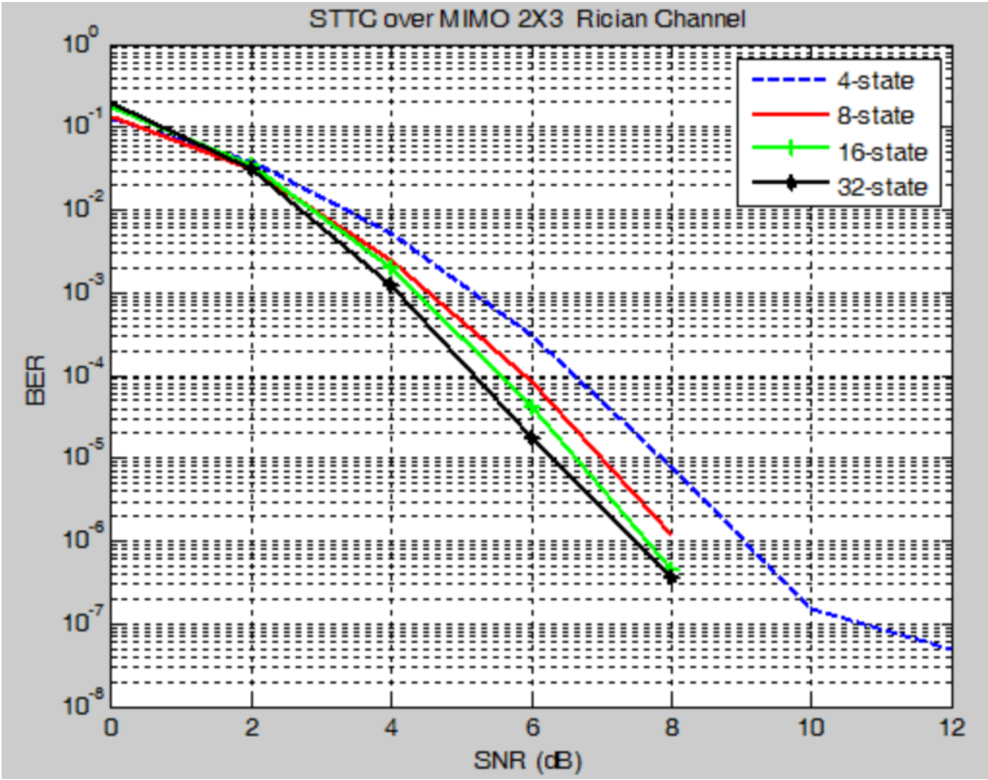


Figure 5-10: Performance of 2-PSK with two transmit and Three receive antenna

The performance of STTC over Rician fading channel using two transmit and three receive antennas. As shown in above figure, the performance of the system increases whenever the number of states gets increased from 4 states to 32 states. Similarly there is increased in diversity gain than the above Figure 5-7, Figure 5-8 or Figure 5-9. BER is better than in the earlier cases. If we check at BER of 10^{-6}, the gain in SNR value is about 3dB which is an acceptable value for data and voice transmission.

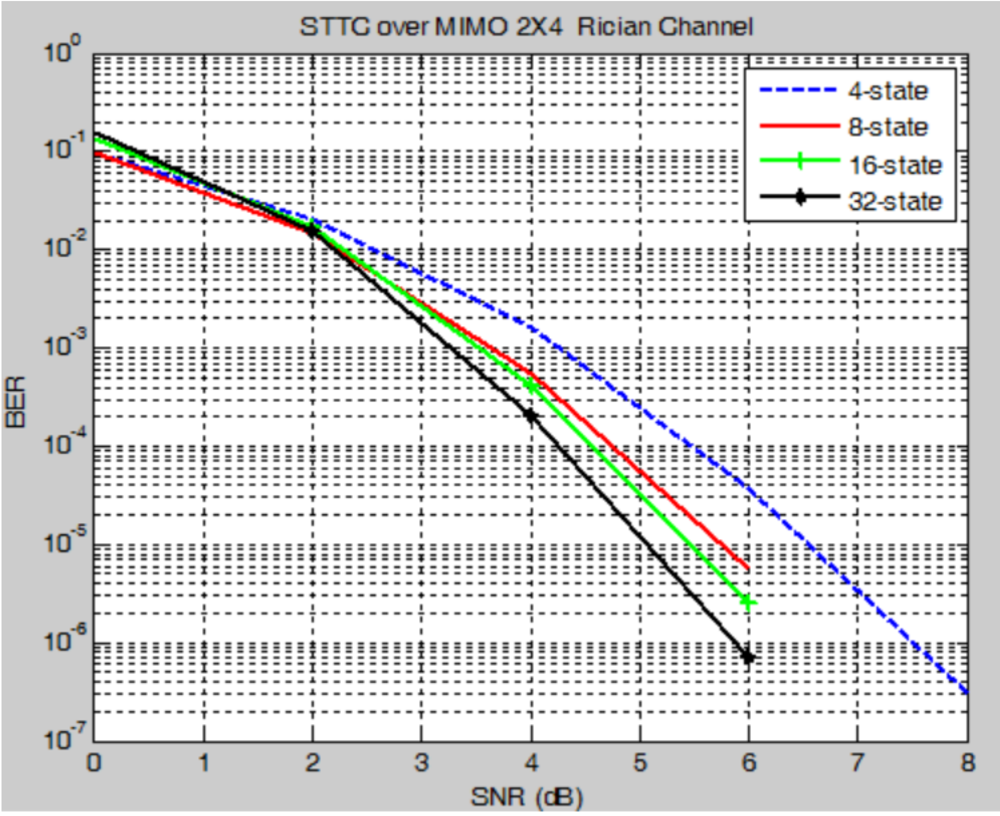


Figure 5-11: Performance of 2-PSK with two transmit and Four receive antenna

The performance of STTC over Rician fading channel using two transmit and four receive antenna for 2-PSK. The figure shows that the output performance to be better than in the earlier Figure 5-7, Figure 5-8, Figure 5-9 and Figure 5-10. This happens because it has the highest diversity gain. BER gets improves from $10^{-4.3}$ to $10^{-6.4}$ when increasing from 4 states to 32 states at the SNR value of 8dB. Similarly at the BER of 10^{-6} , there is about 2dB gain in SNR value when the number of states increases from 4 to 32 states. From the comparative analysis of above figures it can be concluded that the performance of the system goes on increasing whenever the number of states goes on increasing. Similarly there is improvement in the performance with the increment of number of receiving antennas. In general, the coding advantage of the above codes can be improved by constructing encoders with more states.

5.3 STTC Performance Over Nakagami Fading Channel

The performance of STTC over Nakagami fading channel for different constrain length is presented below. First the number of transmitter antennas are assumed to be 1. The number of the receiver antennas are also assumed to be 1. Then the number of transmitter antennas is increased to 2. The number of the receiver antenna is still 1- The number of the receiver antenna is then increased to 2, 3, and then 4 at the end.

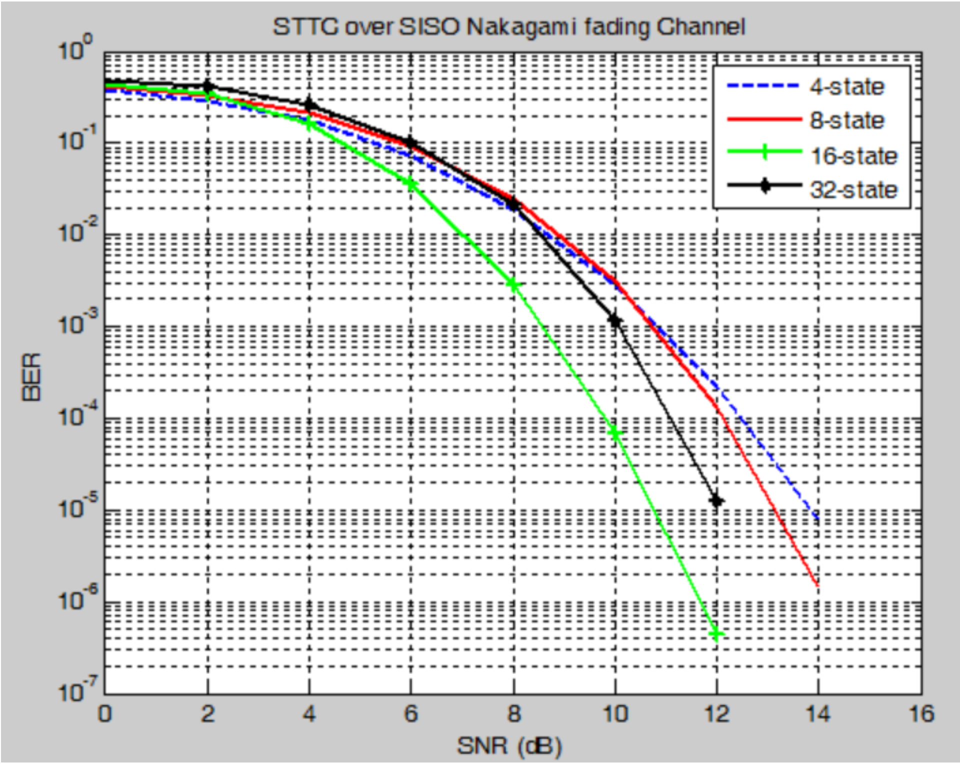


Figure 5-12: Performance of 2-PSK with one transmit and one receive antenna

The system perform on different states on the Nakagami fading channel is shown in above figure5-12. This is the case when a single antenna is used at both transmitter and receiver. The figure depicts that for a bit error rate of 10^{-3}, the gain in SNR value is about 1dB while moving from 4 states to 32 states. This shows that there is an improvement in gain if we move from 4 to 32 states. It can be seen that as the number of states in the trellis increases, the coding gain increases and so does the performance. In general, the coding advantage of the above codes can be improved by constructing encoders with more number of states.

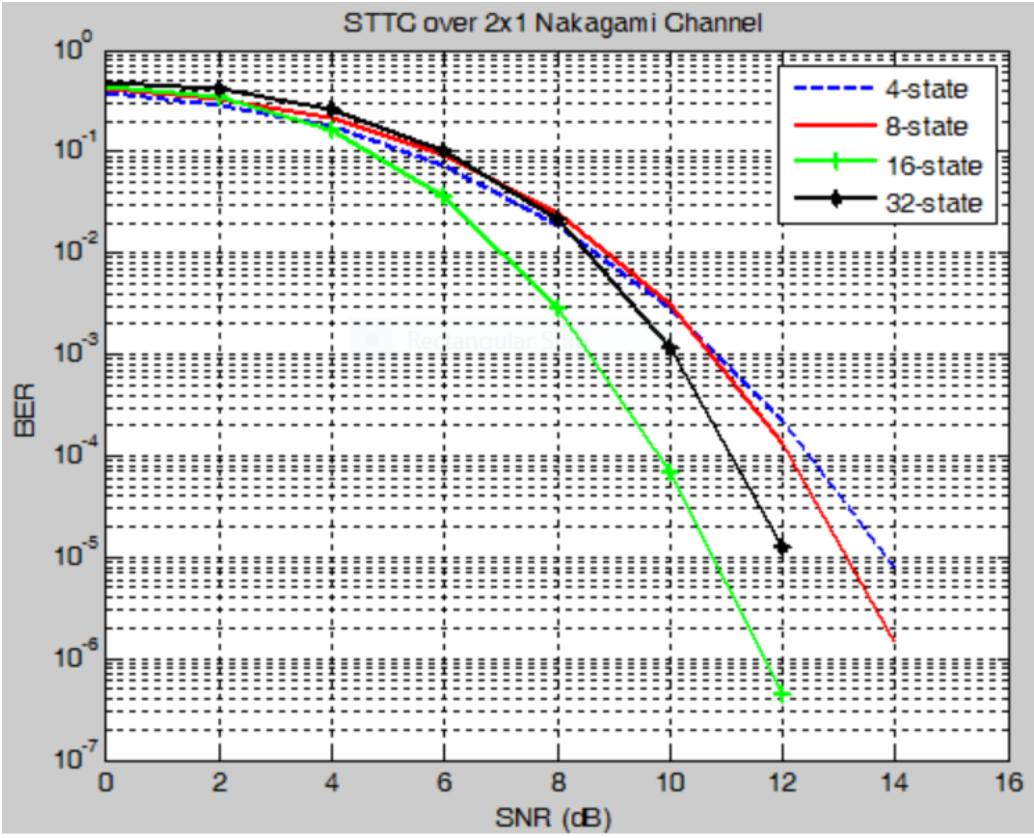


Figure 5-13: Performance of 2-PSK with two transmit and one receive antennas

The system perform while using the two antennas at transmitter and a single at the receiver for 2-PSK STTC. System performance improves while moving from 4 states to 16 states. For being a single receive antenna, a complete analysis of distance spectrum is needed to claim a coding gain advantage. The performance is almost identical to SISO except that it has two transmitting antenna at the transmitter and perform the transmit diversity advantage too. Due to this advantage the BER is lower than the SISO. When the BER is 10^{-3} , then there is gain of 2dB while moving from 4 states to 32 states. This happens due to coding in STTC. Comparing between the earlier figure 5-12 case of SISO and this MISO at the SNR value of 10 dB the BER improvement in this case is $10^{-4.2}$ to $10^{-4.5}$, this shows the capacity increases in this MISO compared to SISO case.

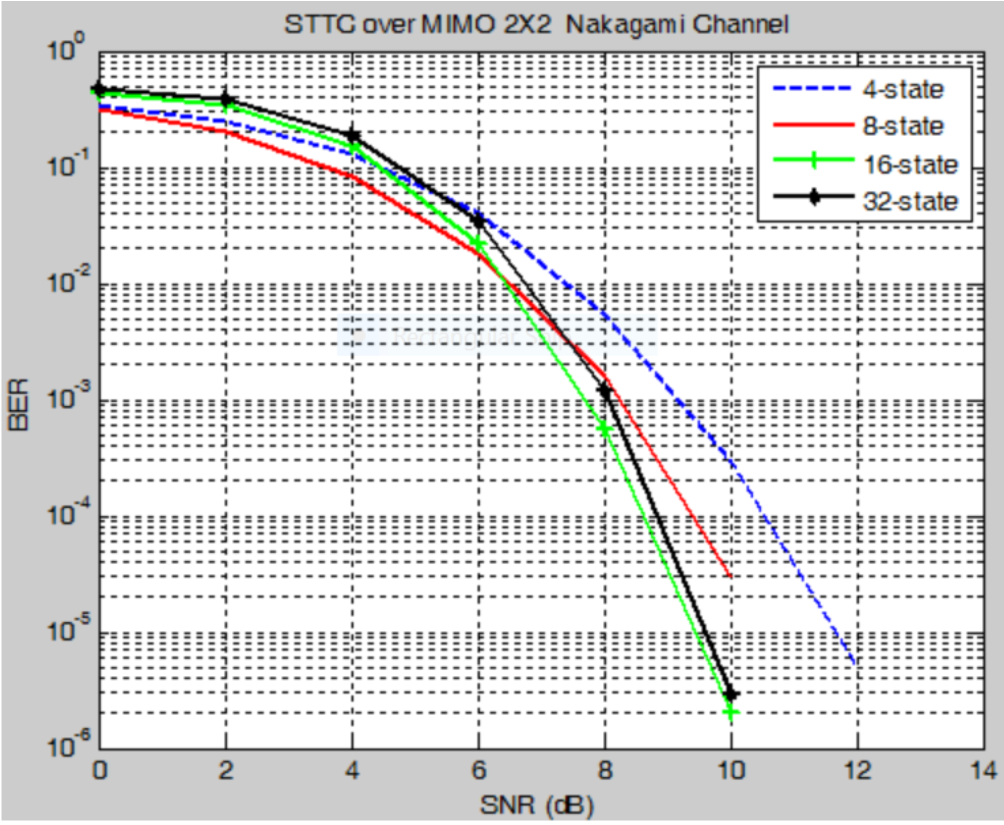


Figure 5-14: Performance of 2-PSK with two transmit and two receive antennas

MIMO system with two transmit and two receive antennas using 2- PSK in STTC. As above the figure shows, the performance of the system improves whenever the number of states increases from 4 states to 32 states. Similarly there is increased in diversity gain than in Figure 5-14 by two. So BER is better here than the earlier figure 5-14. At BER of 10^{-3} , there is 2dB gain improvement when moving from 4 to 8 states. Similar improvement is seen for increasing the states . As can be seen, increasing the number of states on higher level improves the performance. This improvement is more pronounced at higher SNR. We can also see the effect of receive diversity in this figure providing a coding advantage by using two receive antennas instead of one.

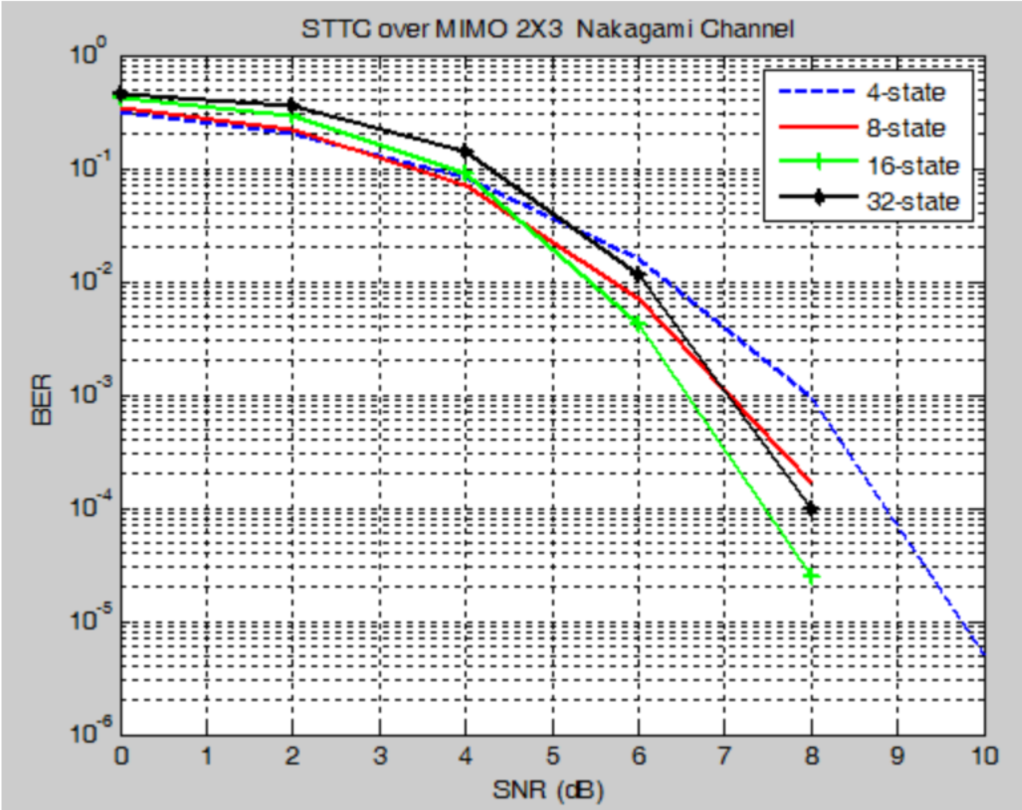


Figure 5-15: Performance of 2-PSK with two transmit and three receive antennas

Performance of STTC over Nakagami fading channel using two transmit and three receive antennas. As shown in above figure, the performance of the system increases whenever the number of states gets increased from 4 states to 32 states. Similarly there is increased in diversity gain than the above Figure 5-13, Figure 5-14 or Figure 5-15. BER is better than in the earlier cases. If we check at BER of 10^{-3}, the gain in SNR value is about 3dB which is an acceptable value for data and voice transmission.

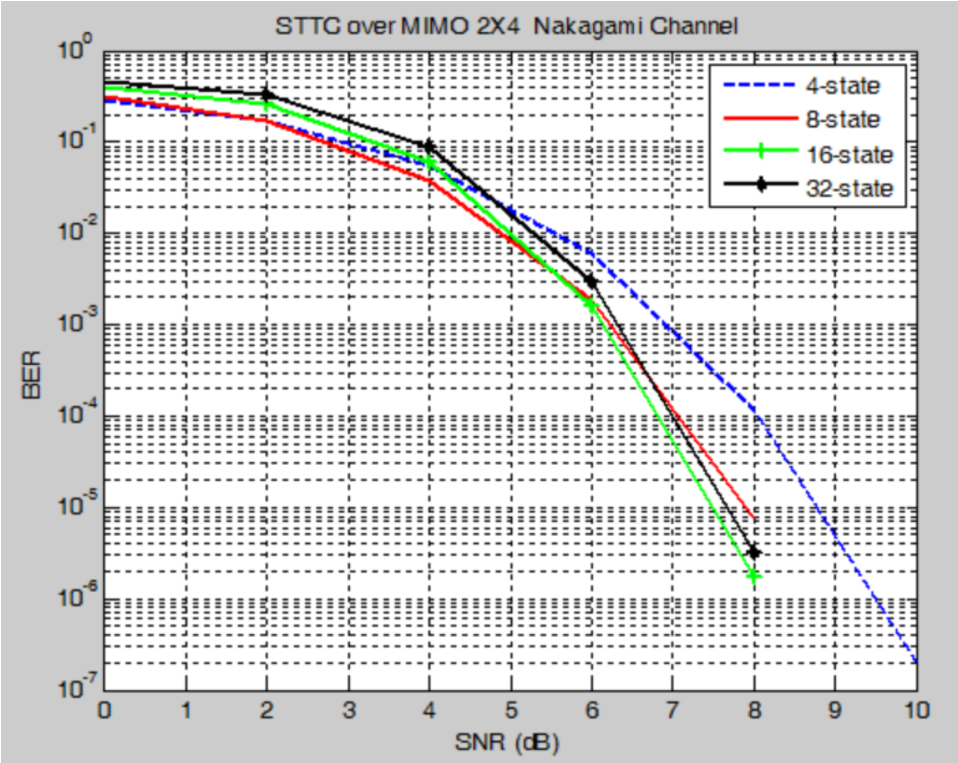


Figure 5-16: Performance of 2-PSK Nakagami Fading channel with two transmit and four receive antennas

Performance of STTC over Nakagami fading channel using two transmit and four receive antenna for 2-PSK. The figure shows that the output performance to be better than in the earlier Figure 5-12, Figure 5-13, Figure 5-14 and Figure 5-15. This happens because it has the highest diversity gain. BER gets improves from $10^{-4.3}$ to $10^{-6.4}$ when increasing from 4 states to 32 states at the SNR value of 1dB. Similarly at the BER of 10^{-3} , there is about 1.6 dB gain in SNR value when the number of states increases from 4 to 32 states. From the comparative analysis of above figures it can be concluded that the performance of the system goes on increasing whenever the number of states goes on increasing. Similarly there is improvement in the performance with the increment of number of receiving antennas. In general, the coding advantage of the above codes can be improved by constructing encoders with more states.

Summary

Simulation results for various STTC codes were depicted and also observed the factors affecting the performance of STTC. The performance analysis is made over two channels, viz Rayleigh fading channel, Rician fading channel and Nakagami fading channel. In all channels, the performance is improved by increasing the number of states. Here for all channel it is observed and compared with that of the SISO channel. The observation is made by keeping the number of transmit antennas constant at 1 and 2 while increasing the number of receive antennas from 1 to 4. It provides a significant improvement in the performance in every case as the number of states increases for both the channels. Similarly it proves that the performance is being best as the diversity order increases in the Rayleigh,Rician and Nakagami fading channel. From this, it can be concluded that the space time trellis code not only provides the diversity gain but also the coding gain. This is a remarkable advantage of using STTC in any system for better performance. The general comparison of all the channels of 2X2is shown in figure below that shows that the Nakagami channel is the best channel in comparison with BER vs SNR.

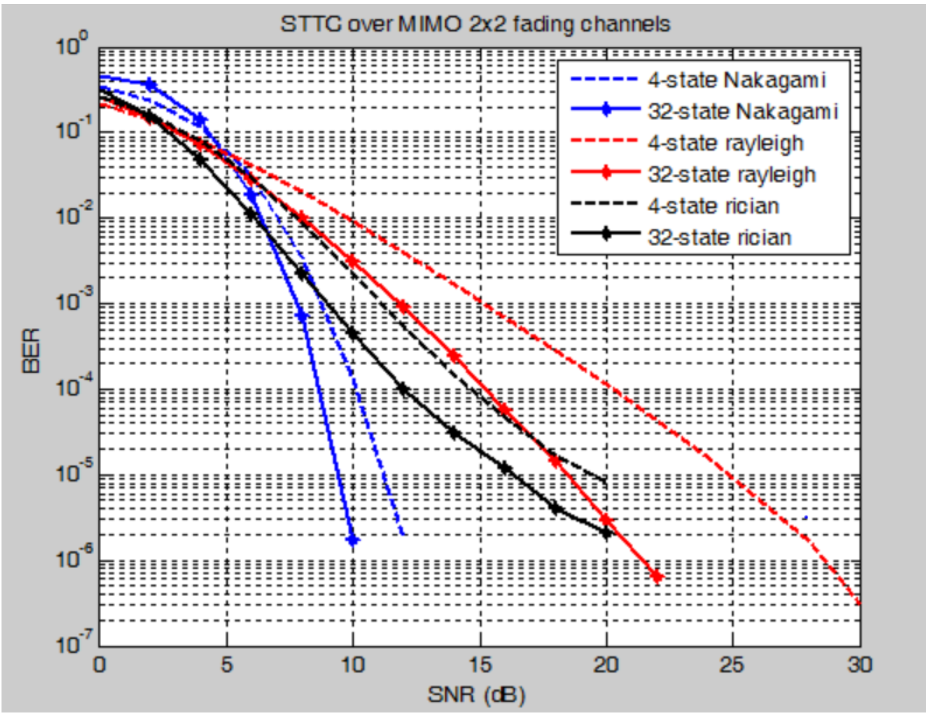


Figure 5-17:Performance of Nakagami,Riciaan and Rayleigh MIMO 2x2

CHAPTER SIX: CONCLUSION

6.1 Conclusion

The implementation of Space-Time Trellis Code has been studied in detail. The diversity methods are used here for improving the operating aspects of wireless communication system. STTC are able to achieve significant improvement in the system by combining coding, modulation, diversity techniques in any communication operating devices. The performance analysis of the system using STTC under Rayleigh, Rician and Nakagami fading channel was made. The performance curves were derived for 2-PSK, 4, 8, 16, and 32 state, using different diversity order for Rayleigh, Rician and Nakagami fading channel scenarios. The signals were assumed to undergo flat Rayleigh fading,Rician and Nakagami fading through a quasi- static wireless channel. The result shows that there is an improvement in error performance as the number of states increases. It is noted that 32 state trellis codes are superior to 4 state trellis codes This means that the performance of 32 state code relative to 4 state code has improved. The gain is different for different diversity order. It is seen that there is a gain of 10dB in case of SISO, 5dB for 2x1, 8dB for 2x2, 7dB for 2x3 and 4dB for 2x4 Rayleigh fading channel. Similarly for the Rician fading channel the gain of 6dB is obtained for SISO, 5dB for 2x1, 4dB for 2x2, 2dB for 2x3 and 2dB for 2x4.Nakagami fading also has the significant improvement in BER. It was verified that when the number of the states along with diversity order increased, the performance gain also get increased.

Capacity in wireless communication systems has been rapidly growing world- wide. The main reason behind it is the increasing data rate requirements. As the available radio spectrum is limited, higher data rates along with error correction can only be achieved by designing more efficient signaling techniques. STTC are able to achieve the significant improvement by using the error correcting techniques which provides the quality in transmission of data by offering reliability.

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Appendix A

Trellis Codes

The trellis codes used in the simulations are shown in Table 1 and Table 2. The details of these codes can be found in [1], [6],[8] and [25].

v	(a_0^1, a_0^2)	(a_1^1, a_1^2)	(a_2^1, a_2^2)	(b_0^1, b_0^2)	(b_1^1, b_1^2)	(b_2^1, b_2^2)
2	(0,2)	(2,0)	-	(0,1)	(1,0)	-
3	(0,2)	(2,0)	-	(0,1)	(1,0)	(2,2)
4	(0,2)	(2,0)	(0,2)	(0,1)	(1,2)	(2,0)

Table 1. Coefficient Pairs for 4PSK, 4-, 8-, and 16-State, STTCM Codes

v	(a_0^1, a_0^2)	(a_1^1, a_1^2)	(b_0^1, b_0^2)	(b_1^1, b_1^2)	(c_0^1, c_0^2)	(c_1^1, c_1^2)
3	(0,4)	(4,0)	(0,2)	(2,0)	(0,1)	(5,0)

Table 2. Coefficient Pairs for 8PSK, 8-State, STTCM Code

The generator matrix, for example, for the 4PSK case is

$$G = \begin{vmatrix} 0 & 2 \\ 0 & 1 \\ 2 & 0 \\ 1 & 0 \end{vmatrix}$$

where the elements are taken from the MPSK constellation. Each **G** matrix has the dimensions of $(I + S)\, X\, n$, where i= log_2M represents the number of information bits transmitted, *s* represents the number of shift registers in the encoder, and *n* represents the number of transmit antennas. The elements of this matrix define the coefficient pairs described earlier in the encoder structure. The matrix for any number of states (4, 8, 16, 32), for a two-transmit antenna space-time code is

$$
G = \begin{vmatrix} a_0^1 & a_0^2 \\ b_0^1 & b_0^2 \\ a_1^1 & a_1^2 \\ b_1^1 & b_1^2 \\ a_2^1 & a_2^2 \\ b_2^1 & b_2^2 \\ \vdots & \vdots \\ a_{v_1}^1 & a_{v_1}^2 \\ b_{v_2}^1 & b_{v_2}^2 \end{vmatrix}
$$

The codes presented here provide the best tradeoff between data rate, diversity advantage, and trellis complexity.

	a_0^1, a_0^2	a_1^1, a_1^2	b_0^1, b_0^2	b_1^1, b_1^2	Det	Tr	Rank
Code A	(0,2)	(2,1)	(0,1)	(1,0)	4.0	4.0	2
Code B	(0,2)	(1,2)	(2,3)	(2,0)	4.0	10.0	2
Code C	(0,2)	(2,2)	(2,3)	(0,2)	0	10.0	1

FROM [2],© 2001 IEEE

Appendix B

Different properties of STTC

Table 5.1 Upper Bound of the Rank Values for STTC

	$M_T = 2$	$M_T = 3$	$M_T = 4$	$M_T = 5$	$M_T \geq 6$
$v = 2$	2	2	2	2	2
$v = 3$	2	2	2	2	2
$v = 4$	2	3	3	3	3
$v = 5$	2	3	3	3	3
$v = 6$	2	3	4	4	4

From: [2]. © 2001 IEEE.

Table 5.3 Generator Sequences for Varying Number of Transmit Antennas Based on Rank and Determination Criteria

Modulation	*v*	*Number of Transmit Antennas*	*Generator Sequences*	*Rank (r)*	*det*	*tr*
QPSK	2	2	g^1 [(0, 2), (2, 0)] g^2 [(0, 1), (1, 0)]	2	4.0	
QPSK	4	2	g^1 [(0, 2), (2, 0), (0, 2)] g^2 [(0, 1), (1, 2), (2, 0)]	2	12.0	
QPSK	4	3	g^1 [(0, 0, 2), (0, 1, 2), (2, 3, 1)] g^2 [(2, 0, 0), (1, 2, 0), (2, 3, 3)]	3	32	16
8PSK	3	2	g^1 [(0, 4), (4, 0)] g^2 [(0, 2), (2, 0)] g^3 [(0, 1), (5, 0)]	2	2	4
8PSK	4	2	g^1 [(0, 4), (4, 4)] g^2 [(0, 2), (2, 2)] g^3 [(0, 1), (5, 1), (1, 5)]	2	3.515	6

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Table 5.4 Generator Sequences for Varying Number of Transmit Antennas Based on Trace Criterion

Modulation	*v*	*Number of Transmit Antennas*	*Generator Sequences*	*Rank (r)*	*det*	*tr*
QPSK	2	2	g^1 [(0, 2), (1, 2)] g^2 [(2, 3), (2, 0)]	2	4.0	10.0
QPSK	4	2	g^1 [(1, 2), (1, 3), (3, 2)] g^2 [(2, 0), (2, 2), (2, 0)]	2	8.0	16.0
QPSK	2	4	g^1 [(0, 2, 2, 0), (1, 2, 3, 2)] g^2 [(2, 3, 3, 2), (2, 0, 2, 1)]	2	—	20.0
8PSK	4	2	g^1 [(2, 4), (3, 7)] g^2 [(4, 0), (6, 6)] g^3 [(7, 2), (0, 7), (4, 4)]	2	0.686	8.0
8PSK	4	4	g^1 [(2, 4, 2, 2), (3, 7, 2, 4)] g^2 [(4, 0, 4, 4), (6, 6, 4, 0)] g^3 [(7, 2, 2, 0), (0, 7, 6, 3), (4, 4, 0, 2)]	2	—	20.0

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Example1

An example that shows the STTC encoding for 4 PSK with 4 states code and with two transmit antennas.

Let us take the randomly generated bits be :

Randomly generated binary data: 0111100001

Corresponding symbols for 4 PSK, x=1 3 2 0 1

Number of transmit antennas : 2

Generator matrix: $G=\begin{bmatrix} 2 & 0 \\ 1 & 0 \\ 2 & 0 \\ 0 & 2 \\ 0 & 1 \end{bmatrix}$

Here in the above generator matrix the first column in the generator matrix is the data for the first transmit antenna and the second column is for the second transmit antenna.

If we take C1 and C2 to be the output symbols that are transmitted through the first antenna and second antenna respectively than

C1 = [0 1 3 2 0]

C2 = [1 3 2 0 1]

An actual encoded sequence can be represented as a path on this trellis diagram. Where x is the input input symbol and c1 and c2 are the symbols transmitted from transmit antenna 1 and transmit antenna 2 respectively. Here, the initial state is taken to be state 0, as is the normal practice. The first symbol is 1. Referring to the figure below we see that for present state 0 and input symbol , the next state is 1 with an output of c1: 1, c2:0, the second symbol is 3.

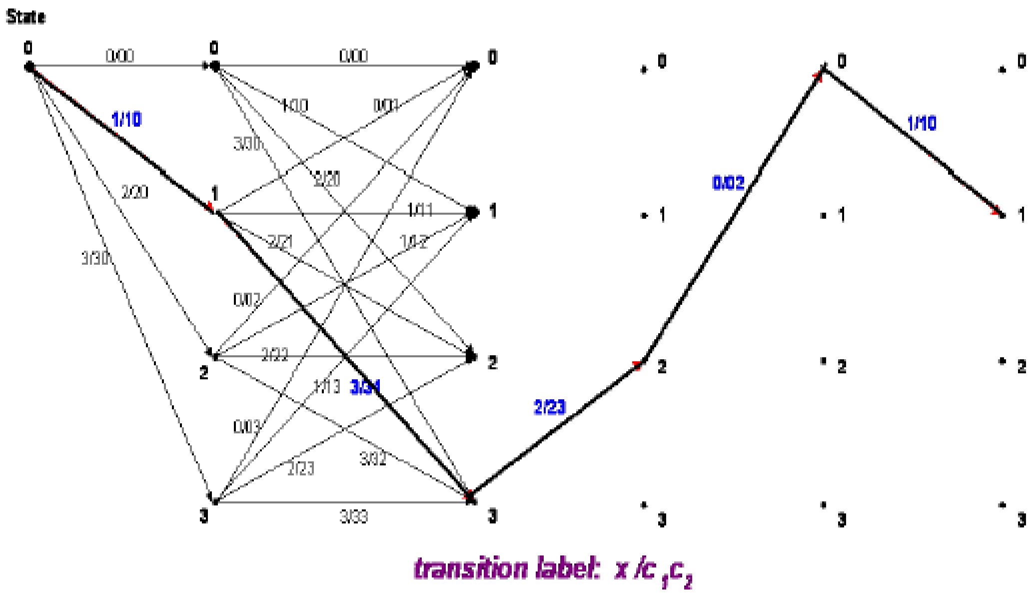

Figure: Trellis Diagram For Example1

Example 2:

<u>Viterbi Algorithm</u>

It is the maximum likelihood decoding and returns that x for which in p(y/x) is maximized.

we consider the decoding of a signal to obtain the maximum a posterior (MAP) estimate of the underlying state sequence. The MAP state sequence ***s****MAP* of a model *M* given an observation signal sequence $\boldsymbol{X}$=[$\boldsymbol{x}$(0),….., $\boldsymbol{x}$(T–1)] is obtained.

The MAP state sequence estimate is used in such applications as the calculation of a similarity score between a signal sequence $\boldsymbol{X}$ and an HMM *M*, segmentation of a non-stationary signal into a number of distinct quasi-stationary segments, and implementation of state-based Wiener filters for restoration of noisy signals

Table for the viterbi decoder

State	Binary description
a	00
b	10

c	01
d	11

Here a b c and d describes the state condition of the veterbi algorithm.

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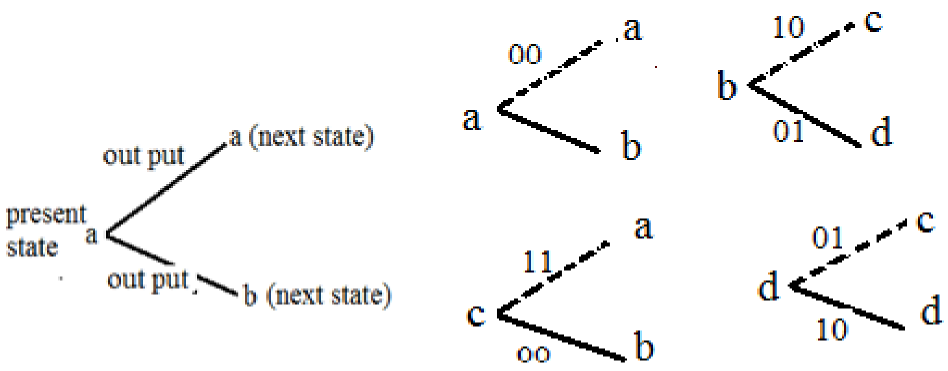
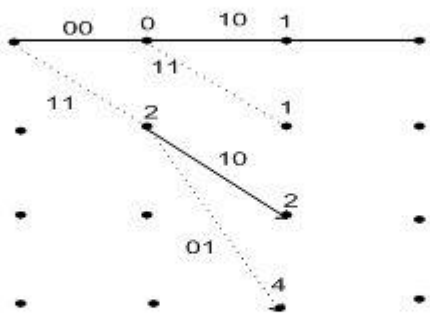


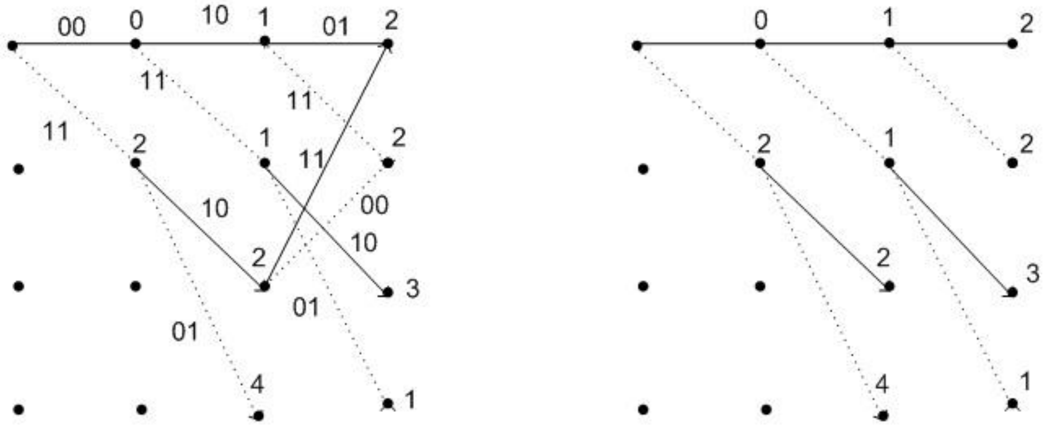
Here in the above figure state a ,b ,c, d are the present state and the alphaets in the arrow head represents the state that can be moved from the present stste to the next state. The numbers above the line (i.e 00, 01,10, 11) are the outputs while going from the present state to the next state the doted line represents the next state and out put when the input is 0 (zero) and the solid line represents the next state and output when the input is 1.

The MAP state sequence estimate is used in such applications as the calculation of a similarity score between a signal sequence ***X*** and an HMM *M*, segmentation of a non stationary signal into a number of distinct quasi-stationary segments, and implementation of state-based Wiener filters for restoration of noisy signals

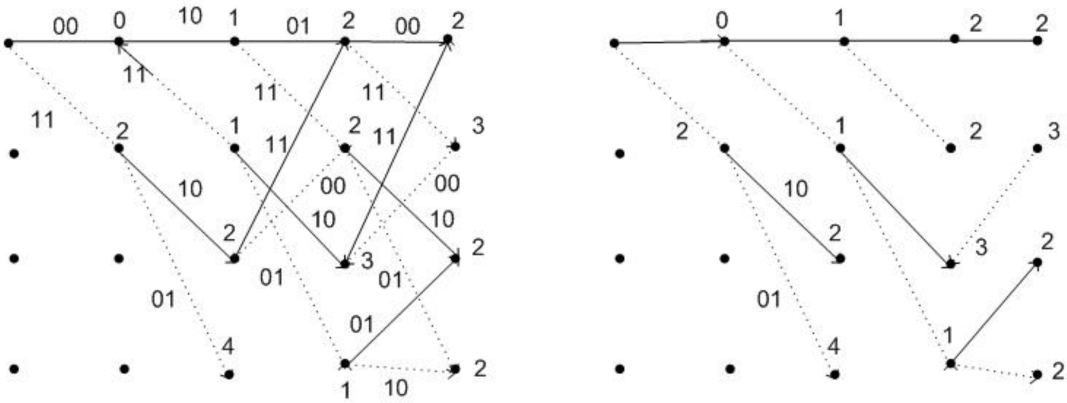
Here the transmitted signal is 000000. The received signal must be exactly the transmitted signal but by question here the received signal is 0010010000. The received signal has errors in two places, there are two ones in place of zero due to errors.



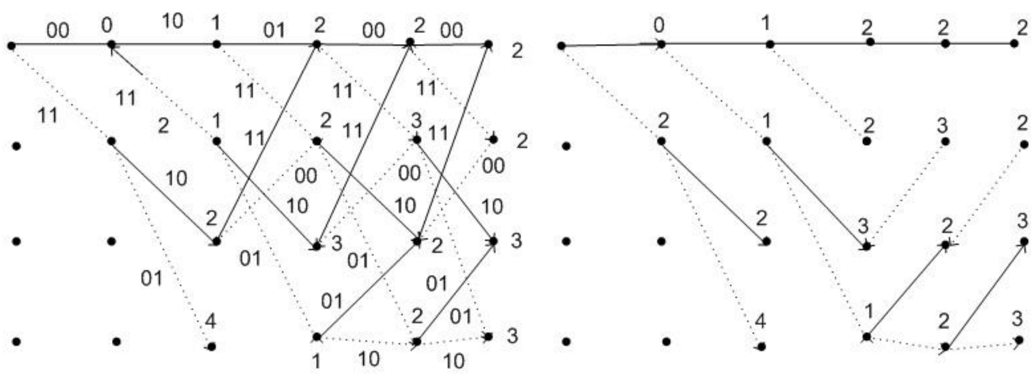
For j=3



For j=4



For j=5



In the above figures First column is for j=M and second column are survivors.

Finally we get the survivors of 2, 2, 3 and 3 at different at a, b, c and d respectively. Here we are neglecting the path that follow the maximum hamming distance if we go through the minimum path than the two errors that occurred in the above received sequence will be corrected.