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Simulations and Performance Analyses of Multi-user Alamouti's Space Time Block Coded MIMO CDMA Systems

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DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

Submitted for the award of Bachelor of Science in Electrical and Electronic Engineering

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Abstract

This thesis explores Code Division Multiple Access (CDMA) systems and conducts a comprehensive study of its fundamentals. CDMA has already made a firm position in the arena of fast growing 3G communications and vanquished by reigning over other multiple access technologies, for its use of spread-spectrum technique and provision of providing a robust transmission by combating various channel impairments. Further advanced studies have been done on space time block coded CDMA systems for multi-user which yields a new standard for transmission over Rayleigh fading channels using multiple transmit antennas. The combination of space time block code and CDMA system has the aptitude of increasing performance in cellular network. With a simplistic approach, the performance of this system is compared with the typical CDMA system which manifests that, using space time block code and multiple transmit antennas for multi-user CDMA system provide remarkable performance without any need of extra processing or sacrifice in bandwidth. Along with space-time block code, space-time trellis code is also analyzed and compared theoretically on the basis of MIMO implementation, with extended performance evaluation. For further performance analyses, diversity techniques have been manifested and this insight has been comprehended by mathematically manipulating Alamouti's transmit diversity scheme, which surely offers remarkable performance improvement, which, later, has been justified from the results obtained from simulations.

DECLARATION

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Above declarations are true. Understanding these, the thesis has been submitted for evaluation.

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Date, Signature(s) of Author(s)

The thesis is acceptable. It fulfils all criteria set by the department

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Contents

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n	Noise and interference
$n(t)$	Gaussian random function
t	Time
σ	Standard deviation
$p(n)$	Probability density function
σ^2	Variance
T_b	Bit time
T_s	Symbol time
E_b	Energy per bit
H_N	Hadamard matrix
τ	Time shift
B	Bandwidth
N	Noise power
P_r	Received signal power
$N_0/2$	Noise power spectral density
E_s	Energy per symbol
Y_{nT}	Received signal
X_{nT}	Encoded codeword
H	Fading channel
V_{nT}	Receiver noise
S	Signal
ρ	Instantaneous received SNR
C	Capacity

$\boldsymbol{R}$	Received symbol
$\boldsymbol{k}$	Number of users
$\boldsymbol{c}$	Length of PN-sequence
$\boldsymbol{M_r}$	Receive antennas
$\boldsymbol{M_t}$	Transmit antennas
$\boldsymbol{K}$	Block of symbols
$\boldsymbol{h}$	Channel
$\boldsymbol{\alpha}$	Attenuation
$\boldsymbol{\theta}$	Phase of the channel

Acknowledgements

This thesis is a result of research of several months and this is by far the most significant scientific accomplishment in our life. It would be impossible without support and appreciation of our project supervisor, Mr. Rishad Ahmed Shafik and co-supervisor Mr. Md. Shahriar Rahman. We thank them for their generous support throughout the work.

To our parents

Chapter 1

Introduction and Literature Review

1.1 Introduction

At present, wireless communication is experiencing an explosive growth rate, compared to past decades. Quality of service is now one of the greatest concerns. The next generation wireless systems are supposed to meet the ever increasing demands, such as, high voice quality and bit rate, coverage, bandwidth and power efficiency, less effect of channel impairments, ability to be deployed in diverse environments, and so on. Consequently, the remote units need to be small and lightweight to provide better service and work efficiently in any sort of environments [1]. At the same time the cost effectiveness along with quality of service should also be taken into account. To meet up all these ambitious objectives, Code Division Multiple Access (CDMA) can be regarded as a remarkable technology [6].

CDMA is a multiple access technique which unfolds transmission of multiple simultaneous users using same time- and frequency-slots. Distinction of users is done by using a unique code, named PN-sequence, which is further elaborately discussed in chapter 2. CDMA deploys spread-spectrum technique which makes it resistant to channel impairments and results in enhanced performance.

Among the channel impairments, noise and fading can be regarded as great challenges to the system designers to deal with. Due to these impairments, sometimes severe performance degradation occurs. Since these problems can not be removed fully from the channel, hence protective measures should be taken. It is possible to mitigate the effects of these impairments by using proper detection techniques. Certain algorithms are used for detection of single and multiple users. But still multipath fading is regarded as a great obstacle to smooth transmission systems. CDMA is a well known technology to combat multipath fading.

An effective approach to increase the performance of the CDMA systems is the use of diversity techniques. In most scattering environments, antenna diversity is a practical, effective and, hence, a widely applied technique for reducing the effect of multipath fading [1]. The number of antennas at the transmitter or the receiver will decide the type of the system that will finally be implemented. Space-time processing will either be receive diversity or transmit diversity. In Receive Diversity the Channel can be estimated and there can be multiple antennas at the receiver. The major problem with using the receive diversity approach is the cost, size, and power of the remote units. The use of multiple antennas and radio frequency (RF) chains (or selection and switching circuits) makes the remote units larger and more expensive. As a result, diversity techniques have almost exclusively been applied to base stations to improve their reception quality [3].

Diversity techniques utilize the prospects of certain codes which are used to ensure the enhanced performance of the systems. Space Time Block Code (STBC) and Space Time Trellis Code (STTC) are well known among these codes. Diversity techniques using STBC for multi-user CDMA systems offer a remarkable performance improvement over conventional CDMA systems. To be more precise, Alamouti's transmit diversity scheme is simply an outstanding means of improving the system over Rayleigh fading channel condition. Along with manipulation of STBC using Monte Carlo simulations, theoretical study of STTC has also been done, including comprehensive comparison of performance.

Numerous researches are going on based on Alamouti's simple transmit diversity scheme which also includes certain channel assumptions. Sometimes it is assumed that the channel is perfectly known at the receiver. It is known as Non-blind approach, which may not always be regarded as practical because for real time scenario, perfect channel estimation can not be possible due to effects of channel impairments. This leads to another technique known as Blind approach. Both these approaches have been analyzed here along with their performance analyses, which mean nothing but the extraction of Signal to Noise Ratio (SNR) versus Bit Error Rate (BER) figures, from the simulations.

The outline of this thesis is as follows. In Chapter 2, we briefly introduce the CDMA system and its fundamentals with necessary figures and analyses, while Chapter 3 of this thesis presents Multiple Input Multiple Output (MIMO) systems and its implementation in perspective of 3G communication techniques. STBC and STTC are then introduced and diversity techniques using STBC has been discussed considering Alamouti's simple transmit diversity scheme with sufficient mathematical manipulation. Alamouti's scheme with both two transmit antennas, one receive antenna and two transmit antennas, two receive antennas have been implemented here and a study on their capacities is also discussed. In Chapter 4, MIMO CDMA systems with STBC have been discussed considering both Blind and Non-blind conditions. Chapter 5 includes analyses of all necessary performance curves obtained from Monte Carlo simulations and finally the thesis in concluded by the conclusions and future plans discussed in Chapter 6.

1.2 Literature Review

This section includes the reviews of certain literatures which rendered much useful knowledge from where many innovative and intuitive ideas were formed, which can be observed throughout this thesis.

A Simple Transmit Diversity Technique for Wireless Communications

Author: Siavash M. Alamouti, *Senior Member, IEEE*

Abstract— This paper presents a simple two-branch transmit diversity scheme. Using two transmit antennas and one receive antenna the scheme provides the same diversity order as maximal-ratio receiver combining (MRRC) with one transmit antenna, and two receive antennas. It is also shown that the scheme may easily be generalized to two transmit antennas and M receive antennas to provide a diversity order of $2M$. The new scheme does not require any bandwidth expansion any feedback from the receiver to the transmitter and its computation complexity is similar to MRRC.

Space–Time Block Coding for Wireless Communications: Performance Results

Authors: Vahid Tarokh, *Member, IEEE*, Hamid Jafarkhani, *Member, IEEE*, and A. Robert Calderbank, *Fellow, IEEE*

Abstract— We document the performance of space–time block codes which provide a new paradigm for transmission over Rayleigh fading channels using multiple transmit antennas. Data is encoded using a space–time block code, and the encoded data is split into n streams which are simultaneously transmitted using n transmit antennas. The received signal at each receive antenna is a linear superposition of the n transmitted signals perturbed by noise. Maximum likelihood decoding is achieved in a simple way through decoupling of the signals transmitted from different antennas rather than joint detection. This uses the orthogonal structure of the space–time block code and gives a maximum likelihood decoding algorithm which is based only on linear processing at the receiver. We review the encoding and decoding algorithms for various codes and provide simulation results demonstrating their performance. It is shown that using multiple transmit antennas and space–time block coding provides remarkable performance at the expense of almost no extra processing.

Advantages of CDMA and Spread Spectrum Techniques over FDMA and TDMA in Cellular Mobile Radio Applications

Authors: Peter Jung, *Member, IEEE,* Paul Walter, *Senior Member, IEEE,* and Andreas Steil

Abstract— In this paper a unified theoretical method for the calculation of the radio capacity of multiple-access schemes such as FDMA (frequency-division multiple access), TDMA (time-division multiple access), CDMA (code-division multiple access) and SSMA (spread-spectrum multiple access) in noncellular and cellular mobile radio systems shall be presented for AWGN (additive white Gaussian noise) channels. The theoretical equivalence of all the considered multiple-access schemes is found.

However, in a fading multipath environment, which is typical for mobile radio applications, there are significant differences between these multiple-access schemes. These differences are discussed in an illustrative manner revealing several advantages of CDMA and SSMA over FDMA and TDMA. Furthermore, novel transmission and reception schemes called coherent multiple transmission (CMT) and coherent multiple reception (CMR) are briefly presented.

On the capacity of a cellular CDMA System

Authors: Klein S. Gilhousen, *Senior Member, IEEE,* Irwin M. Jacobs, *Fellow, IEEE,* Roberto Padovani, *Senior Member, IEEE,* Andrew J. Viterbi, *Fellow, IEEE,* Lindsay A. Weaver, Jr., and Charles E. Wheatley III, *Senior Member, IEEE*

Abstract— The use of spread spectrum or code division techniques for multiple access (CDMA) has long been debated. Certain advantages, such as multipath mitigation and interference suppression are generally accepted, but past comparisons of capacity with other multiple access techniques were not as favorable. This paper shows that, particularly for terrestrial cellular telephony, the interference suppression feature of CDMA can result in a many-fold increase in capacity over analog and even over competing digital techniques.

Blind Unique Identification of Alamouti Space-Time Coded Channel Via Signal Design and Transmission Technique

Authors: Lin Zhou, Jian-Kang Zhang and Kon Max Wong, *Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario Canada L8S 4K1*

Abstract— In this paper, we present a simple signal design and transmission technique to uniquely and blindly identify Alamouti space-time coded channels under both noise-free and complex Gaussian noise environments in which p^{th}-order and q^{th}-order statistics (*p* and q are co-prime) of the received signals are available. A closed-form solution to determine the channel coefficients is obtained by exploiting specific properties of the Alamouti space-time code and the linear Diophantine equation theory. When only finite received data are given, we propose using the semi-definite relaxation algorithm to approximate maximum likelihood (ML) detection so that the joint estimation of the channel and symbols can be efficiently implemented. Simulation results show that our signal design and transmission method yields lower mean-square error in the estimation of the channel when compared to other existing methods and that the average symbol error rate approaches that of the coherent detector which needs perfect channel information at the receiver.

Performance of Alamouti Space-Time Code in Time-Varying Channels with Noisy Channel Estimates

Authors: Jittra Jootar, James R. Zeidler and John G. Proakis, *Department of Electrical & Computer Engineering, University of California, San Diego, La Jolla, CA 92093-0407*

Abstract— In this paper, we derive the theoretical performance of the Alamouti space-time code in time-varying Rayleigh fading channels with noisy channel estimates. The receiver algorithms presented in this paper are the maximum-likelihood (ML) symbol detector with the linear combining scheme, which was suggested by Alamouti [1], and the ML space-time decoder. The bit error probability for the linear combining scheme and the sequence error probability for the ML space-time decoder are presented as functions of the pilot filter coefficients, the multi-path power profile, the normalized Doppler frequency, the pilot SNR and the data SNR. We also compare the bit error performance of the linear combining scheme with the bit error performance of the system without transmit diversity. The results indicate that the Alamouti space-time code with the linear combining scheme is outperformed by the no transmit diversity system at high Doppler frequency or low pilot SNR.

Multi-User Detection for DS-CDMA Communications

Author: Shimon Moshavi, Bellcore

Abstract— Direct-sequence code-division multiple access (DS-CDMA) is a popular wireless technology. In DS-CDMA communications, all of the users' signals overlap in time and frequency and cause mutual interference. The conventional DS-CDMA detector follows a single-user detection strategy in which each user is detected separately without regard for the other users. a better strategy is multi-user detection, where information about multiple users is used to improve detection of each individual user. This article describes a number of important multi-user DS-CDMA detectors that have been proposed.

Capacity Limits of MIMO Channels

Authors: Andrea Goldsmith, *Senior Member, IEEE,* Syed Ali Jafar, *Student Member, IEEE,* Nihar Jindal, *Student Member, IEEE,* and Sriram Vishwanath, *Student Member, IEEE.*

Abstract— We provide an overview of the extensive recent results on the Shannon capacity of single-user and multiuser multiple-input multiple-output (MIMO) channels. Although enormous capacity gains have been predicted for such channels, these predictions are based on somewhat unrealistic assumptions about the underlying time-varying channel model and how well it can be tracked at the receiver, as well as at the transmitter. More realistic assumptions can dramatically impact the potential capacity gains of MIMO techniques. For time-varying MIMO channels there are multiple Shannon theoretic capacity definitions and, for each definition, different correlation models and channel information assumptions that we consider. We first provide a comprehensive summary of ergodic and capacity versus outage results for single-user MIMO channels. These results indicate that the capacity gain obtained from multiple antennas heavily depends on the available channel information at either the receiver or transmitter, the channel signal-to-noise ratio, and the correlation between the channel gains on each

antenna element.We then focus attention on the capacity region of the multiple-access channels (MACs) and the largest known achievable rate region for the broadcast channel. In contrast to single-user MIMO channels, capacity results for these multiuser MIMO channels are quite difficult to obtain, even for constant channels. We summarize results for the MIMO broadcast and MAC for channels that are either constant or fading with perfect instantaneous knowledge of the antenna gains at both transmitter(s) and receiver(s). We show that the capacity region of the MIMO multiple access and the largest known achievable rate region (called the dirty-paper region) for the MIMO broadcast channel are intimately related via a duality transformation. This transformation facilitates finding the transmission strategies that achieve a point on the boundary of the MIMO MAC capacity region in terms of the transmission strategies of the MIMO broadcast dirty-paper region and vice-versa. Finally, we discuss capacity results for multicell MIMO channels with base station cooperation. The base stations then act as a spatially diverse antenna array and transmission strategies that exploit this structure exhibit significant capacity gains. This section also provides a brief discussion of system level issues associated with MIMO cellular. Open problems in this field abound and are discussed throughout the paper.

From Theory to Practice: An Overview of MIMO Space–Time Coded Wireless Systems

Authors: David Gesbert, *Member, IEEE,* Mansoor Shafi, *Fellow, IEEE,* Da-shan Shiu, *Member, IEEE,* Peter J. Smith, *Member, IEEE,* and Ayman Naguib, *Senior Member, IEEE.*

Abstract— This paper presents an overview of recent progress in the area of multiple-input–multiple-output (MIMO) space–time coded wireless systems. After some background on the research leading to the discovery of the enormous potential of MIMO wireless links, we highlight the different classes of techniques and algorithms proposed which attempt to realize the various benefits of MIMO including spatial multiplexing and space–time coding schemes. These algorithms are often derived and analyzed under ideal independent fading conditions. We present the state of the art in channel modeling and measurements, leading to a better understanding of actual MIMO gains. Finally, the paper addresses current questions regarding the integration of MIMO links in practical wireless systems and standards.

Performance of Alamouti Transmit Diversity Over Time-Varying Rayleigh-Fading Channels

Authors: Antony Vielmon, Ye (Geoffrey) Li, and John R. Barry

Abstract— We analyze the impact of a time-varying Rayleigh fading channel on the performance of an Alamouti transmit-diversity scheme. We propose several optimal and suboptimal detection strategies for mitigating the effects of a time-varying channel, and derive expressions for their bit-error probability as a function of the channel correlation coefficient ρ. We find that the maximum-likelihood detector that optimally compensates for the time-varying channel is very tolerant to time-varying fading, attaining full diversity order even for the extreme case of $\rho = 0$. In contrast, although lower in complexity, the suboptimal schemes suffer a diversity penalty and are thus suitable only for slowly fading channels.

An Overview of MIMO Communications—A Key to Gigabit Wireless

Authors: Arogyaswami J. Paulraj, *Fellow, IEEE*, Dhananjay A. Gore, Rohit U. Nabar, *Member, IEEE*, and Helmut Bölcskei, *Senior Member, IEEE*

Abstract— High data rate wireless communications, nearing 1-Gb/s transmission rates, is of interest in emerging wireless local area networks and home audio/visual networks. Designing very high speed wireless links that offer good quality-of-service and range capability in non-line-of-sight (NLOS) environments constitutes a significant research and engineering challenge. Ignoring fading in NLOS environments, we can, in principle, meet the 1-Gb/s data rate requirement with a single-transmit single-receive antenna wireless system if the product of bandwidth (measured in hertz) and spectral efficiency

(measured in bits per second per hertz) is equal to 109. As we shall outline in this paper, a variety of cost, technology and regulatory constraints make such a brute force solution unattractive if not impossible. The use of multiple antennas at transmitter and receiver, popularly known as multiple-input multiple-output (MIMO) wireless is an emerging cost-effective technology that offers substantial leverages in making 1-Gb/s wireless links a reality. This paper provides an overview of MIMO wireless technology covering channel models, performance limits, coding, and transceiver design.

From Theory to Practice: An Overview of MIMO Space–Time Coded Wireless Systems

Authors: David Gesbert*, Member, IEEE*, Mansoor Shafi*, Fellow, IEEE*, Da-shan Shiu*, Member, IEEE*, Peter J. Smith*, Member, IEEE*, and Ayman Naguib*, Senior Member, IEEE*

Abstract— This paper presents an overview of recent progress in the area of multiple-input–multiple-output (MIMO) space–time coded wireless systems. After some background on the research leading to the discovery of the enormous potential of MIMO wireless links, we highlight the different classes of techniques and algorithms proposed which attempt to realize the various benefits of MIMO including spatial multiplexing and space–time coding schemes. These algorithms are often derived and analyzed under ideal independent fading conditions. We present the state of the art in channel modeling and measurements, leading to a better understanding of actual MIMO gains. Finally, the paper addresses current questions regarding the integration of MIMO links in practical wireless systems and standards.

Space-time Block Codes versus Space-time Trellis Codes

Authors: S. Sandhu, R. Heath and A. Paulraj

Abstract— Two outstanding examples of transmit diversity schemes for the multiple-antenna flat-fading channel are space-time block coding (STBC) and space-time trellis coding (STTC). In this paper we compare the performance of STBC and STTC in terms of frame error rate keeping the transmit power, spectral efficiency and number of trellis states fixed. We discover that a simple concatenation of space-time block codes with traditional AWGN (additive while Gaussian noise) trellis codes outperforms some of the best known space-time trellis codes at SNRs (signal to noise ratios) of interest. Our result holds for a small number of trellis states with one or two receive antennas, and is useful for the design and implementation of multiple-antenna wireless systems.

Chapter 2

CDMA Systems

2.1 Introduction to CDMA Systems

Code Division Multiple Access (CDMA) can be regarded as a military technology. It dates back to the World War II. CDMA was first used then during the war by English allies to foil German attempts at jamming transmissions. The allies decided to transmit over several frequencies, instead of one, which made it quite difficult for the Germans to pick up the complete signal [14].

At present, CDMA is paramount to the worldwide 3G cellular standards. It is a form of Direct Sequence Spread Spectrum (DSSS) communications that supports simultaneous digital transmission of several users' signals in multiple access environments. It provides a unique property of supporting multiplicity of users in the same radio channel with graceful degradation of performance due to multi-user interference. Hence any reduction in interference leads to explicit increase in capacity [6]. The most notable advantage of CDMA is its ability to combat multipath Fading.

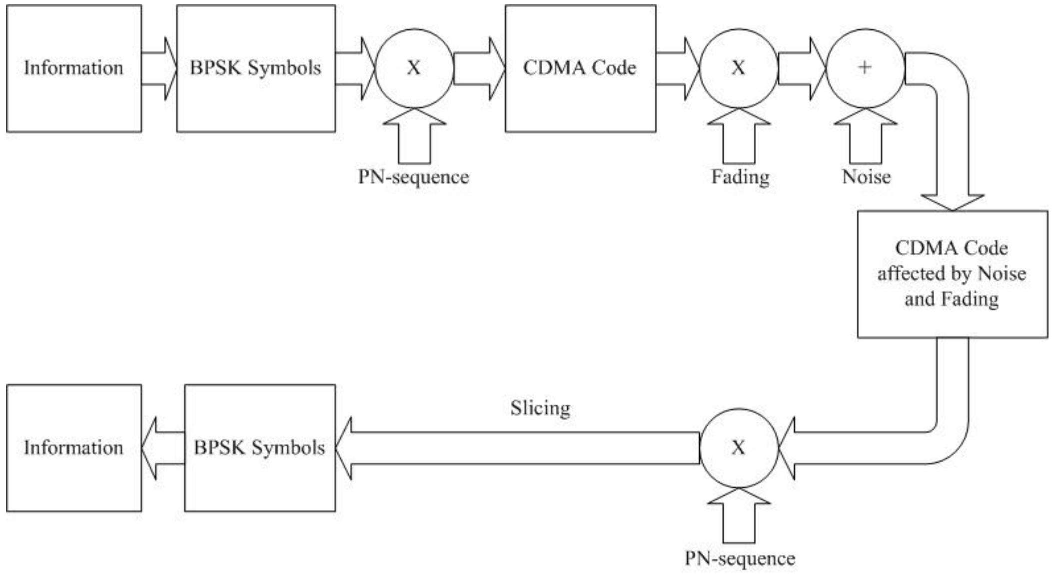

FIGURE 2.1: Basic block diagram of CDMA

CDMA is a technology that can implement a multiple access communication system which allows multiple users to transmit information over the same physical channel [11]. This system is designed to operate efficiently in an interference-limited environment. Not only this, CDMA has a very high spectral density and can accommodate more users per MHz of bandwidth than any other technology. Hence CDMA is proved quite attractive over other conventional multiple access techniques.

In a CDMA system, the information signal is first converted into Binary Phase Shift Keying (BPSK) form, and then multiplied by a code, generally known as PN-sequence, which is also in BPSK form. This multiplication results in CDMA code which is transmitted through the channel. At the receiver, this signal, perturbed by noise and multipath fading, is again multiplied by the corresponding PN-sequence in order to obtain the original signal. Since the effects of interferences can not be omitted, rather it is necessary to use proper detection techniques which may give an acceptable and satisfactory performance.

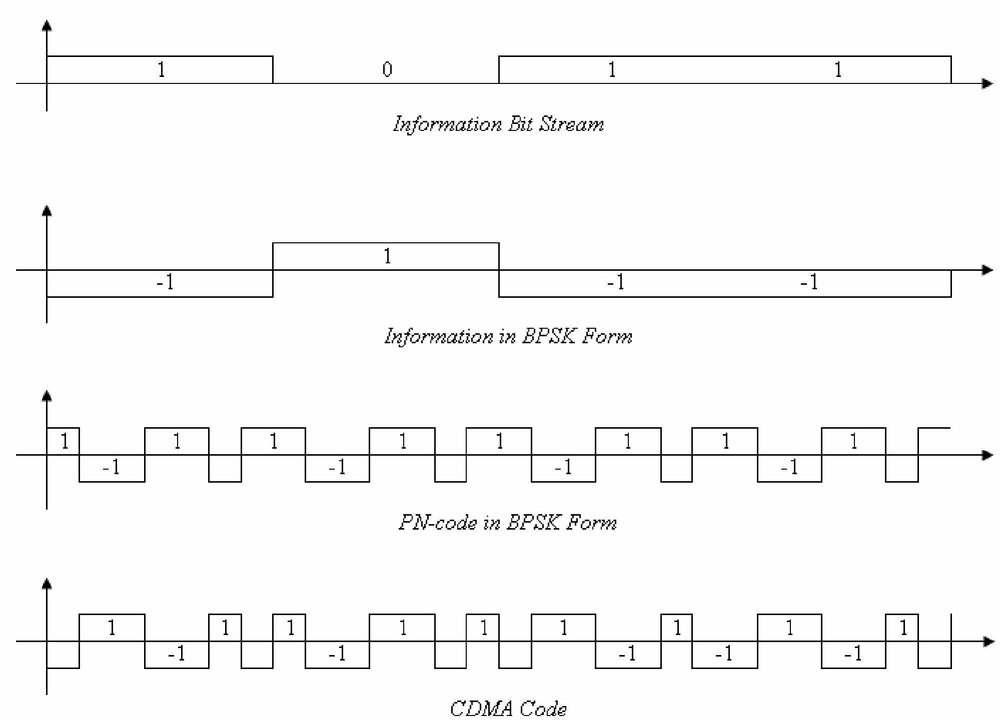

FIGURE 2.2: Generation of CDMA codes

2.2 Introduction to Spread Spectrum Technique

CDMA, that uses Spread Spectrum technique, is often known as Spread Spectrum Multiple Access (SSMA). The spread spectrum is a technique which increases signal bandwidth beyond the minimum necessary for data communication and is also independent of specific information rate [3]. Spreading is done by multiplying PN-sequence with information signal. This way the narrowband signal from a sender is converted into broadband signal. The energy needed to transmit the signal is the same but it is now spread over a large frequency range. Hence, at this stage, the power level is much lower than that of original band without losing data [12].

There are several forms of spread spectrum. Some of them are [3]

- Direct-sequence spread-spectrum (DS-SS)
- Multi-carrier spread-spectrum (MC-SS)
- Frequency hopping spread-spectrum (FH-SS)
- Time hopping spread-spectrum (TH-SS)

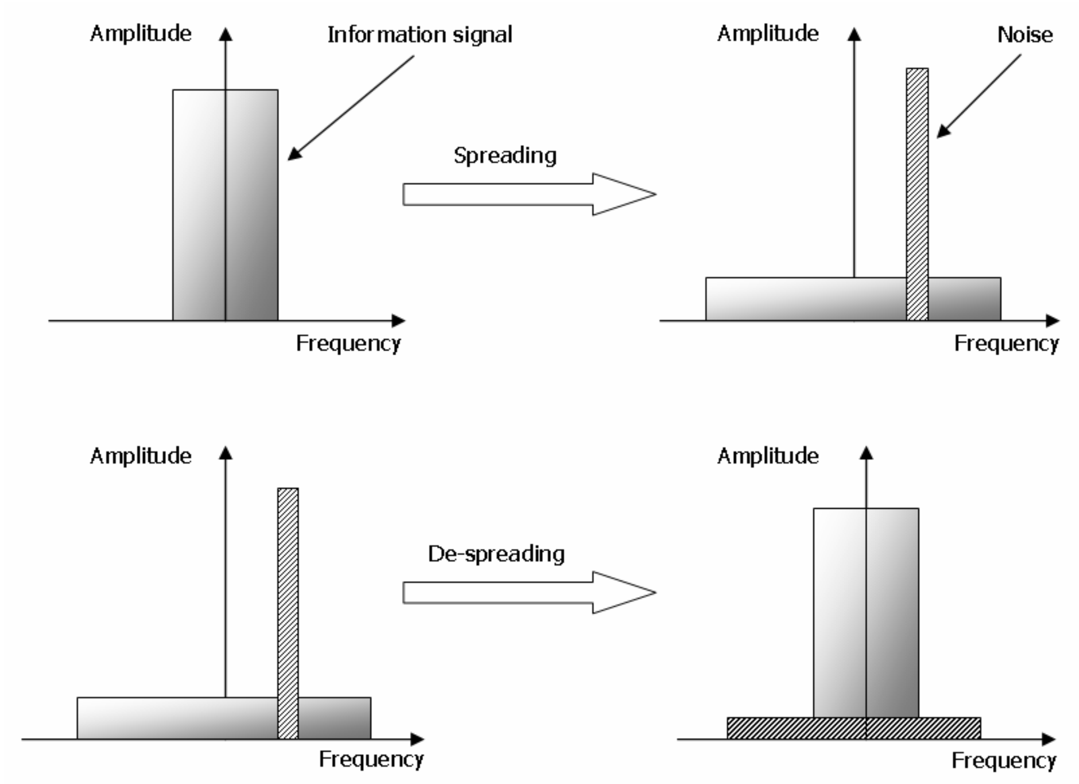

FIGURE 2.3: Spread Spectrum Technique

During transmission, the signal which was converted to broadband information signal previously, gets affected by interference, i.e., fading is multiplied and noise is added with it. The receiver receives this signal and despreads it, converting spread signal into narrowband signal, while spreading the narrowband noise and interference. Thus the receiver synchronizes to the code. A band pass filter is then used to retrieve the information signal only [3].

Spread spectrum techniques offer remarkable benefits including higher capacity and the ability to resist multipath propagation [15]. It also mitigates the performance degradation due to Intersymbol Interference (ISI) and narrowband interference [3].

2.3 Channel Impairments – a challenge to propagation

A channel which can be defined as a medium of transmitting signal, acts partly as a filter to attenuate the signal and distort its waveform. It may be either linear distortion or nonlinear distortion, but can be partly corrected by using proper complementary equalizer at the receiver [3].

The signal is not only distorted by the channel, but it is also contaminated along the path by undesirable signals. These unwanted errors of any communication system are caused by some impairments, like noise, fading, which exist in every communication system and result in performance degradation. Since it is not possible to remove these impairments fully, it is a great challenge, indeed, for the designers to mitigate their effects.

Among all the interferences that make error-free communication an impossible task, noise and fading come first.

2.3.1 Noise

Noise is any unwanted, random and unpredictable signal from environment which can be of even infinite amplitude. The presence of noise superimposed on a signal tends to obscure or mask the original signal [10]. It changes amplitude as well as the phase of transmitted signal. Noise can arise from both man made and natural sources, and also as well as external and internal causes. The man made noise includes such sources as spark-plug ignition noise, switching transients, and other radiating electromagnetic signals. Natural noise includes such elements as the atmosphere, electrical storm, the sun, and other galactic sources. With proper care and good engineering design, these sorts of external noise can be minimized or even eliminated. Internal noise results from thermal motion in electronic devices. Proper design can reduce the effect of internal noise but can never eliminate it. Noise cannot be fully removed from the retrieved signal; but it can be reduced enough to get the signal which is almost similar to original transmitted signal [3, 15].

Noise can be described as a zero-mean Gaussian random process. A Gaussian process *n(t)* is a random function whose value *n* at any arbitrary time *t* is statistically characterized by the Gaussian probability density function [15]

$$p(n) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{n}{\sigma}\right)^2\right] \tag{2.1}$$

where σ^2 is the variance of *n*.

Noise is one of the basic factors that set limits on the receiver's ability to make correct symbol decisions, and thereby limits the rate of communication [3].

2.3.2 Fading

Fading is a common phenomenon which deteriorates the original signal while transmitted through wireless channel. Both the amplitude and phase of the fading varies over time which shows its nature of being uncorrelated [3]. In mobile communication system, a signal can travel from transmitter to receiver over multiple reflective paths. This phenomenon is known as multipath propagation. Multipath propagation causes fluctuations in the received signal both in amplitude and phase. This is known as multipath fading [7]. Time varying multipath fading is regarded as great challenge to wireless transmission. In most scattering environments, antenna diversity is a practical, effective and, hence, a widely applied technique for reducing the effect of multipath fading [1].

Fading may be either large-scale or small-scale. Large-scale fading is affected by prominent terrain contours like hills, forests, large buildings, billboards, etc between the transmitter and receiver, where the transmitted signal gets reflected and signal comes to the receiver in multiple paths. The receiver is often represented as being "shadowed" by such prominences. The statistics of large-scale fading tend to compute the path loss as a function of distance [7]. Path loss means the power loss of signals while propagating through wireless channels.

Small-scale fading indicates notable changes in signal amplitude and phase which can be viewed as an outcome of small changes in the spatial separation between a transmitter and receiver [7, 8]. Small-scale fading can also be referred as Rayleigh fading, which is because if there is large number of multiple reflective paths and no line-of-sight (LOS) signal component, the envelope of the received signal can be statistically described by a Rayleigh pdf.

Fading may also be classified as Flat fading and Frequency Selective fading [3]. In general, for transmission of a narrowband signal, the fading across the entire signal bandwidth is highly correlated, i.e. the fading is roughly equal across the entire signal bandwidth. This is usually referred to as **flat fading**.

On the other hand, if the signal bandwidth is quite larger than the channel coherence bandwidth, then the channel amplitude values at frequencies separated by more than the coherence bandwidth are roughly independent. Thus, the channel amplitude varies widely across the signal bandwidth, which is called **frequency-selective fading**.

However, fading always exist in a communication system. Since it can not be fully removed, effective measures should rather be taken to mitigate the effects of fading, which for example refers to the use of Automatic Gain Control (AGC), a process that will also suppress slow variations of the original signal [3, 15].

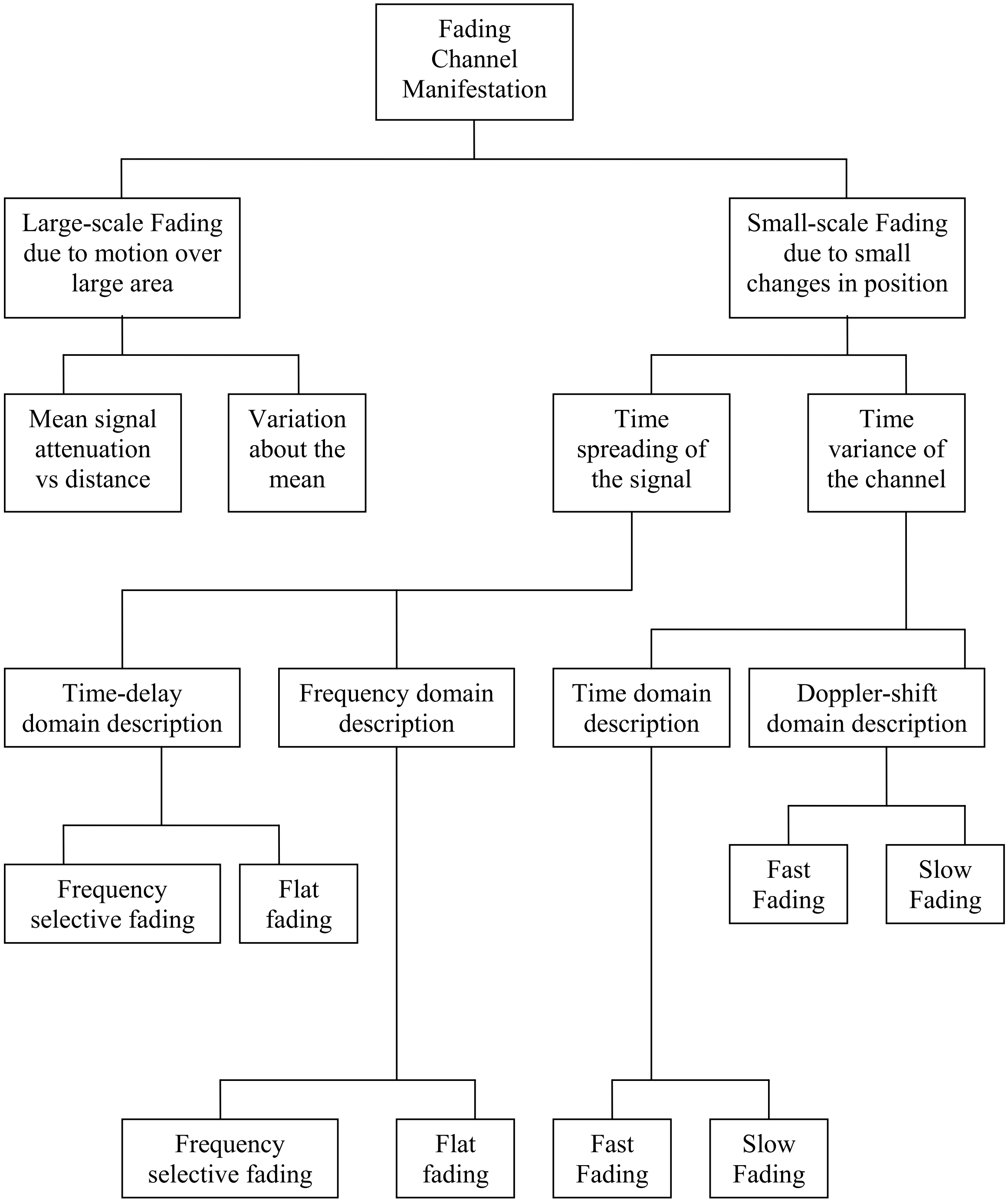

FIGURE 2.4: Fading channel Manifestations [7]

2.4 BPSK

In wireless networks, digital transmission cannot be used. The binary information bit-stream has to be translated into an analog signal first [12]. Binary Phase Shift Keying (BPSK) is one of the basic methods for this translation with a purpose of transmitting data efficiently. If the binary information bit is either 0 (zero) or 1, in BPSK it is converted to 1 or -1 respectively.

In CDMA systems, for transmission, both the information signal and PN-sequence are converted into BPSK form.

For example,

Signal:	1	0	0	1	1	1	0
BPSK:	-1	1	1	-1	-1	-1	1

Since BPSK has a single basis function and only a single bit is transmitted per symbol time T_s, so the bit time $T_b = T_s$. In BPSK, the transmitted signal constellation is given by $\pm\sqrt{E_b}$, where E_b is energy per bit [3].

For BPSK, if only a single bit is damaged while transmission, then the whole symbol is erroneous which is because of the fact that BPSK contains one bit in a symbol. So BPSK exhibits a degraded performance than 4-QAM or 16-QAM techniques. But to add a contradiction, BPSK is preferable over other conventional methods for its tendency of high bit rates at reduced bandwidth [3].

2.5 Spreading Codes

The CDMA systems have different link structures, like forward link and reverse link. Each link uses different spreading codes to channelize individual users. The purpose of using these spreading codes is to distinguish the users and also to spread the bandwidth to provide better performance. The forward link uses Walsh-Hadamard codes, while the reverse link uses the Pseudo-random Noise (PN) codes for channelization [16].

2.5.1 Walsh-Hadamard Codes

All CDMA users simultaneously occupy the same RF band which may lead to mutual interference on the forward link. To avoid this interference and separate the users, Walsh-Hadamard codes are used. Walsh-Hadamard codes are a set of 64 binary orthogonal sequences. These sequences are orthogonal to each other, and they are generated by using the Hadamard matrix [16]. Recursion is used for generating higher order matrices from lower order ones; that is,

$$H_{2N} = \begin{bmatrix} H_N & H_N \\ H_N & \overline{H}_N \end{bmatrix} \tag{2.2}$$

Where $\overline{H}_N$ contains the same but inverted elements of H_N.

2.5.2 PN-sequence

In CDMA systems, each user is distinguished by a seemingly random distinct code which is known as Pseudo-random Noise (PN) Sequence. Since Walsh-Hadamard codes can not be used on the reverse link, PN-sequences are used instead. PN-sequences are not random; they are deterministic, periodic sequences that are known to both the transmitter and receiver [9]. PN-sequences should have the nature of low cross-correlation for the sake of reducing the multi-user interference during demodulation [6]. It is also used to spread the bandwidth of the modulated signal to the larger transmission bandwidth, which refers to the outstanding advantage of CDMA. While the other communication schemes suffer from the limitation of frequency or time space, CDMA can easily overcome it since the code space is quite larger compared to frequency or time, leading to higher capacity compared to other conventional systems [3].

PN-sequences are characterized by the following properties [10, 17]:

- **Balance property**

The number of zeros and ones of a PN code are different only by one. For example, for a binary PN sequence of 000100110101111, it has 8 ones and 7 zeros. So the balance property is satisfied.

- **Run Property**

Run may be defined as a sequence of a signal type of binary digit(s). The length of the run is the number of digits in the run. Then, according to the run property, one-half of all run lengths are unity; one-quarter are of length 2, one-eighth are of length 3,. . . , a fraction $1/2^n$ of all runs are of length n for all finite n.

For example, for a sequence of 000100110101111, there are four zero runs. ½ are of length 1, and ¼ are of length 2. The same is true for the one runs. Hence, run property is checked.

- **Delay and Add property**

If the sequence is shifted, the relative frequencies of agreements and disagreements of the resulting sequence with the original sequence are each ½.

The PN-sequences can further be analyzed by contemporary study of *m*-sequences and Gold sequences.

2.5.2.1 *m*-sequences

It is the most popular set of codes with a periodicity of $n = 2^m - 1$ which can be readily generated by an *m*-stage shift register with linear feedback [6] as shown in Figure 2.5.

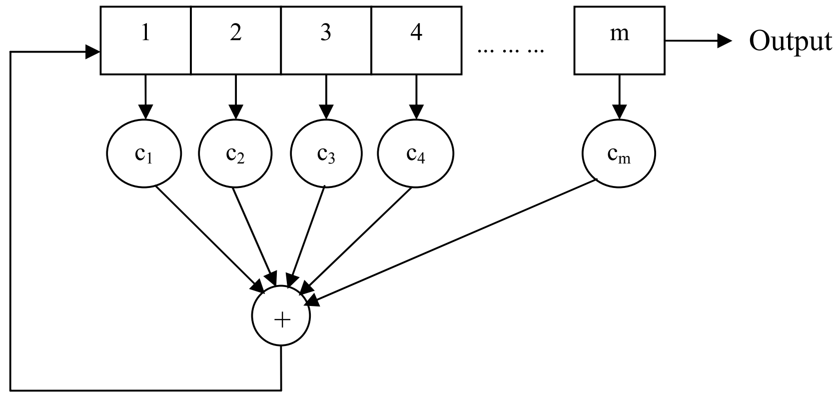

FIGURE 2.5: *m*-stage shift register with linear feedback

The cross-correlations of *m*-sequences are so high that sometimes it can not be regarded as useful in CDMA. Hence another set of spreading codes, which exhibits fairly low cross- correlation are the Gold sequence.

2.5.2.2 Gold Sequences

The Gold sequences were invented in 1967 at the Magnavox Corporation especially for multiple-access applications of spread spectrum [17].

Gold sequence with a period of $n = 2^m - 1$ are derived from a pair of *m*-sequences having the same period. Out of the total number of possible *m*-sequences, that have a periodicity or length of *n*, a pair of *m*-sequences exist, whose cross-correlation equals to either -1, *-t(m)* or [*t(m)-2*], where

$$t(m) = \begin{cases} 2^{(m+1)/2} + 1 & odd\ \ m \\ 2^{(m+2)/2} + 1 & even\ \ m \end{cases} \tag{2.3}$$

Gold sequences can be regarded as quite handy because of the fact that if two distinct *m*-sequences with time shifts τ_1 and τ_2 are modulo-2 added together, the resulting sequence is unique for every unique value of τ_1 or τ_2. Here, the modulo-2 addition stands for the exclusive OR (XOR) operation of the sequences. Thus, a very large number of unique Gold sequences can be generated, which allows for a large number of users in a multi-user system [3, 6].

m	**Number of *m*-sequences**	**Peak Cross-Correlation**		**Number of Gold Sequences**	**Peak Cross-Correlation**
3	2	5		$2^m + 1 = 9$	5
4	2	9		$2^m + 1 = 17$	9
5	6	11		$2^m + 1 = 33$	9
6	6	23		$2^m + 1 = 65$	17
7	18	41		$2^m + 1 = 129$	17
8	16	95		$2^m + 1 = 257$	33

TABLE 2.1: Properties of *m*- and Gold-Sequences [6]

Table 2.1 compares the total number of Gold sequences for m = 3, 4, 5, 6, 7, and 8, and their corresponding peak cross-correlation with the same parameters of *m*-sequences. It is clear from Table 2.1 that the Gold-sequences exhibit equal or lower peak cross-correlation between different sequences of the set, compared to *m*-sequences for all m. There are also more Gold sequences than *m*-sequences for all values of m. Thus, Gold sequences are always preferred to *m*-sequences in CDMA applications, despite having a poor autocorrelation peak, which may be considered as a disadvantage [6].

2.6 SNR

SNR stands for Signal to Noise Ratio. It is the ratio of signal power to the noise power and can be expressed as follows

$$SNR = 10 log_{10}\left(\frac{Signal\ Power}{Noise\ Power}\right) \tag{2.4}$$

Noise power is evaluated by the bandwidth of the transmitted signal and noise spectral properties. If the bandwidth of the complex envelope of the transmitted signal is B, then the bandwidth of the transmitted signal is $2B$. Since the noise is Gaussian distributed, having uniform power spectral density $N_0/2$, the total noise power within the bandwidth of the transmitted signal is [3]

$$N = \frac{N_0}{2} \times 2B = N_0 B \tag{2.5}$$

So the received SNR is given by

$$SNR = \frac{P_r}{N_0 B} \tag{2.6}$$

Here P_r is the received signal power.

There are modulation schemes which uses more than one bit per symbol. Hence the signal power can be expressed as either signal to noise ratio per symbol, E_s/N_0 or signal to noise ratio per bit, E_b/N_0. So SNR can be expressed as

$$SNR = \frac{P_r}{N_0 B} = \frac{E_s}{N_0 B T_s} = \frac{E_b}{N_0 B T_b} \tag{2.7}$$

Here T_s, T_b are symbol period and bit period respectively.

The conventional modulation schemes like BPSK, QPSK and 16-QAM use one, two and four bits per symbol, respectively.

SNR is an important criterion for a communication system. For a system, it is desired that the value of SNR should be high. But it should be remembered by a good designer that cost will be a vital factor while increasing SNR. So, optimum value of signal power should be chosen.

2.7 Bit Error Rate (BER)

BER is the measure of erroneous bits in received signal compared to the original information signal. It is the ratio between incorrect and total transferred information bits.

It can be expressed as follows

$$BER = \frac{Sum\ of\ Errors}{Length\ of\ Bit\ Stream} \tag{2.8}$$

In a communication system, all transmitted bits are not received in their exact shapes at the reception side. It happens due to the interferences of the channel, like noise, fading, path loss, shadowing, etc. After retrieving the main signal from the received signal, it is compared bitwise with the original information signal. If any single bit does not match, it means that the retrieved bit is erroneous. To calculate BER, the errors are accumulated altogether and then divided by the length of the information bit stream.

The higher the BER, the more erroneous the system is. So, it is desired that BER should be less for any communication system.

2.8 Detection Techniques in CDMA Systems

In CDMA systems, the signal received at the receiver is multiplied by the PN-sequences to retrieve the original information signal. For the ideal scenario, with perfect channel condition, this endeavor would have given the exact information signal, hence no error would occur. But practically it is not possible due to the effect of interferences, like noise, fading and other channel impairments. So some detection techniques must have to be applied in order to obtain the transmitted signal at satisfactory level. The detection technique varies for different systems. To provide a system with acceptable performance, detection techniques must be chosen carefully considering the system conditions and all necessary parameters with sufficient effort to mitigate the channel impairments.

2.8.1 Detection of Single user CDMA Systems

For the detection of a single user CDMA system, MLSE algorithm is used, where MLSE stands for Maximum Likelihood Sequence Estimation. The principle of MLSE algorithm is that the detector, which yields the most likely transmitted sequence, chooses that sequence to maximize the probability that the sequence was transmitted, given that a signal is received where the signal extends over the whole information signal. An assumption is also made that all possible transmitted sequences are equally probable [18].

For example, at the receiver, the signal is first divided into sequences of, say, 7 bits. Then if there are four 1's and three -1's in that sequence of 7 bits, MLSE algorithm chooses 1 from that sequence. All the bits, obtained by applying MLSE, are accumulated and thus the transmitted signal is recovered.

One limitation of MLSE is that the detector requires knowledge of received amplitude and phases which are rather estimated, causing this detection an impractical one. Moreover the cost of this detector is also very high. Despite these, MLSE provides remarkable performance and capacity gain [3, 18].

2.8.2 Detection of Multi-user CDMA Systems

For multi-user CDMA systems, interference gets upper hand causing BER higher than that of the single user. When CDMA system is implemented for multiple users, interference occurs between two users. For multi-user systems, PN-sequence used for each user is orthogonal with any other user. Not only this, it is also needed to form a detection technique which offer substantial performance under any condition.

Along with the prominence of lucrative potential benefit, the multi-user detectors are very attractive means of improving the detection process with enhanced capacity and a quality system. These multi-user detectors efficiently utilizes the uplink (mobile station to base station) spectrum which allows the mobiles to operate at low processing gain, saving a great chunk of bandwidth which can later be used to improve downlink (base station to mobile station) capacity. The multi-user detectors also utilize the power very efficiently causing reduction in required transmitted power of the mobiles [18].

A very eminent multi-user detection technique is Decorrelating Detector. It does not require estimation of the received amplitude, hence offers substantial capacity improvement over other conventional detectors.

There are also some other multi-user detectors which are used under certain conditions [18]

- Minimum Mean-Squared Error (MMSE) Detector
- Polynomial Expansion (PE) Detector
- Zero-Forcing Decision-Feedback (ZF-DF) Detector

There is limitation of multi-user detectors, as well. It is not practical to apply these detectors to the mobiles due to the issues of cost, size and weight. So, it is mainly used at the base stations. However improvement of uplink over that of downlink does not improve the overall system capacity [18]. Despite these limitations, the multi-user detectors are quite attractive and provide remarkable performance under many severe conditions.

2.9 Advantages of CDMA Systems

Being a paramount to the 3G wireless communication, CDMA offers many striking advantages over other conventional multiple access techniques, which are as follows [3, 10, 15, 19]:

- **Privacy**

In CDMA system, each user is distinguished by an authorized and distinct code which is only known to that particular user. Since the distribution of these codes is fully confidential, no unauthorized users can intercept the transmission, which ensures the complete privacy of an authorized user.

- **Capacity**

The capacity of CDMA systems is undoubtedly above margin compared to other conventional multiple access techniques, like TDMA and FDMA. It is because there is hard binding of the use of time slots for TDMA or frequency slots for FDMA. Since CDMA is completely unbound to this limitation of time or frequency slots, it can serve several users at a same time using same frequency band. This leads to a quite remarkable increase in capacity compared to either TDMA or FDMA.

- **Fading channels**

If any particular portion of the frequency spectrum is affected by fading, then signals in that range get attenuated. An FDMA user, if unfortunate enough, may experience severe performance degradation if assigned to that frequency range. But since many users share a same frequency band in CDMA, so the degradation is also shared gracefully among all the users.

- **Hand-off**

A handoff occurs in any cellular system when a call switches from one cell site to another due to traveling. In technologies other than CDMA, hand-off occurs when the network informs the mobile about the new channel to which it must switch. Then the mobile stops receiving signal from the old channel and commences to transmit and receive in the new channel. This is known as hard **hand-off**. But in CDMA, hand-off is taken place by only changing the PN-sequence that the user was allocated to. Therefore this arrangement puts the mobile to have almost complete control of the hand-off process. Thus CDMA, known to have **soft hand-off**, rarely experiences drop calls due to failed hand-off.

- **Jam resistance**

CDMA is considered to be resistant to jamming because of the fact that it has frequency band which is much larger than the data bandwidth. Use of the spread-spectrum technique makes CDMA uniquely compatible to fight jamming and multipath fading.

- **Flexibility**

Unlike TDMA, CDMA does not need any precise time co-ordination among various simultaneous transmitters. This has made CDMA a very flexible system indeed.

- **Frequency reuse**

In multi-cell CDMA systems, orthogonal time and frequency slots do not need to be compromised by neighboring cells, which leads to the fact that CDMA can reuse frequencies of every cell. For FDMA and TDMA, the reuse factor is usually 4-7. So, in CDMA, capacity is increased by 4-7 folds.

- **Sectorized antennas**

In CDMA, cells can use directional antennas to sectorize the cell which reduces the interference remarkably. FDMA and TDMA also use sectored antennas but just to decrease the reuse distance.

- **Voice activity**

It is quite a challenge to dynamically allocate time and frequency slots for TDMA and FDMA systems. This is because if the user does not have anything to send, the time or frequency slot allocated to them goes wasted. But in CDMA systems, if a user does not have anything to send, it rather creates less interference to other users of the system.

2.10 Disadvantages of CDMA System

Though CDMA provides many great benefits including better performance and strength to withstand multipath fading, it shows hindrance to some extent as well.

- **Near-Far problem**

CDMA does suffer from the traditional near-far problem. This problem is encountered due to the variation of distance between a user and the base station. Users near the base station can receive strong signal power while the users far from the base station experience weaker signal power. Power control may be a solution to this problem [15].

- **Channel pollution**

One of the big problems faced by CDMA systems is channel pollution. This problem occurs when a subscriber experience too many signals from too many base stations, with none dominant [19]. This problem occurs in a frequent manner in densely populated urban areas. It may also be originated by enormous multipath problems caused by tall buildings. Due to channel pollution, the audio quality degrades quite rapidly. By proper design this problem can be tamed as much as possible to an acceptable level.

Despite these drawbacks, CDMA is undoubtedly considered as the most prominent multiple access technique, due to its enhanced capacity and ability to fight channel impairments.

Chapter 3

MIMO System and Alamouti's Space Time Block Coding

3.1 MIMO System

Multiple Input Multiple Output (MIMO) is the most prominent technology on the list of recent technical advancement with a chance of resolving the bottleneck of traffic capacity in future wireless networks. MIMO refers to radio links with multiple antennas at the transmitter and the receiver. Given multiple antennas, the spatial dimension can be exploited to improve the performance of the wireless link. The performance is often measured as the average bit rate (bit/s) the wireless link can provide or as the average bit error rate (BER) which has the most importance depending on the application. Just a few years after MIMO invention, the technology seems capable to have an impact on large-scale standards-driven commercial wireless products and networks such as broadband wireless access systems, Wireless Local Area Networks (WLAN), third-generation (3G) networks and beyond. MIMO system, sometimes identified as a "volume-to-volume" wireless link, can be defined simply. Given an arbitrary wireless communication system, we consider a link for which the transmitting ends as well as the receiving end is equipped with multiple antenna elements. This setup is illustrated in Figure 3.1.

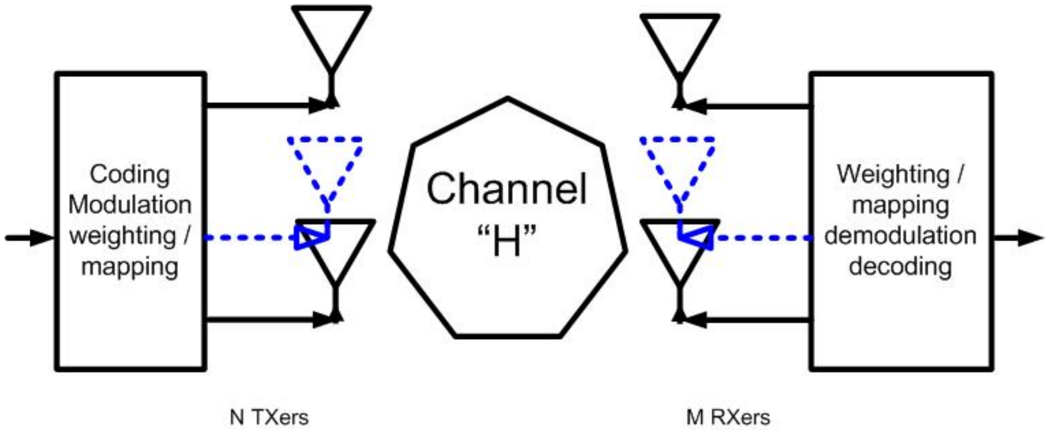

FIGURE 3.1: Transmitters, Channel and Receivers

Figure 3.1 shows a MIMO system with N number of Transmitter antenna and M number of Received antenna. In between the transmitter and the receiver, the channel H plays an important role for communication system. Due to the channel effect, performance of the communication is degraded because fading changes the properties of the transmitted signal. Various steps are required to overcome this effect and to improve the MIMO gains.

MIMO systems can be viewed as an extension of the so-called *smart antennas*, a popular technology using antenna arrays for improving wireless transmission dating back several decades. MIMO systems have the ability to turn multi path propagation, traditionally a stumbling-block of wireless transmission, into a benefit for the user. MIMO effectively takes advantage of random fading and when available, multi path delay spread for multiplying transfers rates [20]. The prospect of many orders of magnitude improvement in wireless communication performance at no cost of extra spectrum (only hardware and complexity are added) is largely responsible for the success of MIMO. This has prompted progress in areas as diverse as channel modeling, information theory and coding, signal processing, antenna design and multi antenna- aware cellular design, fixed or mobile.

3.1.1 MIMO in 3G Wireless Systems and Beyond

MIMO has little commercial implementation in cellular systems as yet and none is currently being deployed for 3G outside pure transmit diversity solutions for MISO. Current MIMO examples include the Lucent's BLAST chip and proprietary systems intended for specific markets such as Iospan Wireless' Airburst system for fixed wireless access . The earliest lab trials of MIMO have been demonstrated by Lucent Technologies several years ago. In the case of 3GPP, some MIMO results are presented here, based on link level simulations of a combination of V-Blast and spreading code reuse [20].

MIMO gains are sensitive to the channel conditions. The conditions in urban channels are known to be suitable for MIMO as it give rise to uncorrelated fading among antenna elements. Receiver complexity both in the base station and in the handsets increases for the gains of MIMO. Some other factors such as incorrect channel estimation, presence of correlation amongst antenna elements, higher Doppler frequencies, etc., will tend to pervert the ideal system performance. A brief discussion on some of the open issues and remaining impediment on the way to a full scale commercialization of MIMO systems is contained below.

3.1.1.1 Antenna Issues

For high spectral efficiencies of MIMO system, antenna element numbers and inter element spacing are key parameters. Hence, the antenna element numbers are limited to a modest number, say four, with an inter element spacing of around. The large spacing is because base stations are usually mounted on elevated positions where the presence of local scatterers to de correlate the fading cannot be always guaranteed. Using dual polarized antennas, four antennas can fit into a linear space of 1.5 m at spacing at 2 GHz [20]. For the terminal, spacing is sufficient to ensure a fair amount of uncorrelated fading because the terminal is present amongst local scatterers and quite often there is no direct path. The maximum number of antennas on the terminal is envisaged to be four, though a lower number says two, is an implementation option. Four dual polarized patch antennas can fit in a linear space of 7.5 cm [20]. These antennas can easily be embedded in casings of lap tops. However, for handsets, even the fitting of two elements may be problematic. This is because; the present trend in handset design is to imbed the antennas inside the case to improve look and appeal. This makes spacing requirements even more critical.

3.1.1.2 Receiver Complexity

MIMO channel estimation results in increased complexity because a full matrix needs to be tracked per path delay instead of a single coefficient. Practical systems typically limit the number of antenna elements to a few; this added complexity is not seen as a bottle neck. Extra RF, hardware, and sophisticated receiver separation algorithms bring extra complexity. To support non-MIMO mode a MIMO receiver should be dual mode. In the MIMO mode, it will have multiple RF chains (equal to the number of RX antennas), and additional base band operations i.e., the space–time combiners and detector to eliminate spatial interference. The additional requirements increase the complexity of a MIMO system to about twice that of a single antenna receiver [20]. There may also be additional processing needed due to dispersive channel conditions resulting from delay spread of the environment surrounding the MIMO receiver. The complexity impact of these is not yet fully accounted for. Homodyne detection may provide direct conversion to base band and, thus, avoid the need for SAW filters in the IF circuitry. This could reduce the RF complexity aspects of MIMO. Whilst the overall cost impact of MIMO complexity is not clear, one thing is clear, MIMO receivers are likely to cost more than conventional receivers and in the terminal the battery life may also be an issue.

3.1.1.3 System Integration and Signaling

With an existing non MIMO network the MIMO system needs to be integrated and be backward compatible. MIMO signaling imposes the support of special Radio Resource Control (RRC) messages. The terminals are supposed to know via broadcast down link signaling if a base station is MIMO capable. The base station also needs to know the mobile's capability, i.e., MIMO or non-MIMO. This capability could be declared during call set up. Handsets are also required to provide feedback to the base station on the channel quality so that MIMO transmission can be scheduled if the channel conditions are favorable. These downlink and uplink RRC messages are then mapped on to the layer 2 signaling messages [20].

3.1.1.4 MIMO Channel Model

MIMO system's performance is very much influenced by the underlying channel model especially the degree of correlation amongst the elements of the channel matrix, delay spread issues, etc. While the propagation models for conventional radio systems have been standardized in [20], there is no agreed MIMO channel model by the ITU as yet.

3.1.1.5 CSI at Transmitter

Channel Side Information (CSI) indicates the knowledge of the complete MIMO channel transfer function. The channel capacity is a function of the eigenmodes of the channel. The MIMO capacity will be benefited from the transmitter having knowledge of the channel state and may use water filling instead of equal power allocation or some partial form of feedback. Furthermore, knowing the channel correlation matrix, the transmitter could optimize channel coding, bit allocation per sub stream in addition to amplifier power management. Various power allocation algorithms are discussed in [20] which are optimum during different channel conditions. The feedback of accurate and timely CSI to the transmitter is another open issue [20].

When full CSI is available at the transmitter, it is possible to transmit data on the MIMO channel eigenmodes. A MIMO system with N transmit antennas and M receive antennas has $min(N,M)$ eigenmodes. The gain of these eigenmodes is proportional to the singular values of the MIMO channel, so they have disparate power. Adaptive modulation techniques to transmit over these eigenmodes, to maximize the bit rate or minimize the BER of the transmission can be used.

When CSI is not available at the transmitter, transmit diversity at a low implementation complexity can be achieved with orthogonal space-time block codes

(STBC). Multiple antennas at a portable device imply that the antenna spacing has to be small. This implies that the signals that enter the different antennas will be correlated and the performance will degrade.

3.2 Space Time Codes

Space time codes are very effective means of improving the performance of CDMA systems. Space Time Block Code and Space Time Trellis Code are of main concern here.

Space Time Block Code (STBC) represents a block of input symbols producing a matrix output whose columns represent time and rows represent antennas. Unlike traditional single antenna block codes for the AWGN channel, most Space Time Block Codes do not provide coding gain. Their key feature is the provision of full diversity with extremely low encoder/decoder complexity. In addition, they are optimal over all unitary codes with respect to the union bound on error probability. The best known codes for real constellations have been designed for a practical range of transmit antennas [13, 4].

Space-time trellis codes operate on one input symbol at a time producing a sequence of vector symbols whose length represents antennas. Like traditional TCM (Trellis Code Modulation) for single antenna channel, space time trellis codes provide coding gain. Since they also provide full diversity gain, their key advantage over space time block codes is the provision of coding gain. Their disadvantage is that they are extremely difficult to design and require a computationally intensive encoder and decoder.

Consider a system with M_r receive antennas and M_t>1 transmit antennas. The channel is flat fading and quasi static. It is unknown at the transmitter but is known at the receiver. At time nT, the channel output corresponding to the n^{th} input block spanning T symbol times is

$$Y_{nT} = HX_{nT} + V_{nT} \tag{3.1}$$

where the received signal $\boldsymbol{Y}_{nT}$ is $M_r \times T$, the fading channel $\boldsymbol{H}$ is $M_r \times M_t$, the encoded codeword $\boldsymbol{X}_{nT}$ is $M_t \times T$, and receiver noise $\boldsymbol{V}_{nT}$ is $M_r \times T$. When $\boldsymbol{H}$ is treated as a random variable, its entries are i.i.d. (independent, identically distributed) circular complex Gausssian random varables with variance 0.5 in each dimension, i.e. $h_{ij} \sim N_c$ (0,1). The entries of $\boldsymbol{V}_{nT}$ are i.i.d., $v_{nTi,j} \sim N_c(0,N_0)$ and independent over n. The average total power transmitted on M_t antennas can be defined as

$$P = \frac{E_s}{M_t N_0} \tag{3.2}$$

The codeword $\boldsymbol{X}_{nT}$ is encoded using either a concatenated STBC or an STTC. Both of these schemes are described in detail in the following two sections.

3.2.1 Space Time Block Codes

The input to the encoder is a stream of modulated symbols from a real or complex constellation. The encoder operates on a block of K symbols producing an $M_t \times T$ code word $\boldsymbol{X}_{nT}$ whose rows correspond to transmit antennas and columns correspond to symbol times. At the receiver, maximum likelihood decoding is simplified by the orthogonal structure imposed on the codeword.

The system used here is shown in Fig. 3.2, where an outer TCM encoder/decoder is concatenated with the SBC encoder / decoder.

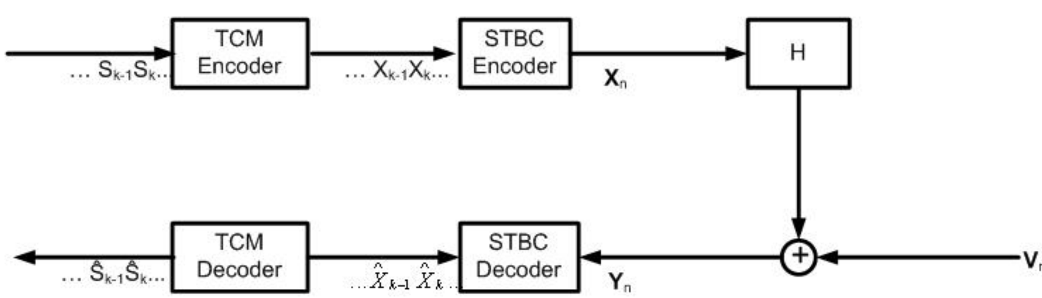

FIGURE 3.2: Concatenated Space Time Block Coding System

The coding gain of the end to end system is only due to the outer TCM encoder since we consider full rate STBCs. The STBC decoder outputs scalar symbols which are then processed by the TCM decoder using the conventional scalar Viterbi algorithm.

3.2.2 Space Time Trellis Codes

Space time trellis codes encode the input symbol stream into an output vector symbol stream. Unlike space time block codes, space time trellis codes map one input symbol at a time to M_t x 1 vector outputs. Since the encoder has memory, these vector code words are correlated in time. Decoding is via maximum likelihood sequence estimation.

The system diagram for STTC is shown in Fig. 3.3, where the coding gain is due to the STTC coder itself.

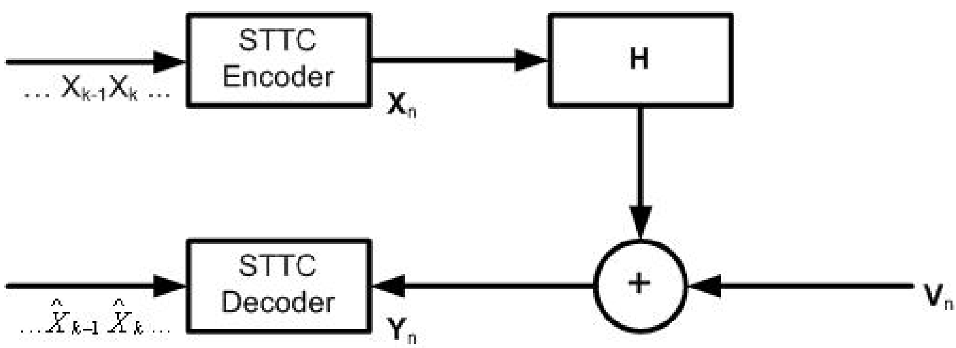

FIGURE 3.3: Space -Time Trellis Coding System

3.3 Transmit Diversity Scheme

In most situations, the wireless channel suffers attenuation due to destructive addition of multi paths in the propagation media and to interference from other users. The channel statistic is significantly often Rayleigh distributed which makes it difficult for the receiver to reliably determine the transmitted signal unless some less attenuated replica of the signal is provided to the receiver. This technique is called diversity, which can be provided using temporal, frequency, polarization, and spatial resources.

Diversity scheme is divided in two classes:

- Transmit Diversity
- Received Diversity

Transmit diversity scheme will be described here in two sections:

- Classical Transmit Diversity Scheme
- Alamouti's Transmit Diversity Scheme

3.3.1 Classical Transmit Diversity Schemes

Antenna diversity is a practical, effective and, hence, a widely applied technique for reducing the effect of multipath fading in scattering environments. According to the classical approach, the use of multiple antennas at the receiver and perform combining or selection and switching can improve the quality of the received signal. But then the cost, size, and power of the remote units are increased. Not only this, the use of multiple antennas and radio frequency (RF) chains (or selection and switching circuits) makes the remote units larger and more expensive. On the other hand, using diversity techniques at the base stations to improve their reception quality can be a good technique because a base station often serves hundreds to thousands of remote units and it is more economical to add equipment to base stations rather than the remote units. These all make transmit diversity schemes very attractive.

For transmit diversity scheme two steps can be followed:

- One antenna and one transmit chain may be added to a base station to improve the reception quality of all the remote units in that base station's coverage area.
- Add more antennas and receivers to all the remote units.

In delay diversity scheme [4] for a single base station; in which copies of the same symbol are transmitted through multiple antennas at different times, hence creating an artificial multipath distortion. For resolving multi path distortion and to obtain diversity gain a Maximum Likelihood Sequence Estimator (MLSE) or a Minimum Mean Squared Error (MMSE) equalizer is used.

According to Space–time trellis coding [20], symbols are encoded according to the antennas through which they are simultaneously transmitted and are decoded using a maximum likelihood decoder. This scheme combines the benefits of forward error correction (FEC) coding and diversity transmission to provide considerable performance gains. The cost for this scheme is additional processing, which increases exponentially as a function of bandwidth efficiency (bits/s/Hz) and the required diversity order. Therefore, for some applications it may not be practical or cost-effective.

3.3.2 Alamouti's Transmit Diversity Scheme

On the other hand Alamouti's transmit diversity scheme is applicable to improve the signal quality at the receiver on one side of the link by simple processing across two transmit antennas on the opposite side. The obtained diversity order is equal to applying Maximal-Ratio Receiver Combining (MRRC) with two antennas at the receiver. The scheme may easily be generalized to two transmit antennas and receive antennas to provide a diversity order of $2M$. This scheme provides the following advantages in wireless communication systems [5].

- No feedback requirement from the receiver to the transmitter.
- Computation complexity is small.
- No bandwidth expansion is required.
- Error performance, data rate or capacity all are improved.
- The range or the coverage area increased.

The results of the decreased sensitivity are

- Higher level modulation schemes increase the effective data rate.
- Smaller reuse factors in a multi cell environment increase system capacity.

This scheme is applicable for multi path fading effected limited capacity system and also a cost-effective way to meet the market demands for quality and efficiency without a complete redesign of existing systems. It also reduces the effect of fading at the remote units using multiple transmit antennas at the base stations. These all indicates that Alamouti's scheme is obviously a superb candidate for next-generation wireless systems.

Alamouti's transmit diversity technique can be sub-divided into the following two schemes:

- Scheme-I: two transmit antennas, one receive antenna
- Scheme-II: Two transmit antennas, two receive antennas

3.3.2.1 Scheme-I: Two Transmit Antennas, One Receive Antenna

For the scenario, where the combination of two transmitters and one receiver is employed, a diversity scheme, proposed by S. M. Alamouti, has been adopted. This particularly simple and prevalent scheme, with two transmit antennas and one receive antenna (Figure 3.4), uses simple coding which is the only STBC that can achieve its full diversity gain without needing to sacrifice its data rate. As per Alamouti's scheme the transmitter sends out data in groups of 2 (two) bits. The scheme may be defined by the following three functions [1]:

- The encoding and transmission sequence of information symbols at the transmitter;
- The combining scheme at the receiver;
- The decision rule for maximum likelihood detection.

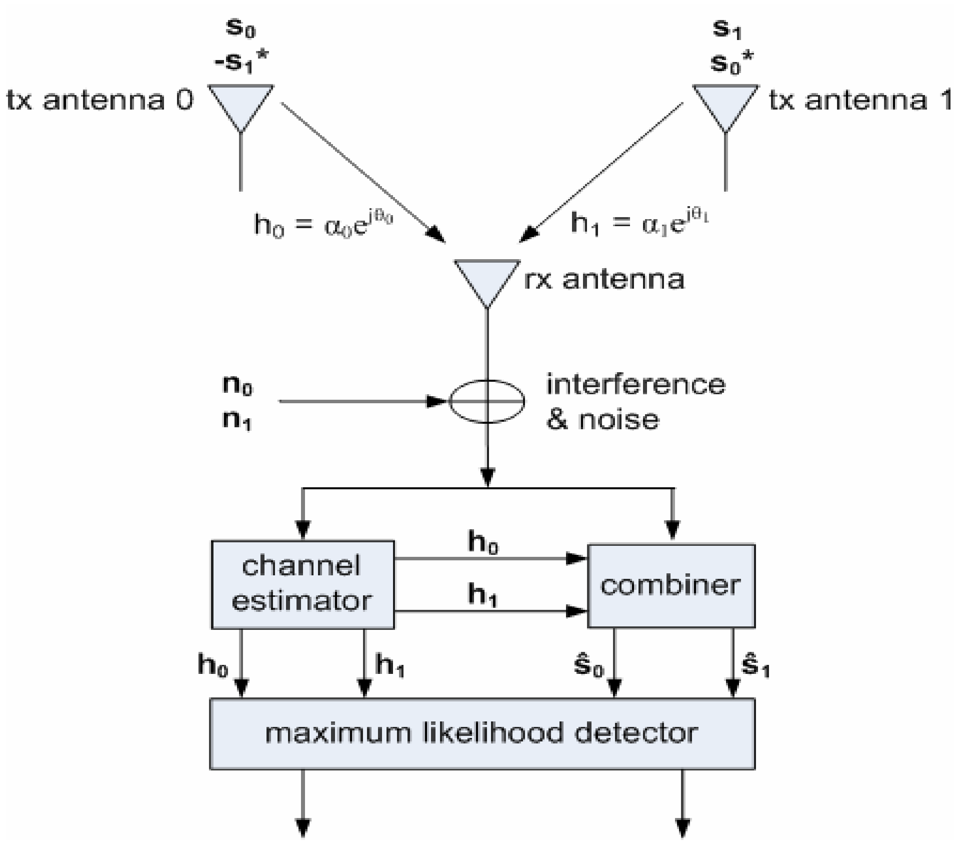

FIGURE 3.4: The two-branch transmit diversity scheme with one receiver

3.3.2.1.1 The Encoding and Transmission Sequence

At a given symbol period, two signals, transmitted from two antennas: antenna zero and antenna one, are denoted by s_0 and s_1 simultaneously. During the next symbol period, signal ($-s_1^*$) is transmitted from antenna zero, and signal s_0^* is transmitted from antenna one where * stands for complex conjugate operation. The encoding is done in space and time (and hence space–time coding). The assumption made for this scheme is that the channel state remains fairly constant over the transmission of 2 (two) consecutive symbols [1].

Assuming that fading is constant across two consecutive symbols, the channel at time t may be modeled as

$$h_0(t) = h_0(t+T) = h_0 = \alpha_0 e^{j\theta 0}$$
$$h_1(t) = h_1(t+T) = h_1 = \alpha_1 e^{j\theta 1} \qquad (3.3)$$

Where ***T*** is the symbol duration.

The received signals, $\boldsymbol{r_0}$ and $\mathbf{r_1}$ at time ***t*** and ***(t + T)*** respectively can be expressed as

$$r_0 = r(t) = h_0 s_0 + h_1 s_1 + n_0$$
$$r_1 = r(t+T) = -h_0 s_1^* + h_1 s_0^* + n_1 \quad (3.4)$$

Where $\boldsymbol{n_0}$, $\boldsymbol{n_1}$ are complex random variable representing receiver noise and interference.

3.3.2.1.2 The Combining Scheme

The combiner builds the following two combined signals that are sent to the maximum likelihood detector

$$\hat{s}_0 = h_0^* r_0 + h_1 r_1^*$$
$$\hat{s}_1 = h_1^* r_0 - h_0 r_1^* \quad (3.5)$$

3.3.2.1.3 The Maximum Likelihood Decision Rule

Finally in the maximum likelihood detector, signals are chosen either $\boldsymbol{s_0}$ or $\boldsymbol{s_1}$ according to corresponding decision rule. Thus, the scheme has been proved quite handy for reducing complexity and simplifying transmission channel in a skillful and efficient manner.

3.3.2.1.4 Capacity of Scheme-I

Capacity is generally associated with a particular communication channel rather than a transmission scheme. However, it is also possible to consider the maximum achievable rate of some STBCs, by treating the channel as a standard AWGN (Additive White Gaussian Noise) channel and re-assigning the received SNR according to the properties of the code. This quantity is referred as $C_E = log_2 (1 + \rho)$ as the effective capacity, where ρ is the post-detection SNR achieved by the code. By considering the 2:1 Alamouti STBC just discussed in 3.4.1.1, channel matrix is h^{-T} = $[h_1 \ h_2]$ and the SNR seen at the receiver is given by $\rho/2 \ (|h_1|^2+|h_2|^2)$.

The instantaneous capacity supported by the channel is then given by

$$C_{2:1|h} = \log_2 \det [I_1 + (\rho/2) \ h^{-T} h^*]$$
$$= \log_2 [1 + \rho/2 \ (|h_1|^2+|h_2|^2)]$$
$$= (\rho/2) \ C_{E,scheme-I} \quad (3.6)$$

Therefore it is obvious that the Alamouti code is able to achieve the maximum capacity offered by the 2:1 MISO (Multiple Input Single Output) channel. Note that this statement is not meant to imply that the Alamouti STBC does in fact achieve full channel capacity, only that it is not restricted by its structure to some fraction of the available capacity.

3.3.2.2 Scheme-II: Two Transmit Antennas, Two Receive Antennas

When a higher order of diversity is needed and multiple receive antennas at the remote units are feasible, it is possible to provide a diversity order of *2M* with two transmit and *M* receivce antennas [20]. In this section, a special case considering two transmitters and two receivers (figure 3.5) has been illustrated briefly in almost similar fashion as already done in previous section. The generalization to M receive antennas is trivial.

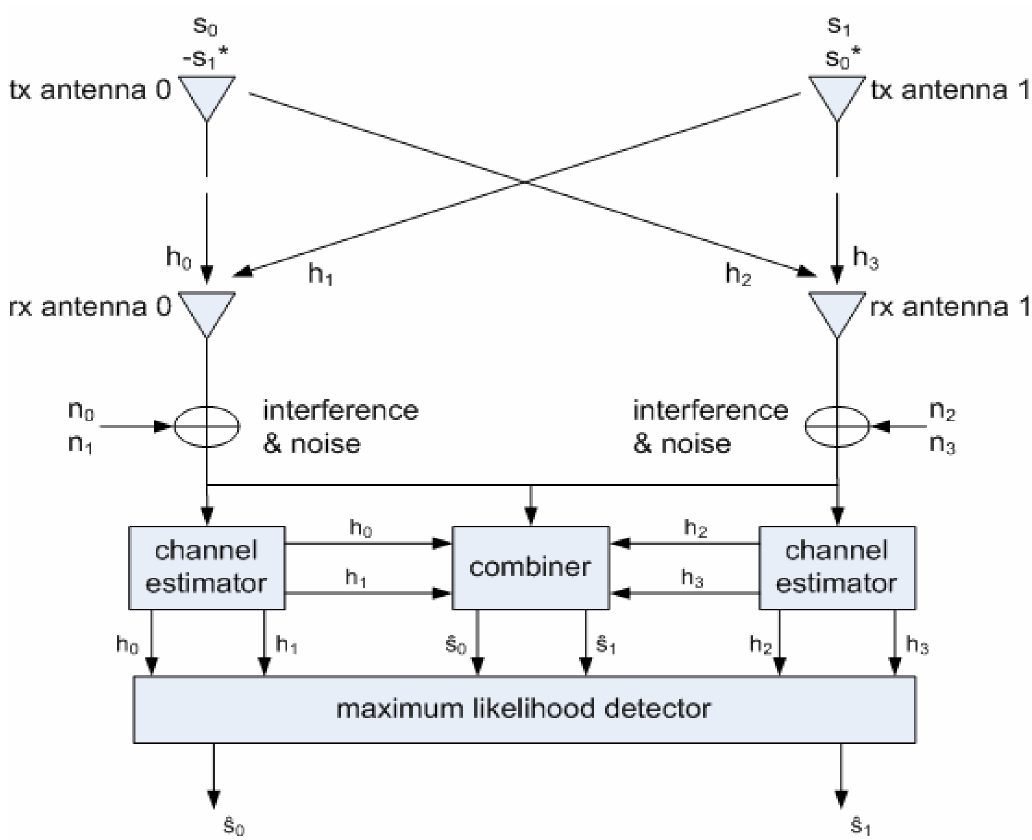

FIGURE 3.5: The new two-branch transmit diversity scheme with two receivers

3.3.2.2.1 The Encoding and Transmission Sequence

The encoding and transmission sequence for this configuration is identical to the case discussed in 3.3.2.1.1 The channel at time *t* can be modeled by complex multiplicative distortions, $h_0(t)$, $h_1(t)$, $h_2(t)$, $h_3(t)$ between transmit antenna zero and receive antenna zero, transmit antenna one and receive antenna zero, transmit antenna zero and receive antenna one, transmit antenna one and receive antenna one, respectively.

Assuming that fading is constant across two consecutive symbols, it can be written

$$
\begin{aligned}
h_0(t) &= h_0(t+T) = \alpha_0 e^{j\theta_0} \\
h_1(t) &= h_1(t+T) = \alpha_1 e^{j\theta_1} \\
h_2(t) &= h_2(t+T) = \alpha_2 e^{j\theta_2} \\
h_3(t) &= h_3(t+T) = \alpha_3 e^{j\theta_3}
\end{aligned} \qquad (3.7)
$$

Where *T* is the symbol duration.

The received signals can then be expressed as

$$\begin{aligned} r_0 &= h_0 s_0 + h_1 s_1 + n_0 \\ r_1 &= -h_0 s_1^* + h_1 s_0^* + n_1 \\ r_2 &= h_2 s_0 + h_3 s_1 + n_2 \\ r_3 &= -h_2 s_1^* + h_3 s_0^* + n_3 \end{aligned} \tag{3.8}$$

The complex random variables, n_0, n_1, n_2 and n_3 represent receiver thermal noise and interference.

3.3.2.2.2 The Combining Scheme

The combiner builds the following two combined signals that are sent to the maximum likelihood detector

$$\begin{aligned} \hat{s}_0 &= h_0^* r_0 + h_1 r_1^* + h_2^* r_2 + h_3 r_3^* \\ \hat{s}_1 &= h_1^* r_0 - h_0 r_1^* + h_3^* r_2 - h_2 r_3^* \end{aligned} \tag{3.9}$$

3.3.2.2.3 The Maximum Likelihood Decision Rule

The maximum likelihood detector chooses either s_0 or s_1 according to corresponding decision rule, as was done in previous scheme.

3.3.2.2.4 Capacity of Scheme II

Considering the scheme discussed in Section 3.3.2.2, the channel matrix and the received SNR are given by

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \tag{3.10}$$

and

$$\rho_{scheme\text{-}II} = (\rho/2)\,[|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2] \tag{3.11}$$

where ρ is the instantaneous received SNR and $\rho_{scheme\text{-}II}$ is the instantaneous received SNR for Scheme-II, *H* is channel matrix.

The instantaneous capacity of the channel is given by

$$\begin{aligned} C_{2:2|H} &= \log_2 \det(I^2 + \rho/2\ HH^*) \\ &= \log_2 [1 + (\rho/2)\,(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2) + (\rho/2)^2 \det(HH^*)] \end{aligned} \tag{3.12}$$

Which is certainly more than that of scheme-I. Strict inequality follows by defining $\det(HH^*) = \prod_{i=1}^{rank\ H} \sigma_i^2$, where σ_i is the eigenvalue of the *H* matrix. Thus we can see that although the structured use of channel resources made by the Alamouti STBC leads to efficient detection algorithms, there is an implicit sacrifice of effective capacity. This class of codes is only optimal in terms of diversity advantage and rate for the 2:1 (Tx-2, Rx-1) MISO channel.

Chapter 4

Space Time Block Coded CDMA System

4.1 Wireless Channel and Space Time Block Coded CDMA System

Wireless channel is one of the most important parts in communication system. The path between the transmitter and the receiver may be defined as wireless channel. The received signal characteristics may be different from the transmitted signal because it experiences many impediments in the channel. So channel estimation is very important in designing a communication model.

In Space Time Block Coded MIMO CDMA system, the transmit diversity scheme can be classified in the following two techniques according to the channel condition.

- Non blind technique
- Blind technique

4.1.1 Non Blind Technique

The channel condition is known at the receiving end in non blind technique. It means, receiver knows the characteristic of the channel. Alamouti's STBC diversity technique comprises of this technique which has been analyzed in chapter 3. This scheme is applicable only when the channel changes very slowly compared to the symbol rate (flat Rayleigh fading channels). However the wireless channels are highly variant and finding a general model, which hold in all scenarios, seems to be difficult for fast Rayleigh fading channels [5]. The fading conditions change so rapidly that channel estimation is difficult or requires long training sequences that need to be performed by sending pilot codes causing wastage of bandwidth. Besides, perfect channel estimation may turn out to be very costly if not impossible. Non blind scheme is impractical because of these limitations.

Hence there may be a need for non-coherent detection at the receiving side where neither the transmitter nor the receiver has access to channel state information; channel estimation may not be used as this may help reduce the cost and the decoding complexity of the handset. In such situations it is useful to develop modulation techniques that do not require channel estimates at the transmitter or receiver which introduces Blind Technique.

4.1.2 Blind Technique

Blind Technique ensures that receiver does not know any information about the channel condition. It's a new detection scheme for transmit diversity technique in CDMA system and a suitable substitute to Alamouti's STBC technique. In this scheme, no assumptions are made regarding to the channel state and more amount of detection complexity are required. The main benefit of this complexity is to get rid of high cost due to the channel estimation. The underlying principle of this process is to start the transmission of the symbols with the transmission of 2 pilot symbols that are known to the receiver in advance. This will give the Receiver equation manipulator 2 constants that can be used to generate the next 2 bits based upon the previous 2 bits. The next 2 bits will then be used as constants to estimate the next 2 received symbols. This will thus generate a chain symbol that will result in detection of all the bits recursively. The following assumptions are made in this scheme [2, 5]:

- Fade Coefficients are Constant over every 4 Consecutive Transmissions.
- Fair assumption since Symbol Duration (T) << (1 / Doppler Frequency).
- Constellation Points have Equal Energy à Normalized to (1 / 2).
- Receiver knows s_0, s_1 (Pilot Symbols), r_0, r_1, r_2, … (Received Symbols).

The second modification of this scheme will remove the assumption that all the Constellation Points have Equal Energy Normalized to ½. The transmission sequence is exactly similar to Alamouti's method as described below.

4.1.2.1 The Encoding and Transmission Sequence

At a given symbol period, two signals are simultaneously transmitted from the two antennas. The signal transmission is shown in Table 4.1:

	antenna 0	**antenna 1**
Time t	s_0	s_1
Time t + T	$-s_1^*$	s_0^*

TABLE 4.1: Transmission Sequence

The encoding is done in space and time (space–time coding). The encoding, however, may also be done in space and frequency. Instead of two adjacent symbol periods, two adjacent carriers may be used (space–frequency coding). For 2 consecutive symbols it is assumed that channel state remains fairly constant over the transmission.

The received symbols can be detected by the following equations described below:

Received Symbols:

$$r_0 = r(t) = h_0 s_0 + h_1 s_1 + \text{noise}$$
$$r_1 = r(t+T) = h_1 s_0^* - h_0 s_1^* + \text{noise}$$
$$r_2 = r(t+2T) = h_0 s_2 + h_1 s_3 + \text{noise}$$
$$r_3 = r(t+3T) = h_1 s_2^* - h_0 s_3^* + \text{noise} \qquad (4.1)$$

The received symbols will be manipulated mathematically to obtain intermediate constants.

4.1.2.2 Intermediate Processing

$$A = r_0 r_3^* - r_2 r_1^* = (|h_0|^2 + |h_1|^2) \,.\, (s_2 s_1 - s_3 s_0) + \text{noise}$$
$$B = r_2 r_0^* + r_1 r_3^* = (|h_0|^2 + |h_1|^2) \,.\, (s_2 s_0^* + s_3 s_1^*) + \text{noise}. \qquad (4.2)$$

The intermediate constants obtained as a result of the above manipulations will be used further to obtain the symbols S_2, S_3 by using the following equations.

4.1.2.3 Final Processing

$$S_2 = A.S_1^* + B.S_0 = (R_0 R_3^* - R_2 R_1^*)S_1^* + (R_2 R_0^* + R_1 R_3^*)S_0$$
$$S_3 = -A.S_0^* + B.S_1 = -(R_0 R_3^* - R_2 R_1^*)S_0^* + (R_2 R_0^* + R_1 R_3^*)S_1 \qquad (4.3)$$

Thus, s_2, s_3 are a function of s_0, s_1. Similarly, s_4, s_5 are a Function of s_2, s_3. The recursive nature of this method will keep generating 2 bits at a time depending upon the values of the previous bits.

4.1.2.4 Modified Blind Scheme

When equal energy does not exist in the signal constellations, modifications of the equations to account for the unequal energy values are required. The equations that need to be written to implement the scheme are as follows:

$$h_0 = \frac{r_0 s_o^* - r_1 s_1}{|s_0|^2 + |s_1|^2} = h_0 + \frac{s_0^* N_0 + s_1 N_0}{|s_0|^2 + |s_1|^2}$$

$$h_1 = \frac{r_0 s_1^* + r_1 s_0}{|s_0|^2 + |s_1|^2} = h_0 + \frac{s_1^* N_0 + s_0 N_0}{|s_0|^2 + |s_1|^2} \quad (4.4)$$

The other equations remain fairly similar to the Blind Scheme.

4.1.2.5 Received Symbols

$r_0 = r(t) = h_0 s_0 + h_1 s_1$ + Noise.

$r_1 = r(t+T) = h_1 s_0^* - h_0 s_1^*$ + Noise.

$r_2 = r(t+2T) = h_0 s_2 + h_1 s_3$ + Noise.

$r_3 = r(t+3T) = h_1 s_2^* - h_0 s_3^*$ + Noise. (4.5)

The received symbols will be manipulated mathematically to obtain intermediate constants.

4.1.2.6 Intermediate Processing

$A = r_0 r_3^* - r_2 r_1^* = (|h_0|2 + |h_1|2) . (s_2 s_1 - s_3 s_0)$ + Noise

$B = r_2 r_0^* + r_1 r3^* = (|h_0|2 + |h_1|2) . (s_2 s_0^* + s_3 s_1^*)$ + Noise. (4.6)

Thus the receiver forms estimates for h_0, h_1 and employs these estimates and the receive words r_2, r_3 for decoding s_2, s_3. Once s_2, s_3 are computed, the receiver substitutes r_0, r_1, s_0, s_1 *by* r_2, r_3, s_2, s_3 respectively and then computes the new estimates of h_0 and h_1 that are later used to decode s_4 and s_5. This process is then recursively carried out.

4.1.2.7 Problems Associated with the Blind Scheme

- Transmission of Pilot Symbols is required. Pilot signals are the un-modulated PN codes associated with each channel, used to synchronize and track the locally generated PN codes for despreading.

- Equal energy for all the Constellation Points is assumed. The Constellation Points may not have Equal Energy in modified form of the Blind Scheme.

- Do not offer resistance to propagation of errors. Errors in any bits will propagate down causing multiple errors and the scheme will fail completely if this goes unchecked. Also, if any bits are totally wiped out during the transmission through the channel then the next bits arriving at the receiver will be wrongly detected.

- Plot of BER vrs. SNR is 3-dB worse than the Simple Transmit Diversity Scheme. This effectively implies that the Bit Error Rate will be more than that for the previous scheme for the same Signal to Noise Ratio. (This comparison is discussed in Chapter 5)

Chapter 5

Simulations and Results

Throughout the whole thesis, numerous simulations were accomplished for better understand and analysis of theoretical aspects. The simulation tool used for this purpose is Matlab. 10^7 samples have been taken for each simulation. In this chapter the performance curves as well as the tentative results will be analyzed.

In CDMA systems, the signals are transmitted in the form of BPSK which has been discussed in Chapter 2. Figure 5.1 demonstrates the constellation diagram of transmitted information signal which reveals that the signals are of either 1's or -1's, which indicates the BPSK form.

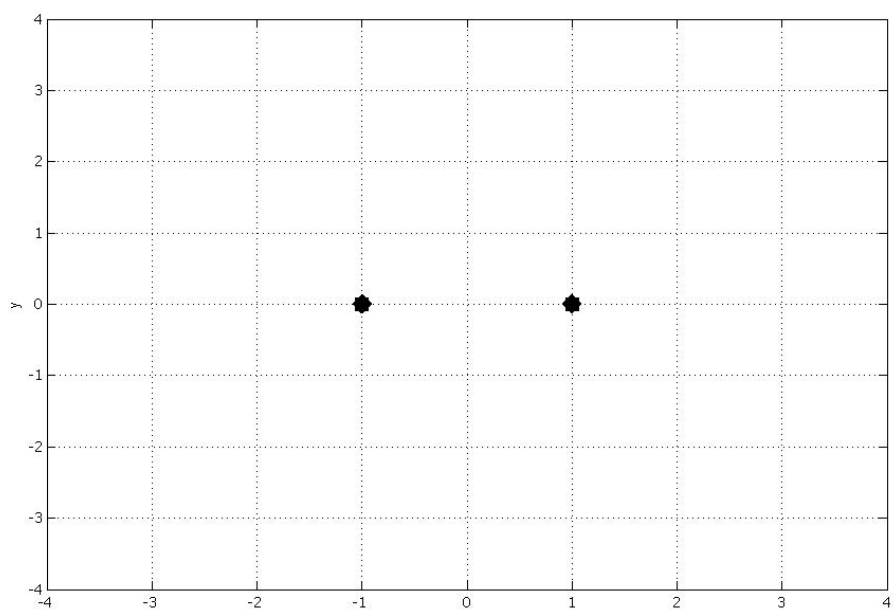

FIGURE 5.1: Constellation diagram of transmitted information signal

The hindrance that the transmitted signals experience is fading, at first and then noise, which are multiplicative and additive in nature, respectively. Fading tries to dim the transmitted information signal. In this thesis, uncorrelated Rayleigh fading was considered. Figure 5.2 shows that both the magnitude and phase are completely uncorrelated with each other. In Figure 5.3 constellation diagram of fading is shown. From here fading magnitude as well as phase can be sketched.

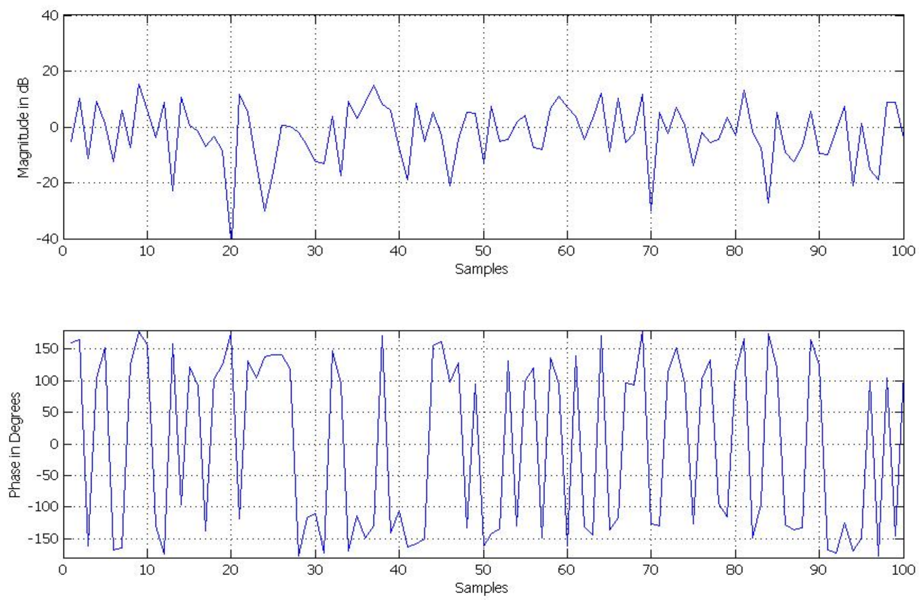

FIGURE 5.2: Magnitude and phase of the fading

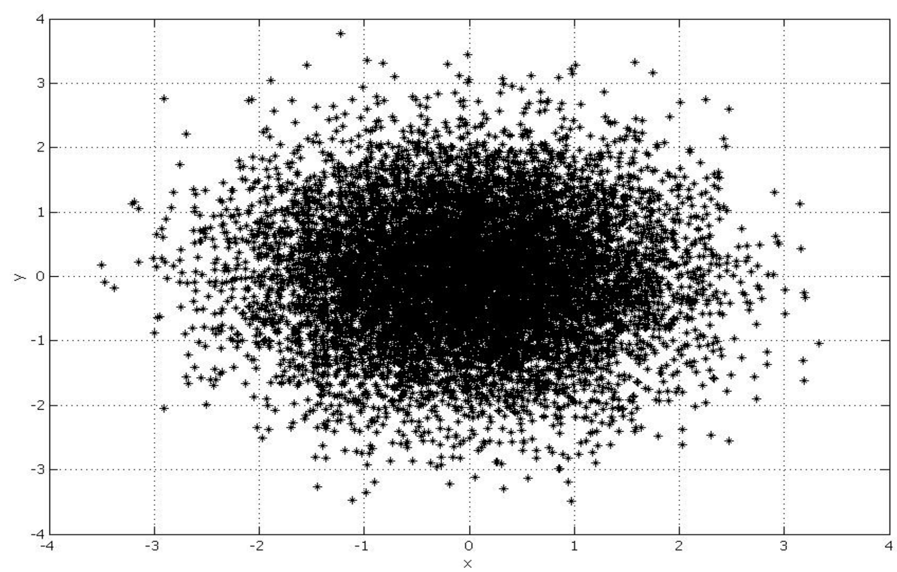

FIGURE 5.3: Constellation diagram of Fading

Figure 5.4 displays the histogram of fading. From this figure, it is quite clear that the fading forms a shape which indicates a Rayleigh distribution.

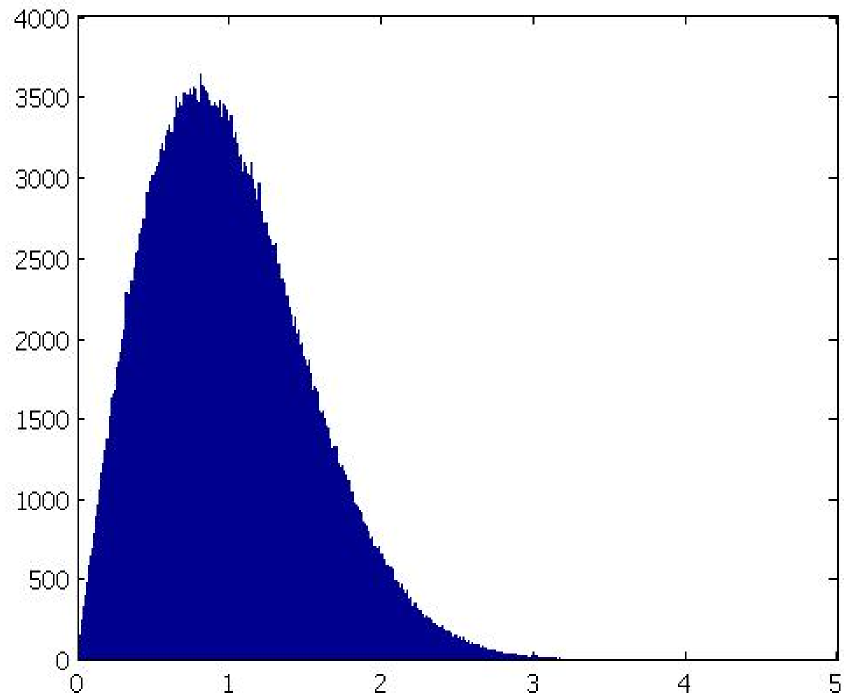

FIGURE 5.4: Histogram of Fading

At the receiver, the fading affected received signal further gets affected by noise. It is desired for a communication system that noise power should be least resulting a higher value of SNR. When SNR has quite a larger value, the effect of noise on the signal is less, but it should also be taken into account that an inferior SNR will cause the noise to fabricate the received signal hazy.

This notion has been deployed in Figure 5.5. The figure depicts that the constellation is smeared for lower valued SNR while for high SNR the constellation of received signal is almost same as the transmitted one. This scenario is observed when the effect of fading is not considered.

When the simultaneous effects of both noise and fading are considered, the constellation diagram is smeared for high or less values of SNR. For high SNR, the constellation is little bit compact due to the fact that it is less dominating by the noise.

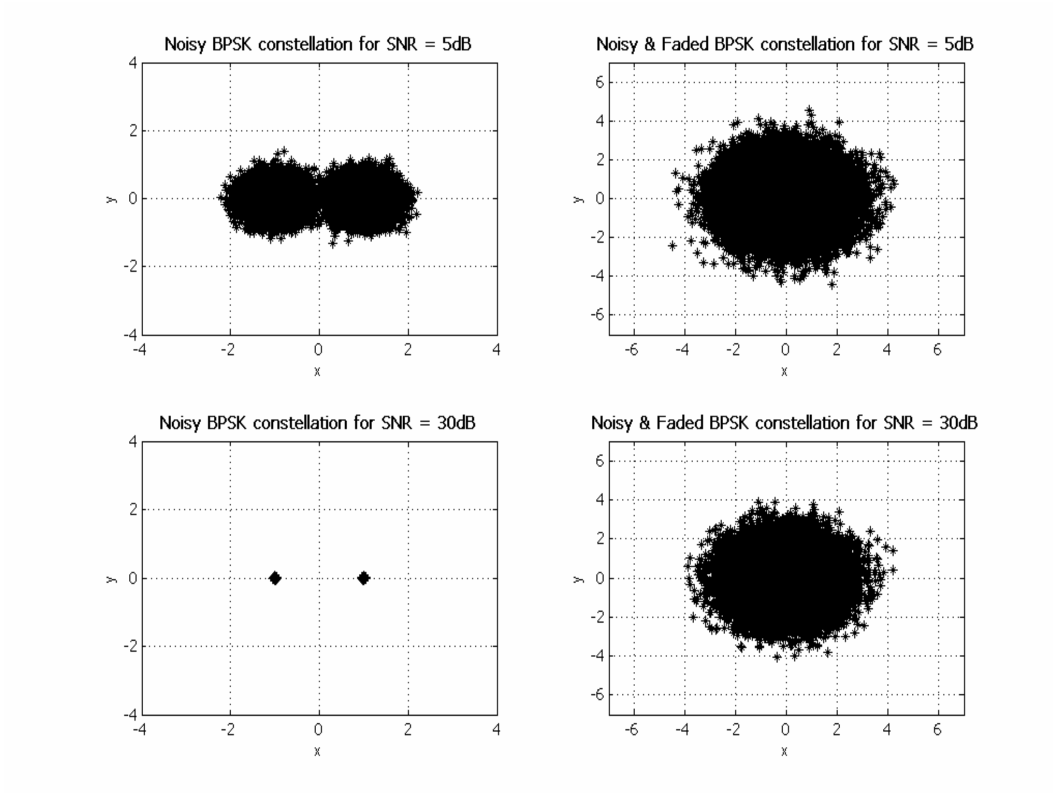

FIGURE 5.5: Constellation diagram for different SNRs (both considering and without considering noise)

In CDMA systems, the information signal is encoded by the PN-sequence which is unique for individual users. The decoding of this signal, received by the receiver, is again done by the same corresponding PN-sequence.

In this thesis, the PN-sequence is varied for the same length of information signal. PN-sequences of 7, 15 and 31 bits are considered here. It has been observed that a prolonged PN-sequence yields comparatively better performance. The traditional performance analysis of any communication system is done by analyzing the standard SNR versus BER curves obtained by simulations. It is generally desired that the value of the BER should be as least as possible.

From Figure 5.6, it can be viewed that for a PN-sequence of length of 31 bits, the best performance is obtained than that of either 7-bits or 15-bits of PN-sequences. The PN-sequence of 15 bits implies a moderate performance which is in between those of 7-bits and 31-bits of PN-sequences. Implementation by 7-bits of PN-sequence exhibits the worst performance among these three.

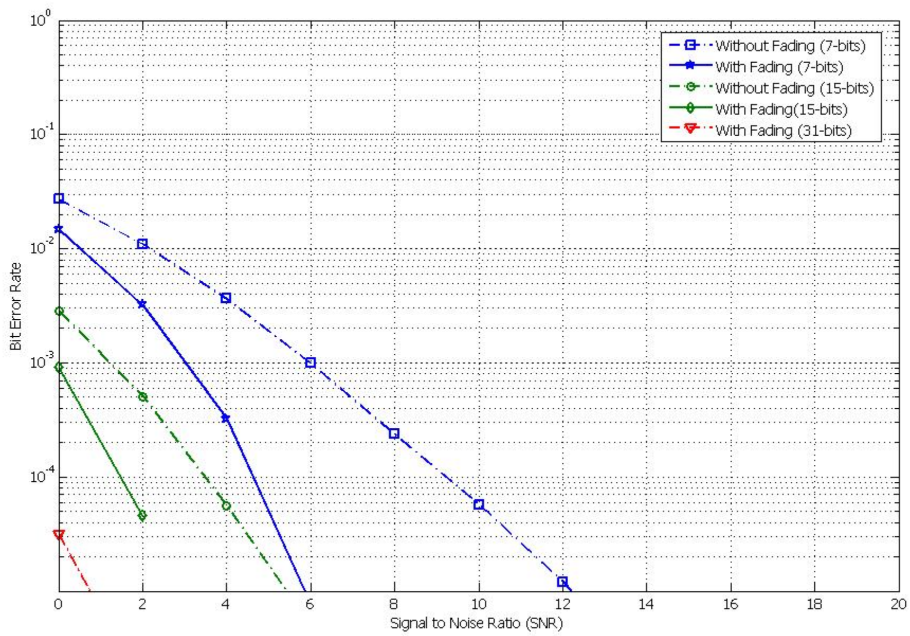

FIGURE 5.6: Performance curves for varying PN-sequences (7, 15, 31 bits)

It should be noted that the performance curves are attained here considering the impact of noise only and then considering the effects of both noise and fading. Definitely, the analyses considering both noise and fading would give worse result compared to that of considering only noise. But considering both the noise and fading is certainly more practical as the impact of fading can not be omitted for real scenario.

So far the performance analyses were done for single user only. The performance scenario is completely changed when multiple users are considered for simulation. The new thing that is to be considered is Intersymbol Interference (ISI). ISI causes explicit deterioration of the performance. As the number of the users is increased, the performance degrades comprehensively.

In Figure 5.7, 5.8 and 5.9, the number of users is varied and the performance is analyzed accordingly. It has been observed that increasing number of users degrades the performance of the system for all the cases. Figure 5.10 shows the combined performance curves where both the number of users as well as length of PN-sequence is varied.

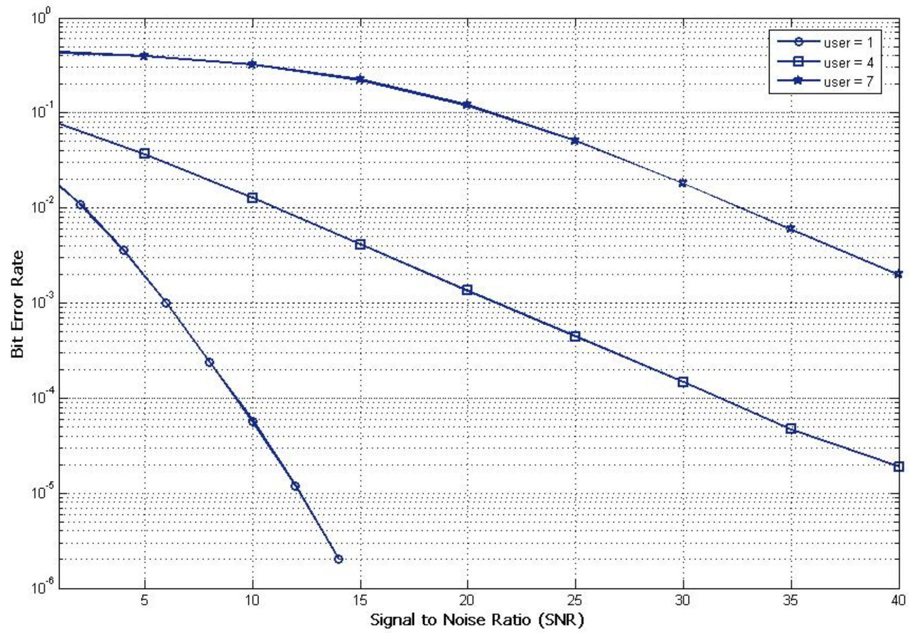

FIGURE 5.7: Performance curves varying number of users (for PN-sequence = 7 bits)

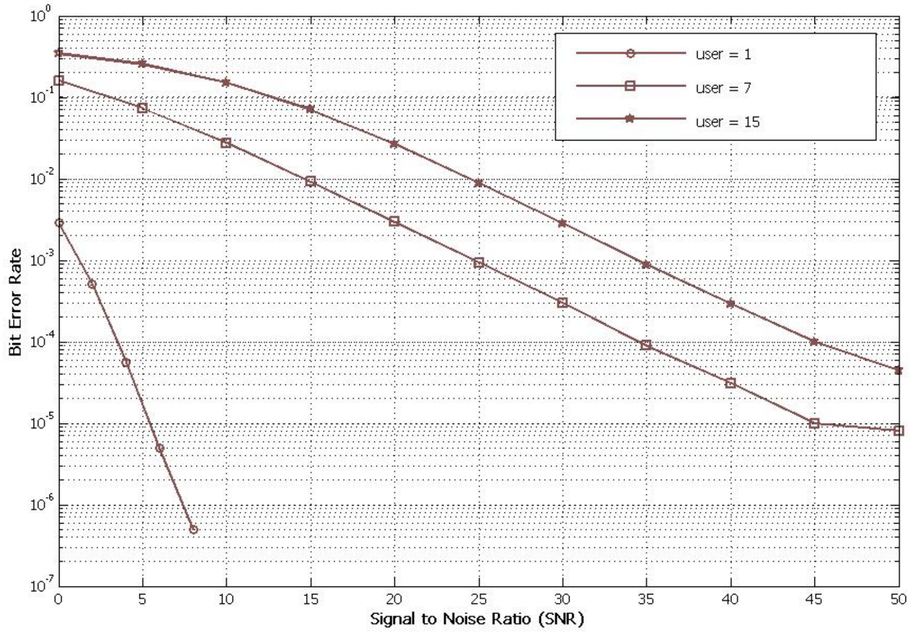

FIGURE 5.8: Performance curves varying number of users (for PN- sequence = 15 bits)

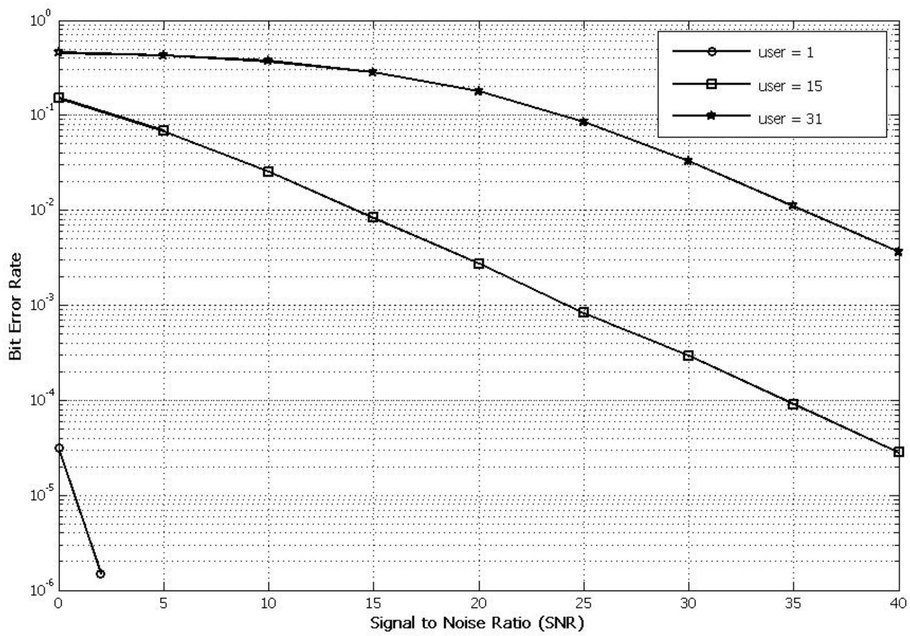

FIGURE 5.9: Performance curves varying number of users (for PN- sequence = 31 bits)

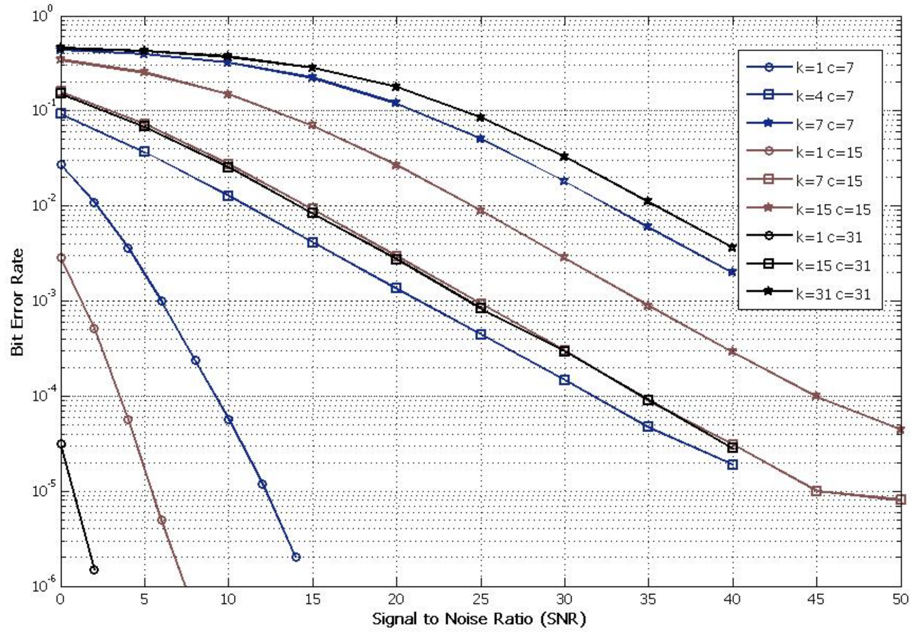

FIGURE 5.10: Combined performance curves varying both number of users and PN-sequences (k = number of users, c = length of PN-sequences)

In Figure 5.11, BER is compared for different diversity techniques discussed earlier in Chapter 3 and 4. It is quite clear from the figure that performance of single user CDMA system with a code length of 7-bits is comprehensively better than that of BPSK in Rayleigh faded channel, but for higher values of SNR, it experiences performance degradation than Alamouti's scheme with BPSK. Alamouti's 2:1 scheme for CDMA improves the performance of the system by almost 7dB than typical CDMA systems (with code length = 7 and one user, i.e. no multiple access interference). Here it should be noted that channel conditions are known to the receiver for Alamouti's scheme, hence called non-blind technique, whereas for the two approaches channel state is not estimated, which results in performance degradation by almost 1dB.

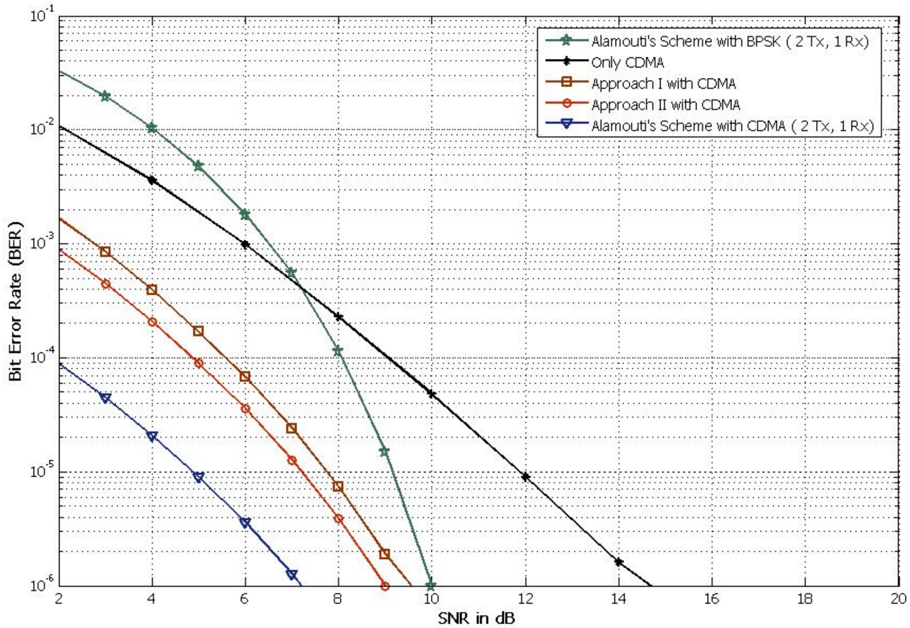

FIGURE 5.11: Stylized BER versus SNR performance of different diversity techniques

For both the blind approaches, if any bit goes missing during transmission, the next bits arriving at receiver would be erroneous and if it goes unchecked, the schemes will fail completely. Since '*h'* coefficients are modified continuously over the period of reception, Approach II offers comparatively better performance than that of Approach I by around 0.3dB. So from the foregoing analysis, it is quite clear that Alamouti's 2:1 diversity technique for CDMA is the best among all the techniques described previous chapters. But it should also be taken in account that the blind approaches are much more practical than Alamouti's scheme. This is because Alamouti's scheme assumes that the channel is perfectly known, which may not be always possible.

Now the number of users, as well as diversity gain has been varied and the system behaviors are monitored. Figure 5.12 unfolds this scenario. Using two transmit antennas and two receive antennas would give around 1-3dB performance improvement than using two transmit antennas and one receive antenna.

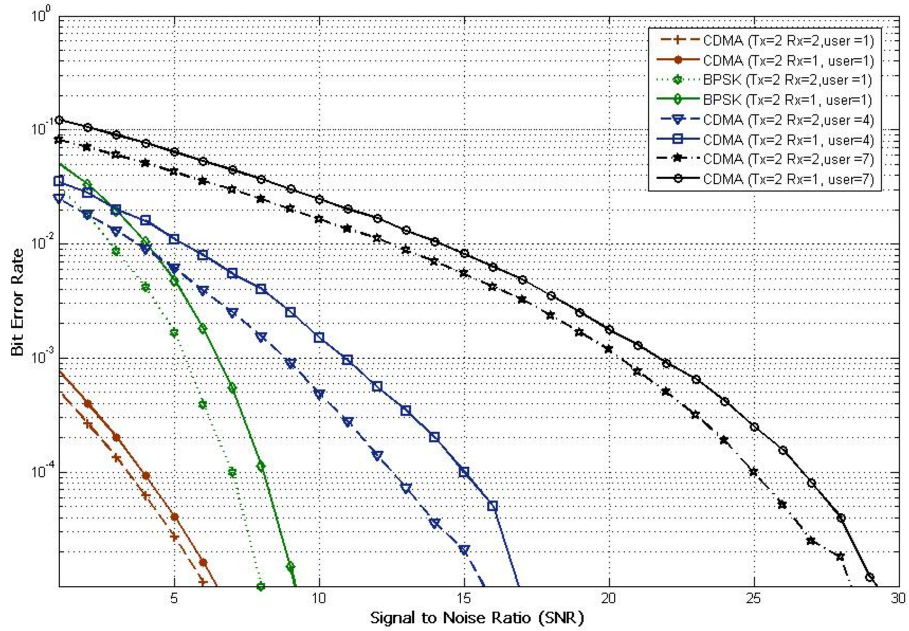

FIGURE 5.12: Comparison of performance for different diversity techniques varying number of users and diversity gain

When the number of subscribers is increased, certainly the performance degrades as stated earlier. There is no exception of this condition. It can be visualized that the performance is improved by around 4dB for CDMA system than BPSK using Alamouti's STBC technique for both the cases. It signifies that for sending a signal with equal bit error rate, it will require less power to transmit for CDMA system than typical BPSK system using Alamouti's STBC technique.

Chapter 6

Conclusions and Further Research

When the thesis was commenced, single user CDMA system had been modeled using Monte Carlo simulation techniques. Subsequent works had been accomplished encompassing this model. Performance has been analyzed by monitoring change of BER with the variation of the SNR. A generic single user CDMA system has been further extended to multiple user CDMA system. Mitigation of fading is one of the most significant issues, which was handled very carefully. Coherent detection techniques have been practiced here to mitigate the effect of fading over the information signal.

Then Alamouti's STBC diversity technique has been implemented for typical CDMA system in Rayleigh fading condition, which yields a remarkable performance. Using STBC in CDMA system is advantageous over traditional CDMA system resulting better BER performance, lower complexity and higher user capacity. In CDMA, where users simultaneously share the same spectrum, each user is an interferer to each of the other users in the same cell as well as nearby cells. Hence, the capacity per cell is inversely proportional to SNR. When Alamouti's STBC technique using multiple antennas is applied for CDMA systems, SNR is decreased which results an increase in capacity.

We would like to extend the tentative objectives of the project accomplished so far by further work on this diversity technique over other emerging technologies like Multi-Carrier CDMA (MC-CDMA), Wideband CDMA (WCDMA) etc. and to analyze the performance improvement. The successful implementation of these techniques is supposed to reveal the fact that the performance of these systems will improve subsequently. May be these thoughts would no more be a thought rather it would hopefully evolve into reality in near future.

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Appendix A

Glossary

3G	3^{rd} Generation

A

AGC	Automatic Gain Control
AWGN	Additive White Gaussian Noise

B

BER	Bit Error Rate
BPSK	Binary Phase Shift Keying

C

CDMA	Code Division Multiple Access
CMR	Coherent Multiple Reception
CMT	Coherent Multiple Transmission
CSI	Channel Side Information

D

DS-CDMA	Direct Sequence Code Division Multiple Access
DSSS	Direct Sequence Spread Spectrum

F

FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FHSS	Frequency Hopping Spread Spectrum

I

ISI	Intersymbol Interference

L

LOS	Line of Sight

M

MAC	Multiple Access Channel
MCSS	Multi Carrier Spread Spectrum
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MLSE	Maximum Likelihood Sequence Estimation
MMSE	Minimum Mean-Squared Error
MRRC	Maximal Ratio Receiver Combining

N

NLOS	Non Line of Sight

P

PE	Polynomial Expansion
PN-sequence	Pseudo-random Noise Sequence

Q

QAM	Quadrature Amplitude Modulation

R

RF	Radio Frequency
RRC	Radio Resource Control

S

SNR	Signal to Noise Ratio
SSMA	Spread-Spectrum Multiple Access
STBC	Space Time Block Code
STTC	Space Time Trellis Code

T

TCM	Trellis Code Modulation
TDMA	Time Division Multiple Access
THSS	Time Hopping Spread Spectrum

V

VBLAST	Vertical Bell Labs Layered Space Time

W

WLAN	Wireless Local Area Networks

Z

ZF-DF	Zero-Forcing Decision-Feedback

APPENDIX B

Sample MATLAB Code for Monte-Carlo Simulation

B.1 MATLAB code for multiple user CDMA system

```
% Implementation of a multi-user CDMA system for user = 7, PN-sequence = 7 bits
% Accomplished by – M. Shahriar Mamun, Jamil Hussain, Md. Hasibul Haque


clc;
close all;
clear all;

tic;

no_of_packets = 1e3;
packet_length  = 1e4;

bit1 = 7;
pn_code = - ( 2 * (randn(7,7) > 0) - 1);

snr = 0 : 1 : 40;

% Declaring zero matrix of size (7 X 9) for calculating BER
ber_noisy = zeros(bit1, length(snr));
ber_faded = zeros(bit1, length(snr));

for  packets = 1:1:no_of_packets,

   bpsk_symbols1 = - (2 * (randn(1, packet_length) > 0) - 1);
   bpsk_symbols2 = - (2 * (randn(1, packet_length) > 0) - 1);
   bpsk_symbols3 = - (2 * (randn(1, packet_length) > 0) - 1);
   bpsk_symbols4 = - (2 * (randn(1, packet_length) > 0) - 1);
   bpsk_symbols5 = - (2 * (randn(1, packet_length) > 0) - 1);
   bpsk_symbols6 = - (2 * (randn(1, packet_length) > 0) - 1);
   bpsk_symbols7 = - (2 * (randn(1, packet_length) > 0) - 1);
```

```
bpsk_symbols =    [ bpsk_symbols1;
                    bpsk_symbols2;
                    bpsk_symbols3;
                    bpsk_symbols4;
                    bpsk_symbols5;
                    bpsk_symbols6;
                    bpsk_symbols7 ] ;


  % Spreading
  cdma_code = pn_code * bpsk_symbols;

  % Declaring complex fading
  fading_real = randn(1,packet_length);
  fading_imag = randn(1,packet_length);
  pre_fading_mag = sqrt(fading_real.^2 + fading_imag.^2);
  fading_mag = pre_fading_mag ./ mean(pre_fading_mag);
  fading = fading_mag .* exp (sqrt(-1) .* atan(fading_imag ./ fading_real));

  cdma_faded = cdma_code .* repmat(fading,[bit1 1]);

  signal_power = var (cdma_code);

  for i = 1: length(snr);

    noise_power = signal_power ./ (10 .^ (snr(i) / 10));
    noise = sqrt(noise_power) .* (randn(1, packet_length) + sqrt(-1) * randn(1, packet_length));

    % Implementation without fading
    cdma_noisy = cdma_code + repmat(noise, [bit1 1]);

    % Implementation with both fading & noise
    cdma_noisy_faded = cdma_faded + repmat(noise, [bit1 1]);

    % Detection
    cdma_rec_noisy = pn_code' * cdma_noisy;
    cdma_rec_faded = pn_code' * cdma_noisy_faded;

    % ZF fading equalization
    cdma_rec_faded = cdma_rec_faded ./ repmat(fading,[bit1 1]);

    % Detection using de-correlation receiver
    cdma_rec_noisy1 = (pn_code' * pn_code) \ cdma_rec_noisy;
    cdma_rec_faded1 = (pn_code' * pn_code) \ cdma_rec_faded;

    % Slicing
    post_cdma_noisy = (cdma_rec_noisy1 >= 0.0) + (cdma_rec_noisy1 < 0) * (-1);
    post_cdma_faded = (cdma_rec_faded1 >= 0.0) + (cdma_rec_faded1 < 0) * (-1);

    % Detected_symbols
    detected_bits_noisy = (post_cdma_noisy == -1); %implementation without fading
    detected_bits_faded = (post_cdma_faded == -1); %implementation with fading & noise
```

```
        binary_seq = (bpsk_symbols == -1);

        bit_errors_noisy(:, i) = sum(xor(detected_bits_noisy, binary_seq) , 2);
        bit_errors_faded(:, i) = sum(xor(detected_bits_faded, binary_seq) , 2);

    end;


    ber_noisy = ber_noisy + bit_errors_noisy ./ length(binary_seq);
    ber_faded = ber_faded + bit_errors_faded ./ length(binary_seq);

end;

% Determining "bit error rate(BER)" without fading
ber_noisy1 = ber_noisy / no_of_packets;

% For user-1
user1_noisy = ber_noisy1(1,:);

% Determining "bit error rate(BER)" with fading & noise
ber_faded1 = ber_faded / no_of_packets;

% For user-1
user1_faded = ber_faded1(1,:);

figure(1);
semilogy(snr, user1_noisy);
title('BER versus SNR for BPSK with CDMA considering only noise');
xlabel('SNR in dB');
ylabel('Bit Error Rate');
ylim([1e-6 1]);
xlim([1 40]);


figure(2);
semilogy(snr, user1_faded);
title('BER versus SNR for BPSK with CDMA considering fading');
xlabel('SNR in dB');
ylabel('Bit Error Rate');
ylim([1e-6 1]);
xlim([1 40]);

toc
```

B.2 MATLAB code for single user CDMA system implementing Alamouti's Space Time Block Code technique (Tx = 2, Rx = 2)

```
% Both Antenna with CDMA
% Accomplished by – M. Shahriar Mamun, Jamil Hussain, Md. Hasibul Haque


clc;
clear all;
close all;

tic;

amp =1;
N = 280;
biterr1=zeros(1,30);

biterr_cdma1 = zeros(1, 30);
Blocks = 1e7;

NoTx = 2;
NoRx = 2;

cs1 = [-1 -1 1 1 -1 1 -1];

for d=1:Blocks,
  for SNR=1:30   % loop for different SNRs

    fac = 10^(SNR/10);
    sig = sqrt(1/(fac));

    % Generation of Two DS-CDMA sequences
    q = amp * (2 * (randn(1, N/14) >= 0.5) - 1);
    s22(1:1:N/2) = repmat(q', 1, 7)';

    % Multiplying with Chip sequence
    s21_cs = s22 .* repmat(cs1, 1, (N/14));

    % Adding the two signals and adding noise;
    s1 = s21_cs;

    % Generation of Two DS-CDMA sequences
    s = amp * (2 * (randn(1, N/14) >= 0.5) - 1);
    s21(1:1:N/2) = repmat(s', 1, 7)';

    % Multiplying with Chip sequence
    s21_cs = s21 .* repmat(cs1, 1, (N/14));
```

```
% Adding the two signals and adding noise;
s2 = s21_cs;
x1(1:2:N) = s1;
x2(1:2:N) = s2;
x1(2:2:N) = -s2;
x2(2:2:N) = s1;

h11 =  sqrt(0.5) * (randn(1,N/14) + sqrt(-1) * randn(1,N/14));
h11(1:2:N) = repmat(h11', 1, 7)';
h11(2:2:N) = h11(1:2:N);
h12 = sqrt(0.5) * (randn(1,N/14) + sqrt(-1) * randn(1,N/14));
h12(1:2:N) = repmat(h12', 1, 7)';
h12(2:2:N) = h11(1:2:N);
h12 = sqrt(0.5) *(randn(1,N/14) + sqrt(-1) * randn(1,N/14));
h12(1:2:N) = repmat(h12', 1, 7)';
h12(2:2:N) = h12(1:2:N);
h21 = sqrt(0.5) * (randn(1,N/14) + sqrt(-1) * randn(1,N/14));
h21(1:2:N) = repmat(h21', 1, 7)';
h21(2:2:N) = h21(1:2:N);
h22 = sqrt(0.5) * (randn(1,N/14) + sqrt(-1) * randn(1,N/14));
h22(1:2:N)  =  repmat(h22', 1, 7)';
h22(2:2:N) = h22(1:2:N);

% Adding Noise to the received signal
ns = sig*randn(1,N) + i*sig*randn(1,N);

% Multiplying Rayleigh channel with the signal and adding noise
t1_r1 = (x1 .* h11) + (x2 .* h12) + ns;
t1_r2 = (-conj(x2) .* h11) + (conj(x1) .* h12) + ns;
t2_r1 = (x1 .* h21) + (x2 .* h22) + ns;
t2_r2 = (-conj(x2) .* h21) + (conj(x1) .* h22) + ns;

xh1 = (conj(h11) .* t1_r1) + (h12 .* conj(t1_r2)) + (conj(h21) .* t2_r1) + (h22 .* conj(t2_r2));
xh2 = (conj(h12) .* t1_r1) - (h11 .* conj(t1_r2)) + (conj(h22) .* t2_r1) - (h21 .* conj(t2_r2));


%Correlation Detector for DS-CDMA;
sh1(1:N/2)  =   xh1(1:2:N) .* repmat(cs1, 1, (N/14));
sh21(1:N/2) =  xh2(1:2:N) .* repmat(cs1, 1, (N/14));


count1 = 1;
count2 = 1;


for iCount = 1:7:N/2,
   sr22(count2) = (real(sum(sh1(iCount:iCount+6)) >= 0) * 2) -1;
   count2 = count2 + 1;
end;


for iCount = 1:7:N/2,
   sr21(count1) = (real(sum(sh21(iCount:iCount+6)) >= 0) * 2) -1;
   count1 = count1 + 1;
```

```
        end;

        %BER of Correlation Detector CDMA-1
        a2_cdma1(SNR) = sum(s21(1:7:N/2) ~= sr21);

        %BER of Correlation Detector CDMA-2
        a1_cdma2(SNR) = sum(s22(1:7:N/2) ~= sr22);

    end;

    %BER of CDMA Channel-1
    biterr1 = biterr1 + a1_cdma2;

    %BER of CDMA Channel-2
    biterr_cdma1 = biterr_cdma1 + a2_cdma1;
end

errrate_cdma1 = biterr1/(N*Blocks/14);
errrate_cdma2 = biterr_cdma1/(Blocks*N/14);


figure;
semilogy(1:30, errrate_cdma1);
title('STBC 2:2 MIMO with CDMA for single user');
xlabel('Signal To Noise Ratio');
ylabel('Bit Error Rate');
legend('Alamouti's Scheme with DS-CDMA (Tx = 2, Rx = 2)');
toc;
```