PERFORMANCE EVALUATION OF DIFFERENT DS-CDMA RECEIVERS USING CHAOTIC SEQUENCES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology
In
VLSI Design & Embedded systems

By

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Department of Electronics & Communication Engineering
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Under the guidance of

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CERTIFICATE

This is to certify that the Thesis Report entitled ***“Performance evaluation of different DS-CDMA receivers using chaotic sequences ”*** submitted by Mr. **G.Venkat Reddy (20507005)** in partial fulfillment of the requirements for the award of Master of Technology degree in Electronics and Communication Engineering with specialization in “VLSI design & Embedded systems” during session 2006-2007 at National Institute Of Technology, Rourkela (Deemed University) and is an authentic work by him under my supervision and guidance.To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

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ACKNOWLEDGEMENTS

First of all, I would like to express my deep sense of respect and gratitude towards my advisor and guide **Prof. S.K.Patra**, who has been the guiding force behind this work. I am greatly indebted to him for his constant encouragement, invaluable advice and for propelling me further in every aspect of my academic life. His presence and optimism have provided an invaluable influence on my career and outlook for the future. I consider it my good fortune to have got an opportunity to work with such a wonderful person.

Next, I want to express my respects to **Prof. G.S.Rath, Prof.G.Panda, Prof. K.K. Mahapatra,** and **Dr. S. Meher** for teaching me and also helping me how to learn. They have been great sources of inspiration to me and I thank them from the bottom of my heart.

I would like to thank all faculty members and staff of the Department of Electronics and Communication Engineering, N.I.T. Rourkela for their generous help in various ways for the completion of this thesis.

I would also like to mention the name of **T.G.Mutyala Rao** for helping me a lot during the thesis period.

I would like to thank all my friends and especially my classmates for all the thoughtful and mind stimulating discussions we had, which prompted us to think beyond the obvious. I’ve enjoyed their companionship so much during my stay at NIT, Rourkela.

I am especially indebted to my parents for their love, sacrifice, and support. They are my first teachers after I came to this world and have set great examples for me about how to live, study, and work.

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CONTENTS

ABSTRACT

Direct sequence-code division multiple access (DS-CDMA) technique is used in cellular systems where users in the cell are separated from each other with their unique spreading codes. In recent times DS-CDMA has been used extensively. These systems suffers from multiple access interference (MAI) due to other users transmitting in the cell, channel inter symbol interference (ISI) due to multipath nature of channels in presence of additive white Gaussian noise(AWGN). Spreading codes play an important role in multiple access capacity of DS-CDMA system. M-sequences, gold sequences etc., has been traditionally used as spreading codes in DS-CDMA. These sequences are generated by shift registers and periodic in nature. So these sequences are less in number and also limits the security.

This thesis presents an investigation on use of new type of sequences called chaotic sequences for DS-CDMA system. These sequences are generated by chaotic maps. First of all, chaotic sequences are easy to generate and store. Only a few parameters and functions are needed even for very long sequences. In addition, an enormous number of different sequences can be generated simply by changing its initial condition. . Chaotic sequences are deterministic, reproducible, uncorrelated and random-like, which can be very helpful in enhancing the security of transmission in communication. This Thesis investigates the performance of chaotic sequences in DS-CDMA communication systems using various receiver techniques.

Extensive simulation studies demonstrate the performance of the different linear and nonlinear DS-CDMA receivers like RAKE receiver, matched filter (MF) receiver, minimum mean square error (MMSE) receiver and Volterra receiver using chaotic sequences and the performance have been compared with gold sequences.

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ACRONYMS AND ABBREVIATIONS

AWGN	additive white Gaussian noise
BER	bit error ratio
BPSK	binary phase shift keying
CDMA	code division multiple access
CIR	carrier to interference ratio
CLB	chip level based
FIR	finite impulse response
FLANN	Functional link artificial neural network
DS	direct sequence
ISI	inter symbol interference
LMS	least mean square
LOS	line of sight
LPI	low probability of interception
MAI	multiple access interference
MF	matched filter
MMSE	minimum mean square error
MUD	multi user detection
PG	processing gain
PPB	preprocessing based
PN	pseudonoise
PSD	power spectral density
RLS	recursive least square
SNR	signal to noise ratio
SS	spread spectrum
SSMA	spread spectrum multiple access
TDL	tapped-delay-line
VS	Volterra series

NOMENCLATURE

f_{chip}	chip frequency
T_{bit}	bit period
$x(n)$	data bits
M	length of spreading sequence
$S_D(f)$	Power spectral density of the original unspread signal
$S_{SS}(f)$	Power spectral density of the spreading sequence
g_P	Processing gain
W_{SS}	Bandwidth of spread signal
W_D	Bandwidth of Data signal
T_{chip}	chip time period
σ^2	Noise power
$s(kL+n)$	transmitted signal
$C_{i,n}$	ith bit of nth user
$x_i(k)$	data bit of ith user
f_0	coherence bandwidth
T_0	coherence time
$S(\tau)$	multipath intensity profile
$\underline{y}(n)$	received signal vector
ω	Tap weight vector
$\tilde{x}(n)$	soft output
$\hat{x}(n)$	hard estimate
L	tap weights
F	transformation mapping function
r	bifurcation parameter
C_k	Binary sequences
C_d	Spreading sequence vector of the desired user d
$\hat{D}$	The estimated transmitted bit of the desired user *d*

$\mathbf{y}$	received signal
H_{ch}	multipath channel
f_{Pen}	penalty function,
N_{train}	number of training bits
e(k)	the error associated with filter output y(k).
µ	Step size
$v(kN+n)$	output for the kth symbol of length N with n
$y(kN+n)$	The filter input
v (k)	Volterra expanded sequence

Chapter-1

INTRODUCTION

1.1INTRODUCTION

Spread spectrum techniques have been wildly used in wired and wireless communications. The spreading of the signal spectrum gives us many advantages such as robustness against interference and noise, low probability of intercept, realization of Code Division Multiple Access(CDMA) and so on. In order to spread the bandwidth of the transmitting signals, pseudo-noise (PN) sequences have been used extensively in spread-spectrum communication systems [1]. Obviously, the maximal length shift register sequences (M-sequences) and Gold sequences are the most popular spreading sequences in spread spectrum systems. This Thesis presents chaotic sequences as spreading sequences in DS/CDMA system. The main advantages of such usage are increased security of the data transmission and ease of generation of a great number of chaotic sequences[2]. Since the PN DS/SS systems are not considered the best choice of the message being transmitted, a more effective method, the chaotic DS/SS system, is therefore proposed. In the thesis, the focus of the study is heavily built upon the theory of chaos. Among the advantages of the use of chaotic sequences in DS/SS are the availability of a great numbers, the ease of their generation, and their inherent improvement in the security of transmission. These fascinating features of the chaotic DS/SS system make itself an alternative to PN sequences in terms of generating more effective codes.

The chapter begins with an exposition of the principal motivation behind the work undertaken in this thesis. Following this, section 1.3 provides a brief literature survey on Chaos background. Section 1.4 outlines the contributions made in this thesis. At the end, section 1.5 presents the thesis layout.

1.2 MOTIVATION OF WORK

In order to spread the bandwidth of the transmitting signals, the binary pseudo-noise (PN) sequences[3] have been used extensively in spread spectrum communication (SS) systems. It is a deterministic, periodic signal that is known to both transmitter and receiver, whose appearance has the statistical properties of sampled white noise. It appears, to an unauthorized listener, to be a similar to those of white noise. Therefore, it is not easily intercepted by adversary.

Much research has been done over the past decades in order to analyze the properties of these sequences and to try to find easier ways to generate the most effective codes. Obviously, the maximal length shift register sequences (M-sequences) and Gold sequences are the most popular spreading sequences in spread spectrum systems. The M-sequences are the longest codes that can be generated with given a shift register of fixed length, that have relatively smaller cross-correlation values than the peak magnitude that restrict regretfully to their number. The m-sequences have very desirable autocorrelation properties. However, large spikes can be found in their cross-correlation functions, especially when partially correlated. Another limiting property of m-sequences is that they are relatively small in number. Therefore, the number of sequences is usually too small and not suitable for spread spectrum systems. Furthermore, another method for generating PN sequences with better periodic cross-correlation properties than M-sequence has been developed by Gold [4]. The Gold sequences are constructed by taking a pair of specially selected M-sequences.

The set of sequences having zero auto-correlation and cross-correlation plays an important role in typical DS-CDMA systems. A periodic sequence with zero out-of-phase is called a perfect or an orthogonal sequence, it can mitigate the multi-path interference. Similarly, a set of periodic sequences with zero cross-correlation values is set of uncorrelated sequences. However, it is impossible to be found in single sequence spreading code. Recently some researchers have given up the use of M-sequences and gone for instead random binary sequences. Although the correlation properties of these sequences are not as desirable as the ones of M-sequences, which is superior to traditional code in particular designated.

Even the problem of the number of PN sequences was neglected; there is yet another shortcoming of the conventional DS/SS systems that has not been solved. The use of any specific kind of binary spreading sequences means that squaring the spread signal would remove the signature sequence filtering out only the outspread modulated carrier. That is, the communication is easily intercepted by adversary receivers.

The concept of pseudo-noise sequences, even M sequence and Gold code have been comment on what the native properties of security and number be not considered the best choice of the message being transmitted. This thesis uses a different type of spreading sequence for use in DS-SS systems called chaotic sequences. These sequences are created using discrete, chaotic maps [5]. The sequences so generated with both Logistic map and Tent Map as well-known, even though completely deterministic and initial sensitive, have characteristics similar to those of random noise. Surprisingly, the maps can generate large numbers of these noise-like sequences having low cross-correlations. The evaluated performance of the systems will be compared in the presence of additive white Gaussian noise noise(AWGN) for difference number of users. The noise-like feature of the chaotic spreading code is very desirable in a communication system. This feature greatly enhances the LPI (low probability of intercept) performance of the system.

1.3 BACKGROUND LITERATURE SURVEY

In the past few decades, there has been a great deal of interest in the study of non-linear dynamical system from which chaos developed [6]. The diverse applications of chaos to various areas are growing. However, not until the past ten years that chaos is of great interest in communication and more research are undergoing in either theory or practice.

The most significant feature of the chaotic system is its sensitively dependence on its initial condition. It is properly illustrated by the finding of Professor E.N. Lorenz, teaching Meteorology at MIT. In 1961, Prof. Lorenz attempted to solve a much-simplified model and finally he did succeed in simulating real weather patterns for weather predictions. However, something drew his attention: when he slightly changed the initial conditions in the model, the resulting weather patterns changed completely after a very short period. He discovered the fact that very simple differential equations could possess sensitive dependence on initial conditions. Through the sensitive dependence of chaotic systems on their initial conditions, a large number of uncorrelated, random-like, yet deterministic and reproducible signals can be generated. Moreover, since chaotic dynamical system is a deterministic system, disguising modulation as noise would be easily made upon its random-like behavior.

Another very interesting application of the chaotic sequences appears in communications, because those sequences have the properties required for spread spectrum (SS). The SS is a modulation technique that the information is spreaded in frequency by a sequence of bits, here called chips, totally independent of the information. The great advantage of this kind of modulation is that, it permits different users to communicate in the same band of frequency and at the same time. In this work, we will spread the information by using a periodic pseudo-sequence. This modulation is called direct sequence spread spectrum (DS-SS). The use of chaotic sequences for spectral spreading in a direct-sequence spread spectrum system (DS/SS) has been shown to provide several advantages over conventional binary sequences, particularly pseudonoise sequences which are frequently used in digital communication.

The most important characteristics of the periodic sequence are: the autocorrelation and the cross-correlation. The autocorrelation is important in the synchronization between the periodic pseudo-sequence generated at the transmitter and at the receiver. The cross-correlation of the periodic pseudo-sequences must be zero to obtain communication between different users at the same band of frequency and at the same time.

1.4 OBJECT OF THE WORK

The work proposed here intends to test the chaotic sequence based DS-CDMA system[7] for different receiver techjniques. This thesis presents an investigation on use of new type of sequences called chaotic sequences for DS-CDMA system. These sequences are generated by chaotic maps. First of all, chaotic sequences are easy to generate and store. Only a few parameters and functions are needed even for very long sequences. In addition, an enormous number of different sequences can be generated simply by changing its initial condition. . Chaotic sequences are deterministic, reproducible, uncorrelated and random-like, which can be very helpful in enhancing the security of transmission in communication.

In this work it is proposed to carry out the following studies.

Implementation of chaotic sequences for the DS-CDMA downlink receiver.

Investigate BER performance of different linear and nonlinear receivers for DS-CDMA system using chaotic sequences and comparison with gold sequences.

1.5 THESIS OUTLINE

This thesis is organized into six chapters. Following this introduction, Chapter 2 provides a more detail discuss on DS-CDMA system. Chapter 3 discusses the background of chaotic nonlinear systems and generation of chaotic sequences. In Chapter 4, various linear receivers like Matched filter, MMSE receiver etc., are studied and BER performance of different linear receivers using chaotic sequences is evaluated and it is compared with the receivers using gold sequences. Following these BER performances of various nonlinear receivers using chaotic sequences has been analyzed in Chapter 5. Finally Chapter 6 provides concluding remarks and future work.

Chapter-2

DS-CDMA SYSTEM AND OVERVIEW

2.1 INTRODUCTION

In this section the principle of spread spectrum and its application in multiple access is discussed. Multiple access schemes are used to allow many mobile users to share simultaneously a finite amount of radio channels in a fixed radio spectrum. The sharing of the spectrum is required to achieve high capacity by simultaneously allocating the available bandwidth to multiple users.

Following this introduction, spread spectrum (SS) communication technique is discussed in the section 2.2. The application of this SS technique to produce a multiple access system is described in the section 2.3. The section 2.4 deals with the construction of a simplified form of a baseband signal to be transmitted, while section 2.5 considers the effects of multipath channel on this signal. Section 2.6 discusses the simplest receiver structure using matched filter (MF). Principle structure of multiuser detector is described in section 2.7. While generation of Gold sequence is discussed in section 2.8 and the chapter ends with the concluding remark.

2.2 SPREAD SPECTRUM COMMUNICATION TECHNIQUES

As a simple, expansion of the bandwidth is not sufficient to be termed as the spread spectrum, but the bandwidth expansion must be accomplished with the separate signature, or known as spreading sequence. Both transmitter and the receiver know this spreading sequence. It is also independent of the data bits [8]. All the sequences are randomly distributed, and there is no correlation between any two sequences.

Let the sequence of data bits x (n) have the period T_{bit} and the spreading sequence of length M (in this work we have taken a spreading sequence of length 31) generally called chips to distinguish them from the data bits have the frequency f_{chip} where $f_{chip} >> (1/T_{bit})$. In other words it is assumed that $f_{chip} >> f_{bit}$.

From the above assumption that the transmitted data is random and independent, the power spectral density of the original unspread signal is given by [9]

$$S_D(f) = T_{bit}\left(\frac{\sin \pi f T_{bit}}{\pi f T_{bit}}\right)^2 \tag{2.1}$$

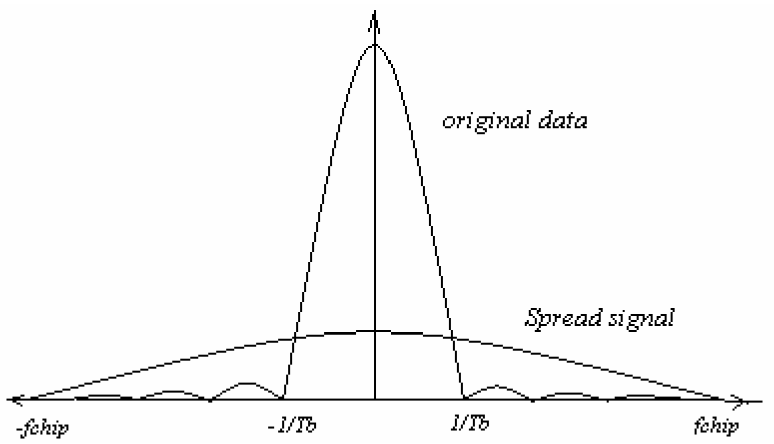


Figure 2.1: Spread spectrum concept in frequency domain

And assuming that spreading sequence is pseudorandom in nature, and is given by

$$S_{SS}(f) = \frac{1}{f_{chip}} \left(\frac{\sin \pi f / f_{chip}}{\pi f / f_{chip}} \right)^2 \qquad (2.2)$$

The relationship between the above spectral densities is sketched in the Figure 2.1.

The increased in performance due to the bandwidth expansion and contraction process is termed as processing gain g_P .This processing gain can be represented as the ratio of bandwidth associated with the spread signal W_{SS} and that of the data signal W_D .

$$g_P = \frac{W_{SS}}{W_D} = \frac{T_{bit}}{T_{chip}} \qquad (2.3)$$

The processing gain (PG) is normally expressed in decibel form as

$$G_P=10 \log_{10} (g_P) \qquad (2.4)$$

The SS signal is largely tolerant to external interfering factors, there will be degradation in performance as the number of SS signals in the same cell increases.

. To make a good comparison, the background noise is expressed in terms of a modified form of signal to noise ratio (SNR), it takes account the processing gain.

$$\frac{E_b}{N_0} = 10 \log_{10} \left(g_P / 2\sigma^2 \right) \qquad (2.5)$$

Where E_b/N_0 is the signal to Gaussian noise ratio, and σ^2 is the Gaussian noise variance.

2.3 DS-CDMA TRANSMITTER PRINCIPLES

The simplest transmitter for downlink of a DS-CDMA is shown in the Figure 2.3. The transmitted signal $s(kL+n)$, at time $t = nT_{\text{bit}}$ is constructed by coherently summing the spreading sequence of each user, $C_{i,n}$ by that users bit $x_i(k)$ over all active users , to give

$$s(kL+n) = \sum_{i=1}^{U} C_{i,n}\, x_i(\text{k}) \qquad (2.6)$$

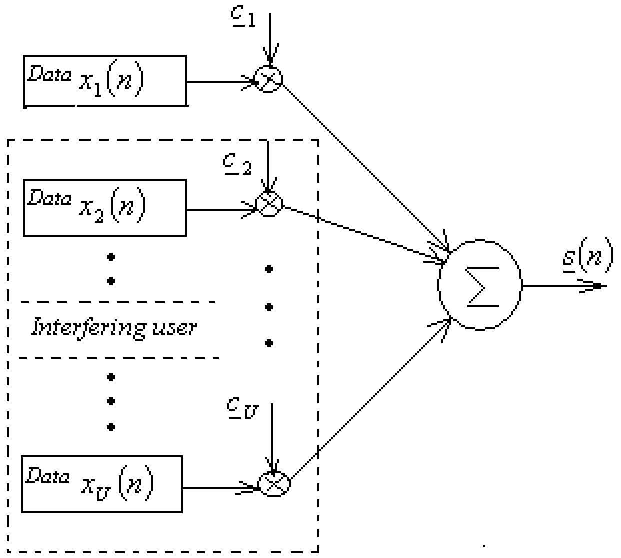


Figure 2.2: Simplified synchronous DS-CDMA downlink transmitters for U active users

In the uplink case the process is same except that the users are no longer synchronized, and which is modeled by inserting user-specific time delay on the resulting spread signal.

2.4 MULTIPATH CHANNEL BACKGROUND

The received signal consists of direct line of site (LOS) components and a few non LOS components. In addition to background noise, the received signal consists of a combination of individual reflected signals from the obstacles, like buildings etc, between the transmitter and the receiver and those arrives at various delays, according to the length of each associated RF paths [10]. This situation is called multipath channel. This is also time varying, due to the motion of the receiver with respect to the transmitter.

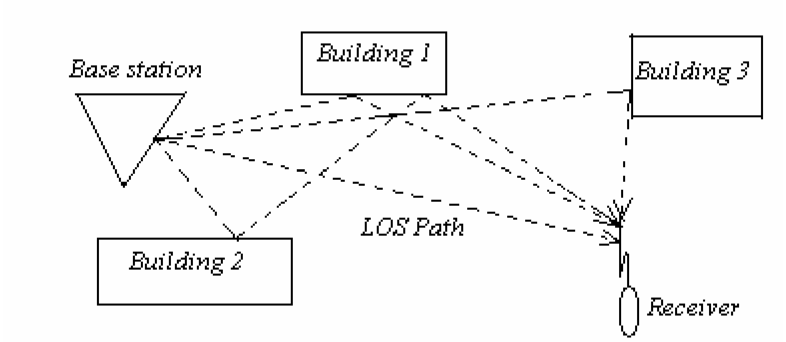


Figure 2.3: Example of multipath, the received signal consists of many reflections and delayed versions of the transmitted signal.

2.4.1 Channel effects

There are two main parameters of the channel, first is the range of frequency over which the channel effects remain same, called the coherence bandwidth, denoted as f_0, and the time duration over which the channel response is invariant is called the coherence time and denoted as T_0. These may be calculated from the two dual functions S(τ), the multipath intensity profile and S(ν), the Doppler power spectral density, which are the measure of the received signal power as the function of delay time τ and the Doppler shift ν respectively.

2.5 DS-CDMA RECEIVER PRINCIPLES

The work of the receiver is to recover the data x(n) by converting the spectrum of the received signal vector $\underline{y}(n)$. This is done by multiplying the received signal with the required spreading sequence, which is generated locally by the receiver. The received signal, consisting of M_r chips is passed to the block of delay elements, where Z^{-1} represents a delay of one chip, until the complete M_r chip signal has been read. These values are then passed to multiplier block in parallel, which forms the scalar product of $\underline{y}(n)$ and the tap weight vector $\underline{\omega} \in C^{M_r}$, where M_r is the number of tap weights, in this Figure 2.4 it is 8. This finite impulse response block produces a soft output $\tilde{x}(n)$, which is then passed through the decision block to give a hard estimate, $\hat{x}(n)$, of the original data bit x(n).

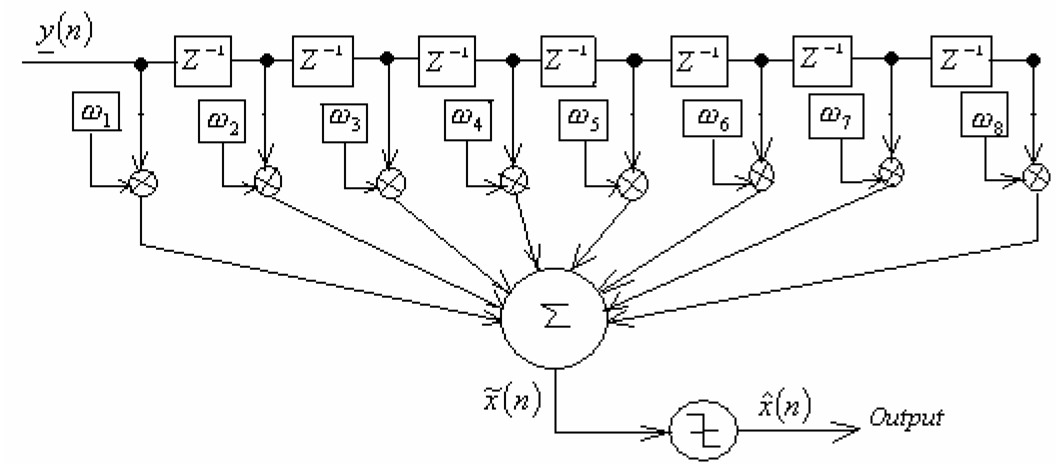


Figure 2.4: DS-CDMA correlator receiver with 8 tap weights

This is the structure of simplest receiver, commonly known as MF receiver with L tap weights $W_n : 1 \le n \le L$, matched to the original spreading sequence of the desired user. In practice, synchronization of the chip level signal is a highly non-trivial process. The performance of this receiver has been shown to degrade considerably as the number of simultaneously transmitting users increases . Hence improving the capacity of SS systems is achieved either by reducing the total interference by enhancing the single user detection methods or by making use of multiple access interference (MAI) through improved interference cancellation or multiuser detection technique (MUD).

2.6 PSEUDO NOISE (PN) DS/SS SYSTEM

Spread spectrum signals for digital communications were originally invented for military communication, but nowadays are used to provide reliable communication in a variety of commercial applications including mobile and wireless communications, which provide resistance to hostile jamming, hide the signal by transmitting it at low power, or make it possible for multiple users to communicate through the same channel. .In conventional DS/SS, in order to spread the bandwidth of the transmitting signals, the binary pseudo-noise (PN) sequences have been used extensively in spread spectrum communication (SS) systems. It is a deterministic, periodic signal that is known to both transmitter and receiver, whose appearance has the statistical properties of sampled white noise. It appears, to an unauthorized listener, to be a similar to those of white noise. Therefore, it is not easily intercepted by adversary.

The basic elements of a pseudo-noise DS/SS systems are illustrated in Figure 1 as the following.

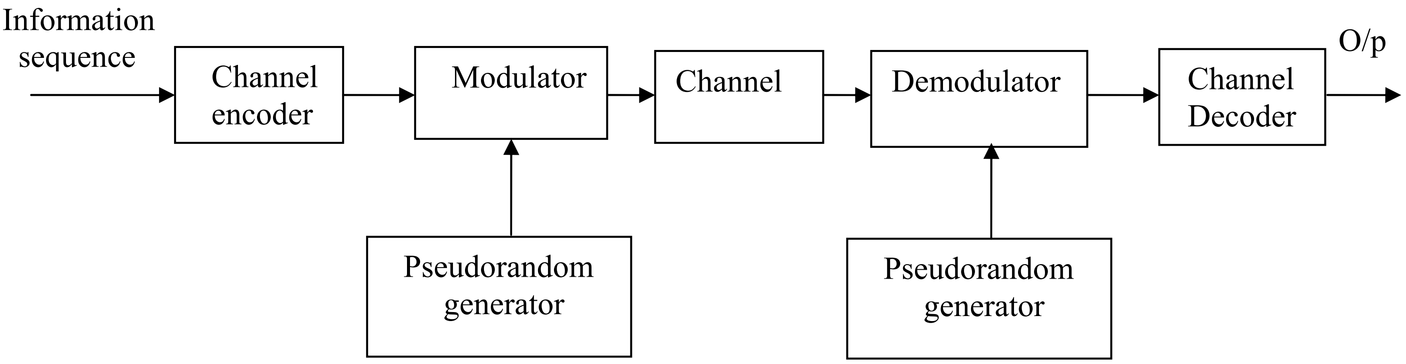


Figure 2.5 PN DS/SS system

The channel encoder and decoder, the modulator and demodulator are the basic elements of a conventional digital communication system. The two pseudorandom generators, interfacing with the modulator and demodulator, were employed by the spread spectrum system to produce a pseudorandom or pseudonoise (PN) binary-valued sequence that is used to spread the transmitted signal in frequency at the modular and to despread the received signal at the demodulator.

2.7 PSEUDO-RANDOM SEQUENCES

A pseudorandom(PN) sequence is a code sequence of 1's and 0's whose autocorrelation has properties similar to those of white noise. Some of the popular PN sequences are Maximal length shift register sequences(m-sequences), gold sequences etc.,

2.7.1 Maximal length shift register Sequence (m-sequence)

Maximal length shift register sequences are by definition, the longest codes that can be generated by a given shift register or a delay element of a given length. In binary shift register sequence generators, the maximum length sequence is 2^n-1 chips, where n is the number of stages in the shift register. A shift register sequence generator consists of a shift register working in conjunction with appropriate logic, which feeds back a logical combination of the state of two or more of its stages to input. The output of a sequence generator, and the contents of its n stages at any sample (clock) time, is a function of the outputs of the stages

Number Of Stages	**Code Length**	**Maximal Taps**
2	3	[2,1]
3	7	[3,1]
4	15	[4,1]
5	31	[5,2][5,4,3,2][5,4,2,1]
6	63	[6,1][6,5,2,1][6,5,3,2]
7	127	[7,1][7,3][7,3,2,1][7,4,3,2] [7,6,4,2][7,6,3,1][7,6,5,2][7,6,5,4,2,1][7,5,4,3,2,1]
8	255	[8,4,3,2][8,6,5,3][8,6,5,2] [8,5,3,1][8,6,5,2][8,7,6,1] [8,7,6,5,2,1][8,6,4,3,2,1]
9	511	[9,4][9,6,4,3][9,8,5,4][9,8,4,1] [9,5,3,2][9,8,6,5][9,8,7,2] [9,6,5,4,2,1][9,7,6,4,3,1] [9,8,7,6,5,3]
10	1023	[10,3][10,8,3,2][10,4,3,1][10,8,5,1] [10,8,5,4][10,9,4,1][10,8,4,3] [10,5,3,2][10,5,2,1][10,9,4,2]
11	2047	[11,1][11,8,5,2][11,7,3,2][11,5,3,5] [11,10,3,2][11,6,5,1][11,5,3,1] [11,9,4,1][11,8,6,2][11,9,8,3]
12	4095	[12,6,4,1][12,9,3,2][12,11,10,5,2,1] [12,11,6,4,2,1][12,11,9,7,6,5] [12,11,9,5,3,1][12,11,9,8,7,4] [12,11,9,7,6,][12,9,8,3,2,1] [12,10,9,8,6,2]
13	8191	[13,4,3,1][13,10,9,7,5,4] [13,11,8,7,4,1][13,12,8,7,6,5] [13,9,8,7,5,1][13,12,6,5,4,3] [13,12,11,9,5,3][13,12,11,5,2,1] [13,12,9,8,4,2][13,8,7,4,3,2]
14	16,383	[14,12,2,1][14,13,4,2][14,13,11,9] [14,10,6,1][14,11,6,1][14,12,11,1] [14,6,4,2][14,11,9,6,5,2] [14,13,6,5,3,1][14,13,12,8,4,1] [14,8,7,6,4,2][14,10,6,5,4,1] [14,13,12,7,6,3][14,13,11,10,8,3]
15	32,767	[15,13,10,9][15,13,10,1][15,14,9,2] [15,1][15,9,4,1][15,12,3,1][15,10,5,4] [15,10,5,4,3,2][15,11,7,6,2,1] [15,7,6,3,2,1][15,10,9,8,5,3] [15,12,5,4,3,2][15,10,8,7,5,3] [15,13,12,10][15,13,10,2][15,12,9,1] [15,14,12,2][15,13,9,6][15,7,4,1] [15,4][15,13,7,4]

Table 2.1: Feedback connections for linear m-sequences

fed back at the preceding sample time. Feedback connections have been tabulated for maximal code generators for 3 to 15 stages and listed in Table 3.1.

Implementation

Linear feedback shift registers (LFSR) can be implemented in two ways. The Fibonacci implementation consists of a simple shift register in which a binary-weighted modulo-2 sum of the taps is fed back to the input. (The modulo-2 sum of two 1-bit binary numbers yields 0 if the two numbers are identical and 1 if they differ: 0+0=0, 0+1=1, 1+1=0.)

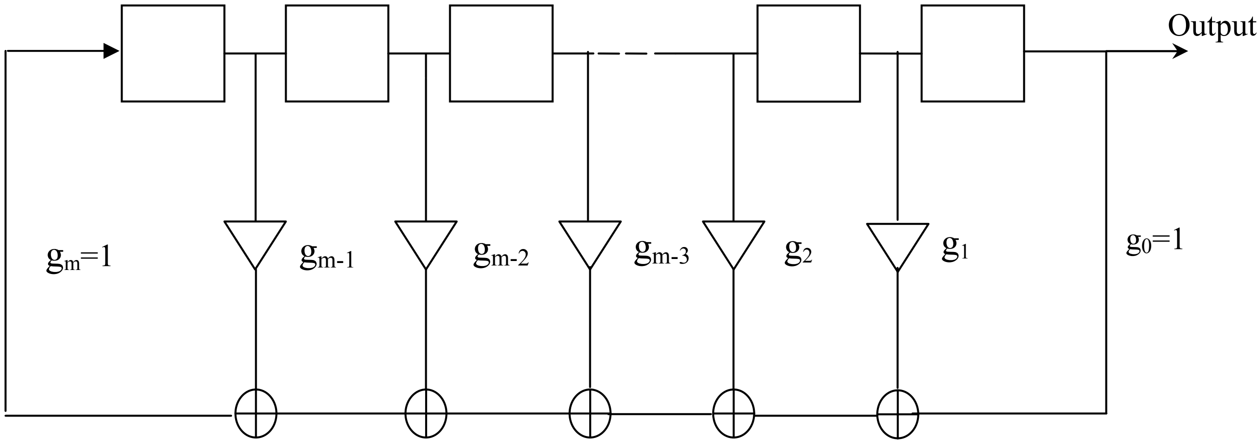


Figure 2.6: Fibonacci implementation of LFSR

For any given tap, weight g_i is either 0, meaning "no connection," or 1, meaning it is fed back. Two exceptions are g_0 and g_m, which are always 1 and thus always connected. Note that g_m is not really a feedback connection, but rather is the input of the shift register. It is assigned a feedback weight for mathematical purposes. The Galois implementation consists of a shift register, the contents of which are modified at every step by a binary-weighted value of the output stage.

2.7.2 Gold sequences

For CDMA applications, m-sequences are not optimal. For CDMA, we need to construct a family of spreading sequences, one for each which, in which the codes have well-defined cross-correlation properties. In general, m-sequences do not satisfy the criterion. One popular set of sequences that does are the Gold sequences. Gold sequences are attractive because only simple circuitry is needed to generate a large number of unique codes.

A Gold sequence is constructed by the XOR of two m-sequences with the same clocking. Figure 2.7 shows the schematic for Gold code generation.

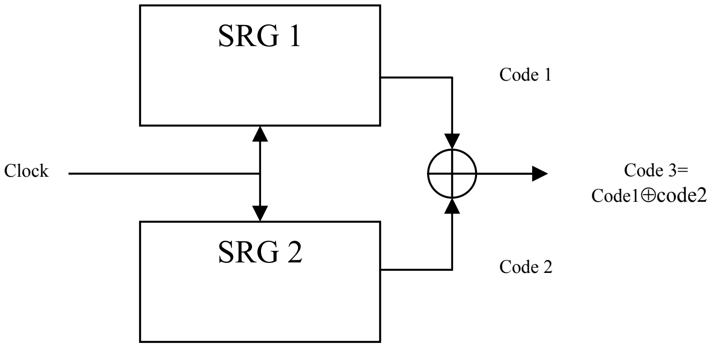


Figure 2.7: Gold code sequence generator configuration

To achieve increased capacity, at an expense of altering the correlation properties slightly, a pair of m-sequences may be used to generate a set of Gold sequence , which have the property that the cross-correlation is always equal to –1, when the phase offset is zero. Non-zero phase offset produces a correlation value from one of the three possible values. In this work a pair of specially selected m-sequences (where m = 5) is taken, and performing the modulo-2 sum of the two sequences for each of the $L=2^m-1$ cyclically shifted version of one sequence relative to the other sequence. Thus L Gold sequence is generated as illustrated in Figure 2.8.

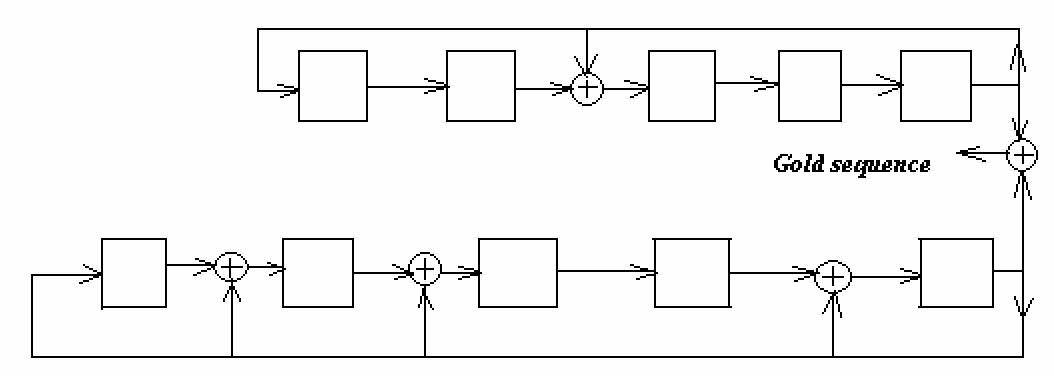


Figure 2.8 Generation of Gold sequences of length 31

In this section we discussed about the basic principles of SS communication and implementation of the DS-CDMA. The transmitter and receiver structure have been discussed. In this section we also reviewed the Gold sequence generation. By far, the maximum-length shift-register sequences (*m*-sequence) are the most widely known binary PN code sequences. The most undesirable property of m-sequence is that they are relatively small in number. For example, for a sequence of $N=63$, there are only 6, and for $N=255$, there are only 16 possible different sequences to use. Therefore, m-sequences are not suitable for PN DS/SS systems.

A generation of Pseudo-noise is core for spread spectrum systems. The classical M-sequences and Gold sequences are not suitable, since their number and security is not friendly to DS-SS systems.

2.8 CONCLUSION

This chapter reviewed the basic principles of SS communications and described the implementational aspects of DS-CDMA. The simplified transmitter structure for downlink scenario has been outlined, the model for communication channel is introduced. Simplest chip level processed MF receiver has been discussed in brief. Process of generation of 31 chip Gold sequence was described at the end.

Chapter-3

INTODUCTION TO CHAOTIC SYSTEMS

3.1 INTRODUCTION

In the past few decades, there has been a great deal of interest in the study of non-linear dynamical system from which chaos developed. The diverse applications of chaos to various areas are growing. However, not until the past ten years that chaos is of great interest in communication and more research are undergoing in either theory or practice.

The most significant feature of the chaotic system is its sensitively dependence on its initial condition. It is properly illustrated by the finding of Professor E.N. Lorenz, teaching Meteorology at MIT. In 1961, Prof. Lorenz attempted to solve a much-simplified model and finally he did succeed in simulating real weather patterns for weather predictions. However, something drew his attention: when he slightly changed the initial conditions in the model, the resulting weather patterns changed completely after a very short period. He discovered the fact that very simple differential equations could possess sensitive dependence on initial conditions.

Following this introduction, Chaotic system is discussed in the section 3.2. The section 3.3 deals with the Chaotic sequences. Chaotic maps like Logistic and Tent map are disucussed in section 3.4. Section 3.5 gives an idea of correlation properties of Chaotic sequences .The generation of binary Chaotic sequences and application of them to DS-CDMA is described in the section 3.6.

3.2 CHAOTIC SYSTEM

A chaotic dynamical system is an unpredictable, deterministic and uncorrelated system that exhibits noise-like behavior through its sensitive dependence on its initial conditions, which generates sequences similar to PN sequence. The chaotic dynamics have been successfully employed to various engineering applications such as automatic control, signals processing and watermarking. Since the signals generated from chaotic dynamic systems are noise-like, super sensitive to initial conditions and have spread and flat spectrum in the frequency domain, it is advantageous to carry messages with this kind of signal that is wide band and has high communication security. Then, numerous engineering applications of secure communication with chaos have been developed.

3.3 CHAOTIC SEQUENCES

A chaotic sequence [11] is non-converging and non-periodic sequence that exhibits noise-like behaviour through its sensitive dependence on its initial condition. Chaotic systems have sensitive dependence on their initial conditions. A large number of uncorrelated, random-like, yet deterministic and reproducible signals can be generated by changing initial value. These sequences so generated by Chaotic systems are called chaotic sequences. Chaotic sequences are real valued sequences. Since the spreading sequence in a Chaotic Spread Spectrum(SS) is no longer binary, the application of the chaotic sequences in DS-CDMA is thus limited. A further attempt to transform continuous values to binary ones by using digital encoding technique is therefore used to adopt it in DS-CDMA. Some criteria are performed. Moreover, since chaotic dynamical system is a deterministic system, disguising modulation as noise would be easily made upon its random-like behavior. The use of chaotic sequences for spectral spreading in a direct-sequence spread spectrum system (DS/SS) has been shown to provide several advantages over conventional binary sequences, particularly pseudo-noise sequences which are frequently used in digital communication.

3.4 CHAOTIC MAPS

This thesis proposes a different type of spreading sequence for use in DS-SS systems called chaotic sequences. Chaotic sequences are created using discrete, chaotic maps. Some of the popular chaotic maps are logistic map , tent map etc., The sequences so generated with both Logistic map[12] and Tent Map[13] as well-known, even though completely deterministic and initial sensitive, have characteristics similar to those of random noise. Surprisingly, the maps can generate large numbers of these noise-like sequences having low cross-correlations. The noise-like feature of the chaotic spreading code is very desirable in a communication system. This feature greatly enhances the LPI (low probability of intercept) performance of the system.

In this thesis, a generation of both logistic and Tent Map is given to extend expressly the range of parameters for chaotic behavior of the map, which is used to develop a chaotic scheme for DS/SS communication systems. These chaotic maps are utilized to generate infinite sequences with different initial parameters to carry different user paths, as meaning that the different user paths will spread spectrum based on different initial condition.

All infinite sequences should be generating by finding the largest parameters sets to similar to noise-like, and correlation is slight relative under different parameters. In typical DS-SS system, the content of spreading code is same code to spreading binary bit stream.

The thesis is out of accord with the traditional use. Per uniform user path, the infinite sequences are dividing into sequential subsets based on spreading factory, as every successive bit stream of input data are spread by corresponding subsets, that a composite subsets by chaotic sequences. Similarly, the out-spreading detector also knew the sequential rule of the subsets code. The spreading schemes passed in all agreeable rules.

3.4.1 Generalization of Logical Map:

One of the simplest and most widely studied nonlinear dynamical systems capable of exhibiting chaos is the logistic map.

$$F(x,r) = rx(1-x) \, , \tag{3.1}$$

or written in its recursive form,

$$x_{n+1}=rx_n(1-x_n) \quad , \quad 0\leq x_n\leq 1 \, , \quad 0\leq r\leq 4 \, , \tag{3.2}$$

here , F is the transformation mapping function, and r is called the bifurcation parameter, that is shown in Figure 3.1 with $2.8 < r < 4$. Depending on the value of r, the dynamics of this system can change attractively, exhibiting periodicity or chaos. The first bifurcation occurs at $r = 3$, leading to a stable period-2 cycle which eventually lose stability, as r« 3.45, giving rise to a stable period-4 cycle. As r increases further, the scenario repeats itself over and over again : each time a period-2^k cycle of the map F loses stability through a bifurcation of the map F-, which gives rise to initially stable period- 2-cycle, where F is often-mentioned logistic map with a periodic point of prime period k.

For $0 < r < r_c$ = 3.57., the sequence $\{x_n\}$ of values of r *at* which cycles of period $2k$ appear has a finite accumulation point r«3.57. For $r_c < r < 4$, the sequence is, for all practical purposes, non-periodic and non-converging. The resultant sequence will be chaotic sequence.

The orbit diagram is an attempt to capture the dynamics of F for different values of r. The orbit of x, under F against the scaling parameter r for an initial condition $x_0=0.1$, as shown in Figure 3.1.

Further, a very interesting and useful feature of chaotic maps is their sensitivity to the initial value x_0, any small disturbance in the value of x_0 results in completely different output sequence.

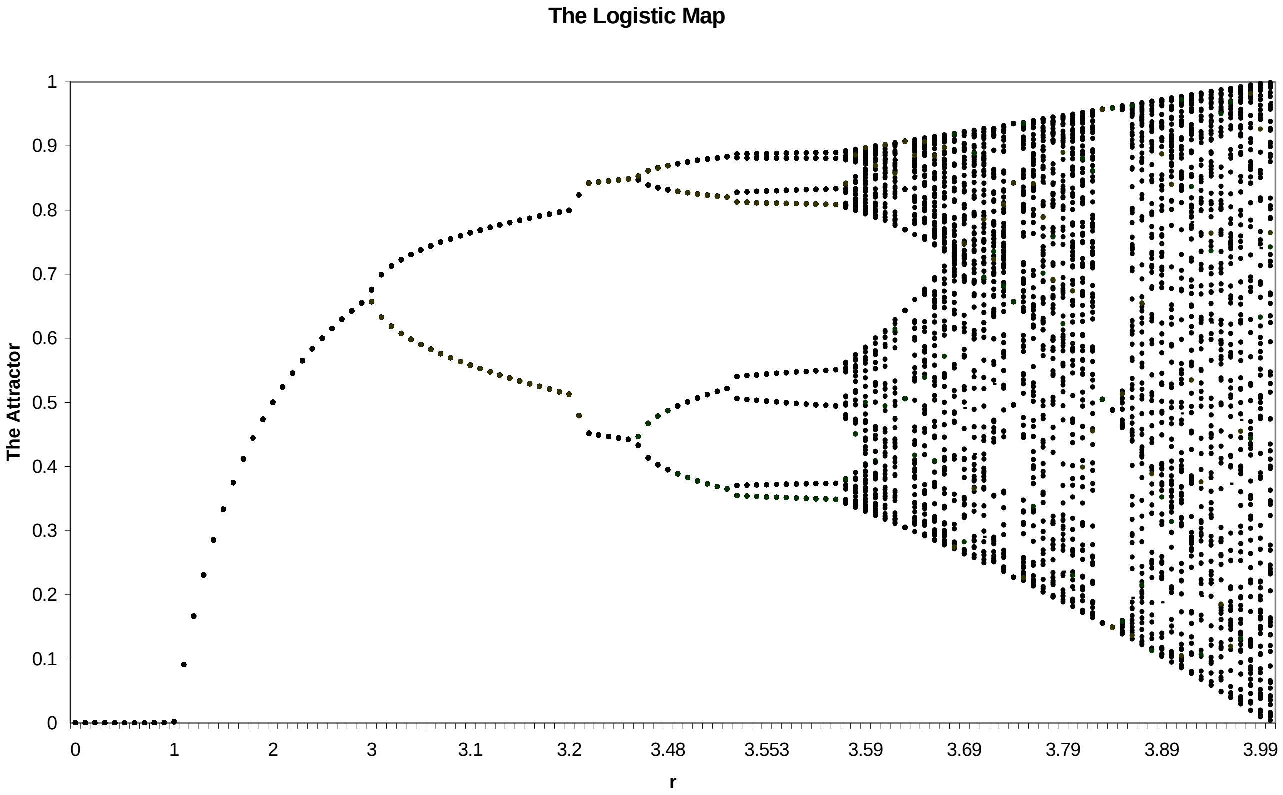


Figure 3.1 Bifurcation diagram of logistic map with initial value x_0=0.1

Simultaneously, it is mathematically proven that , except for negligibly short intervals where the sequence has odd periodicities, this particular range of values of *r* causes the logistic map to be chaotic over {0 ,1}. Figure 3.2 can be used to show that the Logistic map is also chaotic by geometry of the iterated map and restricted to {0, 1} value at *r* = 1. However, further investigation provides that map has indeed, a period-2 cycle for *r* slightly greater than three, equivalently, or fixed point is depicted in this figure.

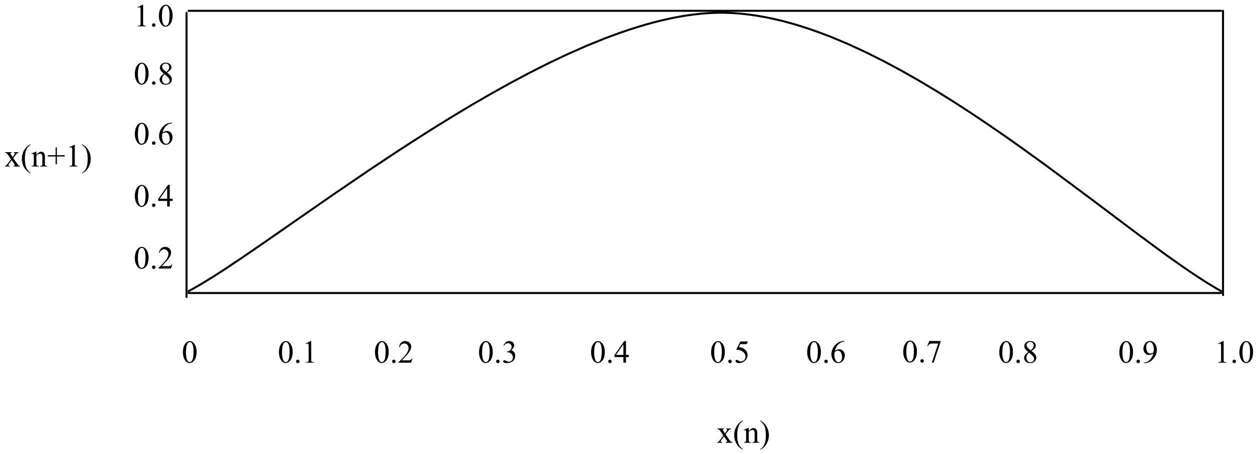


Figure 3.2 Graph of the Logistic function $x_{n+1} = 4x_n (1 - x_n)$ for one dimension

Further, this map has a very sensitive dependence upon its initial value x_0, for those values of r. This sensitive dependence can be illustrated by giving a large initial points range to the iterative map. After a few iterations, the two resulting sequences will look completely uncorrelated. Figure 3.3 illustrates this point. There are three maps that behave in a similar the different dynamical system, whose time domain seems like very chaotic.

3.4.2 Generalization of Tent Map:

The state space description of the first-order generalized Tent map is as follows:

$$x_{n+1} = a - b|x_n - c| \equiv F(x_n) \qquad (3.3)$$

The graph of the function when *a=1, b* =1.99 and *c*=0 is shown in Figure 3.4, that a chaotic map is generated with range {-1, 1}.To find out what range of *a*, *b* and *c* can make this system chaotic for the existence of the period doublings and bifurcation points according to theorem, as follows.

Suppose *F:R→R* is continuous and *F* has periodic point of prime period 3. Then *F* also has periodic points of all other periods and *F* is chaotic. Based on theorem, can drive the map chaotic by examining the solution of the equations $F^k(x) = x$, where *k* is period-*k cycles*, known the parameter range for chaotic map. Based on the theorem, we can easily find the parameters range that can drive the map chaotic by examining the solution of the equation $F^3(x) = x$.

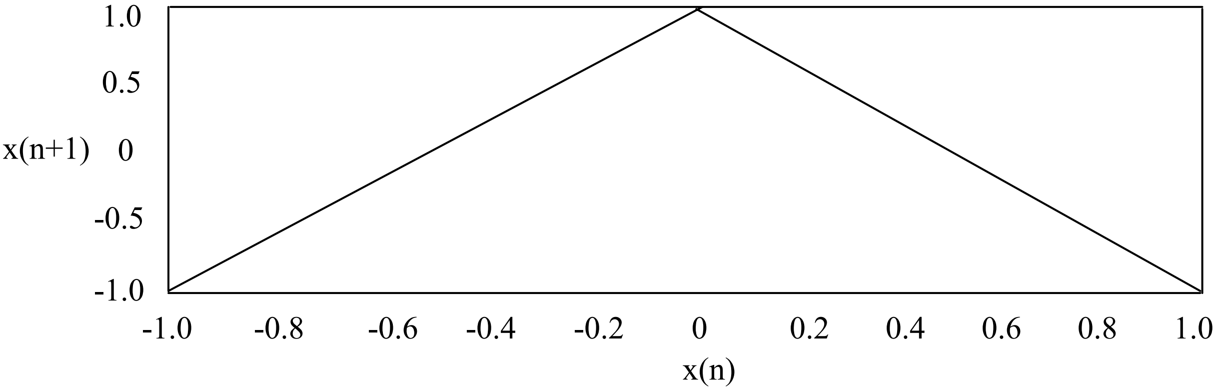


Figure 3.3 Graph of the Tent function $x_{n+1} = 1 - 1.99\,|x_n|$

The apparently chaotic regime comprises infinitely many parameters of that obtained chaotic map in $a \geq 1$, $1.5 \leq b \leq 2$, and $c \leq 1$. For our purpose, we have instructed a few bifurcation diagrams with parameter *b* range. Figure 3.5 is the bifurcation diagram with *a* =1, c=0 and $1.5 \leq b \leq 2$. This map has very wide range of parameter *b* that can make the system have chaotic behavior, which the chaotic sequences value is location on the interval range {-1 1}. Obviously, the number of both ones and negative ones would be judge balanced, the parameter b should have to assign $1.8 \le b \le 2$ ranged useful.

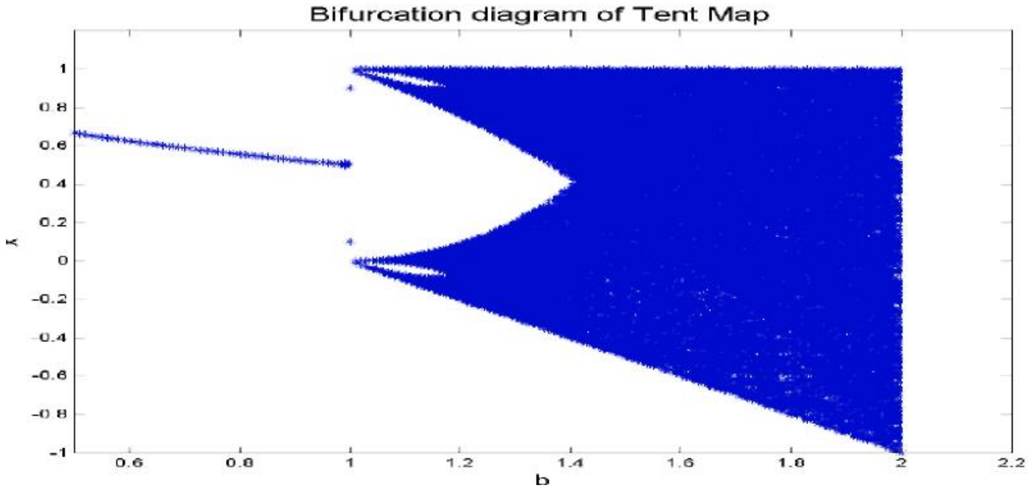


Figure 3.4 The bifurcation diagram of Tent map with a=1 and c=0.

3.5 THE CORRELATION PROPERTIES OF CHAOTIC SEQUENCES

The most important characteristics of the periodic sequence are: the autocorrelation and the cross-correlation. The autocorrelation is important in the synchronization between the periodic pseudo-sequence generated at the transmitter and at the receiver. The cross-correlation of the periodic pseudo-sequences must be zero to obtain communication between different users at the same band of frequency and at the same time.

Chaotic sequences are Noise like waveform and possess Wideband spectrum. Chaotic sequences have very low values of the cross correlation function among them. This is an important issue with regard to security, because the receiver cannot be figured out from a few points of the chaotic sequence. Consequentially, the chaotic sequences also permit more users in the communication system and the system obtains a greater security, since the difficulty they present to be reconstructed for Multiple-user systems.

For practice, one simple way would be to assign an initial condition to each user. From the receptor starts a chaotic map with known initial condition and generating same lengths of chips, despreading process for every information bit. This method is very easy to implement and very secure. Only the desired receptor is able to decode the data information.

The binary chaotic sequences[14] can also be obtained by applying a threshold function to real valued chaotic sequences. Fig. 3.5 shows a generated real value chaotic sequence, the corresponding binary sequence and the auto-correlation, cross-correlation functions of the two sequences. It is directly seen that binary chaotic sequences enjoy good correlation properties. The generation of families of binary chaotic sequences of good cross-correlation properties is an interesting topic of research.

The two codes are almost random. Though the initial conditions of codes 1 and 2 are very close to each other, the generated codes are completely different. The displayed good auto-correlation properties simplify the synchronization of such codes. The low cross-correlation properties are useful in increasing the user's capacity in DS-SS system.

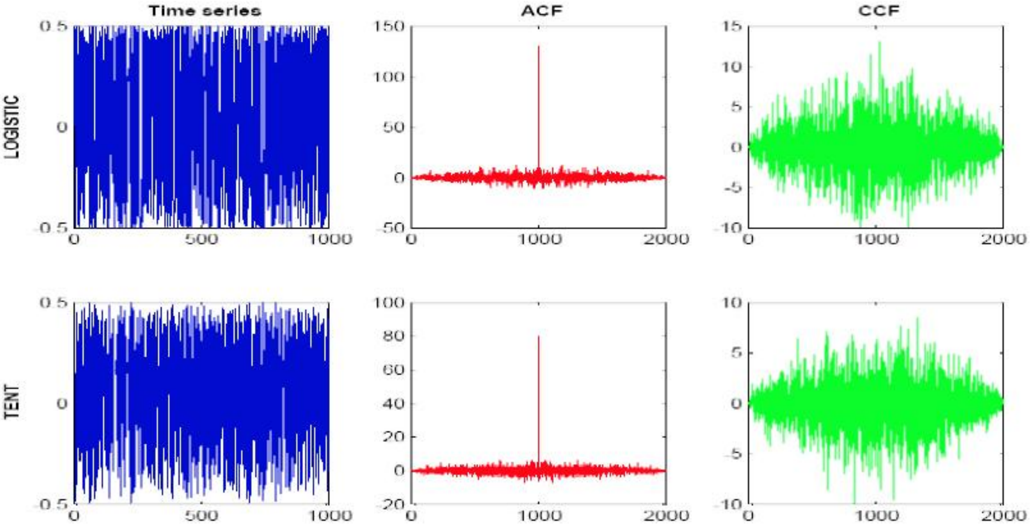


Figure 3.5 Auto-correlation (ACF) and cross-correlation function (CCF) of chaotic sequences of length 2000. (Logistic map with r=4)

3.6 CHAOTIC DS/SS SYSTEM

Chaotic sequences are real valued sequences. Since the spreading sequence in a Chaotic Spread Spectrum (SS) is no longer binary, the application of the chaotic sequences in digital communication is thus limited. A further attempt to transform continuous values to binary ones by using digital encoding technique is therefore used to adopt it in digital communication. Some criteria are performed.

In most of various applications of chaos, a number of investigators have proposed techniques to use a chaotic real-valued trajectory itself rather than its binary version, that is, analog techniques. Binary sequences play an important role in modern digital communication systems. Such a situation led us to define two types of binary sequence based on a chaotic real-valued orbit generated by ergodic maps [15]; one is referred to as a chaotic threshold sequence and the other as a chaotic bit sequence.

3.6.1 Generation of chaotic spreading sequence:-

One major difference between chaotic sequences and PN sequences is that chaotic sequences are not binary.Therefore chaotic sequences must be transformed into binary sequences[16]. There are various methods of generating binary sequences from chaotic real sequences .Various types of binary function are defined to get binary sequences based on a chaotic real-valued orbit generated by ergodic maps.

Method1:-

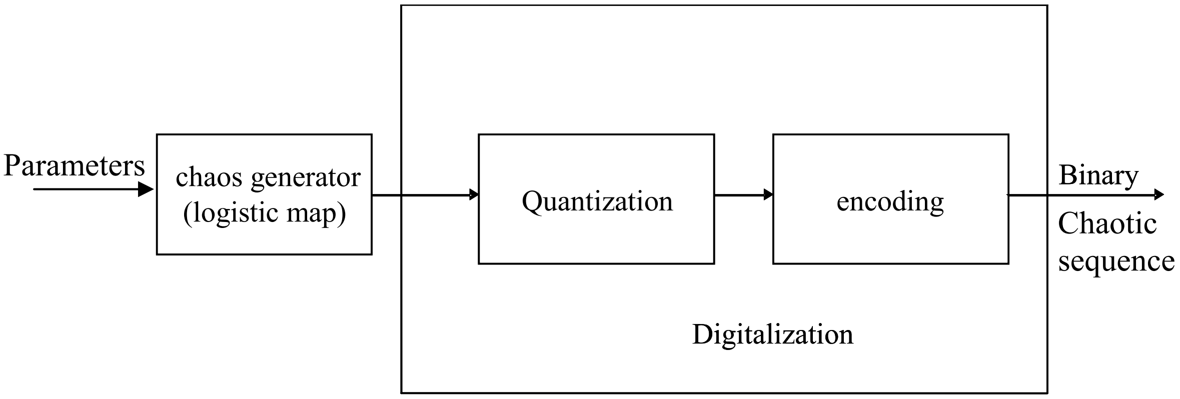


Figure 3.6 Generation of binary chaotic sequences

The block diagram of generation of binary Chaotic sequences by this method is given in diagram 3.6.The chaotic sequences are transmitted into quantization and encoding block. The quantization performs an equal-interval quantization of the floating point input signal varying from -1 to +1. The output signal is quantized into whole units, the unit size determined by the number of bits used in the binary representation. The coding block converts the quantized signal into a stream of bits. The sequence obtained in this way is called chaotic bit sequence.

Method 2: Let w be the real valued Chaotic sequence .For transforming this real valued sequence to binary sequence we define a threshold function $\theta_t(w)$ as

$$\begin{aligned}\theta_t(w) &= 0, \quad w < t \\ &= 1, \quad w \geq t\end{aligned} \qquad (3.4)$$

Where t is the threshold value.

Using these functions, we can obtain a binary sequence which is referred to as a chaotic threshold sequence.

Method 3:

Binary sequences{ C_k}[17] can be obtained from a continuous chaotic signal x(t) by Defining

$$C_k = g\{x(t) - E_t(x(t))\}\Big|_{t=kTd} \qquad (3.5)$$

where g(x) = 1 for x ≥ 0 and g(x) = -1 for x < 0. E(x(t)) denotes the mean function over the continuous time and Td is the basic period of x(t) . By applying equation (3.5) to the logistic map in equation (3.1) in a chaotic regime, it is possible to obtain different by varying initial conditions or parameter values of the system. The sequences generated in this way are expected to have a low cross correlation.

In chaotic DS/SS system [18], each user is assigned a different initial value $x_{n,0}$, where n is the nth user. Each user starting with his unique initial value , keep on iterating the chaotic map and gets the real valued chaotic sequence. This real chaotic sequence is transformed to binary (± 1) for its use in DS/SS by using various methods as explained above. In case of tent map, each user is assigned a different bifurcation parameter whereas each user is assigned different initial value in case of logistic map. In this Thesis, logistic map is used to generate the real valued Chaotic sequences. For transformation of these real valued sequences into binary sequences Method3 given by equation (3.5) is used.

In this Thesis, Chaotic sequences are proposed to be used as spreading sequences in DS/SS systems. Chaotic sequences have been proven easy to generate and store. Merely a chaotic map and an initial condition are needed for their generation, which means that there is no need for storage of long sequences. Moreover, a large number of different sequences can be generated by simply changing the initial condition. More importantly, chaotic sequences can be the basis for very secure communication. The secrecy of the transmission is important in many applications. The chaotic sequences help achieve security from unwanted reception in several ways. First of all, the chaotic sequences make the transmitted signal look like noise; therefore, it does not attract the attention of an unfriendly receiver. That is, an ear-dropper would have a much larger set of possibilities to search through in order to obtain the code sequences.

At last, although the generation of the chaotic sequences is simple for the transmitter and the intended receiver with the knowledge of parameter and functions involved, the exact regeneration is very difficult for a receiver that has to estimate them. A slight error in the estimation leads to exponentially increasing errors. This is due to the sensitive dependence of chaotic systems on the initial conditions and their parameters. In many cases, the received sequences will be contaminated by noise, which would further complicate any attempt at the estimation. Additionally, since the code sequences do not repeat for each bit of information, even if the code sequence for one bit is successfully discovered, the other bits would still remain undecoded.

Advantages:

1. Sensitive dependence on the initial conditions, which is desirable for multiuser communications (different orthogonal sequences) and also for secure communications;
2. Infinitely long period without increasing the generator, which is desirable for multiuser communications and also secure communications;
3. The generators can be built identically for both the transmitter and receiver by digital implementation;

Disadvantage: to synchronize the received chaos sequence with local generated at the receiver end is a complex study. The performance of SS system using NRZ chaos sequence is the same obtained with the SS system using PN sequence

3.7 CONCLUSION

In this chapter Chaotic system is explained and also the generation of Chaotic sequences. From Chaotic maps like Logistic and Tent map are disucussed .Properties and advantages of Chaotic sequences are also given .The generation of binary chaotic sequences and application of them to DS-CDMA is described .

Chapter-4

PERFORMANCE OF LINEAR RECEIVERS FOR DS/SS SYSTEM WITH CHAOTIC SPREADING SEQUENCES

4.1 INTRODUCTION

A direct sequence code division multiple access (DS-CDMA) communications system receiver has three main obstacles to overcome. The first one is multiple access interference (MAI) from other users, which is a direct result of using DS-CDMA. In a cellular system, MAI will be non-stationary due to slow power variations caused by fading and it may undergo step changes when a new user starts or stops transmission (the birth or death of a signal).The transmission channel is responsible for the other two obstacles intersymbol interference caused by multipath and additive noise. To overcome these, many receiver structures have been proposed for the reception of DS-CDMA in a cellular environment.

This chapter reviews linear receiver structures for DS-CDMA.A brief overview of Linear receivers is given in section 4.1. Matched filter receiver is dicussed in section 4.2. MMSE receiver is discussed in section 4.3. In section 4.4 performance of different linear receivers like Matched filter, MMSE receiver and RAKE receiver using chaotic spreading sequences is investigated. The performance of nonlinear receivers using chaotic spreading codes is compared with that of gold sequences.

4.2 SINGLE USER RECEIVER

The task of the receiver is to recover the intended data $x(n)$ by collapsing the spectrum of the received signal vector $\underline{y}(n)$. This is performed by integrating the product of the received signal with a locally held replica of the required user's spreading sequence. Practically, this is achieved by the correlator receiver, shown in Figure 4.1. The received signal, consisting of N_r chips is passed to the block of delay elements, where Z^{1} represents a delay of one chip, until the complete N_r-chip signal has been read in.

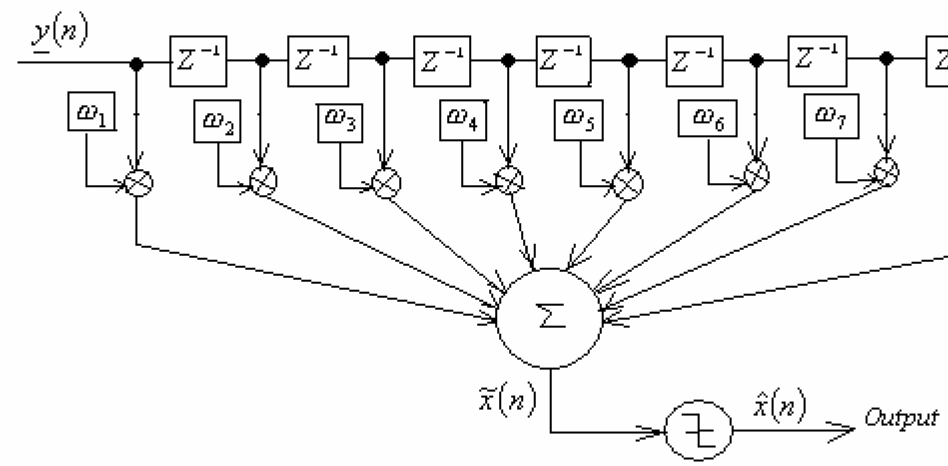


Figure 4.1: DS-CDMA correlator receiver with 8 tap delay.

These values are then passed in parallel to the multiplier block, which forms the scalar product of $\underline{y}(n)$ and the tap weight vector $\underline{w} \in C^{N_r}$ where N_r is the number of tap weights, which is set to 8 in the figure 4.1. This filter block produces a soft output, $\tilde{x}(n)$ which is then passed to the sign-decision block to give a hard estimate, $\hat{x}(n)$ of the original data bit, $x(n)$ for the user of interest. Techniques to achieve synchronization involve the use of a pilot signal, which may be modeled by one additional user, whose data is constant. Perfect timing will be assumed in the following, except where stated.

4.3 MULTIUSER RECEIVER

Multiuser receivers[19] are a class of receivers that use knowledge of all the PN sequences to exploit the structure of the MAI. Instead of being separately estimated, as in a single user detection, the users are jointly detected for their mutual benefit. A CDMA receiver can either process the received signal at the chip rate or symbol rate (user bit rate).Figure 4.2 shows chip rate receivers, which consists of a bank of *matched filters* (MFs) or RAKEs. A bank of MFs is for the non-dispersive AWGN channel, whereas RAKEs[20] are considered for multipath channels. Current mobiles have a simple RAKE because of its simplicity, whereas base stations can have a bank of MFs (or RAKEs) as depicted in figures 4.2 and 4.3. However, structure Figure 4.2 suffers from MAI and therefore has limited performance. Performance improvement can be gained, when carrier to interference ratio (CIR) information from the interferers is taken into account to combat MAI, as structure in Figure 4.3 suggests. This structure is known as the *multiuser detector* (MUD) and is usually suggested for the asynchronous uplink receiver. It could also be used in a modified version as a single user detector in mobiles and might be implemented in the next generation of mobile systems.

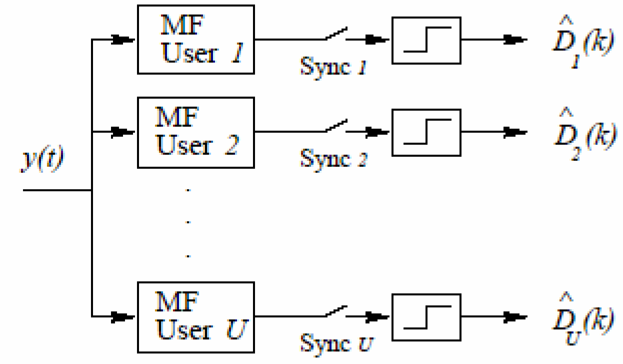


Figure 4.2: Conventional bank of single user receivers with MFs or RAKEs.

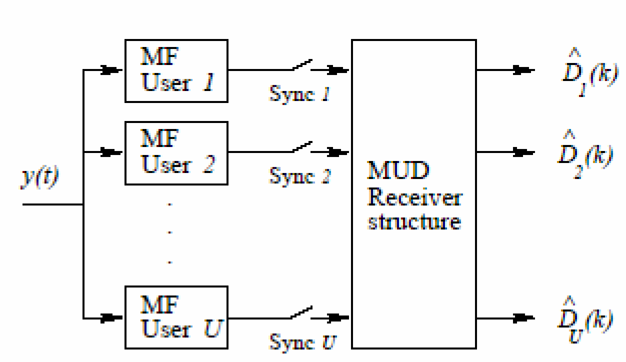


Figure 4.3: Verdu's proposed multiuser detector scheme with MFs for the AWGN channel.

A receiver structure which processes the received signal at the chip rate is known as a *chip level based* (CLB) receiver. Receivers, shown in Figure 4.3, which process at the symbol rate and consist of a front end bank of filters, will be called *preprocessing based* (PPB) receivers.

Because all optimum receivers are too complex for practical applications, the search for simpler and near optimum receivers became vital and goes on. Most proposals are based on the multiuser concept, which is preprocessing based (PPB) for several reasons. First, they relate to Verdu's MUD receiver, since they consider it optimum.

4.4 LINEAR RECEIVER

The general form of a linear receiver is given by $\hat{\mathrm{D}} = \mathrm{sgn}(\mathrm{w}^{\mathrm{T}}.\mathrm{y})$ where the *sgn(.)* function returns the sign of the operand and where the filter weight vector **w** is chosen to minimize a cost function, while $\hat{D}$ is the estimated transmitted bit of the desired user d and **y** is the received signal, see Figure 4.4 and 4.5.

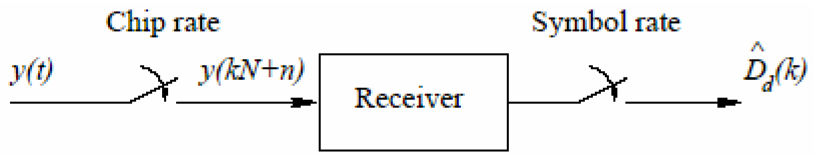


Figure 4.4: Chip rate based receiver.

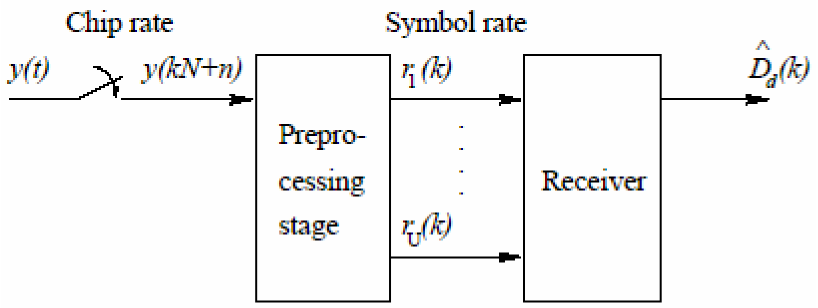


Figure 4.5: Symbol rate based receiver.

4.4.1 Matched Filter

The conceptually simplest receiver, the matched filter (MF) receiver, is simply the correlator receiver with M tap weights, $w_j : 1 \le j \le M$, matched to the complex conjugate time-reverse of the original spreading sequence of the required user which, without loss of generality, we may take to be user 1. The simplest CDMA receiver is the MF receiver, where w is replaced by Cd , the Spreading sequence vector of the desired user. In a multipath fading channel, w corresponds to the convolution between C_d and H_{ch}, implemented as a RAKE.

In practice, the acquisition and synchronization of the chip-level signal is a highly non-trivial task. A very simple and well known detector for SS signals is the matched filter detector, as shown in figure 4.6. The matched filter detector basically consists of a tapped-delay-line (TDL) filter of which the number of taps equals the spreading sequence length *N*. The output vector *(K)* of the tapped delay line $\underline{y}(k)=[y(k),y(k-1),...,y(k-N+1)]^T$ is multiplied with a vector of constant weight $\underline{w}$. $\underline{w}=[w_0,w_1,...,w_{N-1}]^T$. The resulting scalar product is applied to a decision function e.g. a s*ign* function. For the matched filter case, the weights w_k are matched to the user specific sequence code. $w_l = pn_u(N-1-l)$, *for* 0≤ *l*< *N*. So that the matched filter output can be summarized as follows: $\tilde{D}(k)=\underline{w}^T.\underline{y}(k)=\sum_{l=0}^{N-1} w_l.y(k-l)$

Provided that the receiver is perfectly synchronized to the transmitter, the TDL extracts a set of chips that represents a particular sequence and the multiplication with the weights is equivalent to despreading operation. A following decision device such as s*ign* function leads

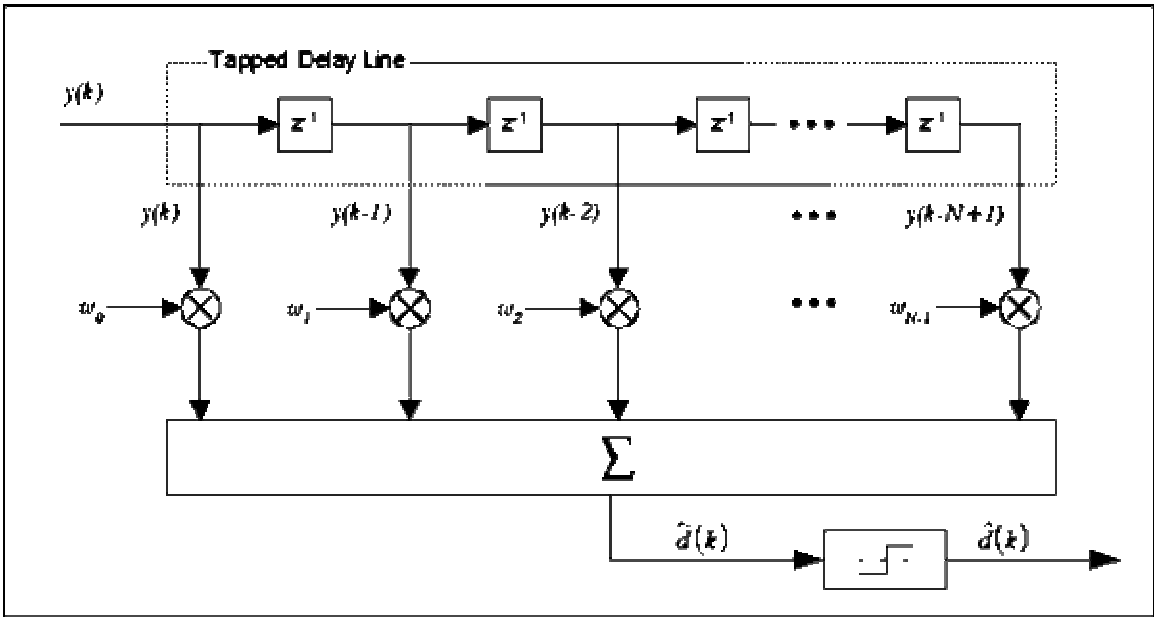


Figure 4.6: Matched filter

to the final estimate $\hat{D}(k)$ of the transmitted data bit *D(k)*, hence $\hat{D}(k) = \operatorname{sgn}\left(\tilde{D}(k)\right)$. The theoretical performance P_e of a MF receiver for a single cell system with *U* users, long random codes, where *N* is the number of chips (processing gain) in AWGN is:

$$P_e^{MF} = Q\left(\sqrt{\frac{N}{\sigma^2 + (U-1)}}\right), \qquad (4.1)$$

$$\text{where } Q(x) = 0.5erfc\left({x}/{\sqrt{2}} \right) \qquad (4.2)$$

and σ^2 denotes the noise power, derived from:

$$E_b/N_o = N/2\sigma^2 \qquad (4.3)$$

Where $\sigma^2 = N_o/2$ is the two sided noise power spectral density and E_b is the bit energy.

In a single user system, the matched filter is the optimum receiver for signals corrupted by only AWGN. In a multi user environment, however, the performance degrades rapidly with increasing number of users. The matched filter is multiple-access limited-and strong interferers with high power compared to the desired user cause severe problem. This latter effect is called the near-far problem. Due to these problems, other solution has been searched for. The optimal linear receiver for multi-user detection is MMSE receiver and is described in the next section.

4.4.2 MMSE receiver

The motivation for the use of adaptive algorithms lies in the desire to change the individual taps of the receiver filter to respond to changes in the communication channel. The traditional implementation of adaptive receivers is that a sequence of a priori known training data is incorporated into the data stream at prearranged times. It is important to acknowledge that this effectively reduces the overall data rate of the system, which is the main drawback of this approach.

The goal of any adaptive algorithm is to use this training data to force the receiver tap weights to minimize some cost or penalty function, $f_{Pen}(.)$, of the difference metric between the original data bit and its estimated value. The only requirement for this penalty function is that it be a monotonic increasing function of the absolute value of its argument, with a global minimum at zero. Here, the number of training bits is given by N_{train} and the sequence of training data by $\{x(n): 1 \le n \le N_{train}\}$.

MMSE receiver is an adaptive filter[21] as shown in Figure 4.7, in which the number of receiver tap weights Nr is set to length of the spreading code M.

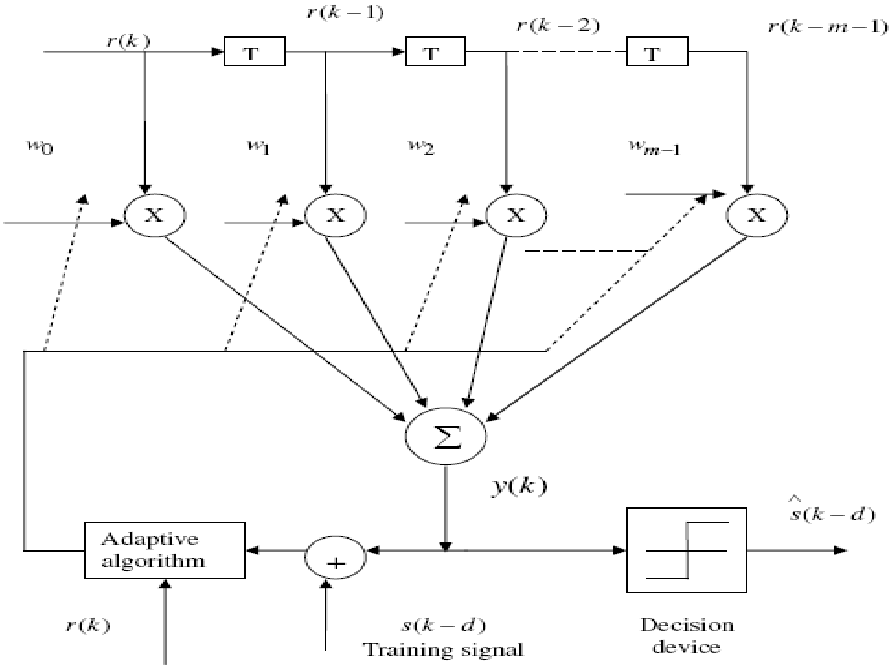


Figure 4.7 MMSE receiver

The MMSE criteria provide equalizer tap coefficients w(k) to minimize the mean square error at the equalizer output before the decision device. This condition can be represented as

$$J = \varepsilon | e(k) |^2 \tag{4.4}$$

$$e(k) = s(k-d) - y(k) \tag{4.5}$$

Where e(k) is the error associated with filter output y(k). However, the MMSE criteria optimize the equalizer weights for minimizing the MMSE under noise and ISI. Minimization of MMSE criteria provides equalizers that satisfy the Wiener criterion. The evaluation the equalizer weights with these criteria requires computation of matrix inversion and the knowledge of the channel, which in most cases is not available. With this penalty function, the resulting target tap weights have been shown to be given by the Wiener filter, so that these algorithms may be viewed as an iterative approximation to the Wiener filter However, adaptive algorithms like LMS and RLS can be used to recursively update the equalizer weights during the training period.

Two adaptive methods which employ this least square error penalty function are the least mean square (LMS) and the more complex recursive least squares (RLS) algorithms. LMS algorithm is depicted schematically in Figure 4.8.

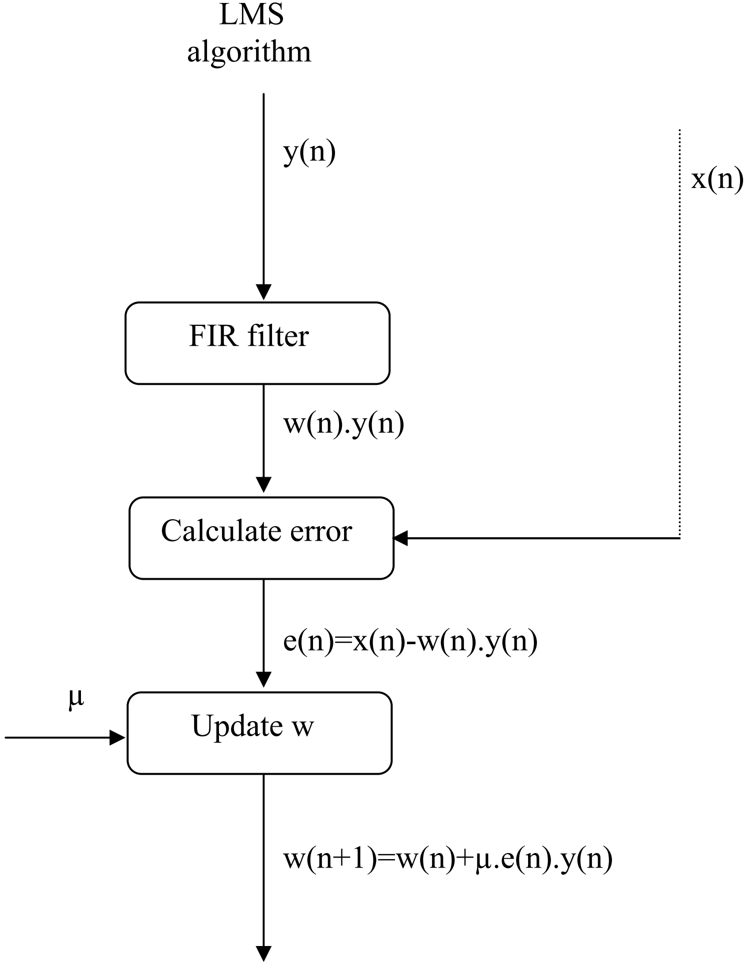


Figure 4.8 LMS algorithm

In LMS algorithm, correlation with an FIR filter is performed to obtain a (soft) estimate, $\hat{x}$, of the training data bit x(n) , as in the correlator receiver. The error e(n) in this estimate is then used to update the tap weights of the FIR receiver filter. In the LMS algorithm, this is performed by simple weighting of the error by step size μ.

4.5 SIMULATION RESULTS

In order to validate the proposed chaotic spreading sequences for DS-CDMA applications, extensive simulation studies were conducted. All the simulation studies were conducted on a 2.80 GHz PC with 256 MB of RAM with Microsoft windows XP operating system. All the simulations are done in Matlab. During the training period the receiver parameters were optimized/ trained with 1000 random samples and the parameters so obtained were averaged over 50 experiments. The parameters of the receiver were fixed after the training phase. The receiver weights were trained using gradient search algorithm like LMS.

Bit error rate (BER) was considered as the performance index. In this section, the BER performance of the different linear receivers like matched filter and MMSE receiver using chaotic spreading sequences is done and the performance is compared with gold sequences. In all the experiments randomly generated +1/-1 samples were transmitted for each user. In all the simulations, chaotic spreading sequences and gold sequences of 31 chips are considered. These samples were spread using chaotic spreading sequences of length 31 corresponding to each of the users. For comparison with gold sequences, the maximum permissible user’s in the system is restricted to 31. After spreading, the sequences were added and transmitted through the non-dispersive channel. The channel corrupted the transmitted signal with AWGN. The channel output was fed to the various linear receiver structures like Matched filter and MMSE receiver. A total of 10^5 bits were transmitted by each user and a minimum of 1000 errors were recorded. The tests were conducted for different levels of E_b/N_0. Additionally tests were also conducted by varying number of active users in the system for fixed value of E_b/N_0 .

4.5.1 Performance comparison for channel without ISI: - In this section, a non-dispersive channel is considered. In figure 4.9 the BER performance against the number of users of Matched filter is evaluated using chaotic spreading sequences and compared with gold sequences with 31 chips. Figure 4.9 compares the BER performance of Matched filter receiver and MMSE receiver using chaotic spreading sequences with that of gold sequences .The chip length of both the gold and chaotic spreading codes are taken as 31 chips. Here E_b/N_0 was fixed as 7dB .The result shows that chaos based MF receiver performs inferior to gold based MF receiver. It has nearly 3dB performance penalty at BER of 10^{-3} .It is also seen that chaos based MMSE receiver performs inferior to gold based MMSE receiver. It has nearly 1dB performance penalty at BER of 10^{-3}. The result also shows that chaos based MMSE receiver performs superior to chaos based MF receiver. It has nearly 3dB performance penalty at BER of 10^{-3}. The result also shows that gold based MMSE receiver performs superior to gold based MF receiver. It has nearly 1dB performance penalty at BER of 10^{-3}. It is seen that Chaotic sequence sequences performance increases significantly by using MMSE receiver when compared to MF receiver.

In Figure 4.10 performance of matched filter receiver was investigated for varying E_b/N_0 conditions. Performance for Chaotic spreading sequences and gold sequences for 4 and 7 users are plotted in Figure 4.10. It is seen that when the number of users is 4, there is a 2dB performance difference at a BER of 10^{-3} between chaos based MF and gold based MF receiver. This difference is increased to almost 5dB at a BER of 10^{-3} in case of 7 users. In both the cases chaotic sequences performance is inferior to gold sequences. For this it is also seen that there is 3dB performance penalty at BER of 10^{-3} for chaotic sequences based MF

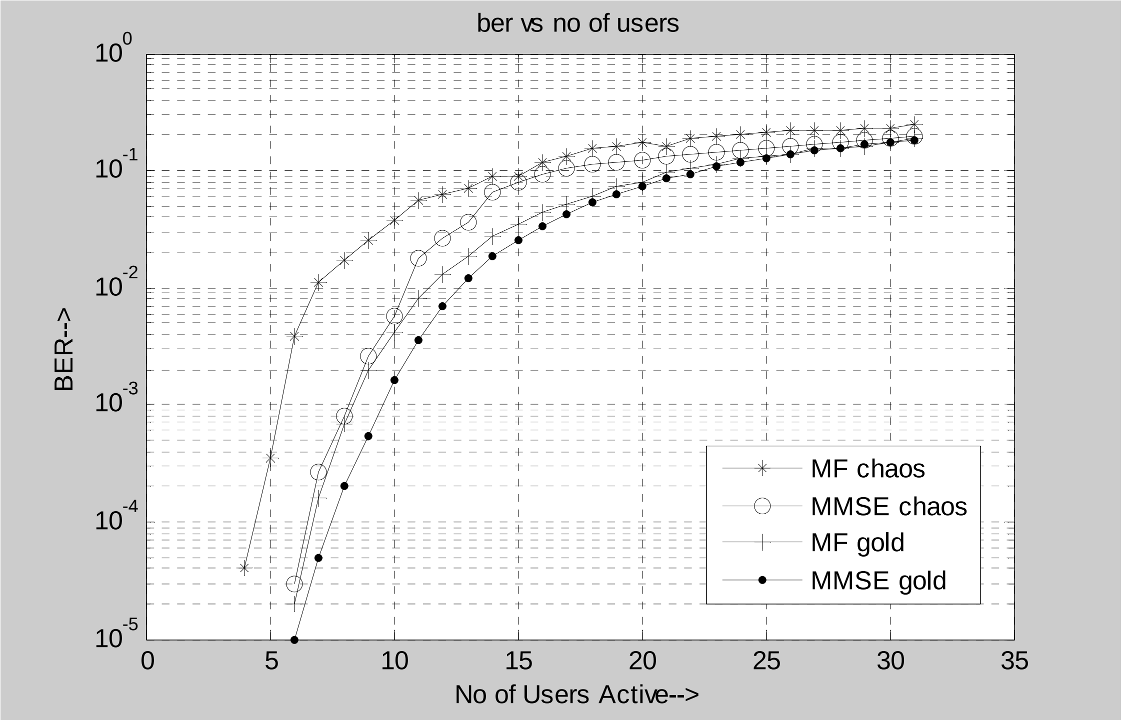


Figure 4.9: BER against the number of users of linear receivers in AWGN at E_b/N_0=7dB using chaotic spreading sequences and gold sequences with 31chips.

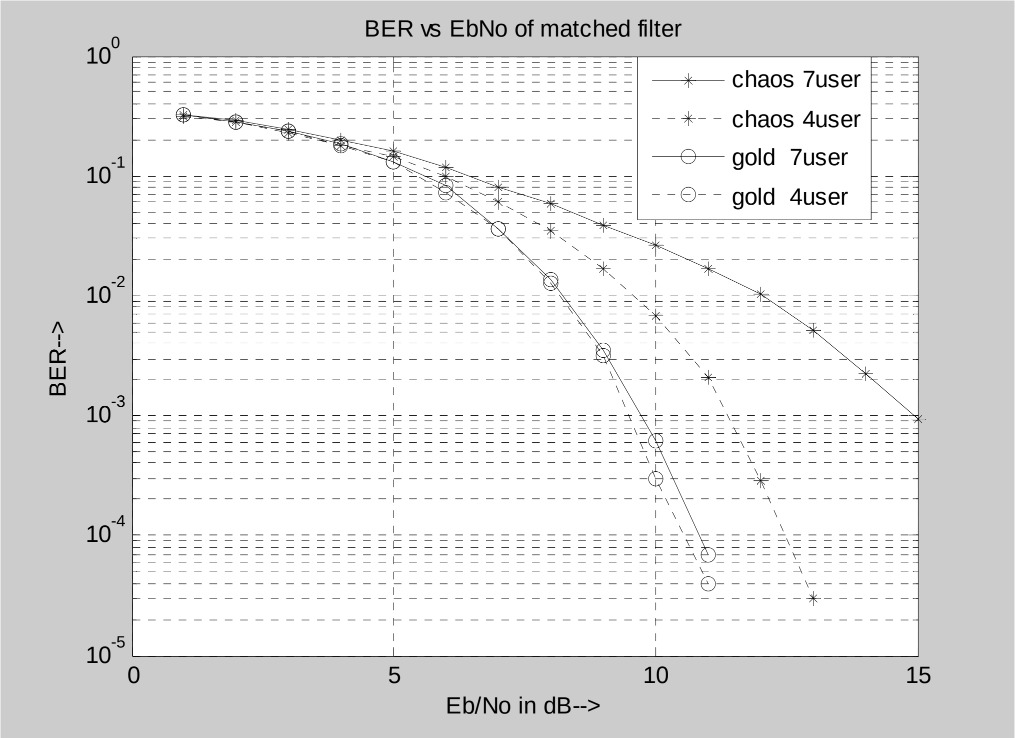


Figure 4.10 BER performance of Matched filter for varying E_b/N_0 for 4 users and 7users being active in the system being active in the system in AWGN

when users are changed from 4users to 7 users. So as the number of users increases chaos based MF receiver performance degrades very much when compared to gold based MF receiver.

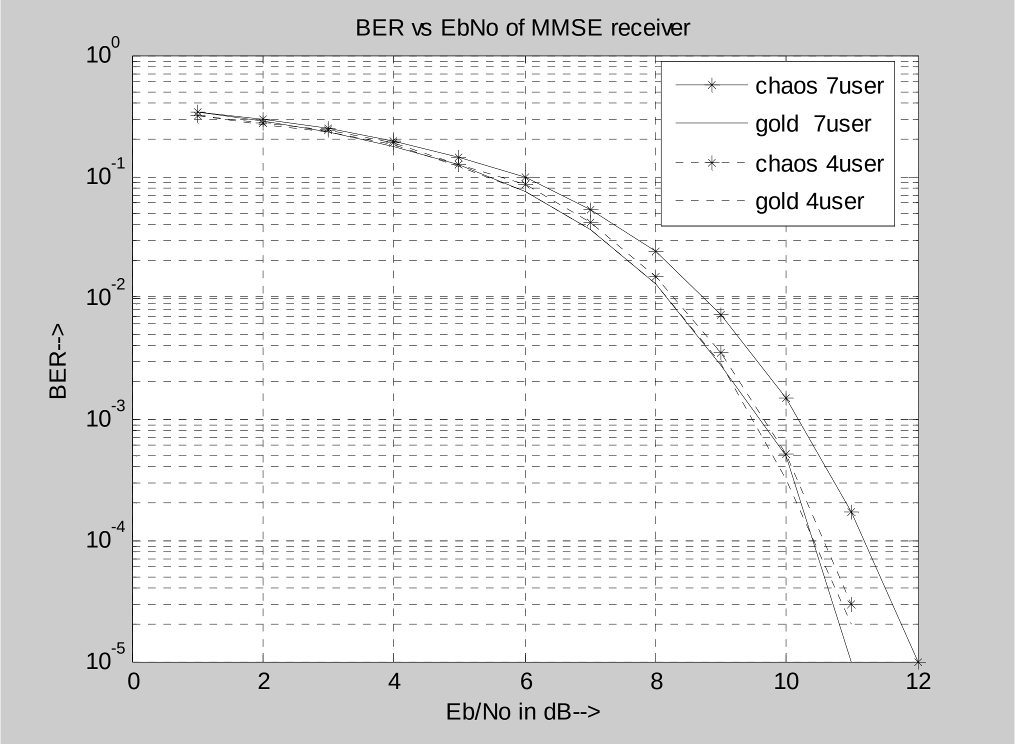


Figure 4.11 BER performance of MMSE receiver for varying E_b/N_0 for 4 users and 7 users being active in the system in AWGN channel

In Figure 4.11 performance of MMSE receiver was investigated for varying E_b/N_0 conditions. Performance for chaotic spreading sequences and gold sequences for 4 and 7 users are plotted in Figure 4.11 It is seen that when the number of users is 4, there is a 0.2dB performance difference at a BER of 10^{-3} between chaos based MMSE and gold based MMSE receiver. This difference is increased to almost 1dB at a BER of 10^{-3} in case of 7 users. In both the cases chaotic sequences performance is very close to that of gold sequences. For this it is also seen that there is 0.8dB performance penalty at BER of 10^{-3} for chaotic sequences based MMSE when users are changed from 4users to 7 users. So as the number of users increases chaos based MMSE receiver performance degrades slightly when compared to gold based MMSE receiver.

In Figure 4.12 Performance of different linear receivers was investigated for varying E_b/N_0 conditions. Performance for Chaotic spreading sequences for 4 and 7 users are plotted in Figure 4.12. It is seen that when the number of users is 4, there is almost 2.2dB performance difference at a BER of 10^{-3} between chaos based MF and chaos based MMSE receiver. This

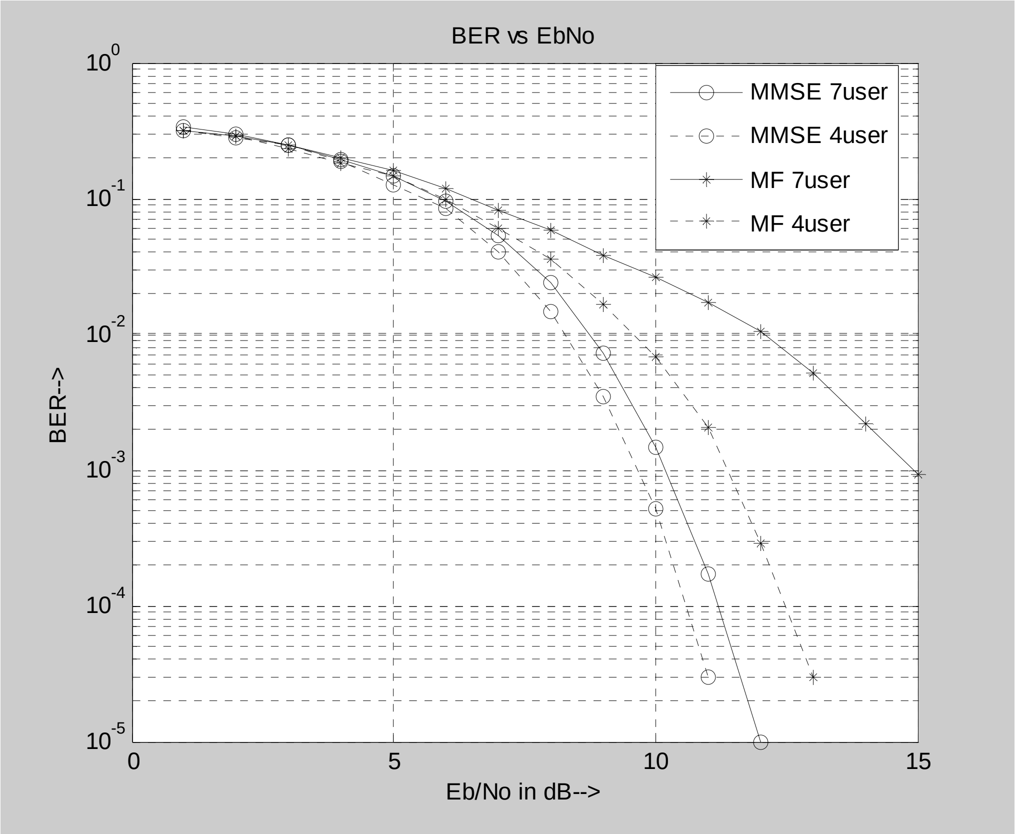


Figure 4.12 Comparison of BER performance of MF and MMSE receiver for varying E_b/N_0 for 4 and 7 users in AWGN using chaotic spreading codes with 31 chips

difference is increased to almost 4.6dB at a BER of 10^{-3} in case of 7 users. In both the cases MF receiver performance is inferior to MMSE receiver. For this it is also seen that there is 3dB performance penalty at BER of 10^{-3} for chaotic sequences based MF when users are changed from 4 users to 7 users. For this it is also seen that there is only almost 1dB performance penalty at BER of 10^{-3} for chaotic sequences based MF when users are changed from 4 users to 7 users .So as the number of users increases chaos based MF receiver performance degrades very much when compared to chaos based MMSE receiver. In all the cases it is seen that MMSE receiver performs very well than MF receiver.

4.5.2 Performance comparison for channel with ISI:- In this section , we consider a stationary multipath channel $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$ .In AWGN the number of chips of transmitted is number of chips of the spreading sequence i.e., 31 in this case. In case of multipath channel, inter symbol interference (ISI) is induced from the previous and next symbol into account. So the number of chips will increase. Here, the multipath channel consists of 3 taps. Hence all receiver structures exploit N+ (L-1) = 31+ (3-1) = 33 chips instead of 31. Matched filter is used in AWGN channel whereas Rake receiver is used in Multipath channel.

Figure 4.13 compares the BER performance of RAKE receiver and MMSE receiver using chaotic spreading sequences with that of gold sequences .The chip length of both the gold and chaotic spreading codes are taken as 31 chips. Here E_b/N_0 was fixed as 7dB .The result shows that chaos based RAKE receiver performs inferior to gold based RAKE receiver. It has nearly 3dB performance penalty at BER of 10^{-3} .It is also seen that chaos based MMSE receiver performs inferior to gold based MMSE receiver. It has nearly 1dB performance penalty at BER of 10^{-3}. The result also shows that chaos based MMSE receiver performs superior to chaos based RAKE receiver. It has nearly 3dB performance difference at BER of 10^{-3}.

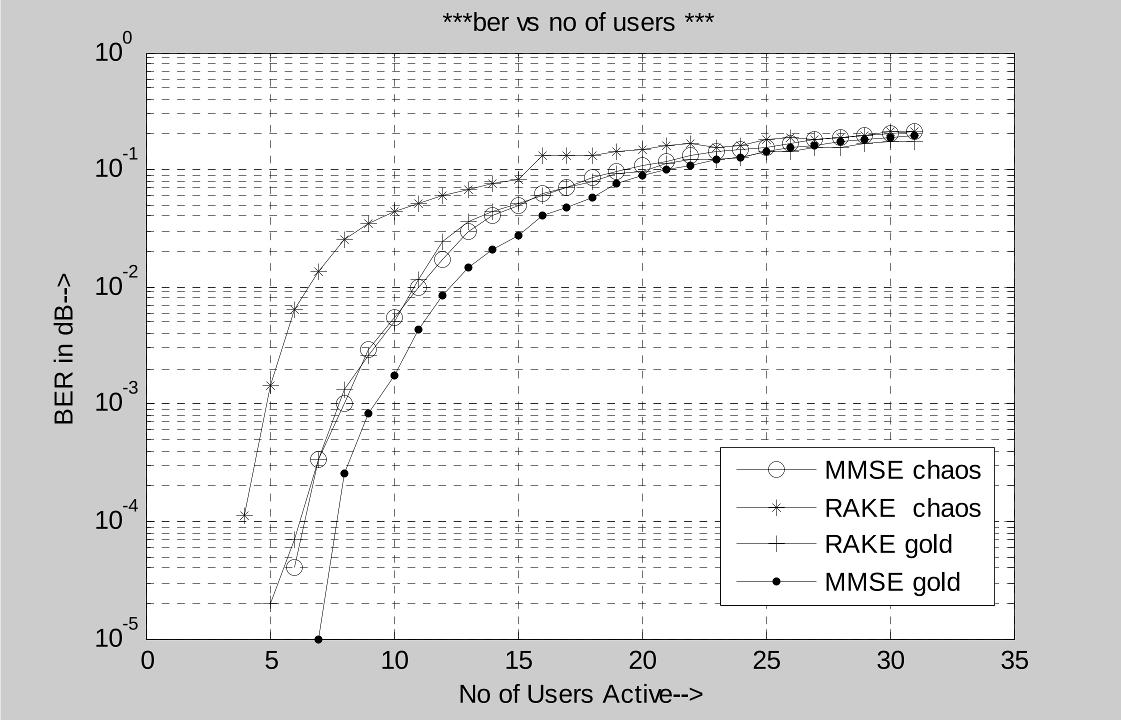


Figure 4.13: BER against the number of users of linear receivers in AWGN at E_b/N_0=7dB using chaotic spreading sequences and gold sequences with 31chips in multipath channel $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$

In Figure 4.14 performance of RAKE receiver was investigated for varying E_b/N_0 conditions. Performance for Chaotic spreading sequences and gold sequences for 4 and 7 users are plotted in Figure 4.14. It is seen that when the number of users is 4, there is a 1dB performance difference at a BER of 10^{-3} between chaos based RAKE and gold based RAKE receiver. This difference is increased to almost 3.5dB at a BER of 10^{-3} in case of 7 users. In both the cases chaotic sequences performance is inferior to gold sequences. For this it is also seen that there is 2.5dB performance penalty at BER of 10^{-3} for chaotic sequences based

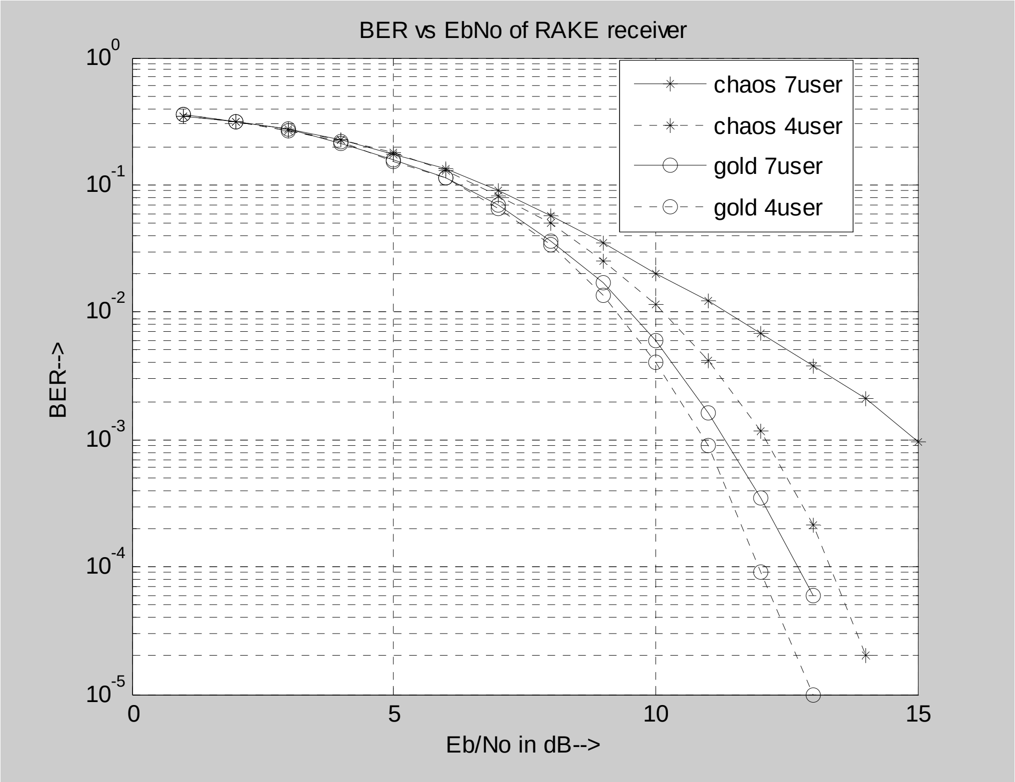


Figure: 4.14 BER performance of RAKE receiver for varying E_b/N_0 for 4 and 7 users being active in the system in multipath channel $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$

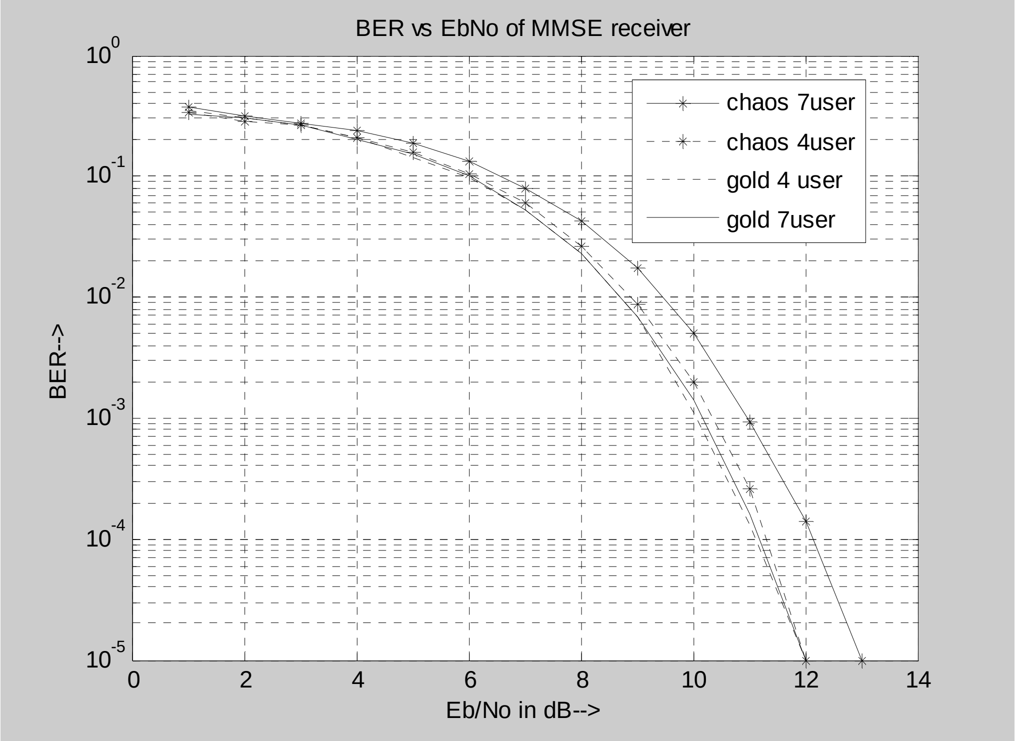


Figure 4.15: BER performance of MMSE receiver for varying E_b/N_0 for 4 and 7 users being active in the system in multipath channel $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$

RAKE when users are changed from 4users to 7 users. For this it is also seen that there is 0.5dB performance penalty at BER of 10^{-3} for gold sequences based RAKE when users are changed from 4users to 7 users .So as the number of users increases chaos based RAKE receiver performance degrades very much when compared to gold based RAKE receiver.

In Figure 4.15 performance of MMSE receiver was investigated for varying E_b/N_0 conditions. Performance for Chaotic spreading sequences and gold sequences for 4 and 7 users are plotted in Figure 4.15. It is seen that when the number of users is 4, there is a 0.4dB performance difference at a BER of 10^{-3} between chaos based MMSE and gold based MMSE receiver. This difference is increased to almost 1dB at a BER of 10^{-3} in case of 7 users. In both the cases chaotic sequences performance is very close to that of gold sequences. For this it is also seen that there is 0.8dB performance penalty at BER of 10^{-3} for chaotic sequences based MMSE when users are changed from 4users to 7 users. . For this it is also seen that there is 0.1dB performance penalty at BER of 10^{-3} for gold sequences based MMSE when users are changed from 4users to 7 users. So as the number of users increases chaos based MMSE receiver performance degrades slightly when compared to gold based MMSE receiver.

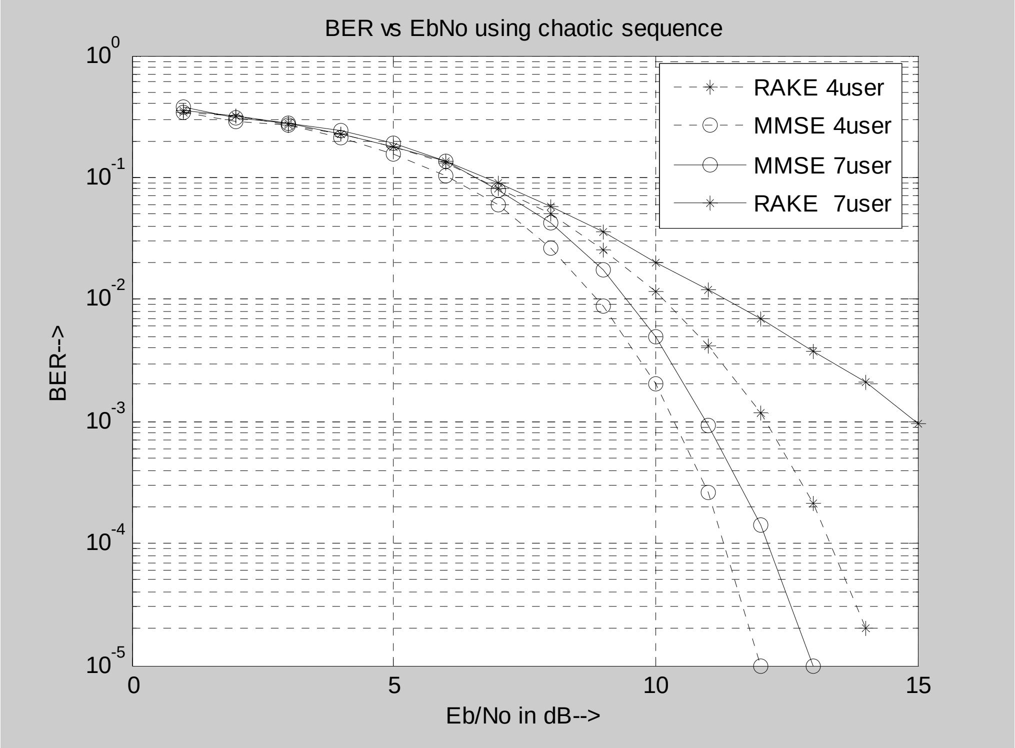


Figure 4.16: Comparison of BER performance of RAKE and MMSE receiver for varying E_b/N_0 for 4 and 7users in multipath channel $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$ using chaotic spreading codes with 31 chips

In Figure 4.16 performance of different linear receivers was investigated for varying E_b/N_0 conditions. Performance for Chaotic spreading sequences for 4 and 7 users are plotted in Figure 4.16. It is seen that when the number of users is 4, there is almost 2 dB performance difference at a BER of 10^{-3} between chaos based RAKE and chaos based MMSE receiver. This difference is increased to almost 4 dB at a BER of 10^{-3} in case of 7 users. In both the cases RAKE receiver performance is inferior to MMSE receiver.

For this it is also seen that there is 3dB performance penalty at BER of 10^{-3} for chaotic sequences based RAKE when users are changed from 4 users to 7 users. For this it is also seen that there is only almost 0.7dB performance penalty at BER of 10^{-3} for chaotic sequences based MMSE when users are changed from 4 users to 7 users .So as the number of users increases chaos based RAKE receiver performance degrades much when compared to chaos based MMSE receiver. In all the cases it is seen that MMSE receiver performs very well than RAKE receiver.

4.6 CONCLUSION

In this chapter various linear receivers like Matched filter, MMSE receiver and RAKE receiver is explained. BER performance of different linear receivers using chaotic sequences is evaluated and it is compared with the receivers using gold sequences. It is seen that chaotic sequence based DS-CDMA performs inferior to gold sequences. The results also showed that MMSE receiver performs better than Matched filter receiver for chaotic sequence based DS-CDMA.

Chapter-5

PERFORMANCE OF NONLINEAR RECEIVERS FOR DS/SS SYSTEM WITH CHAOTIC SPREADING SEQUENCES

5.1 INTRODUCTION

Due to multipath effects the orthogonality among the spreading codes at the receiver is destroyed and linear filters are no longer optimum. The optimum receiver is nonlinear. It has been shown that nonlinear equalizer structures can be applied successfully to DS-CDMA.

In this chapter, the performance of chaotic sequence based CDMA system performance is analyzed for two classes of nonlinear receivers[22]. They are

1. Volterra receiver
2. Functional link artificial neural network (FLANN)

In this chapter, Volterra receiver is discussed in section 5.2. Section 5.3 discusses about Functional Link Artificial Neural Network receiver. In section 5.4 performance of different nonlinear receivers like Volterra receiver and FLANN receiver using chaotic spreading sequences is investigated. The performance of nonlinear receivers using chaotic spreading codes is compared with that of gold sequences.

5.2 VOLTERRA RECEIVER

The general Volterra series (VS)[23] is given as an infinite series expansion , which is not useful for practical applications. Thus, one must work with a truncated VS, such as the third-order VS given in (5.1), which consists of products up to 3rd-order.

$$\begin{aligned} v(kN+n) = & \sum_{a=0}^{N-1} h_1(a) y(kN+n-a) + \\ & \sum_{a=0}^{N-1} \cdot \sum_{b=0}^{N-1} h_2(b,a) y(kN+n-a) y(kN+n-b) + \\ & \sum_{a=0}^{N-1} \cdot \sum_{b=0}^{N-1} \cdot \sum_{c=0}^{N-1} h_3(a,b,c) y(kN+n-a) y(kN+n-b) y(kN+n-c) \end{aligned} \tag{5.1}$$

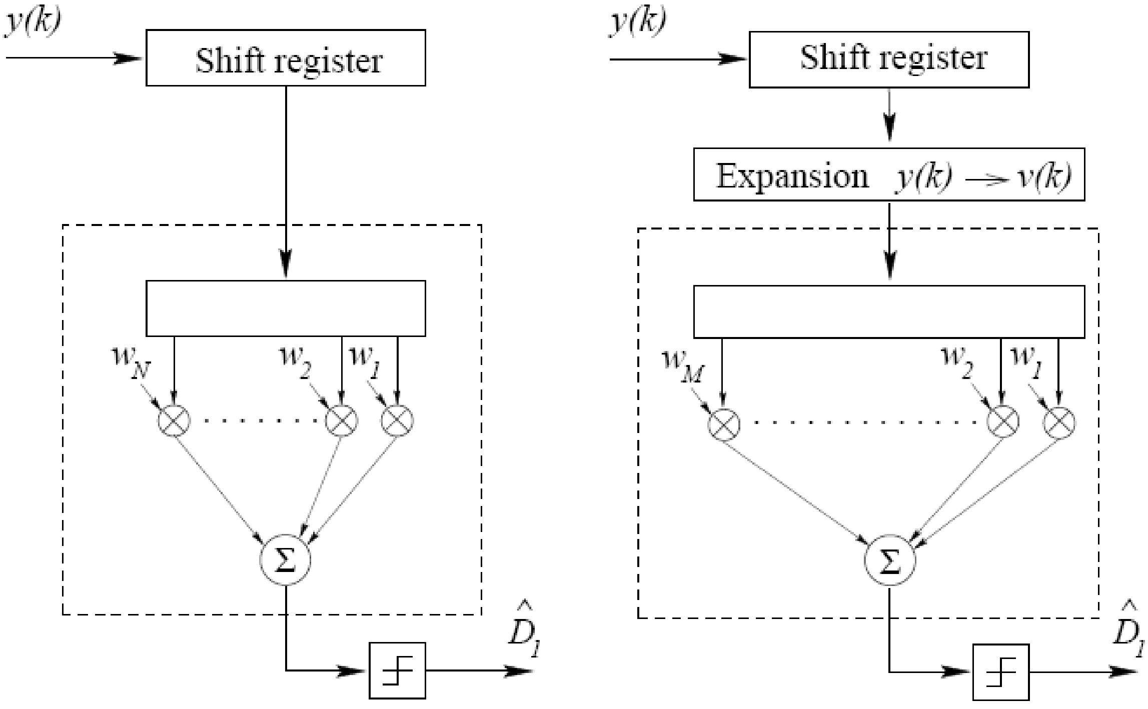
Where $y(kN+n)$ denotes the filter input and $v(kN+n)$ the output for the kth symbol of length N with n=1,2…….N chips. The term h_0 in (5.1) denotes the 0th-order Volterra kernel (coefficients, or weights w) of the system. Without loss of generality, it can be assumed that the kernels are symmetric (e.g. $h_2(a,b) = h_2(b,a)$). The symmetric terms can be omitted since they do not contribute any additional information, which results in half the number of coefficients for h_0. Thus the Volterra kernels h_0 are fixed for any of the possible permutations. Hence, (5.1) can be rewritten for a symbol synchronized receiver:

$$\begin{aligned}\hat{D}_d(y(k)) = \operatorname{sgn}(&\sum_{a=0}^{N-1} h_1(a)y(kN-a) + \sum_{a=0}^{N-1}.\sum_{b=0}^{N-1} h_2(a,b)y(kN-a)y(kN-b) + \\ &\sum_{a=0}^{N-1}.\sum_{b=0}^{N-1}.\sum_{c=0}^{N-1} h_3(a,b,c)y(kN-a)y(kN-b)y(kN-c))\end{aligned} \tag{5.2}$$

Where $\widehat{D}_d$ stands for the kth estimated transmitted bit of the desired user d. A possible filter structure is depicted in Figure 5.1(b). It becomes apparent from equation (5.2), that the term in sgn(.) is a sum of products between a received sequence y(k) and Volterra coefficients h_0.

5.2.1 Volterra expansion

The Volterra expansion [24] and the expansion sequence are analyzed for a one user CLB CDMA system in AWGN. Due to the binomial growth in number of coefficients, the analysis is presented with a short spreading code of length N=3. In order to apply the Volterra filter to the received signal y(k) , it must first be expanded to a larger sequence, denoted by v(k).



(a) *Common N-tap FIR.* **(b)** *Volterra based approach with M-taps.*

Figure 5.1 Conventional FIR filtering and the Volterra approach

Figure 5.1 shows the difference between a simple FIR filter and a Volterra based FIR filter. The expansion process is a mapping from the input space N to the Volterra space M, y(k)=>v(k), where N is the number of chips and M the number of Volterra coefficients. The M elements of v (k) are computed corresponding to the desired order o of the VS (5.2). This process is depicted for a 1st and 3 rd-order system in Figure 5.2. The second-order sequence can be omitted for equiprobable and antipodal signals, for reasons which will be explained later.

The expansion v of figure 5.2 is given by (5.1) and (5.2) and is defined as:

$$v = [v_1, v_2, v_3 \ldots\ldots\ldots v_M]$$

$$v_1 = \sum_{u=1}^{U} D_u c_{u,1} + g(1)$$

$$\vdots$$

$$v_N = \sum_{u=1}^{U} D_u c_{u,N} + g(N) \tag{5.3}$$

$$v_{N+1} = \{\sum_{u=1}^{U} D_u c_{u,1} + g(1)\}^3$$

$$v_{N+2} = \{\sum_{u=1}^{U} D_u c_{u,1} + g(1)\}^2 \{\sum_{u=1}^{U} D_u c_{u,2} + g(2)\}$$

$$\vdots$$

$$v_M = \{\sum_{u=1}^{U} D_u c_{u,N} + g(N)\}^3$$

where D_u is the transmitted bit of user u and $C_{u,n}$ the nth chip of the uth user's spreading sequence.

The vector length of v is M , where M is the number of filter weights or Volterra coefficients, and is determined by the binomial expression:

$$M(N,O) = \sum_{order=1\ :\ order\in\{1,3,5...\}}^{n} \binom{N+order-1}{order} \qquad (5.4)$$

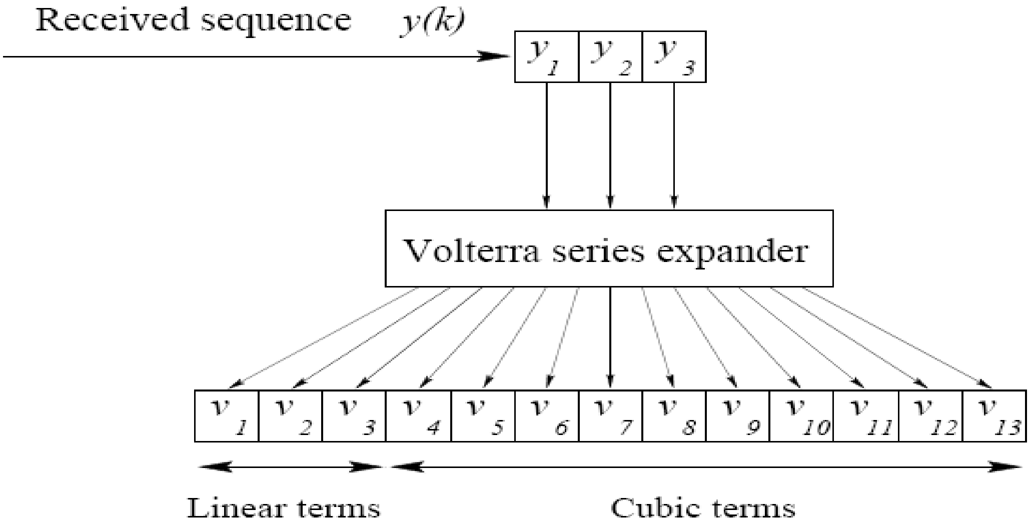


Figure 5.2 The Volterra expansion of combined 1st and 3rd order systems

where N is the length of the input sequence (memory) and O the highest Volterra order. M(N,3) is the number of coefficients for a combined 1st and 3rd-order expansion. Thus, if v of equation (5.3) is of length M(N,3) then it has first M(N,1)=N linear terms and then cubic terms. Tsimbinos and Lever investigated the computational complexity C(N,O) in terms of multiplications needed, given as:

$$C(N,O) = \sum_{o=1}^{O} \frac{(N+o-1)!}{(o-1)!(N-1)!} \qquad (5.5)$$

where C(N,O) does not represent the number of flops, since it does not take the additions into account.

5.3 FUNCTIONAL LINK ANN

Pao originally proposed FLANN [25] and it is a novel single layer ANN structure capable of forming arbitrarily complex decision regions by generating nonlinear decision boundaries. Here, the initial representation of a pattern is enhanced by using nonlinear function and thus the pattern dimension space is increased. The functional link acts on an element of a pattern or entire pattern itself by generating a set of linearly independent function and then evaluates these functions with the pattern as the argument. Hence separation of the patterns becomes possible in the enhanced space. The use of FLANN not only increases the learning rate but also has less computational complexity [26]. Pao *et al* have investigated the learning and generalization characteristics of a random vector FLANN and compared with those attainable with MLP structure trained with back propagation algorithm by taking few functional approximation problems. A FLANN structure with two inputs is shown in Fig

5.3.1 Mathematical derivation of FLANN

Let **X** is the input vector of size $N\times 1$ which represents N number of elements; the n^{th} element is given by:

$$\mathbf{X}(n) = x_n, 1 \le n \le N \tag{5.6}$$

Each element undergoes nonlinear expansion to form M elements such that the resultant matrix has the dimension of $N\times M$.

The functional expansion [27] of the element x_n by power series expansion is carried out using the equation given in (3.18)

$$s_i = \begin{cases} x_n & \text{for } i = 1 \\ x_n^l & \text{for } i = 2,3,4,\ldots,M \end{cases} \tag{5.7}$$

Where $l = 1, 2, \cdots, M$.

For trigonometric expansion, the

$$s_i = \begin{cases} x_n & \text{for } i = 1 \\ \sin\left(l\pi x_n\right) & \text{for } i = 2,4,\ldots,M \\ \cos\left(l\pi x_n\right) & \text{for } i = 3,5,\ldots,M+1 \end{cases} \tag{5.8}$$

where $l = 1, 2, \cdots, M/2$. In matrix notation the expanded elements of the input vector **E**, is denoted by **S** of size $N\times(M+1)$.

The bias input is unity. So an extra unity value is padded with the **S** matrix and the dimension of the **S** matrix becomes $N\times Q$, where $Q = (M+2)$.

Let the weight vector is represented as **W** having Q elements. The output y is given as

$$y=\sum_{i=1}^{Q} s_i \, w_i \tag{5.9}$$

In matrix notation the output can be,

$$\mathbf{Y}=\mathbf{S}\cdot\mathbf{W}^{\mathrm{T}} \tag{5.10}$$

At k^{th} iteration the error signal $e(k)$ can be computed as

$$e(k)=d(k)-y(k) \tag{5.11}$$

Let $\xi(k)$ denotes the cost function at iteration k and is given by

$$\xi(k)=\frac{1}{2}\sum_{j=1}^{P} e_j^2(k) \tag{5.12}$$

where P is the number of nodes at the output layer.

The weight vector can be updated by least mean square (LMS) algorithm, as

$$w(k+1)=w(k)-\frac{\mu}{2}\hat{\nabla}(k) \tag{5.13}$$

where $\hat{\nabla}(k)$ is an instantaneous estimate of the gradient of ξ with respect to the weight vector $w(k)$. Now

$$\hat{\nabla}(k)=\frac{\partial\xi}{\partial w}=-2e(k)\frac{\partial y(k)}{\partial w}=-2e(k)\frac{\partial[w(k)s(k)]}{\partial w}$$

$$=-2e(k)s(k) \tag{5.14}$$

Substituting the values of $\hat{\nabla}(k)$ in (2.35) we get

$$w(k+1)=w(k)+\mu e(k)s(k) \tag{5.15}$$

where μ denotes the step-size $(0\le\mu\le1)$, which controls the convergence speed of the LMS algorithm.

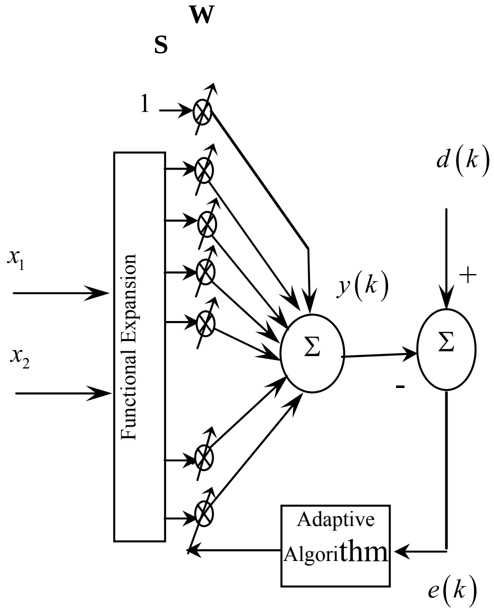


Figure.5.3 Structure of the FLANN model

Simple model of FLANN is given in figure 5.3. Two input sequence is given as input to this network. This sequence is expanded using trigonometric components. The network weights are updated using adaptive algorithm like LMS.

5.4 SIMULATION RESULTS

5.4.1 Performance comparison for channel without ISI

In this section, a non-dispersive channel is considered. Figure 5.4 compares the BER performance of Volterra receiver and FLANN receiver using chaotic spreading sequences with that of gold sequences .The chip length of both the gold and chaotic spreading codes are taken as 31 chips. Here E_b/N_0 was fixed as 7dB .The result shows that chaos based Volterra receiver performs very close to gold based Volterra receiver. It has nearly 0.2dB performance penalty at BER of 10^{-3} .It is also seen that chaos based FLANN receiver performs slightly inferior to gold based FLANN receiver. It has nearly 1dB performance penalty at BER of 10^{-3}. The result also shows that chaos based Volterra receiver performs superior to chaos based FLANN receiver. It has nearly 1dB performance penalty at BER of 10^{-3}. The result also shows that gold based Volterra receiver performs close to gold based FLANN receiver. It has nearly 0.1dB performance penalty at BER of 10^{-3}. It is seen that chaotic sequence sequences performance increases significantly for Volterra receiver when compared to FLANN receiver.

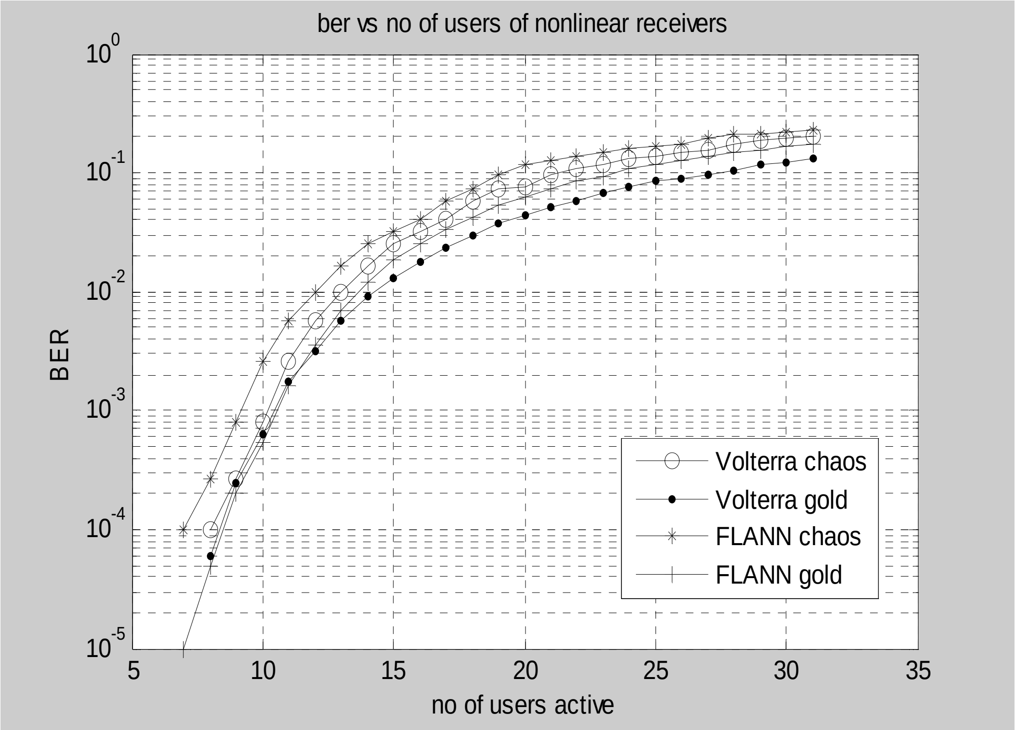


Figure 5.4: BER against the number of users of nonlinear receivers in AWGN at E_b/N_0=7dB using chaotic spreading sequences and gold sequences with 31chips.

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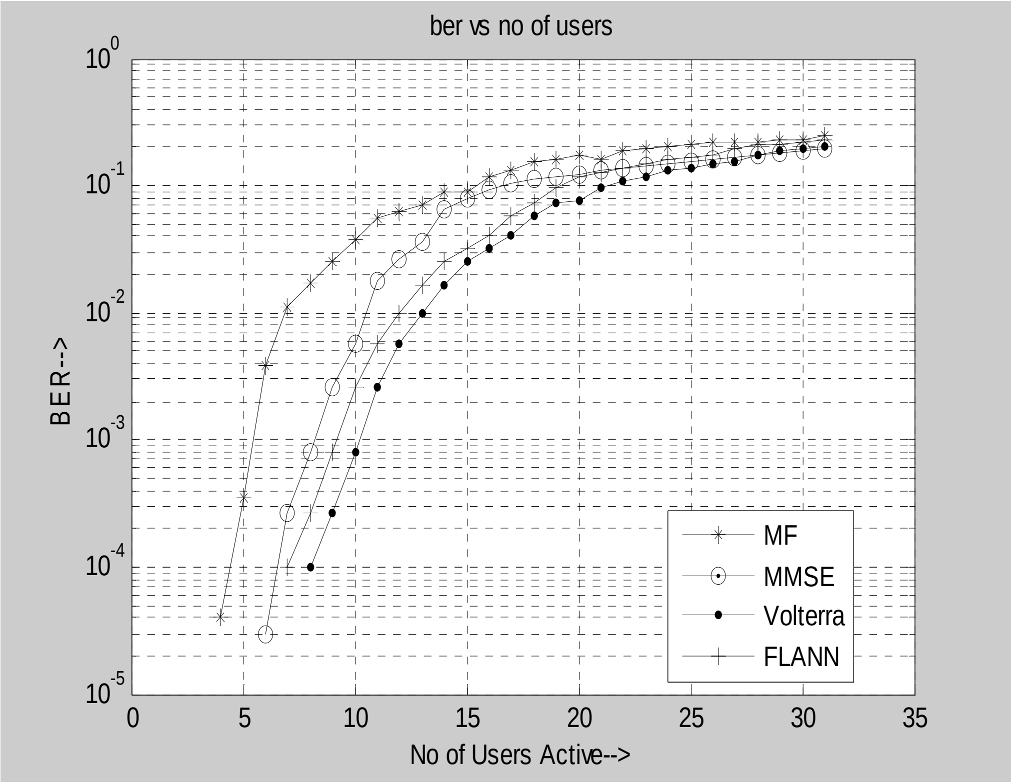

Figure 5.5 BER against the number of users of different receivers in AWGN at E_b/N_0=7dB using chaotic spreading sequences with 31chips

Figure 5.5 compares the BER performance of Volterra receiver and FLANN receiver using chaotic spreading sequences with that of linear receivers for varying number of users active. The chip length of both the gold and chaotic spreading codes are taken as 31 chips. Here E_b/N_0 was fixed as 7dB. It is seen that Volterra receiver performs better than all other receivers .MMSE receiver performs better than MF receiver. FLANN receiver outperforms both MMSE and MF receiver. It is also seen that nonlinear receivers outperforms better than linear receivers.

In Figure 5.6 performance of Volterra receiver was investigated for varying E_b/N_0 conditions. Performance for Chaotic spreading sequences and gold sequences for 7 users are plotted in Figure 5.6. It is seen that when the number of users is 7, there is a 0.2dB performance difference at a BER of 10^{-3} between chaos based Volterra and gold based Volterra receiver. In this case chaotic sequences performance is inferior to gold sequences.

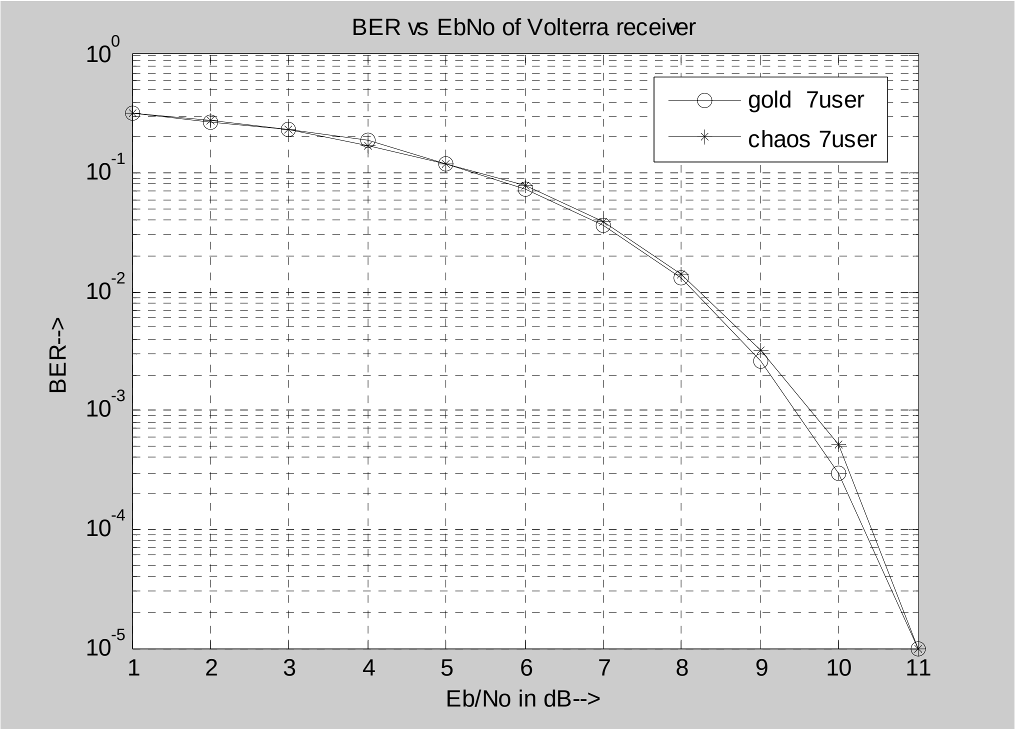

Figure 5.6 BER performance of Volterra receiver for varying E_b/N_0 for 7users being active in the system in AWGN channel

In Figure 5.7 performance of FLANN receiver was investigated for varying E_b/N_0 conditions. Performance for Chaotic spreading sequences and gold sequences for 7 users are plotted in Figure 5.7 .It is seen that when the number of users is 7, there is a 0.2dB performance difference at a BER of 10^{-3} between chaos based FLANN and gold based FLANN receiver. In this case chaotic sequences performance is inferior to gold sequences.

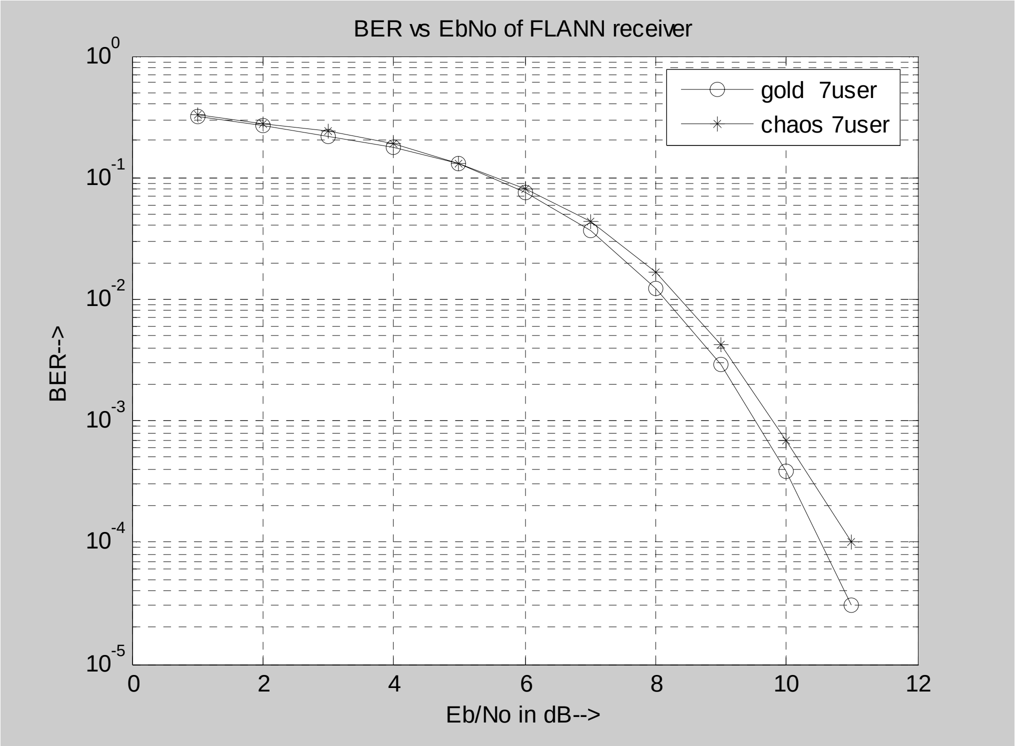

Figure 5.7 BER performance of FLANN receiver for varying E_b/N_0 for 7 users being active in the system in AWGN channel

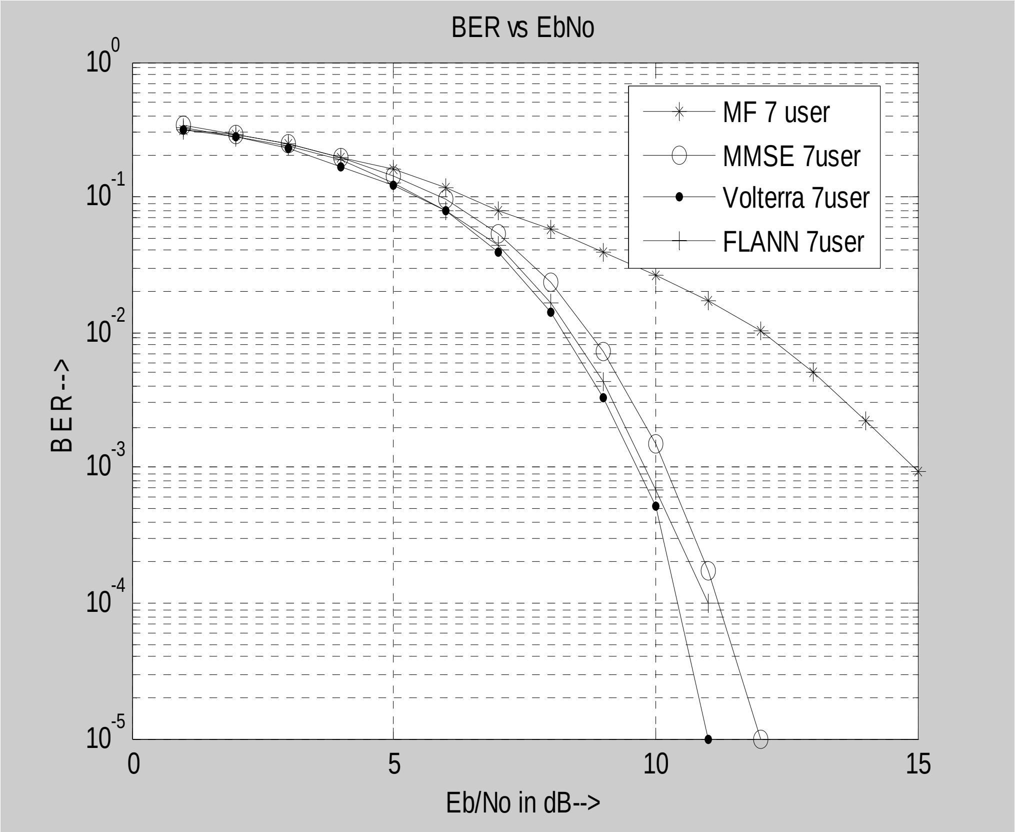

Figure 5.8: Comparison of BER performance of different receivers for varying E_b/N_0 for 7 users in AWGN using chaotic spreading codes with 31 chips

In Figure 5.8 performance of Volterra and FLANN receiver was investigated for varying E_b/N_0 conditions and compared with that of linear receivers. Performance for Chaotic spreading sequences for 7 users are plotted in Figure 5.8. It is seen that Volterra receiver performs better than all other receivers .MMSE receiver performs better than MF receiver. FLANN receiver outperforms both MMSE and MF receiver. It is also seen that nonlinear receivers outperforms better than linear receivers.

5.4.2 Performance comparison for channel with ISI

In this section , we consider a stationary multipath channel $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$ .In AWGN the number of chips of transmitted is number of chips of the spreading sequence i.e., 31 in this case. In case of multipath channel, inter symbol interference (ISI) is induced from the previous and next symbol into account. So the number of chips will increase. Here, the multipath channel consists of 3 taps. Hence all receiver structures exploit N+ (L-1) = 31+ (3-1) = 33 chips instead of 31. Matched filter is used in AWGN channel whereas Rake receiver is used in Multipath channel.

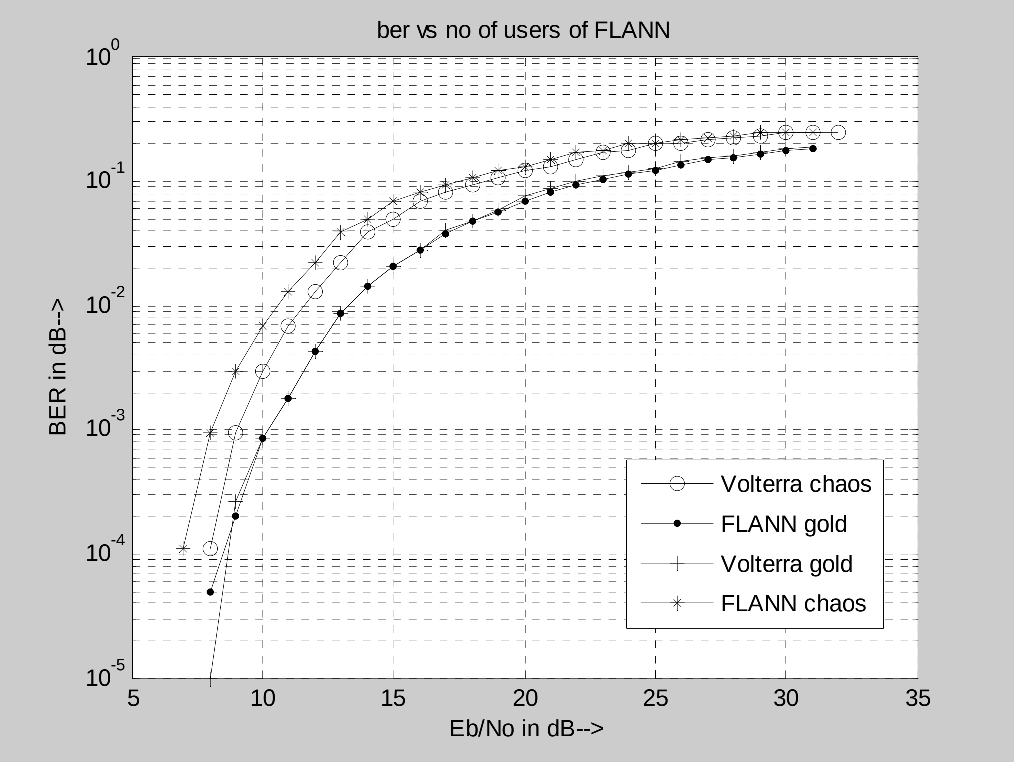

Figure 5.9: BER against the number of users of nonlinear receivers in AWGN at E_b/N_0=7dB using chaotic spreading sequences and gold sequences with 31chips

Figure 5.9 compares the BER performance of Volterra receiver and FLANN receiver using chaotic spreading sequences with that of gold sequences .The chip length of both the gold and chaotic spreading codes are taken as 31 chips. Here E_b/N_0 was fixed as 7dB .The result shows that chaos based Volterra receiver performs slightly inferior to gold based Volterra receiver. It has nearly 1dB performance penalty at BER of 10^{-3} .It is also seen that chaos based FLANN receiver performs slightly inferior to gold based FLANN receiver. It has nearly 2dB performance penalty at BER of 10^{-3}. The result also shows that chaos based Volterra receiver performs superior to chaos based FLANN receiver. It has nearly 1dB performance penalty at BER of 10^{-3}. The result also shows that gold based Volterra receiver performs similar to gold based FLANN receiver. It has nearly 0.1dB performance penalty at BER of 10^{-3}. It is seen that Chaotic sequence sequences performance increases significantly for Volterra receiver when compared to FLANN receiver.

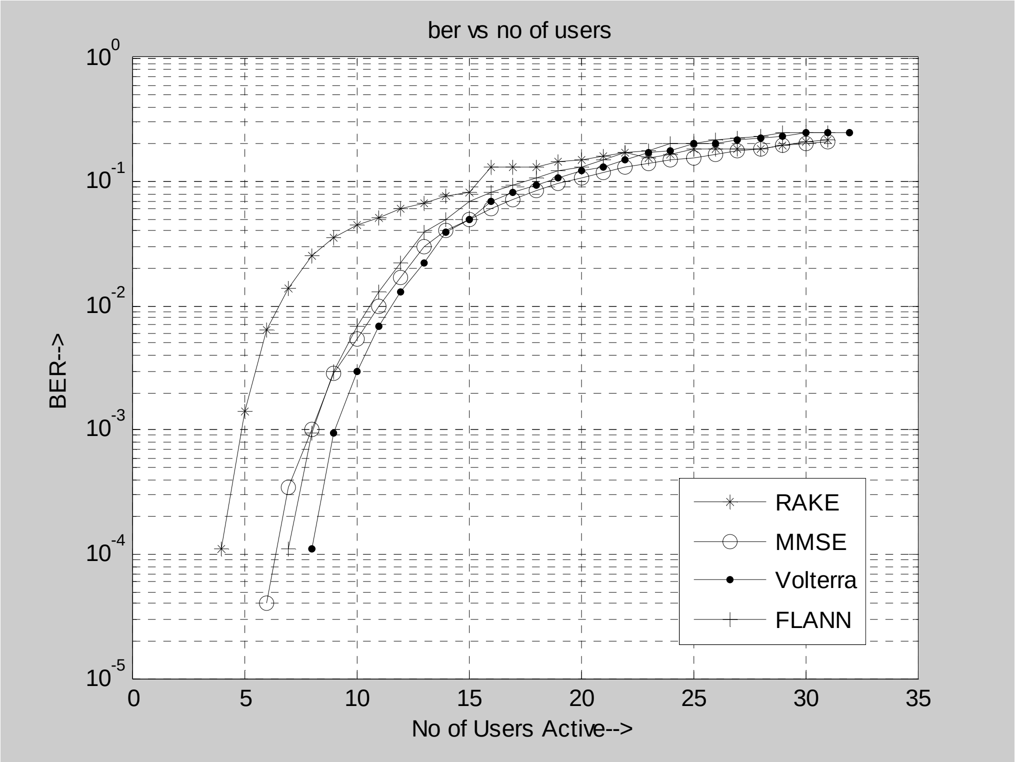

Figure 5.10 BER against the number of users of different receivers in AWGN at E_b/N_0=7dB using chaotic spreading sequences with 31chips in stationary multipath $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$

Figure 5.10 compares the BER performance of Volterra receiver and FLANN receiver using chaotic spreading sequences with that of linear receivers for varying number of users active. The chip length of both the gold and chaotic spreading codes are taken as 31 chips. Here E_b/N_0 was fixed as 7dB. It is seen that Volterra receiver performs better than all other receivers .MMSE receiver performs better than MF receiver. FLANN receiver outperforms both MMSE and MF receiver. It is also seen that nonlinear receivers outperforms better than linear receivers

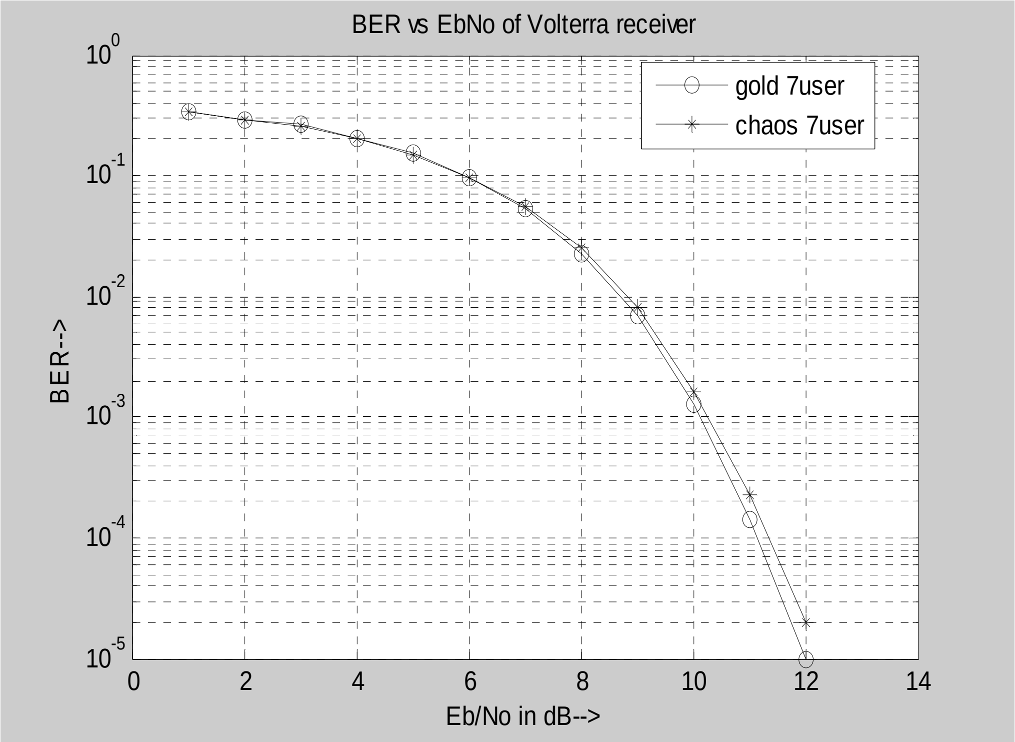

Figure 5.11: BER performance of Volterra receiver for varying E_b/N_0 for 7 users being active in the system in multipath channel $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$

In Figure 5.11 performance of Volterra receiver was investigated for varying E_b/N_0 conditions. Performance for Chaotic spreading sequences and gold sequences for 7 users are plotted in Figure 5.11. It is seen that when the number of users is 7, there is a 0.2dB performance difference at a BER of 10^{-3} between chaos based Volterra and gold based Volterra receiver. In this case chaotic sequences performance is inferior to gold sequences.

In Figure 5.12 performance of FLANN receiver was investigated for varying E_b/N_0 conditions. Performance for Chaotic spreading sequences and gold sequences for 7 users are plotted in Figure 5.12. It is seen that when the number of users is 7, there is a 1dB performance difference at a BER of 10^{-3} between chaos based FLANN and gold based FLANN receiver. In this case chaotic sequences performance is inferior to gold sequences.

In Figure 5.13 performance of Volterra and FLANN receiver was investigated for varying E_b/N_0 conditions and compared with that of linear receivers. Performance for Chaotic spreading sequences for 7 users are plotted in Figure 5.13. For this it is seen that there is 3dB

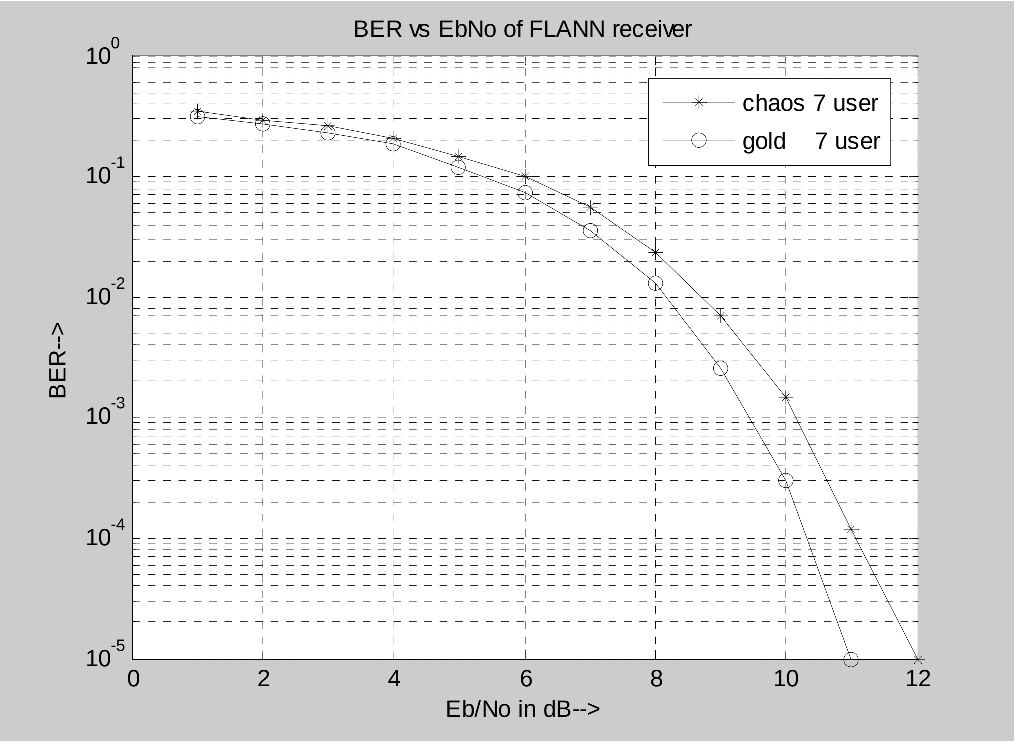

Figure 5.12: BER performance of FLANN receiver for varying E_b/N_0 for 7 users being active in the system in multipath channel $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$

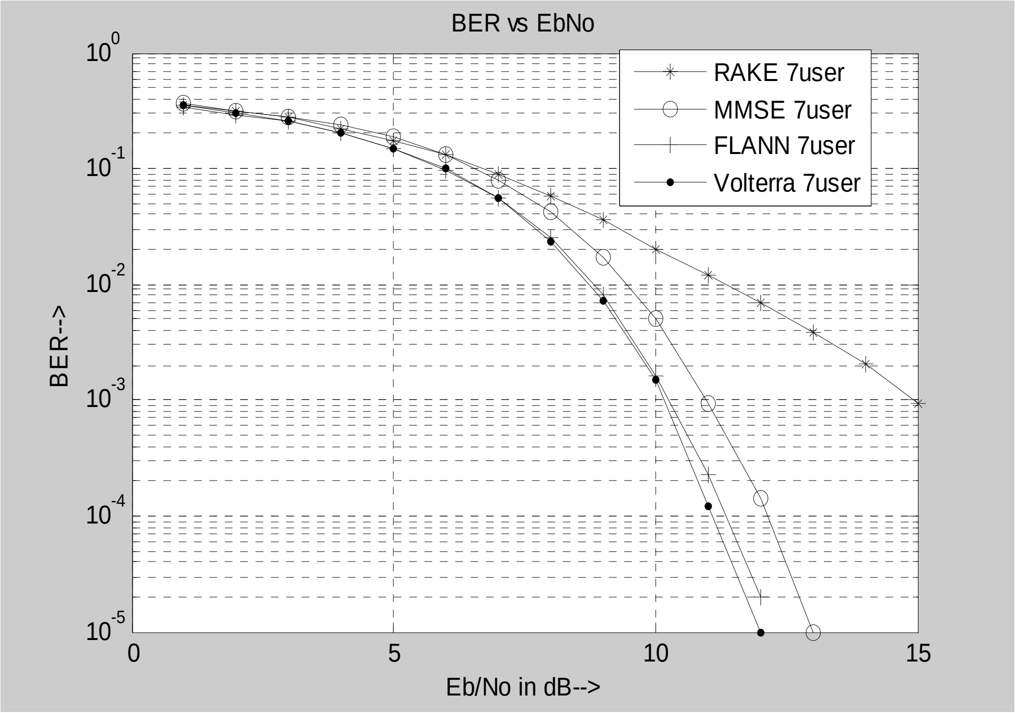

Figure 5.13: Comparison of BER performance of different receivers for varying E_b/N_0 for 7 users in stationary multipath $H_{ch}=1+0.5z^{-1}+0.2z^{-2}$ using chaotic spreading codes with 31 chips.

performance penalty at BER of 10^{-3}. It is seen that Volterra receiver performs better than all other receivers .MMSE receiver performs better than MF receiver. FLANN receiver outperforms both MMSE and MF receiver. It is also seen that nonlinear receivers outperforms better than linear receivers

5.5 CONCLUSION

In this chapter various nonlinear receivers like Volterra receiver and Functional link artificial neural network receiver are explained and BER performances of various nonlinear receivers using chaotic sequences has been analyzed and compared with linear receivers. It is seen that chaotic sequence based DS-CDMA performs inferior to gold sequences. The results also showed that Volterra receiver performs better than FLANN receiver for chaotic sequence based DS-CDMA. It is seen that Volterra receiver performs better than all other receivers. MMSE receiver performs better than MF receiver. FLANN receiver outperforms both MMSE and MF receiver. It is also seen that nonlinear receivers outperforms better than linear receivers.

Chapter 6
CONCLUSIONS

6.1 INTRODUCTION

In this thesis a new type of sequences called chaotic sequences are used for DS-CDMA system. The performance of chaotic sequence based DS-CDMA system for different receiver techniques is evaluated and compared with gold code based DS-CDMA system. This chapter summarizes the work reported in this thesis, specifying the limitations of the study and provides some indications for future work.

Following this introduction section 6.2 lists the achievements from the work. Section 6.3 provides the limitations and section 6.4 presents indications toward future work.

6.2 ACHIEVEMENT OF THE THESIS

In chapter 3, generation of binary chaotic sequences from different chaotic maps has been discussed. In Chapter 4, various linear receivers like Matched filter, MMSE receiver etc., are studied and BER performance of different linear receivers using chaotic sequences is evaluated and it is compared with the receivers using gold sequences. It is seen that chaotic sequence based DS-CDMA performs inferior to gold sequences. The results also showed that MMSE receiver performs better than Matched filter receiver for chaotic sequence based DS-CDMA. Following these BER performances of various nonlinear receivers using chaotic sequences has been analyzed in Chapter 5 and compared with linear receivers. It is seen that chaotic sequence based DS-CDMA performs inferior to gold sequences. The results also showed that Volterra receiver performs better than FLANN receiver for chaotic sequence based DS-CDMA. It is seen that Volterra receiver performs better than all other receivers .MMSE receiver performs better than MF receiver. FLANN receiver outperforms both MMSE and MF receiver. It is also seen that nonlinear receivers outperforms better than linear receivers. Even though chaos based DS-CDMA performance is inferior to gold sequence based DS-CDMA ,it can provide the other advantages of chaotic sequences in DS/SS are the availability of a great numbers, the ease of their generation, and their inherent improvement in the security of transmission. These features of the chaotic DS/SS system make itself an alternative to PN sequences in terms of generating more effective codes.

6.3 LIMITATIONS OF THE THESIS

- Simulations are constrained to baseband only.

- Fading effects is not considered.
- Spreading codes with only 31 length is considered.
- The work investigated in this thesis investigates the receiver in the downlink scenario only.

6.4 SCOPE OF FURTHER RESEARCH

- Simulations can be extended to some more nonlinear receivers like neural network receivers.
- FPGA implementation of Chaotic sequence generator can also be investigated.
- Simulations can be extended to larger spreading codes like 63,127 chip etc.,

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