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Receiver Optimization in Chaos Communication

by

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MS Electronic Engineering

Department of Electronic Engineering
Faculty of Engineering and Technology
International Islamic University, Islamabad.
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Certificate of Approval

It is certified that we have read the project report submitted by **Muhammad Tahir Naseem [131-FET/MSEE/F-07]**. It is our judgment that this report is of sufficient standard to warrant its acceptance by the International Islamic University, Islamabad for degree of MS Electronic Engineering (MSEE).

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بسم الله الرحمن الرحيم

Dedicated to my teachers and parents

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Muhammad Tahir Naseem

Abstract

MUD is an important area of interest to increase capacity needed for future wireless services. The direct-sequence CDMA (DS-CDMA) systems in the third generation of mobile communication systems has raised more interest in exploring the capabilities and capacity of this type of technology. However, the conventional DS-CDMA system has the major problem of multiple-access interference (MAI). The MAI is unavoidable because receivers deal with information which comes from a single source.. As a result, the capacity of these systems decreases. To overcome these limitations, MUD emerges as a promising approach to increase the system capacity.

The problem in CDMA was that the spreading sequences were repeating after a long time. In this thesis, PN generator was replaced by a chaotic generator which comes from non-linear differential equation and also helpful in achieving good security. The beauty of chaotic generator is that the spreading sequences were not repeating. To overcome MAI in chaotic systems, a sub-optimum receiver technique parallel interference cancellation (PIC) is used.

Contents

List of Figures

Acronyms

2G	Second generation
3G	Third generations
4G	Fourth generations
AWGN	Additive White Gaussian noise
BER	Bit error rate
BS	Base station
CDMA	Code division multiple access
COOK	Chaos on off key
DS-CDMA	Direct sequence code division multiple access
DSL	Digital subscriber line
FM	Frequency modulation
GSM	Global system for mobile communication
ISI	Inter-symbol-interference
LCG	Logistic chaos generator
LOS	Line-of-sight
MAI	Multiple access interference
MS	Mobile station
PN	Pseudo noise
SF	Spreading factor
SS	Spread spectrum
FDMA	Frequency division multiple access
TDMA	Time division multiple access
CG	Chaotic Generator
CSK	Chaos Shift Keying
SS-CDMA	Spread Spectrum CDMA
TG	Tent Generator

Chapter 1

Introduction

Chaos theory has dynamic, non-linear behavior and has been studied in the past few decades. Chaos theory is a branch of research being pursued by mathematicians, physicists, chemists, engineers and biologists [1]. With the passage of time, the advancement in the circuit technology, digital signal processing (DSP) and in digital communications, the use of chaos theory in our daily life is possible [2] [3]. There are various applications of chaos theory but not only limited to these: use in computer models for weather prediction, in exploration of fractals which are used in computer art to make interesting shapes and in video games and also for security purposes [4]. Therefore, more work is needed to use the chaos in various applications [5]. We are interested in the use of chaos in security purpose in digital communication systems.

Chaotic signals are neither periodic nor quasi-periodic in time domain and are unpredictable in the long term [6]. This unpredictable behavior behaves it as noise like behavior and spreads it over the large bandwidth in the frequency domain. Chaotic systems can be classified into two types (a) continuous-time

(b) discrete-time. We will focus only on discrete-time chaotic systems. The continuous-time signals can be derived using differential equations.

$$g(x,t) = \dot{x}, \quad x(t_0) = x_0 \tag{1.1}$$

Where g is the set of differential equations that defines the dynamical system and x the vector that defines the current state of system at time t [7] [8].
Chaotic systems are very sensitive due to its initial conditions [9]. A small change in initial condition results in different chaotic signal. Therefore, we can produce large no of chaotic signal by making small change in initial conditions [10]. The auto- and cross-correlation properties are similar to white noise. This property of chaotic system which makes it as noise-like behavior help to use it in spread spectrum communication.

In conventional spread spectrum communication system like (CDMA), the narrowband signal is transmitted by multiplying it with the signature waveform and spreads over the whole bandwidth. Here, the information signal is hidden under the background noise to protect it from the jammers. The use of wideband signals in wireless communications systems also help in combating multipath and multiple access interference (MAI). Multipath occurs when multiple of transmitted signals come with different delays. These multiple copies interfere with each other causing MAI.

Chaotic systems have several advantages over CDMA systems. Firstly, chaotic systems are much easier to use in circuits. Secondly, chaotic systems contain non-linear and random behavior due to its bifurcation property and can be use in system security. The use of chaotic systems helps us in achieving good security, capacity and efficient bit error rate (BER). There are still lot of issues that have to be solved before the use of chaos in practical life. More work is needed in this area for the further study and improvement [11] [12].

1.1 Purpose of the Thesis

This thesis is concerned with that how Chaos used in spread spectrum communication systems where multiple users transmits their data on single line so the bits of users intermingle with each other or multiple access interference (MAI) occurs. To compensate this MAI, we have proposed the suboptimum receiver scheme which is parallel interference cancellation (PIC) which kills the MAI in the data of multiple users.

1.2 Layout of the Thesis

This thesis consists of five chapters as below:

Chapter 2: Chaos Communication

This chapter gives a brief overview of chaotic generators, its security and its applications in engineering. Next we provide the overview of adaptive algorithms and their applications in wireless communication.

Chapter 3: Multiple Access Techniques

Chapter 3 gives overview of multiple access techniques that are used to multiplex data from several users on a single line. Further, we multiple users transmits their data on a single channel, the bits of user mix with each other and multiple access interference (MAI) occurs. To combat MAI, we will first see optimum receiver and later we will introduce suboptimum receiver whose complexity is less than optimum one.

Chapter 4: Chaotic Interference Suppression

In this chapter, we will discuss another scheme to kill the multiple access interference (MAI) which is parallel interference cancellation (PIC) where all the users are treated parallely.

Chapter 5: System Simulation and Conclusion

In this chapter, we summarized the figure of merit named bit error rate (BER).

Chapter 6: Summary and Future Directions

In this chapter, we summarized the main conclusions of this dissertation and possible future directions.

Chapter 2

Chaos Communication

2.1 Introduction

Chaos theory is an interesting topic which has not been yet completed, even more than four decades past having research on it. The main reason is the more unpredictable behavior of the chaotic signals. Chaoticity was first introduced by mathematicians, physicians, statisticians, engineers and biologists [13][14]. Later research has proved that this chaotic behavior is very helpful in circuit theory. Due to the circuit theory, Chaoticity has come in digital signal processing (DSP) and in digital communications. A simple mathematical formula is unable to model a chaotic behavior [15]. In most, these linear deterministic mathematical models applied to these dynamic systems exhibits three types of behaviors (a) converge towards the periodic solution (b) converge towards quasi-periodic solution (c) A solution that approaches to a constant.

A solution that reflects the unpredictable nature of our world is the "Chaos theory". It provides the required kind of system behavior such as non-linear, dynamic or unpredictable etc [16]. A chaotic system can also be defined as a deterministic system that exhibits non-linear system behavior with certain distinguishes features. There are many definitions of chaotic systems but in simple terms it is defined as "A system which has a well defined shape but it never repeat itself". It is a system that becomes aperiodic if its parameters, internal variables, external signals, control variables or even initial conditions are chosen in a specific way. We also call this unpredictable behavior of a deterministic system as a Chaos theory or Chaos system.

2.2 Chaotic Generators

A system that have orbits or set of values which are non-periodic and yet not forever increasing and decreasing and nor approaching a fix point and the things in the system that generates such orbits are called Chaotic generators [17].

Basically, we want chaotic generators to introduce more and more randomness in our system such that values generated by our system cannot be hacked and by using these values we can transmit and receive data. In a more safe way, we can develop chaoticity by using different methods, i.e. it may be some simple polynomial, may be developed by some differential equation and may also be developed by some electronic circuit.

Henri Poincare studied chaos theory in early 1900's on the problem of motion of three objects. By analyzing this he reduced the complex system with the simple system [18]. A continuous motion in the n-dimensional space projected on Poincare section can be shown using discrete transformation (map) F in the (n-1)-dimensional space.

$$P_{n+1} = F(P_n) \tag{2.1}$$

In this thesis, we shall discuss only polynomial equations that exhibit chaotic behavior and we call such polynomials equations as chaotic generators.

Chaotic Generator 1 (CG 1)

$$a_{n+1} = 1 - 2a_n^2 \tag{2.2}$$

This is the simplest type of chaotic generator that exhibits chaotic behavior and is most appreciated in digital communications to modulate the data [19]. To converge this map the initial conditions must be in the interval of [-1, 1].

Chaotic Generator 2 (CG 2)

$$a_{n+1} = ca_n(1 - a_n) \tag{2.3}$$

Chaotic generator 2 is another dynamic generator that is capable to exhibit the chaotic properties [20]. This chaotic generator is sometimes referred to as "Verhulst" model because of introducing by "Pierre Verhulst", in the mid of the 18th century. It is used to model the population growth. After that, mathematicians study this equation and found that this equation also exhibits chaos behavior if parameter c is in the interval $3.57 < c \leq 4$. Initial conditions should be in the same interval [0, 1].

Tent Generator

$$a_{n+1} = a_n^2 - 2 \tag{2.4}$$

It is also one of the important random generators used in digital communications and in digital signal processing [21]. Initial conditions of this generator should be in the interval of [-1, 1]. The output sequences of this generator are always in the interval [-2, 2] so, its initial conditions can also be taken from the interval [-2, 2].

Other Chaotic Generators

Chaotic systems are not limited to only above discussed chaotic generators but there are also other chaotic generators which are described as under.

2x mod 1 generator

$$a_{n+1} = 2a_n \ (\text{mod } 1) \tag{2.5}$$

2x mod 1 generator is also called Dyadic generator. Sometimes, it is also called Bernoulli generator and has been used in communication. The modulus operator gives remainder.

Henon generator

$$a_{n+1} = 1 - ca_n^2 + b_n \tag{2.6}$$

$$b_{n+1} = da_n \tag{2.7}$$

This map was introduced by Michel Henon and is one of the simplest 2-dimensional dynamical generators. It is one of the most studied dynamical systems that exhibit chaotic behavior.

Ikeda generator

$$a_{n+1} = 1 + u(a_n cos\ t_n \text{ - } b_n sin\ t_n) \tag{2.8}$$

$$b_{n+1} = u(a_n sin\ t_n + b_n cos\ t_n) \tag{2.9}$$

$$t_n = 0.4 \text{ - } \frac{6}{1 + a_n^2 + b_n^2} \tag{2.10}$$

Ikeda generator is one of the most studied chaotic generators that have been used in communication that exhibits chaotic behavior [22].

Further study is needed to examine the use of chaotic generators in different fields of communications. Selection of careful chaotic generator is needed for different communication schemes.

2.3 Security of Chaotic Generators

Measurement of the security aspects of any communication system is not an easy task to undertake. To begin with, the auto- and cross-correlation properties are used. If the spreading sequences provide an auto and cross-correlation properties not similar to the white noise, we can say that this would be not suitable for spread spectrum communication. In this thesis chaotic generators also provide auto- and cross-correlation similar to spread spectrum communication. Moreover, the chaotic generators are more secure than CDMA generators.

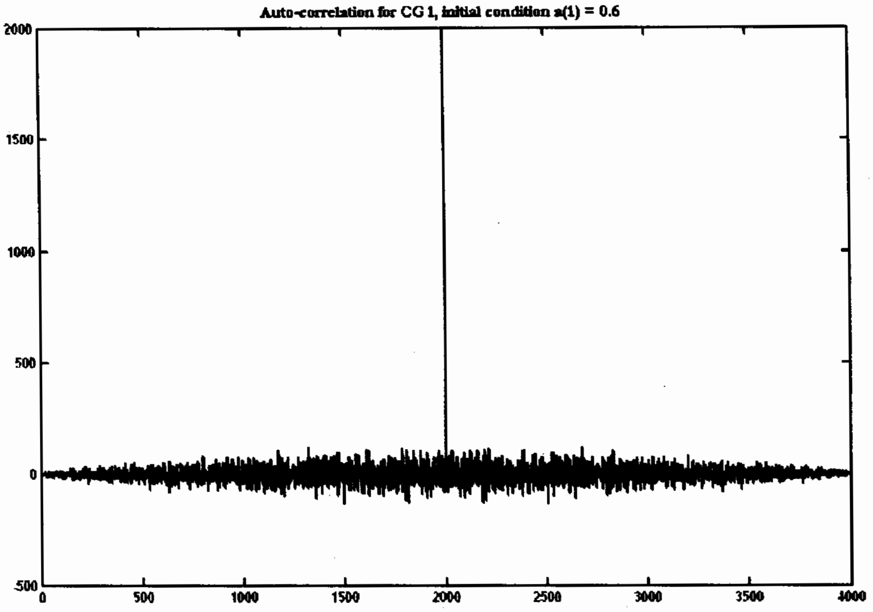

Figure 2.1: Auto-correlation of CG – 1, initial condition: a(1) = 0.6

Figures (2.1) and (2.2) show the auto- and cross-correlation performance of a Chaotic generator 1.It is quite evident from the figure (2.1) that there is maximum correlation between two same sequences otherwise the sequences are uncorrelated and this is the thing we want in spread spectrum communication. It is also clear from the figure (2.2) that cross-correlation of two sequences is zero everywhere, indicating that the two sequences are uncorrelated. The other generators like CG 2 and Tent generator have also auto- and cross-correlation similar to random white noise. Here, just for simplicity only auto- and cross-correlation of CG 1 is shown.

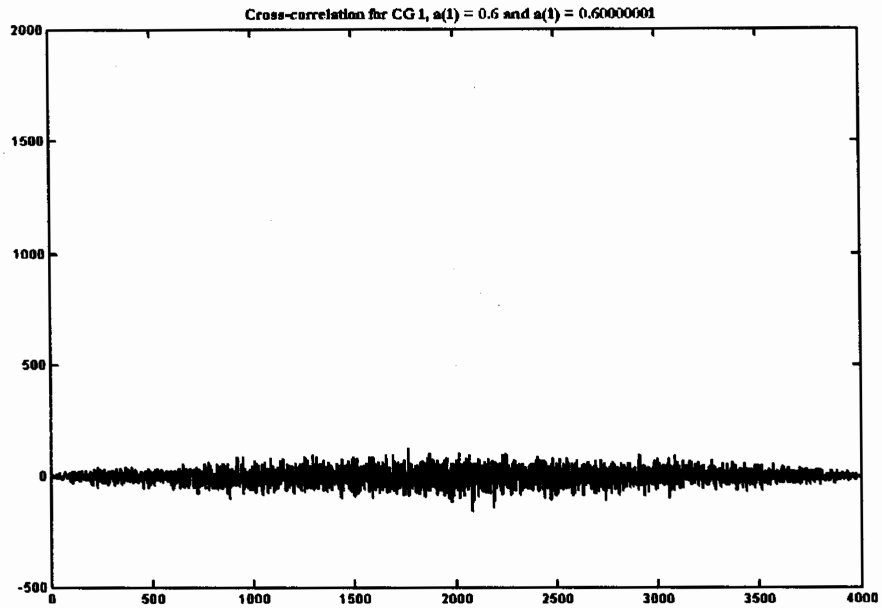

Figure 2.2: Cross-correlation of CG – 1, initial condition: a (1) = 0.6, a (1) = 0.0000006

Figures (2.3) – (2.8) show the orbits generated by using two initial conditions and very close security parameters. More importantly, it also shows that how long or how fast the sequence goes out of orbit. Results shows that exact initial conditions must be known at receiver side to exactly predict the desired signal and also there is no long term prediction in the long term. It can be clearly seen from the figures that CG 2 provides more security than other generators only due to its control parameter c.

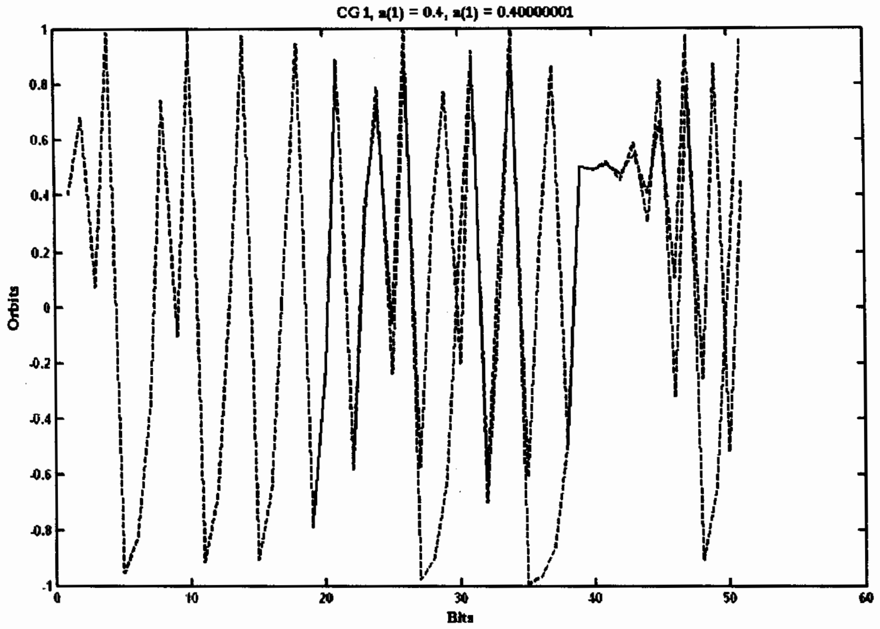

Figure 2.3: Two different chaotic sequences generated by CG 1

Figure (2.3) shows the security of chaotic systems. Here, the orbit of chaotic generator using chaotic generator 1 is shown by slightly varying initial condition. Here, the jammer is only able to see our 27 bits. He is not able to see the other bits and hence, he is not able to see our information. By varying not so close initial conditions, the jammer is never able to see our complete information.

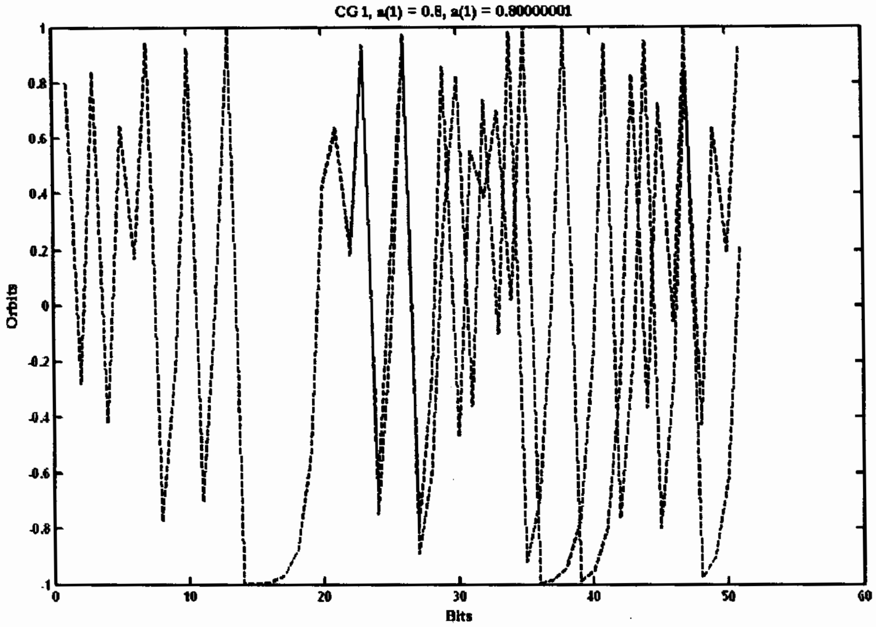

Figure 2.4: Two different chaotic sequences generated by CG 1

Here in figure (2.4) the orbit of chaotic generator is shown but with some other initial conditions than figure (2.3). Here, the jammer is again able to see our only 28 bits. He is not able to see the other bits and hence, he is not able to see our information. Here, in figures (2.3) and in figure (2.4) the jammer is only able to see our 27 bits by estimating close to our initial conditions but if the initial conditions are not so close then the jammer is not able to see our whole information.

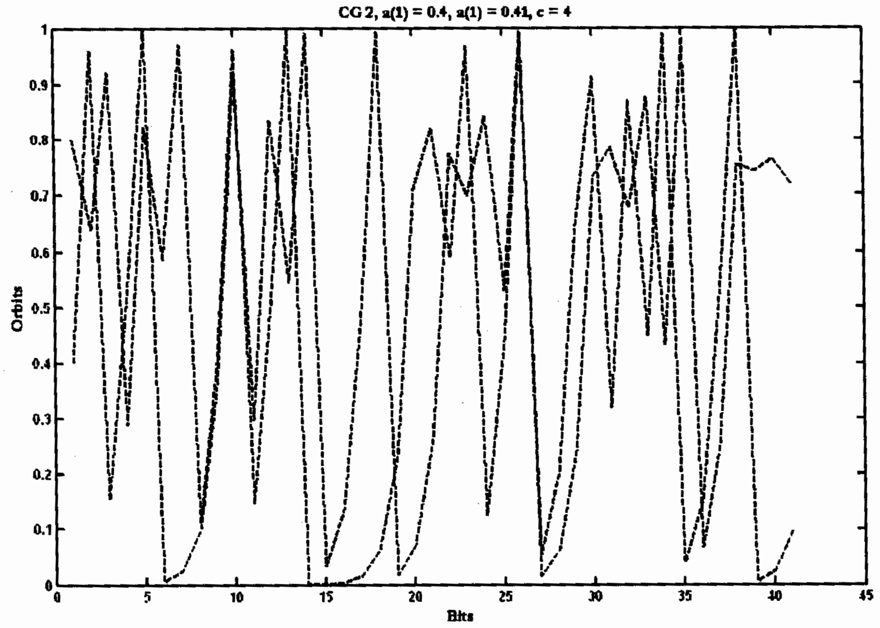

Figure 2.5: Two different chaotic sequences generated by CG 2

Figure (2.5) shows the security of chaotic systems. Here, the orbit of chaotic generator using chaotic generator 2 is shown by slightly varying initial condition. The beauty of chaotic generator 2 is that there are two parameters in its mathematical equation so, it is more secure than other chaotic generators. Here, the jammer is not able to see our even one bit, hence, he is not able to see our information. So, chaotic generator 2 is more secure than other generators.

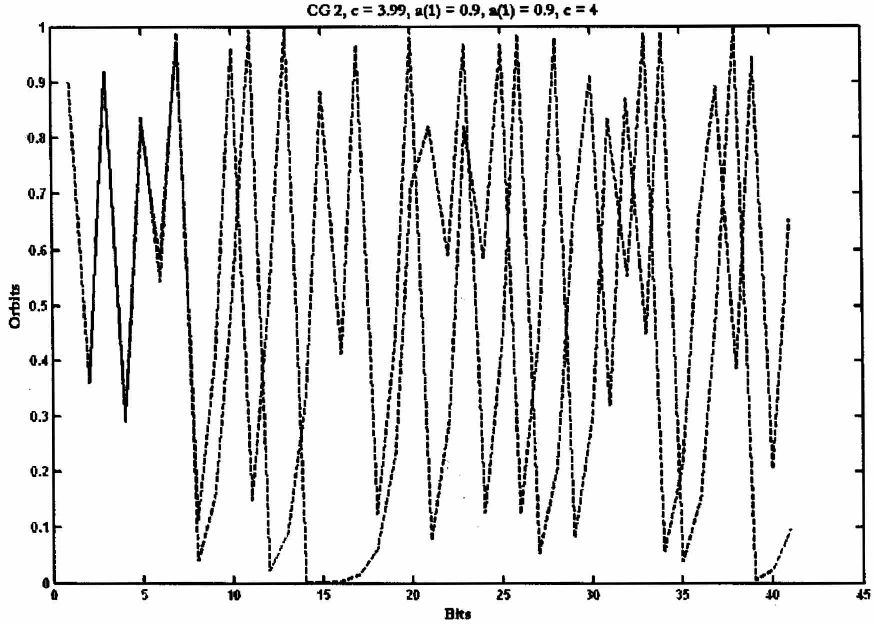

Figure 2.6: Two different chaotic sequences generated by CG 2

Figure (2.6) again shows the security of chaotic systems. Here, the orbit of chaotic generator using chaotic generator 2 is shown by slightly varying initial condition. The beauty of chaotic generator 2 is that there are two parameters in its mathematical equation so, it is more secure than other chaotic generators. Here, the jammer is not able to see our even one bit, hence, he is not able to see our information. So, chaotic generator 2 is more secure than other generators. Here, the security of chaotic generator 2 is shown by slightly varying the control parameter c.

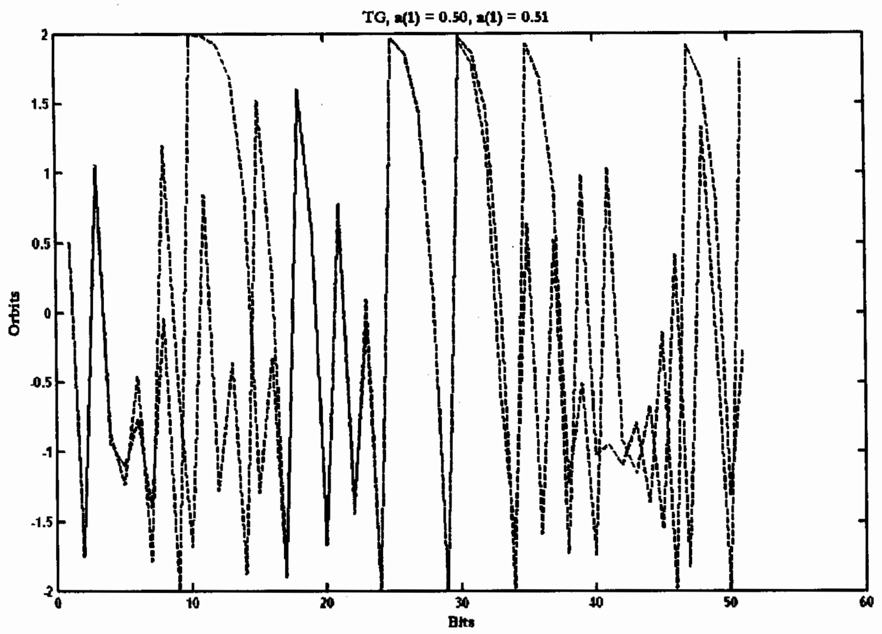

Figure 2.7: Two different chaotic sequences generated by Tent generator (TG)

Figure (2.7) shows the security of chaotic systems. Here, the orbit of chaotic generator using tent generator is shown by slightly varying initial condition. Here, the jammer is only able to see our 8 bits. He is not able to see the other bits and hence, he is not able to see our whole information. The behavior of tent generator can easily be seen by varying its initial conditions. The use of tent generator in digital communications promises to more secure.

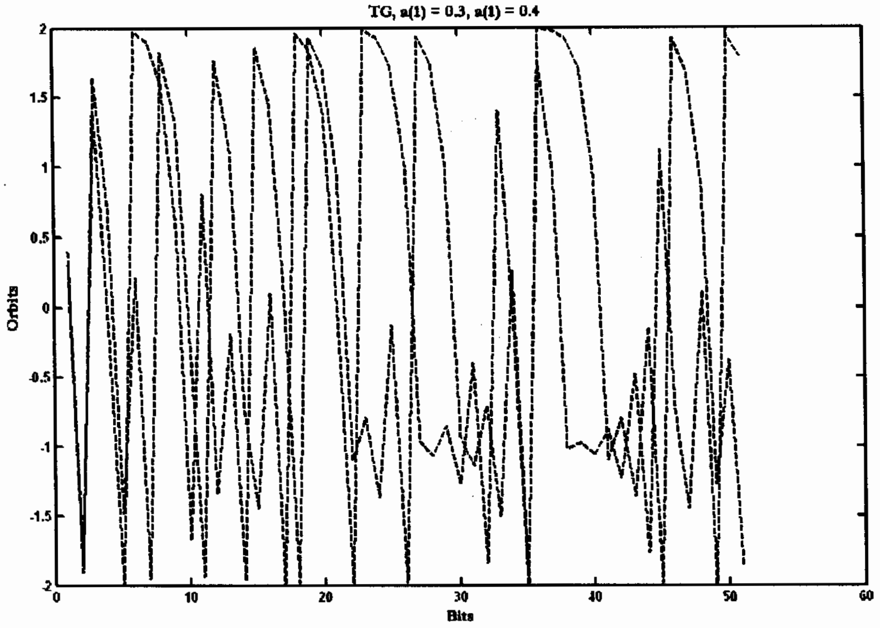

Figure 2.8: Two different chaotic sequences generated by Tent generator (TG)

Figure (2.8) shows the security of chaotic systems. Here, again the orbit of chaotic generator using tent generator is shown by slightly varying initial condition. Here, the jammer is only able to see our 7 bits. He is not able to see the other bits and hence, he is not able to see our whole information.

It is clear evident from the above figures from (2.3) - (2.8) the chaotic systems are very secure than other spread spectrum systems.

2.4 Chaotic Modulation Schemes

The ability to communicate with people on the move has evolved remarkably since Guglielmo Marconi first demonstrated radio's ability to provide continuous contact with ships sailing the English channel. That was in 1897, and since then new wireless communications methods and services have been adopted by people throughout the world [23]. Particularly, during the past ten years, the mobile radio communication industry has grown other technologies. Digital switching techniques have facilitated the large scale deployment of affordable, easy-to-use Dario communication networks. These trends will continue at even greater pace during the next decade.

In this section, we actually want to discuss different schemes which are used to modulate and transmit multiple user's data in wireless communication field. The revolution comes in chaos communication when Pecorra and Carrel theoretically and experimentally proved that if the chaos system is divided into master – slave configuration, the two chaotic systems can be synchronized. [24][25]. This discovery leds a lot of revolution in the communication field and made a bridge between chaos theory and practical implementation of chaos communication. However, the synchronization process requests a more complex chaos system that can be portioned into master – slave configuration. The basic need of synchronization is to track and recover the basic signal from the noisy received signal and maximizing the probability of correctly identifying the transmitted symbols. Moreover, the synchronization process also leads few drawbacks in term so time synchronization, circuit complexity and etc and that's why under poor conditions, communication without synchronization may be preferable. For this purpose, different adaptive algorithms may be used on receiver side to extract the original signal from the noisy channel environment.

Chaotic signals can be used to transmit both analog and digital signals. When we want to modulate an analog signal chaos parameter modulation and chaos masking modulation are two commonly found methods found in the literature [26]. Also chaos shift keying (CSK), chaos shift keying (DCSK), chaos On Off Keying (COOK) and chaos – CDMA are used to modulate the digital signals. In this thesis, we are interested in chaos – CDMA signals. The performance of these systems can vary on different no of users, channel environments and different modulation methods. A brief summary of theses modulation schemes is presented below.

Chaotic Masking Modulation

Chaos masking is actually used to modulate both analog and digital signals and is used a communication carrier. The modulated signal will be $u(t) = x(t) + m(t)$ where $m(t)$ is the original message signal and $x(t)$ is a chaotic signal. At the receiver side, the masking signal is subtracted from the received signal to recover the original information and that's why this process requires more synchronization. The more the synchronization, the more the accuracy.

Chaos Parameter Modulation

In this scheme, we hide our information signal into chaotic parameter (control parameter). Let see a look at Chaos generator 2 (CG-2) and parameter c is in the interval of $3.57 < c \leq 4$ [27, 28]. Here, if we use the values of c which will vary depending on the information signal rather than a fix value. We actually inject the information into control parameter c. and the value of c will vary within the range but now depends upon the information signal. Now at the receiver side, the problem arises design of retrieval scheme to this parameter variation from received signal and this scheme is highly sensitive to the channel noise. However, when noise is present, this scheme gives very poor results. The only way to enhance our performance which is recently used is the use of adaptive algorithms on the receiver side under noisy environment and these adaptive algorithms shows good performance to retrieve the original signal.

Chaos Shift Keying (CSK)

In binary chaos shift keying, different bit energies are used to transmit the binary information [29][30]. Information is sent either by $u_1(t)$ or $u_0(t)$ one at a time. For example, if 1 has to be transmitted, the chaotic signal $u_1(t)$ is to be sent and for 0, the chaotic signal $u_0(t)$ is to be sent. The two chaotic signals can come from two different chaotic systems or come from the same chaotic system but varying control parameters. The transmitted signal is given by

$$u(t)=\begin{Bmatrix} u_1(t) & \text{symbol "1" is transmitted} \\ u_2(t) & \text{symbol "0" is transmitted} \end{Bmatrix}$$

But we shall focus on antipodal CSK modulation technique in which both signals are inverted copies of each other $u_0(t) = -u_1(t)$. The transmitted signal can be written as

$$u(t)=\begin{cases} u_0(t) & \text{symbol "1" is transmitted} \\ -u_0(t) & \text{symbol "0" is transmitted} \end{cases}$$

The demodulation scheme used in this scheme can be coherent and non-coherent. The coherent scheme is like a correlator detector, where the receiver contains the copies of chaotic generators $u_1(t)\ \ and\ \ u_0(t)$.

In non-coherent receivers, the transmitted chaotic signals should have different bit energies. Then by using matched filter, we can easily recover the transmitted signal.

Chaos On Off Keying (COOK)

Chaos on off keying is similar to chaos shift keying, but instead of two different chaotic signals, it works like a on off switch which depends upon 1 or 0. For example when the information bit is “1”, the chaotic signal $u_0(t)$ is sent, otherwise no signal is sent. This scheme is suitable for indoor wireless applications. The transmitted signal is

$$u(t)=\begin{cases} u_0(t) & \text{symbol "1" is transmitted} \\ 0 & \text{symbol "0" is transmitted} \end{cases}$$

Differential Chaos Shift Keying (DCSK)

The differential chaos shift keying was first introduced by [23] and is used when channel conditions are bad or it is impossible to achieve synchronization. It is similar to differential phase shift keying (DPSK) except the transmitted signal comes from the chaotic source. In differential chaos shift keying (DCSK), the transmitted symbol is divided into two identical time slots, one for reference signal and other carries information. If bit "1" is to be sent, the chaotic reference signal is repeated in the second slot. If bit "0" is to be sent, an inverted copy of reference signal will be sent. Hence, the transmitted signal for information bit "1" is

$$u(t)=\left\{\begin{array}{ll} u_0(t) & \text{for}(l-1)T_b \le t < (l-\frac{1}{2})T_b \\ u_0(t-\frac{T_b}{2}) & \text{for}(l-\frac{1}{2})T_b \le t < lT_b \end{array}\right\}$$

If the information bit is "0", then

$$u(t)=\left\{\begin{array}{ll} u_0(t) & \text{for}(l-1)T_b \le t < (l-\frac{1}{2})T_b \\ -u_0(t-\frac{T_b}{2}) & \text{for}(l-\frac{1}{2})T_b \le t < lT_b \end{array}\right\}$$

At the receiver side, the two signals are correlated and decision is made by a threshold device. There are also some other advantages and disadvantages of DCSK. The disadvantage is that bit energy is double and symbol rate is halved. However, the advantage is that it does not require any synchronization and is not sensitive to channel distortion as other coherent schemes because the reference signal and the information signal goes through the same channel.

Chaos CDMA

Conventional CDMA spread spectrum has made great revolutions in our daily communication systems, especially in (3G) mobile systems and in (4G) mobile systems. In order to provide these services, we must have an efficient radio link that provides high frequency, low power transmitter and multiple access communication schemes, where every user appears as a white noise to all other users in the same link. To do so, we spread our information using pseudorandom sequence to increase the bandwidth of transmitted signal Here, we shall use chaotic generator instead of PN generator.

The beauty of chaotic signals is that it produces a bifurcation behaviour which makes it possible to generate "noise-like" signals. The difference between PN generator and chaotic generator is that PN generator is periodic while the chaotic generator produces the output sequences which never repeat itself or we can say that chaotic sequences are aperiodic. Hence, due to its random, noise-like and non-periodic behavior, chaos can be used in the generation of CDMA code sequences.

2.5 Adaptive Algorithms

There are large no of applications of adaptive algorithms. Generally, these applications can be classified into four major groups: identification, inverse modeling, prediction and interference cancelling.

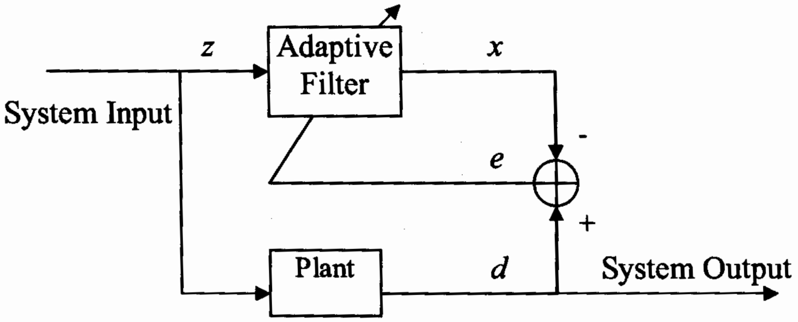

Figure 2.9: Adaptive filtering application configuration: Identification

These different classes are basic building blocks for these applications. All the four cases have same input vector and desired response to calculate an estimation error. This estimation error is then used to update filter coefficients. All four classes are listed below

z = applied input to the adaptive filter
x = output of the adaptive filter
d = desired response
$e = d - y$ = estimation error

1. Identification

Figure 2.9 shows a block diagram for the adaptive algorithm class: Identification. In this type of application, an adaptive filter is used to provide a linear model that represents the best fit to an unknown plant. The plant and the adaptive filter came from the same input. The plant output supplies the desired response for the adaptive filter. If the plant is dynamic, the model will be time varying.

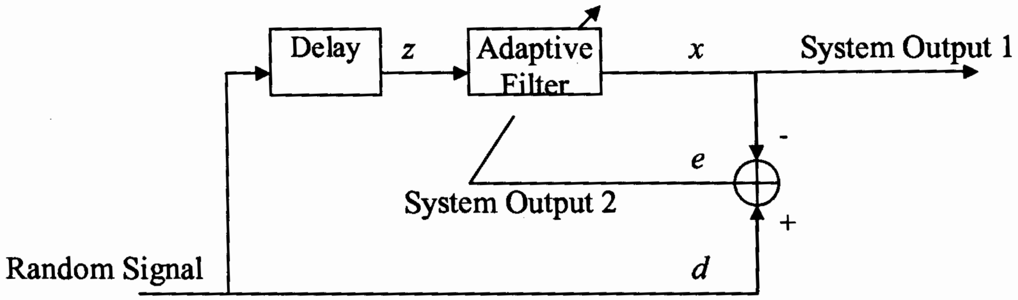

Figure 2.10: Adaptive filtering application configuration: Inverse Modeling

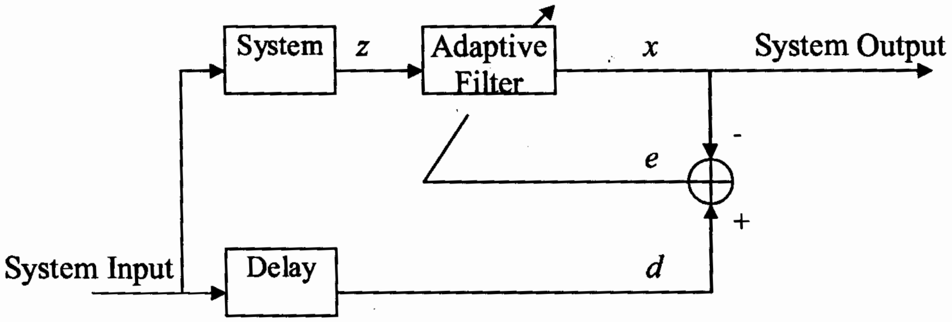

Figure 2.11: Adaptive filtering application configuration: Prediction

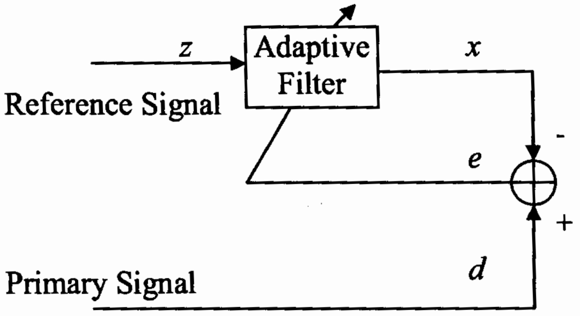

Figure 2.12: Adaptive filtering application configuration: Interference cancellation

2. Inverse modeling

Figure 2.10 shows a block diagram for the adaptive algorithm class: Inverse modeling. Here, the function of the adaptive filter is to provide an inverse model that represents the best fit to an unknown noisy plant. Ideally, in the case of a linear system, the inverse model has a transfer function equal to the inverse of plant's transfer function.

3. Prediction

Figure 2.11 shows a block diagram for the adaptive algorithm class: Prediction. Here, the function of adaptive filter is to provide the best prediction of the present value of a random signal. The present value of the signal thus serves the purpose of a desired response for the adaptive filter. Past values of the signal supply the input applied to the filter. Depending upon the application of the interest, the adaptive filter output or the estimation error

4. Interference cancellation

Figure 2.12 shows a block diagram for the adaptive algorithm class: Interference cancellation. Here, the adaptive filter is used to cancel the unknown interference contained in primary signal, with the cancellation being optimized in some statistical sense. The primary signal serves as the desired response for the adaptive filter. A reference (secondary) signal is employed as the input to the filter. The reference signal is derived from a sensor or a set of sensors located so that it or they supply the primary signal in such a way that the information-bearing signal component is weak or essentially undetectable.

In the literature, there is variety of applications where adaptive algorithms have been used especially in digital communications.

2.6 Applications of Adaptive Algorithms

Adaptive filtering techniques are used to recover signals in an environment where statistics are unknown and are very attractive tools in the communication system. Adaptive filtering techniques are applied in all kind of engineering such as biomedical, mechanical, chemical, control systems, radar and communication engineering. Adaptive filtering techniques are used in wide range of applications like echo cancellation, adaptive equalization, adaptive noise cancellation, channel estimation, adaptive demodulation and adaptive beamforming.

Adaptive filters rely for its operations on recursive algorithms, which make it possible to perform satisfactory in an environment where complete knowledge of relevant signal characteristics is not known a pirori. The algorithm starts from some predetermined set of initial conditions [29], representing whatever we know about the environment. Yet in a stationary environment, we find that after successive iterations of the algorithm it converges to the optimum wiener solution in some statistical sense. In non-stationary environment, the algorithm offers a tracking capability, in that it can track time variations in the statistics of the input data, provided that the variations are sufficiently slow.

A wide variety of recursive algorithms have been developed in the literature for the operation of linear adaptive filters. Depending on their application, adaptive algorithms are chosen based on their performances using the factors listed below [30].

1. Convergence rate

It is defined as the number of iterations required for the algorithm to response to the stationary inputs and to converge close enough to the optimum Wiener solution in the mean-square sense. A fast convergence rate allows the algorithm to adapt rapidly in a non-stationary environment of unknown statistics.

2. Misadjustment

This parameter provides a quantitative measure of the amount by which the final value of mean-square error, averaged over an ensemble of adaptive filters, deviates from the minimum mean-square error produced by the Wiener filter.

3. Tracking

When an adaptive filtering algorithm operates in a non-stationary environment, the algorithm is required to track statistical variations in the environment.

4. Robustness

For an adaptive filter to be robust, small disturbances can only resulting small estimation errors. The disturbances may arise from a variety of factors.

5. Computational complexity

Here we concerned with (a) the number of operations (multiplications, divisions, additions, subtractions) required to make one complete iteration of the algorithm.(b) size of memory locations required to store the data and the program and (c) the investment required to program the algorithm on a computer.

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6. Structure

This refers to the structure of information flow in the algorithm, determining the manner in which it is implemented in hardware For example whose structure exhibits high modularity, parallelism or concurrency is well suited for implementation using very large-scale integration (VLSI).

7. Numerical properties

When an algorithm is implemented numerically, inaccuracies are produced due to quantization errors, which in turn are due to analog-to-digital conversion of the input data and digital representation of internal calculations. In particular, there are basic two issues: numerical stability and numerical accuracy. Numerical stability is an inherent characteristic of adaptive filtering algorithm. Numerical accuracy is determined by the no of bits and filter coefficients. An adaptive filtering algorithm is said to be numerically robust when it is insensitive to variations in the worldlength in its digital implementation.

Least-mean-square (LMS) algorithm is a stochastic gradient algorithm that iterates each tap-weight of the transversal filter in the direction of instantaneous gradient of squared error signal but the drawback of LMS is that its convergence is slow especially when input is colored. On the other hand, recursive least squares (RLS) algorithm converges fastly but its complexity is higher than LMS.

2.7 Applications of Chaos

There are number of applications where chaos is used. Chaos can be used in weather behavior, biomedical signals, laser systems, electronic circuits, chemical reactions, mechanical system, financial data and in other fields. Some of applications of chaotic systems are discussed below.

Electrical Systems

The use of energy is great impact on our daily life. Grid distribution on heavy systems that spreads over large areas uses chaos. The failures may be caused by sudden lightening which will result in the instability of whole power system. These failures can also be detected using chaotic techniques [31].

Data Coding Applications

Chaos is also used in data coding applications like audio compression, video compression, cryptography and channel coding etc.

Mechanical Systems

Techniques of chaotic systems can be used in mechanical systems such as washing machines. Just like chemical engineering, chaos in washing machines provides a better dissolving of the detergent. Chaos can also be used in drilling and smoothing applications

Optical communications

Recent research has shown that chaos can also be used in optical communication. Chaos optical communication using optoelectronic feedback systems with chaotic wavelength fluctuation has been proposed. Recently, lot of promising issues by using chaos in the optical communication are carried out which can be easily found in the literature.

Chemistry and Chemical Engineering

The role of chaos is very important in mixing two fluids utilizing the minimum energy. Typical variables are input flow rates and overall temperature of a chemical concentration. In other words, the better the control of mixing of two chemicals, the better their performance. A chaotic mixer is much faster and efficient mixing method than other systems. It can also be used in combustion applications and in nuclear fusion reactor in heat wave injection [32].

2.8 Conclusions

Although chaos has been studied by different mathematicians past many decades but still science is unable to know that where chaos can be used further. . From the past three decades, much progress has been made in the chaos and in understanding its basic ideas. Although, the chaos has helped man a lot but yet, there are still some challenging issues. The use of adaptive algorithms in chaotic communication is very useful and is also promising in the future.

In this chapter, some basic ideas about the chaos were discussed. Different types of chaotic generators were also introduced and the applications of chaos in various fields of life. There is still lot of room for the chaos to research in the area of wireless communications.

Chapter 3

Multiple Access Techniques

3.1 Introduction

Multiple access schemes are used to allow many mobile users to share simultaneously a finite amount of radio spectrum. The sharing of spectrum is required to achieve high capacity by simultaneously allocation the available bandwidth to multiple users [33]. For high quality communications, this must be done without degration in the performance of the system. In wireless communications systems, it is often desirable to allow the subscriber to send simultaneously information to the base station while receiving information from the base station.

Duplexing may be done using frequency or time domain techniques. Frequency division Duplexing (FDD) provides two distinct bands of frequency foe each user. The forward band provides traffic from the base station to the mobile while; the reverse band provides traffic from mobile to the base station. In FDD, ant duplex channel contains two simplex channels

[34]. The frequency separation between each forward and reverse channel is constant throughput the system, regardless of the particular channel being used. Time division Duplexing (TDD) uses time instead of frequency to provide both a forward and reverse link. In TDD, multiple users share a single radio channel by taking turns in the time domain. Individual users are allowed to access the channel in assigned time slots and each duplex channel has both a forward time slot and a reverse time slot to continue bidirectional communication. If the time separation between the forward and the reverse time slot is small, then the transmission and reception of data appears simultaneously to the users at both the subscriber unit and on the base station side. TDD allows communication on a single channel and simplifies the subscriber equipment since a duplexer is not required.

3.2 Multiple Access Techniques

A limited amount of bandwidth is allocated for wireless services. A wireless system is required to accommodate as many users as possible by effectively sharing the limited bandwidth [35]. Therefore, in the field of communications, the term multiple access could be defined as a means of allowing multiple users to simultaneously share the finite bandwidth with least possible degradation in the performance of the system. There are several techniques how multiple accessing can be achieved. The are four basic schemes

1. Frequency Division Multiple Access (FDMA)

2. Time Division Multiple Access (TDMA)

3. Code Division Multiple Access (CDMA)

4. Space Division Multiple Access (SDMA)

3.2.1 Frequency Division Multiple Access

FDMA is one of the earliest multiple-access techniques used in cellular systems when continuous transmission is required for analog services. In this technique the bandwidth is divided into a number of channels and distributed among users with a finite portion of bandwidth for permanent use as illustrated in figure 3.1. The vertical axis that represents the code is shown here just to make a clear comparison with CDMA. The channels are assigned only when demanded by the users. Therefore when a channel is not in use it becomes a wasted resource. FDMA channels have narrow bandwidth (30 KHz) and therefore they are usually implemented in narrowband systems. Since the user has his portion of the bandwidth all the time, FDMA does not require synchronization or timing control, which makes it algorithmically simple.

Even though no two users use the same frequency band at the same time, guard bands are introduced between frequency bands to minimize adjacent channel interference. Guard bands are unused frequency slots that separate neighboring channels. This leads to a waste of bandwidth. When continuous transmission is not required, bandwidth goes wasted since it is not being utilized for a portion of the time. In wireless communications, FDMA achieves simultaneous transmission and reception by using Frequency division duplexing (FDD). In order for both the transmitter and the receiver to operate at the same time, FDD requires duplexers. The requirement of duplexers in the FDMA system makes it expensive.

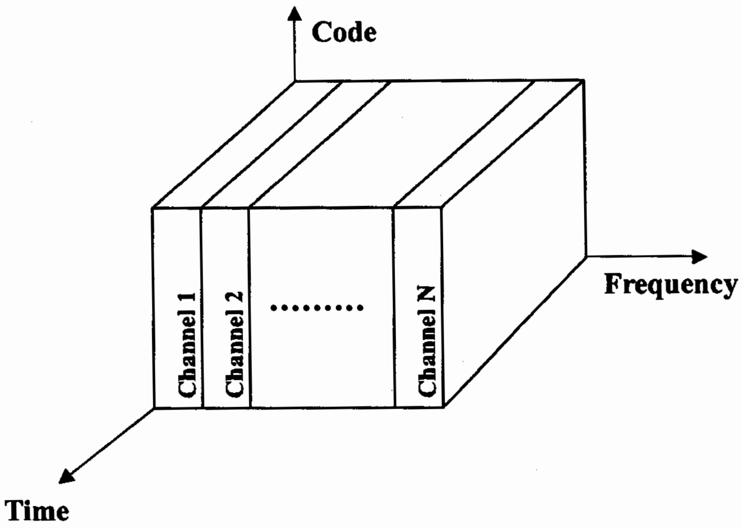

Figure 3.1 Channel usage by FDMA

3.2.2 Time Division Multiple Access

In digital systems, continuous transmission is not required because users do not use the allotted bandwidth all the time. In such systems, TDMA is a complimentary access technique to FDMA. Global Systems for Mobile communications (GSM) uses the TDMA technique [36]. In TDMA, the entire bandwidth is available to the user but only for a finite period of time. In most cases the available bandwidth is divided into fewer channels compared to FDMA and the users are allotted time slots during which they have the entire channel bandwidth at their disposal. This is illustrated in figure 3.2. TDMA requires careful time synchronization since users share the bandwidth in the frequency domain. Since the numbers of channels are less, inter channel interference is almost negligible; hence the guard time between the channels is considerably smaller. Guard time is spacing in time between the TDMA bursts. In cellular communications, when a user moves from one cell to another there is a chance that user could experience a call loss if there are no free time slots available. TDMA uses different time slots for transmission and reception. This type of duplexing is referred to as Time division duplexing (TDD). TDD does not require duplexers.

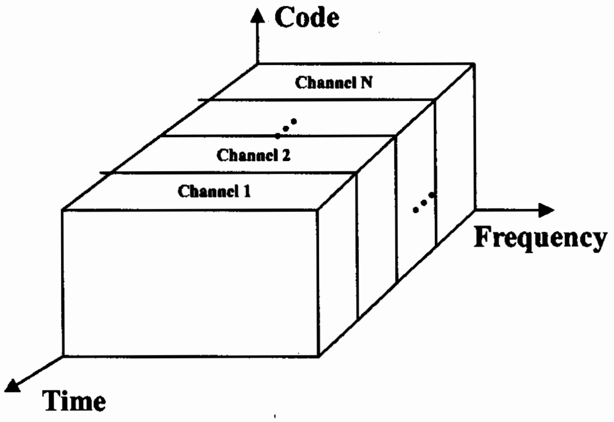

Figure 3.2 Channel usage by TDMA

3.2.3 Code Division Multiple Access

In CDMA, all the users occupy the same bandwidth; however they are all assigned separate codes, which differentiate them from each other as shown in figure 3.3. CDMA systems utilize a spread spectrum technique in which a spreading signal, which is uncorrelated to the signal and has a large bandwidth, is used to spread the narrow band message signal [37]. Direct Sequence Spread Spectrum (DS-SS) is most commonly used for CDMA. In DS-SS, the message signal is multiplied by a Pseudo Random Noise Code (PN code), which has noise-like properties. Each user has his own codeword which is orthogonal to the codes of other users. In order to detect the user, the receiver is required to know the codeword used by the transmitter. Unlike TDMA, CDMA does not require time synchronization between the users.

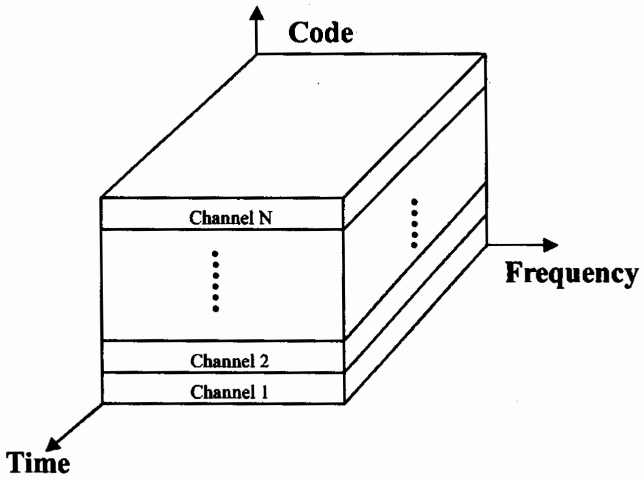

Figure 3.3 Channel usage by CDMA

A CDMA system experiences a problem called self-jamming which arises when the spreading codes used for different users are not exactly orthogonal. While dispreading, this leads to a significant contribution from other users to the receiver decision statistic. If the power of the multiple users in a CDMA system is unequal, then the user with the strongest signal power will be demodulated at the receiver. The strength of the received signal raises the noise floor for the weaker signals at the demodulators. This reduces the probability that weaker signals will be received. This problem, known as the near-far problem can be taken care of by using power control. This ensures that all the signals within the coverage of the base station arrive with same power at the receiver.

3.2.4 Space Division Multiple Access

SDMA utilizes the spatial separation of the users in order to optimize the use of the frequency spectrum. A primitive form of SDMA is when the same frequency is re-used in different cells in a cellular wireless network [38]. However for limited co-channel interference it is required that the cells should be sufficiently separated. This limits the number of cells a region can be divided into and hence limits the frequency re-use factor.

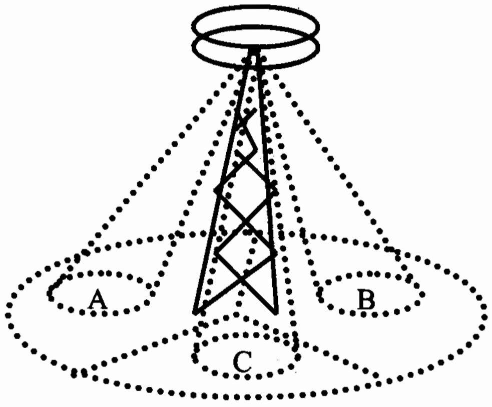

Figure 3.4 Intra-cell SDMA

A more advanced approach can further increase the capacity of the network. This technique would enable frequency re-use within the cell. It uses a Smart

Antenna technique that employs antenna arrays backed by some intelligent signal processing to steer the antenna pattern in the direction of the desired user and places nulls in the direction of the interfering signals. Since these arrays can produce narrow spot beams, the frequency can be re-used within the cell as long as the spatial separation between the users is sufficient. Figure 3.4 shows three users served by SDMA using the same channel within the cell. In a practical cellular environment it is improbable to have just one transmitter fall within the receiver beam width. Therefore it becomes imperative to use other multiple access techniques in conjunction with SDMA. When different areas are covered by the antenna beam, frequency can be re-used, in which case TDMA or CDMA is employed, for different frequencies FDMA can be used.

3.3 Capacity of Multiple Access Methods

The capacity of FDMA, TDMA and CDMA can be compared in terms of information rate under ideal channel conditions for the K number of users [39] having average power $P_i = P$ for all $1 \leq i \leq K$. The capacity of a single user is

$$C = Wlog_2\left(1+\frac{P}{WN_0}\right) \tag{3.1}$$

Where $\frac{1}{2}N_0$ is the power spectral density of the additive white noise.

In FDMA, each user is allocated a bandwidth $\frac{W}{K}$. Hence, the capacity of each user is

$$C_k = \frac{W}{K} log_2 \left[1 + \frac{P}{(\frac{W}{K}) N_0} \right] \tag{3.2}$$

and the total capacity for the K users is

$$C_{tot} = KC_k = Wlog_2 \left[1 + \frac{KP}{WN_0} \right] \tag{3.3}$$

Therefore, the total capacity is equal to a single user with average power $P_{avg} = KP$. For the fixed bandwidth W, the total capacity goes to infinity as no of user's increases linearly with K. On the other hand, as K increases, each user is allocated a smaller bandwidth $\frac{W}{K}$ and consequently, the capacity per user decreases. The capacity $C_{k,norm}$ per user normalized by the channel bandwidth is given as

$$C_{k,norm} = \frac{C_k}{W} = \frac{1}{K} log_2 \left[1 + K \frac{C_k}{W} \left(\frac{\varepsilon_b}{N_0} \right) \right] \tag{3.4}$$

A more simplified form of Equation (3.4) can be obtained by defining the normalized total capacity $C_{norm} = K \frac{C_K}{W}$, which is the total bit rate for all users per unit of bandwidth. Thus, after some little manipulation, Equation (3.4) can be written as

$$C_{norm} = log_2 \left(1 + C_n \frac{\varepsilon_b}{N_0} \right) \tag{3.5}$$

In TDMA system, each user transmits for $\frac{1}{K}$ of the time through the channel of bandwidth W, with the average power KP. Therefore, the capacity per user is

$$C_k = \left(\frac{1}{K}\right) W log_2 \left(1 + \frac{KP}{WN_0}\right) \tag{3.6}$$

Which is identical to the capacity of an FDMA system as Equation (3.2). In TDMA system, it may not possible for the transmitters to contain a transmitter power of KP when K is very large. Hence, there is a practical limit beyond which the transmitter power cannot be increased as K is increased.

In CDMA systems, each user transmits a pseudorandom signal of a bandwidth W and average power P. The capacity of this system depends upon the cooperation among the K users. At one stage, the receiver for each user signal does not know the codes and spreading waveforms of the other users. This is called single-user detection. Hence, the other users appear as a white noise for the particular user. In case of multiuser communication, system contains K single-user matched filters [40]. Assuming that pseudorandom signal of each user is Gaussian, and then each user is corrupted by Gaussian interference of power $(K-1)P$ and noise of power WN_0. Therefore, the capacity per user for single-user detection (SUD) is

$$C_{k,norm} = W log_2 \left(1 + \frac{P}{WN_0 + (K-1)P}\right) \tag{3.7}$$

The capacity $C_{k,norm}$ per user normalized by the channel bandwidth W is

$$C_{k,norm} = \frac{C_k}{W} = log_2\left(1 + \frac{C_k}{W}\frac{\frac{\varepsilon_b}{N_0}}{1+(K-1)(\frac{C_k}{W})(\frac{\varepsilon_b}{N_0})}\right) \tag{3.8}$$

For large no of users, we can use the approximation $ln(1+x) \leq x$ and after little manipulation we can write Equation (3.8) as

$$\frac{C_k}{W} \leq \frac{C_k}{W}\frac{\frac{\varepsilon_b}{N_0}}{1+K(\frac{C_k}{W})(\frac{\varepsilon_b}{N_0})} log_2 e \tag{3.9}$$

And the normalized total capacity $C_{norm} = K\frac{C_K}{W}$ can be written as

$$C_{norm} \leq log_2 e - \frac{1}{\frac{\varepsilon_b}{N_0}} \tag{3.10}$$

$$\leq \frac{1}{ln2} - \frac{1}{\frac{\varepsilon_b}{N_0}} < \frac{1}{ln2} \tag{3.11}$$

In this case, we observe that the total capacity does not increase with K as in TDMA and FDMA.

3.4 Code-Division Multiple Access

We have seen that in TDMA and FDMA, the channel is partitioned into independent subchannels which are non-overlapping. In CDMA, each user is assigned a distinct signature which is used to modulate and spread the user signal over the whole bandwidth. The signature sequences also allow the receiver to demodulate the transmitted signal by multiple users of channel, who transmit the signal simultaneously and asynchronously [41].

In this chapter, we shall see the demodulation and detections of CDMA signals and we shall also see the maximum-likelihood detector whose complexity grows exponentially with the no of users and then to reduce this complexity we came to suboptimum detectors whose complexity grows linearly with the no of users.

3.4.1 CDMA Signal and Channel Models

Consider a CDMA channel that is shared by K simultaneous users. Each user is assigned a particular signature waveform $g_k(t)$ of duration T_b, where T_b is the symbol interval. The signature waveform may be expressed as

$$g_k(t) = \sum_{i=0}^{L-1} b_k(i) h(t - iT_c) \qquad 0 \le t \le T_b \tag{3.12}$$

Where $\{b_k(i), 0 \le i \le L-1\}$ is a PN sequence containing L chips that take values $\{\pm 1\}$ and $h(t)$ is rectangular pulse over which the information is ridden of duration T_c and T_c is the chip interval [32]. Thus we have L chips per symbol and $T_b = LT_c$. Here, we also assume that all signature waveforms have unit energy.

$$\int_0^{T_b} g_k^2(t)\mathrm{dt} \tag{3.13}$$

We assume that binary antipodal signals are transmitted whose values are $\{\pm 1\}$ and let the user block of data be denoted by $\{d_k(m)\}$ and if each user transmits a block of data then from the k^{th} user, the block of data is

$$\mathbf{d}_k = \left[d_k(1), d_k(2) \ldots d_k(N)\right]^{\mathrm{t}} \tag{3.14}$$

And the low-pass transmitted waveform can be written as

$$u_k(t) = \sqrt{\varepsilon_k} \sum_{i=1}^{N} b_k(i) g_k(t - iT_b) \tag{3.15}$$

Where ε_k is the signal energy per bit. The composite signal for K no of users can be written as

$$u(t) = \sum_{k=1}^{K} u_k(t) \tag{3.16}$$

Using Equation (3.15) in Equation (3.16) we have

$$u(t) = \sum_{k=1}^{K} \sqrt{\varepsilon_k} \sum_{i=1}^{N} d_k(i) g_k(t - iT_b) \tag{3.17}$$

The transmitted signal is assumed to be corrupted by AWGN. Hence, the received signal can be written as

$$r(t) = u(t) + n(t) \tag{3.18}$$

Where $s(t)$ is the transmitted signal and is given in Equation (3.17) and $n(t)$ is the white noise, with power spectral density $\frac{N_0}{2}$.

3.4.2 The Optimum Receiver

Optimum receiver is one which selects the bits $\{d_k(i)\ ,1 \le i \le N, 1 \le k \le K\}$ which has maximum probability of occurrence given the received signal $r(t)$. Here, we have assumed that transmission is synchronous [32]. In this type of receiver, each user produces exactly one symbol which interferes with the desired symbol. In the corruption of signal with AWGN, it is sufficient to consider the received signal in the interval $0 \le t \le T_b$. Hence, $r(t)$ can be written as

$$r(t) = \sum_{k=1}^{K} \sqrt{\varepsilon_k}\, d_k(1) g_k(t) + n(t) \qquad 0 \le t \le T_b \tag{3.19}$$

The optimum maximum-likelihood receiver computes the log-likelihood function

$$\Lambda(b) = \int_0^{T_b} \left(r(t) - \sum_{k=1}^{K} \sqrt{\varepsilon_k}\, d_k(1) g_k(t) \right)^2 \mathrm{dt} \tag{3.20}$$

and selects the information sequence $\{d_k(1),\ \ 1 \le k \le K\}$ that minimizes $\Lambda(b)$. By expanding Equation (3.20) we obtain

$$\begin{aligned}\Lambda(b) = \int_0^{T_b} r^2(t)\mathrm{d}t - 2\sum_{k=1}^{K}\sqrt{\varepsilon_k}\, d_k(1)\int_0^{T_b} r(t)g_k(t)\mathrm{d}t \\ + \sum_{j=1}^{K}\sum_{k=1}^{K}\sqrt{\varepsilon_j\varepsilon_k}\, d_k(1)d_j(1)\int_0^{T_b} g_k(t)g_j(t)\mathrm{d}t\end{aligned} \tag{3.21}$$

The Equation (3.21) can be written in terms of correlation metrics which is

$$\begin{aligned}C(\mathbf{r}_k,\mathbf{b}_k) = 2\sum_{k=1}^{K}\sqrt{\varepsilon_k}\, d_k(1)r_k \\ - \sum_{j=1}^{K}\sum_{k=1}^{K}\sqrt{\varepsilon_j\varepsilon_k}\, d_k(1)d_j(1)\rho_{jk}(0)\end{aligned} \tag{3.22}$$

Here, the first integral in Equation (3.21) is common so it can be neglected and also

$$\rho_{jk}(0) = \int_0^{T_b} g_k(t)g_j(t)\mathrm{d}t \tag{3.23}$$

and

$$r_k = \int_0^{T_b} r(t)g_k(t)\mathrm{d}t \qquad 1 \le k \le K \tag{3.24}$$

Equation (3.22) can also be expressed in vector form as

$$C(\mathbf{r}_k,\mathbf{d}_k) = 2\mathbf{d}_k^{\mathrm{t}}\mathbf{r}_k - \mathbf{d}_k^{\mathrm{t}}\mathbf{R}_s\mathbf{d}_k \tag{3.25}$$

Where

$$\mathbf{r}_k = [r_1, r_2, \ldots\ldots\ldots\ldots\ldots r_k]^{\mathrm{t}}$$

And

$$\mathbf{d}_k = \left[\sqrt{\varepsilon_1}\, d_1(1) \ldots\ldots \sqrt{\varepsilon_k}\, d_k(1)\right]^{t}$$

and $\mathbf{R}_s$ is the correlation matrix with elements $\rho_{jk}(0)$. Here, we note that optimum receiver must have knowledge of signal energies in order to compute correlation matrix.

There are 2^k possible combinations of K bits. The optimum detector computes the correlation metrics for each sequence and selects the sequence which has largest correlation metric. Also, the optimum detector has a complexity that grows exponentially with the no of K users. The optimum detector consists of bank of K matched filters followed by matched filters which computes the 2^k correlation metrics. Then, detector selects the bits which contains large correlation metric.

3.4.3.1 The Suboptimum Receiver

We have seen that maximum-likelihood detector has computational complexity that grows exponentially with no of K users but here we shall see another detector which has computational complexity that grows linearly with the K no of users. One of the simplest suboptimum detectors is

3.4.3.2 Conventional single-user detector

In conventional single-user detection, the receiver for each user consists of a matched filter that matches with the signature sequence of particular user and passes output to the detector, which then makes a decision. The conventional detector also assumes that aggregate noise plus interference is white and Gaussian.

For synchronous transmission, the output of matched filter for the k^{th} user in the interval $0 \leq t \leq T_b$ is

$$r_k = \int_0^{T_b} r(t) g_k(t) \mathrm{dt} \qquad 1 \leq k \leq K \tag{3.26}$$

$$= \sqrt{\varepsilon_k} d_k(1) + \sum_{\substack{j=1 \\ j \neq k}}^{K} \sqrt{\varepsilon_j} d_j(1) \, \rho_{jk}(0) + n_k(1) \tag{3.27}$$

where

$$n_k(1) = \int_0^{T_b} n(t) g_k(t) \mathrm{dt} \quad 1 \leq k \leq K \tag{3.28}$$

Since, $n(t)$ is white Gaussian noise with power spectral density $\frac{1}{2} N_0$, the variance of $n_k(1)$ is

$$E[n_k^2(1)] = \frac{1}{2} N_0 \int_0^{T_b} g_k^2(t) \mathrm{dt} \tag{3.29}$$

$$= \frac{1}{2} N_0 \tag{3.30}$$

The first term in Equation (3.27) is signal, the second term is multiple access interference (MAI) and the third term is AWGN. If all the signature waveforms are orthogonal, then the middle term will vanish and SUD will be optimum. On the other hand, if the signature waveforms are not orthogonal then interference from the other users can become more excessive if the power level of all users is large than the k^{th} user. This problem is called near-far problem.

3.4.3.2 Decorrelating detector

To solve the near-far problem in conventional SUD; we came to another class of suboptimum detectors named decorrelationg detector which is not vulnerable to other-user interference. In the case of symbol-synchronous transmission, the received signal from k^{th} user matched filter is

$$\mathbf{r}_k = \mathbf{R}_s\mathbf{d}_k + \mathbf{n}_k \tag{3.31}$$

Where

$$\mathbf{d}_k = \left[\sqrt{\varepsilon_1}d_1(1), \sqrt{\varepsilon_2}d_2(1)\ldots\ldots\sqrt{\varepsilon_k}d_k(1)\right]^{\mathrm{t}}$$

$$\mathbf{n}_k = \left[n_1(1), n_2(1)\ldots\ldots n_k(1)\right]^{\mathrm{t}}$$

with covariance

$$E[n_k, n_k^{\mathrm{t}}] = \frac{1}{2}N_0\mathbf{R}_s \tag{3.32}$$

Since, the noise is Gaussian the probability density function is with mean $\mathbf{R}_s\mathbf{b}_k$ and covariance $\mathbf{R}_s$.

$$p(\mathbf{r}_k \mid \mathbf{d}_k) = \frac{1}{\sqrt{(N_0\pi)^K \det\mathbf{R}_s}}\exp\left[-\frac{1}{N_0}(\mathbf{r}_k - \mathbf{R}_s\mathbf{d}_k)^{\mathrm{t}}\mathbf{R}_s^{-1}(\mathbf{r}_k - \mathbf{R}_s\mathbf{d}_k)\right] \tag{3.33}$$

After minimization of likelihood function of $\mathbf{d}_k$ yields

$$\Lambda(\mathbf{d}_k) = (\mathbf{r}_k - \mathbf{R}_s\mathbf{d}_k)^{\mathrm{t}}\mathbf{R}_s^{-1}(\mathbf{r}_k - \mathbf{R}_s\mathbf{d}_k) \tag{3.34}$$

After minimizing equation (3.34) yields

$$\mathbf{d}_k^0 = \mathbf{R}_s^{-1}\mathbf{r}_k \tag{3.35}$$

The $\mathbf{d}_k$ in Equation (3.35) is optimized and these $\mathbf{d}_k$ are passed to the detector

$$\hat{\mathbf{d}}_k = \operatorname{sgn}(\mathbf{d}_k^0) \tag{3.36}$$

In decorrelationg detector, the near-far problem has eliminated and there is no need for power control. Also, MAI is completely killed but the noise is enhanced.

3.4.3.3 Minimum mean-square-error detector

There is another class of suboptimum detectors which is Minimum MSE detector in which we make some linear transformation $\mathbf{d}^0 = \mathbf{Ar}$ where $\mathbf{A}$ is the matrix which is to be determined as to minimize MSE.

$$J(\mathbf{d}) = E[(\mathbf{d}-\mathbf{d}^0)^t(\mathbf{d}-\mathbf{d}^0)] \tag{3.37}$$

$$= E[(\mathbf{d}-\mathbf{Ar})^t(\mathbf{d}-\mathbf{Ar})] \tag{3.38}$$

The optimum matrix A can be found by using the principle of orthognality $\mathbf{d}-\mathbf{Ar}$ is orthogonal to input vector $\mathbf{r}$.

$$E[(\mathbf{d}-\mathbf{Ar})\mathbf{r}^t] = 0 \tag{3.39}$$

$$E[\mathbf{br}^t] - \mathbf{A}\, E[\mathbf{rr}^t] = 0 \tag{3.40}$$

Also,

$$E[\mathbf{d}_k\mathbf{r}_k^t] = E[\mathbf{d}_k\mathbf{d}_k^t]\mathbf{R}_s^t = \mathbf{DR}_s \tag{3.41}$$

and

$$E[\mathbf{r}_k\mathbf{r}_k^t] = E[(\mathbf{R}_s\mathbf{d}_k + \mathbf{n}_k)(\mathbf{R}_s\mathbf{d}_k + \mathbf{n}_k)^t] \tag{3.42}$$

$$= \mathbf{R}_s\mathbf{D}\mathbf{R}_s^t + \frac{1}{2}N_0\mathbf{R}_s^t \tag{3.43}$$

Where $\mathbf{D}$ is a diagonal matrix. By using Equation (3.40) into Equation (3.42) and solving for $\mathbf{A}$ we get

$$\mathbf{A}^0 = \left(\mathbf{R}_s + \frac{N_0}{2}\mathbf{D}^{-1}\right)^{-1} \tag{3.44}$$

Then,

$$\mathbf{d}_k^0 = \mathbf{A}^0 \mathbf{r}_k \tag{3.45}$$

Then, this optimized $\mathbf{d}_k$ is then passed to detector to make decision.

$$\hat{\mathbf{d}}_k = \mathrm{sgn}(\mathbf{d}_k^0) \tag{3.46}$$

We observe that, MMSE produces a biased estimate of $\mathbf{d}$. Hence, there is some residual multiuser interference.

3.4.3.4 Other types of detectors

So far we have discussed simple algorithms for interference suppression; there are also complex algorithms (e.g. adaptive interference suppression algorithms) to combat ISI and MAI.

Adaptive algorithms for suppressing ISI and MAI are discussed in [42] [43]. There are also adaptive algorithms which does not need training sequences, such kind of algorithms are called blind adaptive algorithms which are discussed in the literature. Turbo-type algorithms for suppressing ISI and MAI are also discussed in [44].

3.4.4 Successive Interference Cancellation (SIC)

In successive interference cancellation (SIC), each stage detects regenerates and cancels out user. Here, the strongest signal is cancelled first because (a) it is easier to synchronize and demodulate. (b) It gives the highest benefits for canceling out the other users. Here, the strongest user has therefore no user for this MAI canceling scheme.

The greatest advantage using SIC is that hardware required is small and it gives great improvement when compared to conventional detector but its drawback is that processing delay is great and signal suddenly drops.

3.4.5 Parallel Interference Cancellation (PIC)

Only difference between SIC and PIC is that in SIC, the interference is cancelled successively while in PIC, the interference from all users is cancelled parallely or we can say that all users are under the same power control.

3.4.6 Multistage Interference Cancellation (MIC)

Multistage interference cancellation (MIC) is a scheme in which multiple iterations are required to detect user bits and canceling the interference. Below the block diagram is shown.

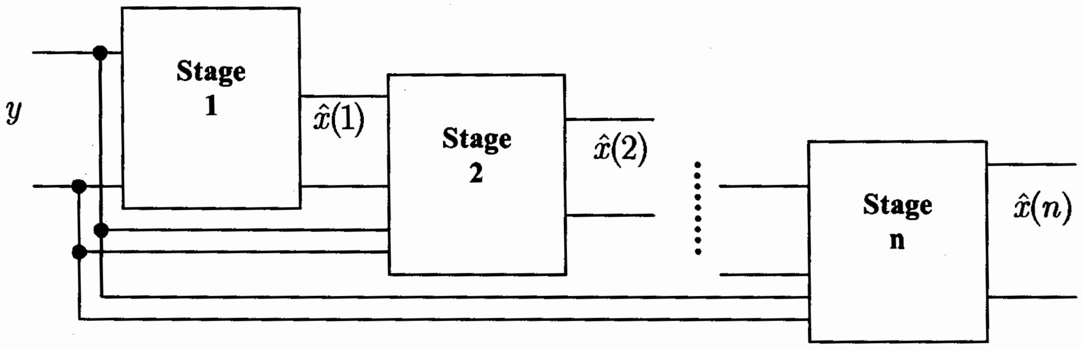

Figure 3.5: Multistage Interference cancellation (MIC)

Here, decisions made at first stage are $\hat{x}_1(1), \hat{x}_2(1)$ and decisions made at second stage are

$$\begin{aligned} \hat{x}_1(2) &= \mathrm{sgn}[y_1 - rc_2\hat{x}_2(1)] \\ \hat{x}_2(2) &= \mathrm{sgn}[y_2 - rc_1\hat{x}_1(1)] \end{aligned} \tag{3.47}$$

There is lot research have been done on SIC and MIC by [45].

3.4.7 Performance of Detectors

Our performance measure in multiuser communication is the probability of error. So, the bit error of a single user is

$$P_k(\gamma_k) = Q(\sqrt{2\gamma_k}) \tag{3.48}$$

Where $\gamma_k = \frac{\varepsilon_k}{N_0}$ and ε_k is the signal energy per bit. For the conventional SUD, the probability of error for the k^{th} user conditioned on $\mathbf{d}_i$ given in the Equation (3.27) is

$$P_k(\mathbf{d}_i) = Q\left(\sqrt{2\left[\sqrt{\varepsilon_k} + \sum_{\substack{j=1 \\ j\neq k}}^{K} \sqrt{\varepsilon_k} d_j(1)\rho_{jk}(0)\right]^2 / N_0}\right) \tag{3.49}$$

Thus, the average probability of error is

$$P_k = (\frac{1}{2})^{K-1} \sum_{i=1}^{2^{K-1}} P_k(\mathbf{d}_i) \tag{3.50}$$

In case of decorrelationg detector, the probability of error is

$$P_k = Q(\sqrt{\frac{\varepsilon_k}{\sigma_k^2}}) \tag{3.51}$$

3.5 Conclusion

In this chapter, we discussed multiple access techniques and then we discussed the optimum receiver and we see that optimum receiver that was maximum-likelihood detector has computational complexity grows exponentially with the no of users and then wee see suboptimum receivers which has computational complexity grows linearly with the no of users. Finally, we see the performance measure of receivers which is the probability of bit error.

Chapter 4

Chaotic Interference Suppression

4.1 Introduction

A lot of research has been done in studying non-linear chaotic systems using chaos theory [46]. Chaos theory has made great achievements in determining stochastic behaviors of chaotic systems and has been used in code-level optimization of CDMA and also used in combating the multiple access interference (MAI) and Inter-Symbol Interference (ISI).

Different methods have been used to multiplex data from multiple users on a single line. Mostly there are two schemes that had been widely used: frequency division multiplexing (FDMA) and time division multiplexing (TDMA). To enhance the security, code division multiplexing (CDMA) is preferable. Spread spectrum CDMA is used to multiply the user bits with the known spreading sequences to spread the user information over the large bandwidth.

In CDMA communication systems, different types of generators are used to generate spreading sequences such as Gold, Kasami code, Walsh code, Hadamard code. The problem in CDMA was that the spreading sequences would repeat after some time which leads to perform unsatisfactorily in terms of system capacity and security [47]. Recent research shows that the chaotic generators can be used to generate spreading sequences to increase the system capacity and may also be used the system security in spread spectrum communication [48]. It is also proved that these sequences have auto- and cross-correlation properties used in spread spectrum systems as we have already shown in chapter 2.

In the third chapter, we studied optimum and suboptimum receivers that compensate for MAI in the transmission of digital bits through band-limited channels. The optimum receiver employed maximum-likelihood sequence estimation for detecting the digital bits from the samples of demodulation filter. The suboptimum receivers employed either a matched filter or a correlator detector.

In this chapter, we consider the problem of receiver design in the presence of channel distortion, which is not known a priori, and AWGN. The channel distortion results in multiple access interference (MAI) which, if left uncompensated, causes high error rates. The solution to this problem is to design a receiver that employs a mean for compensating or reducing the MAI in the received signal and enhances the performance in terms of capacity and security.

4.2 System Model

Figure (4.1) and Figure (4.2) shows the transmitter and receiver system model of DS-CDMA communication system with K users. Each user transmits binary symbols $s(n) \in \{-1,+1\}$. The k^{th} user of the source symbol with T_b

symbol period, denoted by $s_k(n)$ is spread by chaotic sequence of length L with chip duration of T_c. So, the spreading gain or processing gain of a system can be expressed as $L = \frac{T_b}{T_c}$. The k^{th} user spreading code can be written as $\mathbf{c}_k = [c_k(0), c_k(1), c_k(m) \ldots c_k(L-1)]^t$, where $c_k(m) \in \{-1, +1\}$. The AWGN is of zero mean and variance σ_v^2. At the receiver side, the suboptimum receiver parallel interference cancellation (PIC) scheme is used to recover the original transmitted bits.

A non-linear chaotic generator (CG 1) discussed in chapter 2 is used to generate chaotic sequences as follows. The chaotic generator 1 is chaotic in the interval [-1, 1] and is used in much of applications in digital communications and in digital signal processing. In order to converge the chaotic generator 1 the initial conditions on chaotic generator 1 must be in the interval [-1, 1] otherwise the series will diverge and we always want to converge the series to get the best performance. Since the output values of chaotic generator continuous values so, these continuous values of chaotic generator is passed to the quantizer $Q(a)$ which converts these values into binary values. The quantizer works same like sign (.) function. If the continuous values are less than zero it gives -1 and if the continuous values are greater than zero it gives 1.

$$a_{n+1} = 1 - 2a_n^2 \tag{4.1}$$

$$Q(a) = \begin{Bmatrix} 1 & \text{if } a > 0 \\ -1 & \text{otherwise} \end{Bmatrix} \tag{4.2}$$

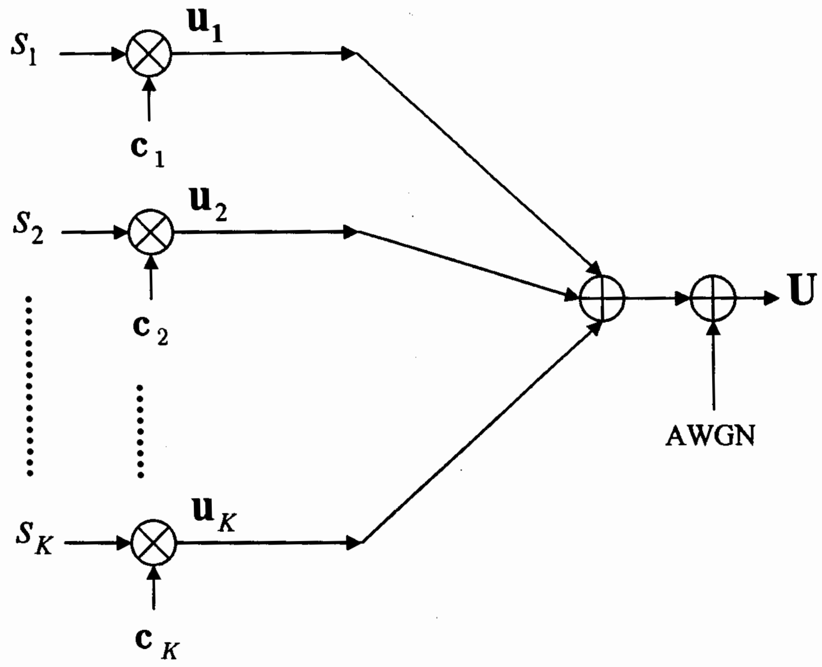

Figure 4.1: Transmitter of Chaos CDMA

For comparison, another non-linear chaotic generator Tent generator is also used. Tent generator is another chaotic generator which provides chaoticity as we have discussed in chapter 2. This generator is also used in much of digital communications and digital signal processing applications. Like chaotic generator 1, this generator also must have initial conditions between [-1, 1]. In order to converge this generator, the initial conditions must be taken from the interval [-1, 1] otherwise the generator will diverge and this is what we want in our system.

$$a_{n+1} = a_n^2 - 2 \tag{4.3}$$

The initial value $a_0 = a(0)$ of chaotic generator is chosen from open interval [-1, 1]. These chaotic sequences are then passed to quantizer to convert the chaotic sequences into binary chaotic sequences which is given in equation (4.2).

For the k^{th} user, the spreading waveform is,

$$c_k(t) = \sum_{i=0}^{L-1} c_k(i)h(t - iT_c) \tag{4.4}$$

Where $c_k(i)$ is a chaotic sequence and $h(t)$ is rectangular pulse over which the information is ridden. Assuming that channel is known to us and signal is received in the interval $0 \le t \le T_b$ then,

$$r(t) = \sum_{k=1}^{K} u_k c_k(t) + n(t) \tag{4.5}$$

The equation (4.5) is the composite received signal which contains Multiple Access Interference (MAI) and noise.

After passing through matched filter (MF) of k^{th} user we have

$$r_k = \int_0^{T_b} r(t)c_k(t)\mathrm{dt} \tag{4.6}$$

$$= \int_0^{T_b} \left[\sum_{k=1}^{K} u_k c_k(t) + n(t) \right] c_j(t)\mathrm{dt} \tag{4.7}$$

$$= u_k + \sum_{\substack{j=1 \\ j \neq k}}^{K} u_j \rho_{jk} + n_k \tag{4.8}$$

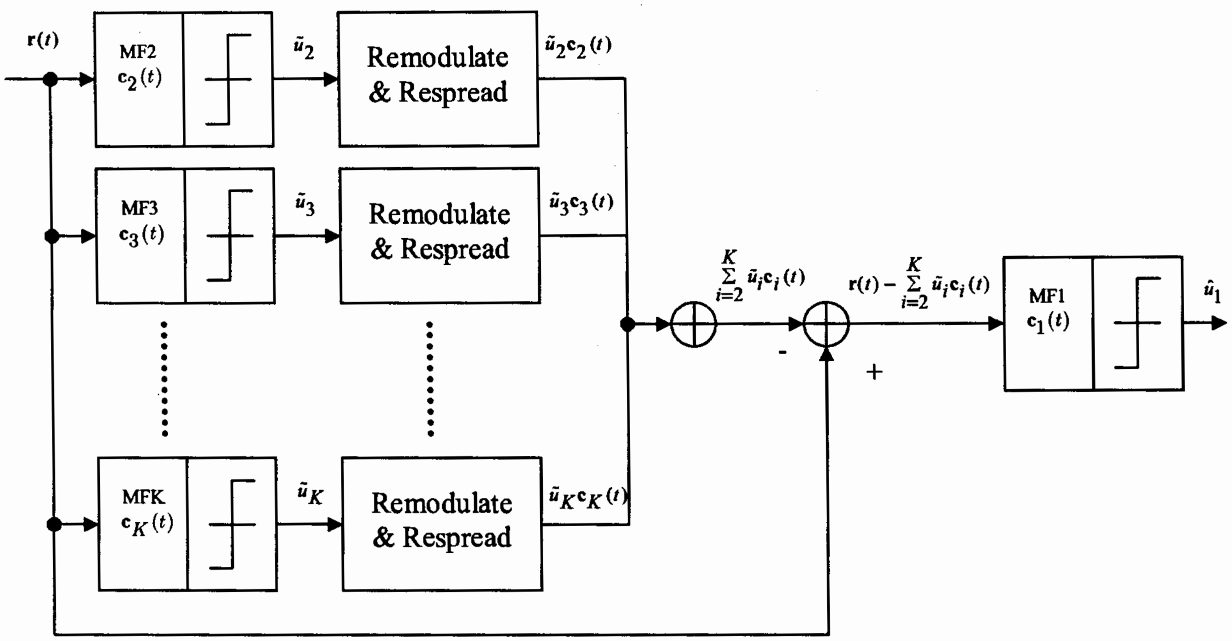

Figure 4.2: Receiver of Chaos CDMA

where the first term in Equation (4.8) is signal, second term is multiple access interference (MAI) and the third term is noise. After passing through matched filter (MF) of user 1

$$o/p = \int_0^{T_b} \left(r(t) - \sum_{i=2}^{K} \tilde{u}_i c_i(t)\right) c_1(t)\,\mathrm{d}t \tag{4.9}$$

Evaluating integral in equation (4.9) we get

$$= \int_0^{T_b} r(t) c_1(t)\,\mathrm{d}t - \sum_{i=2}^{K} \tilde{u}_i \int_0^{T_b} c_i(t) c_1(t)\,\mathrm{d}t \tag{4.10}$$

In the first term of equation (4.10), $r(t)$ is integrated with chaotic spreading sequence of user 1 and the second term is the cross-correlation of i^{th} user with user 1.

$$= r_1 - \sum_{i=2}^{K} \tilde{u}_i \rho_{1i} + n(t) \tag{4.11}$$

The first term in the equation (4.11) is received signal of user 1, the second term is cross-correlation and the third term is noise.

$$= u_1 + \sum_{j=2}^{K} u_j \rho_{1j} - \sum_{j=2}^{K} \tilde{u}_j \rho_{1j} + n_1 \tag{4.12}$$

In equation (4.12) the first term is bits of user 1, the second term is actual MAI and the third term is estimated MAI.

where

$$r_1 = \int_0^{T_b} r(t) c_1(t) \mathrm{dt} \tag{4.13}$$

The equation (4.13) gives the correlation of composite received signal with chaotic sequence of user 1.

$$\rho_{1i} = \int_0^{T_b} c_i(t) c_1(t) \mathrm{dt} \tag{4.14}$$

The equation (4.14) gives the cross-correlation of i^{th} with user 1. In Equation (4.12) if $\tilde{u}_j = u_j$ then second and third term cancel each other and Equation (4.12) simplifies to

$$= u_1 + n_1 \tag{4.15}$$

After passing through $\operatorname{sgn}(.)$ function we have

$$= \operatorname{sgn}(u_1 + n_1) \tag{4.16}$$

$$= \hat{u}_1 \tag{4.17}$$

Where $\hat{u}_1$ is the estimate of u_1.

Chapter 5

System Simulation and Conclusions

In every system there is some figure of merit to make comparison between two things for example in digital signal processing the figure of merit is mean-square-error (MSE) and in digital communications the figure of merit is bit-error-rate (BER). In this chapter, the second figure of merit bit-error-rate (BER) is used to make comparison

In this chapter, the comparison of chaos-based scheme (which uses chaotic generator 1 at transmitter side) is made with another chaos-based scheme (which uses two generators at transmitter side, one of them is chaotic generator 1 and other is tent generator) and at receiver side the suboptimum receiver technique named Parallel Interference Cancellation (PIC) is used to kill the Multiple Access Interference (MAI) in the resulting composite received signal. Chaotic generator and tent generator is discussed in detail in the previous chapters.

Figures (5.1) – (5.5) show the BER performance of chaos-based PIC and chaos-based MF with spreading gain of L = 8, L = 16, L = 32, L = 64 in AWGN environment.

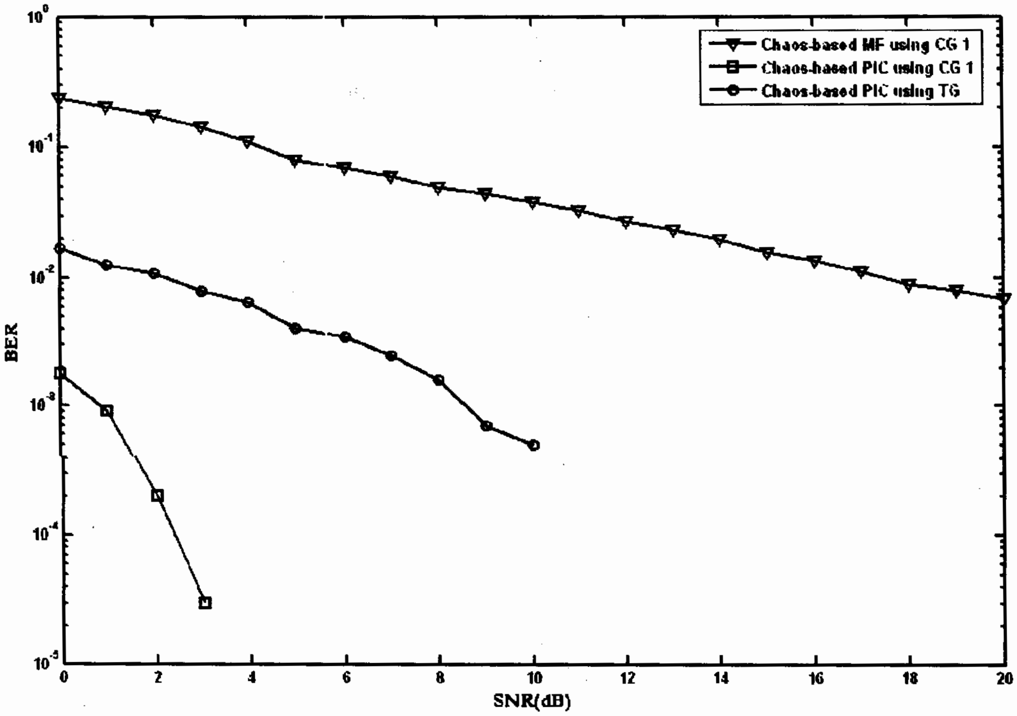

Figure 5.1 BER performance of K = 3 users with chaos –based PIC and chaos-based MF with spreading factor L = 8 in AWGN environment

The figure (5.1) shows the bit error rate (BER) with 3 users having chip length of 8. Here, the comparison of chaos-based MF is made with chaos-based PIC. The graph shows that Parallel Interference Cancellation (PIC) scheme performs very well than matched filter. The top curve is not optimum because it uses matched filter scheme. In the top curve, the signal comes from chaotic source using chaotic generator 1. In the bottom two curves, the signal comes from two chaotic sources (a) Chaotic generator 1 (b) Tent generator.

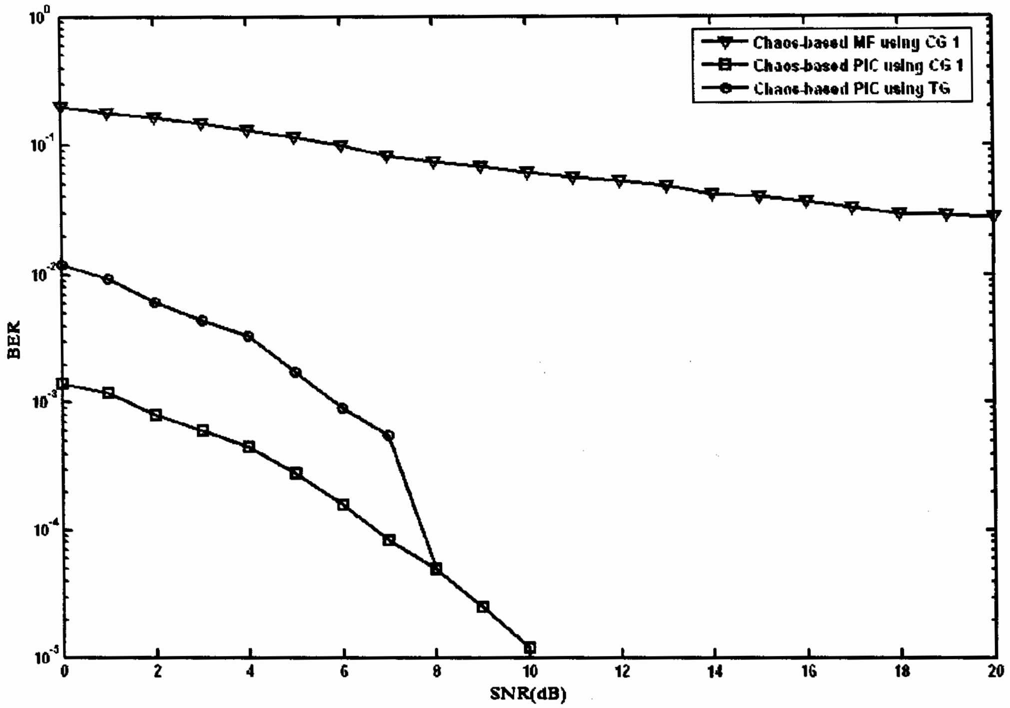

Figure 5.2 BER performance of K = 5 users with chaos –based PIC and chaos-based MF with spreading factor L = 16 in AWGN environment

The figure (5.2) shows the bit error rate (BER) with 5 users having chip length of 16. Here, the comparison of chaos-based MF is made with chaos-based PIC. The graph shows that Parallel Interference Cancellation (PIC) scheme performs very well than matched filter. The top curve is not optimum because it uses matched filter scheme. In the top curve, the signal comes from chaotic source using chaotic generator 1.

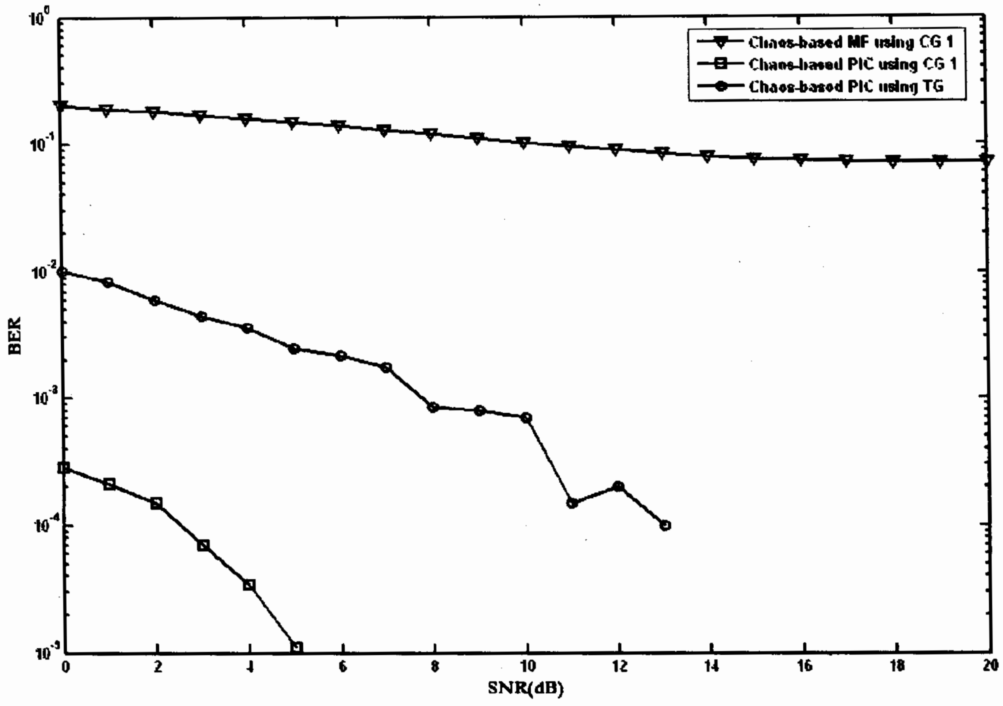

Figure 5.3 BER performance of K = 7 users with chaos –based PIC and chaos-based MF with spreading factor L = 16 in AWGN environment

The figure (5.3) shows the bit error rate (BER) with 7 users having chip length of 16. Here, the comparison of chaos-based MF is made with chaos-based PIC. The graph shows that Parallel Interference Cancellation (PIC) scheme performs very well than matched filter. The top curve is not optimum because it uses matched filter scheme. In the top curve, the signal comes from chaotic source using chaotic generator 1. In the bottom two curves, the signal comes from two chaotic sources (a) Chaotic generator 1 (b) Tent generator.

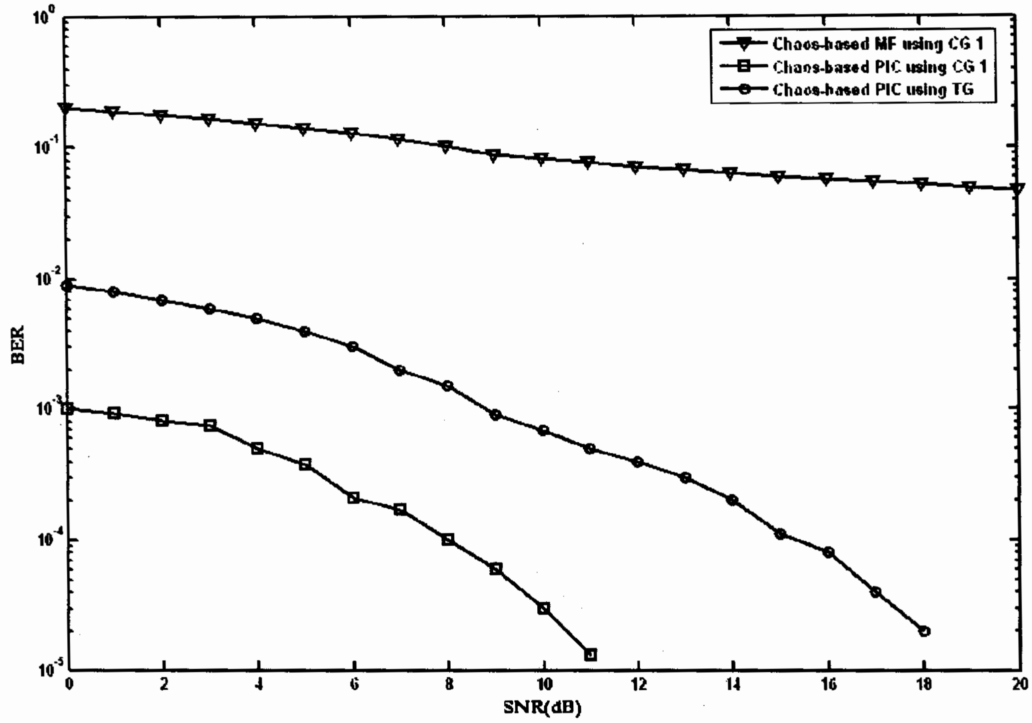

Figure 5.4 BER performance of K = 12 users, chaos –based PIC and chaos-based MF with spreading factor L = 32 in AWGN environment

The figure (5.4) shows the bit error rate (BER) with 12 users having chip length of 32. Here, the comparison of chaos-based MF is made with chaos-based PIC. The graph shows that Parallel Interference Cancellation (PIC) scheme performs very well than matched filter. The top curve is not optimum because it uses matched filter scheme. In the top curve, the signal comes from chaotic source using chaotic generator 1. In the bottom two curves, the signal comes from two chaotic sources (a) Chaotic generator 1 (b) Tent generator

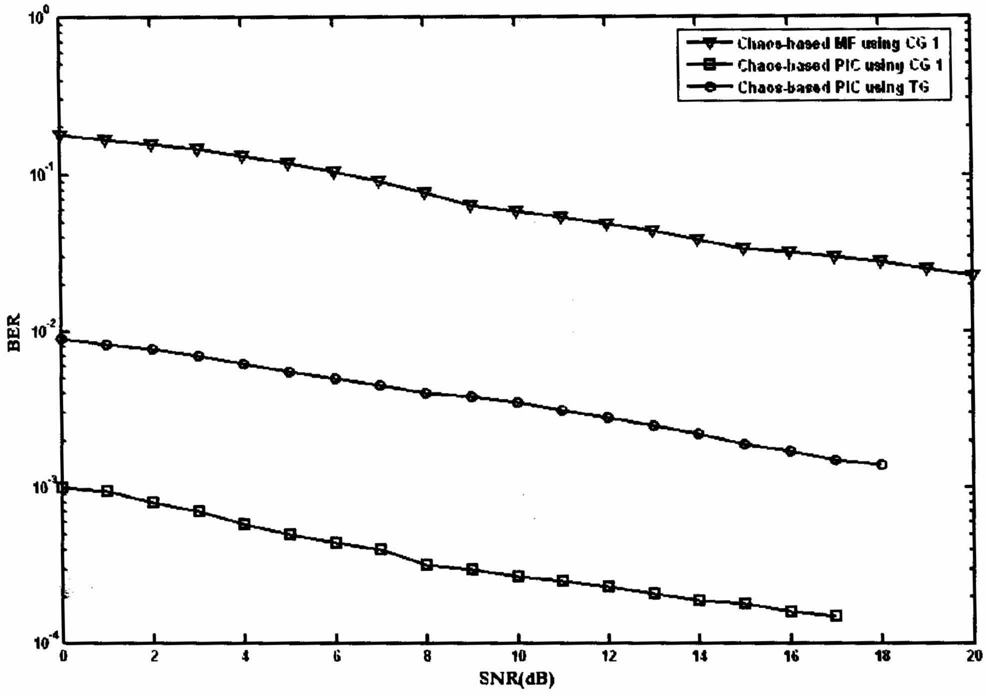

Figure 5.5 BER performance of K = 16 users with chaos –based PIC and chaos-based MF with spreading factor L = 64 in AWGN environment

The figure (5.5) shows the bit error rate (BER) with 16 users having chip length of 64. Here, the comparison of chaos-based MF is made with chaos-based PIC. The graph shows that Parallel Interference Cancellation (PIC) scheme performs very well than matched filter. The top curve is not optimum because it uses matched filter scheme. In the top curve, the signal comes from chaotic source using chaotic generator 1. In the bottom two curves, the signal comes from two chaotic sources (a) Chaotic generator 1 (b) Tent generator.

The scheme of sub-optimum receiver which is parallel interference cancellation (PIC) is discussed in this chapter where the transmitted signals are modulated by a chaotic generator rather than PN generator. A comparison of chaos-based PIC using CG 1 and Tent generator with chaos-based MF is also shown and we also conclude that performance of chaos-based PIC is better than chaos-based MF in terms of BER. Further study is needed to examine this work in different channel environments and using other sub-optimum detection schemes.

Chapter 6

Summary and Future Directions

Chaotic systems are still challenging practically. The basic building blocks to construct chaotic systems already exist but still high level frameworks for chaotic systems are needed in detail. Further research is needed to improve there performance in practical implementation. In this thesis, we have introduced a suboptimum receiver to suppress multiple access interference (MAI) which occurs when multiple users transmits their data on a single channel.

6.1 Summary

A general introduction to chaotic systems is discussed in chapter 1.

In chapter 2, an overview of chaotic generators and chaos theory applications are discussed briefly. The security of chaotic generators is also discussed.

In chapter 3, multiple access techniques are discussed that were mainly frequency division multiple access (FDMA) and time division multiple access (TDMA) and then for the security purpose code division multiple access (CDMA) is proposed in which bits of particular user is spreaded over the whole bandwidth by multiplying with the signature waveforms. Then, we have discussed optimum receiver that is maximum-likelihood (ML) detector and we see that complexity of ML detector grows exponentially with the no of users and later we introduced suboptimum detectors whose complexity grows linearly with the no of users.

In chapter 4, we introduced another scheme parallel interference cancellation (PIC) to suppress multiple access interference (MAI) which occurs when the large no of users transmits their data on a single channel and further we see that the performance of PIC is better than single matched filter or correlator detector.

6.2 Future Directions

A lot of research has been made in chaos but still more work is needed to be done to put the chaos in practical. Based on the basic knowledge, there plenty of room in this thesis that can be extended through further research as clarified below:

- In this dissertation, we discussed parallel interference cancellation scheme (PIC) to suppress the MAI. Further schemes like Multistage Interference Cancellation (MIC), weighted PIC, and partial PIC seems to more promising in this dissertation.
- DSP algorithms can also be used at the receiver end to suppress MAI. Furthermore, use of Kalman filter and Square-root information filtering methods seems to more promising.

- Linear hybrid detection schemes can also seems to be more promising in which group-wise successive interference cancellation (G-SIC) detector is used.
- Linear group-wise PIC and SIC (GPIC-SIC) detector also seems to be more promising.
- Linear group-wise MMSE and SIC (GMMSE-SIC) detector also seems to more promising in chaotic systems.
- Combination of MMSE – PIC also seems to be promising in chaotic systems.
- The use of Pseudo-User PIC (PU-PIC) also seems to be promising.

Bibliography

[1] A.B. Cambel, Applied Chaos Theory – A paradigm for Complexity, Academic Press, Inc., San Diego, CA, June 1993.

[2] G. James, Chaos – making a New Science, Penguin books, New York, NY. May 1987.

[3] G. Nicolis and S. John, Chaos and information processing – A heuristic Outline, World Scientific Publishing Co. Pte., Sinapore, May 1991.

[4] J.M.H. Elmighani, and R.A. Cryan, "New chaotic based communication technique with multiuser provision," IEEE Electronics letters, vol. 30, pp. 1206 – 1207, May 1997.

[5] J.M.H. Elmighani and R.A. Cryan, "Communication using chaotic masking," IEE Colloquium on Exploiting Chaos in Signal Processing, pp. 12/1 – 12/6, May 1994.

[6] J.M.H. Elmighani and R.A. Cryan, "Point-to-point and multi-user communication based on chaotic sequences" in Proc IEEE ICC Colloquium on Exploiting Chaos in Signal Processing, vol. 20, pp. 582 – 584, no. 3, September 1995.

[7] K. Murali, H. Leung and H. Yu, "Design of noncoherent receiver for analog spread-spectrum communication based on chaotic masking," IEEE Trans. Circuits and Systems I: Fundamental Theory and Applications, vol. 50, pp. 432 – 441, no. 11, November 2003.

[8] N. Xie and H. Leung, "An analog multi-user spread-spectrum technique for wireless home automation," IEEE Trans. Consumer Electronics, vol. 48, pp. 1016 – 1025, no. 12, February 2002.

[9] H. Leung and J. Lam, "Design of demodulator for the chaotic modulation communication system," IEEE Trans. Circuits and Systems Fundamentals Theory and Applications, vol. 44, no. 3, pp. 262 – 267, no. 17, August 1997.

[10] T.W.S. Chow, J.C. Feng and K.T. Ng, "An adaptive demodulator for the chaotic modulation communication system with RBF neural network," IEEE Trans. Circuit and Systems I: Fundamental Theory and Applications, vol. 47, no. 6, pp. 902 – 909, no. 51, January 2000.

[11] C. L. Koh and T. Ushio, "Digital communication method based on – synchronized chaotic systems," IEEE Trans. Circuits and Systems Fundamental Theory and applications, vol. 44, pp. 35-37, no. 5, April 1997.

[12] G. Kolumban, "Theoretical noise performance of correlator-based chaotic communication schemes," IEEE Trans. Circuits and Systems Fundamental Theory and Applications, vol. 47, pp. 452-453, no.12, September 2000.

[13] G. Mazzini, G. Setti, and R. Rovatti, "Chaotic complex spreading sequences for asynchronous DS-CDMAU Part I: system modeling and results," IEEE Trans. Circuits and Systems I: Fundamental theory and Applications, vol. 44, pp. 97-99, no. 10, December 1997.

[14] R. Rovatti, G. Mazzini and Gianluca Setti, "Enhanced rake receivers for chaos-based DS-CDMA," IEEE Trans. Circuits and Systems: Fundamental Theory and Applictions, vol. 48, pp. 25-28, no. 7, March 2001.

[15] G. Mazzini, R. Rovatti and Gianluca Setti, "Chaos-based Asynchronous DS-CDMA systems and enhanced rake receivers: Measuring the Improvements," IEEE Trans. Circuits and Systems I: Fundamental theory and Applications, vol. 48, pp. 87-88, no. 12, June 2001.

[16] R. Rovatti, G. Mazzini and Gianluca Setti, "On the ultimate limits of chaos-based asynchronous DS-CDMAUI: Basic Definitions and Results," IEEE Trans. Circuits and Systems I: Fundamental theory and Applications, vol. 51,pp. 21-22, no. 7, July 2004.

[17] J. Schweizer and T. Schimming, "Symbolic dynamics for processing chaotic signals UII: communication and coding," IEEE Trans. Circuits and Systems I, vol. 48, pp. 175-177, no. 11, May 2001.

[18] Y.S. Lau and Z. M. Hussain, "A new approach in chaos shift keying for secure communication," in Proc IEEE International Conference on Information Technology and Applications, vol. 49, pp. 171-173, no.13, July 2005.

[19] F. C. M. Lau, C. K. Tse, M. Ye and S.F. Hau, "Coexistence of chaos based and conventional digital communication systems of equal bit rate," IEEE Trans. Circuits and Systems, vol. 51, pp. 391 – 408, no. 12, February 2004.

[20] F. C. M. Lau and C. K. Tse, "Coexistence of chaos-based and conventional digital communication system," in Proc IEEE ISCAS, vol. 3, pp. 204 – 207, no. 25, May 2003.

[21] G. Kolumban, M.P. Kennedy, Z. Jako and G. Kis, "Chaotic communications with correlator receivers: theory and performance limits," in Proc of the IEEE, vol. 90, pp. 711 – 732, no. 23, May 2002.

[22] A. Abel and W. Schwarz, "Chaos communications principles schemes, and system analysis," Invited paper in IEEE Proc, vol. 90, pp. 257-259, no 5, June 2002.

[23] G. Kolumban, B. Vizari, W. Schwarz and A. Abel, "Differential chaos shift keying: A robust coding for chaotic communication," in Proc of the Fourth Int. workshop on Nonlinear Dynamics of electronics Systems, pp. 87 – 92, no. 23, July 1996.

[24] R. S. Mackay, "Some thoughts on chaos in engineering, in toward the harnessing of chaos," Elservier Science, vol. 90, pp. 711 – 732, no. 23, March 1994.

[25] L. Kocarev, "Chaos-based cryptography: A Brief Overview," IEEE Communication magazine, vol 1, pp. 6 – 21, no. 23, July 2001.

[26] P. Bergamo, P. DSArco, A.D. Santis and L. Kocarev, "Security of public-key crypto systems based on chebyshev polyomials, " IEEE Trans. on circuits and system I, vol 52, pp. 23-25, no. 7, May 2005.

[27] T. Yaung, C.W. Wu and L. O. Chua, "Cryptography Based on Chaotic Systems," IEEE Trans. on circuits and system I, vol 44, pp. 325-327, no 5, January 1997.

[28] B. Chen and G. W. Wornell, "Analog error-correcting codes based on chaotic dynamical systems," IEEE Trans on Communications, vol 46, pp. 225-227, no. 7, August 1998.

[29] D. N. Kalofonos M. Stojanovic and J. G. Proakis, "On the performance of adaptive MMSE detectors for MC-CDMA system in fast fading rayleigh channels," The Ninth IEEE International Symposium on Personal, Indoor and Mobile Radio Communications,, vol. 3, pp. 327-329, no. 23, May 1998.

[30] S. Nahm and W. Sung, "Time-domain equalization for orthogonal multi-carrier CDMA system," Global Telecommunications Conference, vol. 30, pp. 251-254, no. 25, June 1996.

[31] C. R. Johnson, P. Schnitter and T.J. Endres, et al., "Blind Equalization Using the Constant Modulus Criterion: A Review," IEEE Proceedings, vol. 86, no. 10, pp. 1927-1950, no. 23, May 1998.

[32] M. Honig and M. K. Tsatsanis, "Adaptive techniques for multi-user CDMA receivers," IEEE Signal Processing Magazine, vol. 34, pp. 49-61, no. 12, May 2000.

[33] S. Moshavi, "Blind adaptive multiuser detection," IEEE Tran. on Information Theory, vol. 41, pp. 944-960, no. 4, July 1995.

[34] T. Kohda and H. Fujisaki, "Variances of multiple access interference code average agianst data average," Electron. lett, vol. 36, , pp. 251-253, no. 4, June 2000.

[35] S. Kaiser, "OFDM code-division multiplexing in fading channels," IEEE Trans. Communications, vol. 50, pp. 1266-1273, no. 9, August 2002.

[36] S. Hara and R. Prasad, "Overview of multicarrier CDMA," IEEE com munications Magazine, vol. 35, pp. 126-133, no. 23, December 1994.

[37] G. W. Wornell and A. V. Oppenheim, "Estimation of fractal signals from noisy measurements using wavelet," IEEE Trans. Signal Processing, vol 4, pp. 611-623, no. 3, May 1992.

[38] V. Tarokh, H. Jafarkhani and A. R. Calderbank, "Space-time block coding for wireless communications: performance results," IEEE J. Select Areas in Communication., vol. 17, pp. 451-460, no. 3, March 1999.

[39] K. H. Lin, Z. M. Hussain and R. J. Harris, "Space-time OFDM with adaptive beamforming: Performance in spatially correlated channels," in Proc. IEEE TENCON, vol. 17, pp. 671-620, no. 3, November 2004.

[40] S. Catreux, V. Erceg, D. Gesbert and R.W. Jr. Heath, "Adaptive modulation and MIMO coding for broadband wireless data networks", IEEE Communication Magazine, vol. 40, pp. 108-115, no. 2, June 2002.

[41] J.F. Huber, "Mobile next-generation networks", IEEE Multimedia, vol. 11, pp. 72-83, no. 2, January 2004.

[42] M. P. Kennedy and G. Kolumban, "Digital communications using choas,"Elsevier Signal Processing Journal, vol. 80, pp. 1307-1320, no. 3, May 2000.

[43] T. Kohda and A. Tsuneda, "Even- and odd-correlation fucntions of chaotic chebyshev bit sequences for CDMA," in Proc. IEEE Int. Symp. Spread Specturm Technology and Applications, vol 21, pp. 391-395, no. 9, June 1994.

[44] A. Muller and M. H. Elmirghani, "Blind channel estimation and echo cancellation using chaotic coded signals," IEEE Lett. on Communications, vol 3, pp. 72 - 74, , no 3, August 1999.

[45] Z. Zhu and Henry Leung, "Adaptive Identification of Nonlinear Systems with Application to Chaotic Communications," IEEE Trans. On circuits and system, vol 47, pp. 975-978, no. 7, May 2000.

[46] J. M. Liu, H. F. Chen and S. Tang, "Synchronized chaotic optical communications at high bit rates," IEEE Trans. Quantum Electronics, vol 38, pp. 1184 - 1196, no. 11, June 2002.

[47] S. Tang, H. F. Chen, S. K. Hwang and J. M. Liu, "Message encoding and decoding through chaos modulation in chaotic optical communications," IEEE Trans. on circuits and system I, vol 49pp. 163 - 169, no. 2, May 2002.

[48] T. Yang, C. W. Wu and L. O. Chua, "Cryptography based on chaotic systems," IEEE Trans. on circuits and system I, vol 44, pp. 325-327, no. 5, January 1997.

[49] L. Kocarev, "Chaos-based cryptography: A Brief Overview," IEEE Communication Magazine, vol 1, pp. 6 - 21, no. 9, June 2001.

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