AN ANALYTICAL APPROACH FOR PERFORMANCE EVALUATION OF MC-DS-CDMA SYSTEM WITH FADING AND CARRIER FREQUENCY OFFSET

By

Md Ruhul Minhaz
Roll No-100606216F

Under Supervision of:

Dr.Satya Prasad Majumder
Professor, EEE Dept
BUET, Dhaka

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Electrical and Electronic Engineering

Department of Electrical and Electronic Engineering

Bangladesh University of Engineering and Technology

May -2010

APPROVAL CERTIFICATE

This thesis titled "AN ANALYTICAL APPROACH FOR PERFORMANCE EVALUATION OF MC-DS-CDMA SYSTEM WITH FADING AND CARRIER FREQUENCY OFFSET" submitted by Md Ruhul Minhaz, Roll No-100606216F has been accepted as satisfactory in partial fulfillment of the requirements for the degree of **Master of Science in Electrical and Electronic Engineering** on 30 May 2010

BOARD OF EXAMINERS

1. ____

Dr. Satya Prasad Majumder Professor Department of Electrical and Electronic Engineering (EEE) Bangladesh University of Engineering & Technology (BUET) Dhaka-1000, Bangladesh	Chairman

2. ____

Dr. Aminul Hoque Professor and Head Department of Electrical and Electronic Engineering (EEE) Bangladesh University of Engineering & Technology (BUET) Dhaka-1000, Bangladesh	Member (Ex-Officio)

3. ____

Dr. Md. Shah Alam Associate Professor Department of Electrical and Electronic Engineering (EEE) Bangladesh University of Engineering & Technology (BUET) Dhaka-1000, Bangladesh	Member

4. ____

Dr. Farruk Ahmed Professor Department of Electrical and Electronic Engineering Independent University Dhaka, Bangladesh (Ex-Professor, University of Dhaka)	Member (External)

DECLARATION

I hereby declare that this thesis is based on the results found by myself. Materials of work found by other researchers are mentioned by reference. This thesis, neither in whole nor in part, has been previously submitted for any degree.

____

Md Ruhul Minhaz

Author

Counter Signed By

________□□□□□________________

Dr. Satya Prasad Majumder

The Supervisor

ACKNOWLEDGEMENTS

First of all, I am grateful to the Almighty Allah who has given me all the strengths and knowledge to do this work. I, then, wish to express my heartfelt gratitude to my respected supervisor Dr. Satya Prasad Majumder, Professor, Department of EEE, BUET, who gave me his valuable guidance throughout my research work for last two years. Many a times, he allowed me to work in his room at his PC and received my phone calls even at late night. I also remember the contribution of my teachers of Electrical Department of BUET, who have taken my theoretical classes of M Sc Engineering.

I am thankful to Bangladesh Navy for selecting me for this post graduate degree and spare me for quite long time in spite of many administrative and operational limitations. I am grateful to my colleagues who have helped and provided me adequate support for achieving this prestigious degree. I pray for them so that Allah gives them even better rewards in future.

I also acknowledge the valuable supports provided by Mr B K Mizan and Mr Mahmudur Rahman in this regard.

Last, but not the least, I like to express my gratefulness to my wife and my children for their silent understanding and endless physical and mental support to finish my research work.

ABSTRACT

The performance analysis is carried out for a multi-carrier direct sequence (DS) CDMA wireless communication system over a Rayleigh Fading Channel. Performance analysis includes the effect of Multiple Access Interference (MAI), Inter-Carrier Interference (ICI) and the effect of Carrier Frequency Offset (CFO) due to carrier frequency synchronization. The expression of the Carrier to Interference plus Noise Ratio (SINR) is derived for a MC-DS-CDMA system considering the above system limitations. The analysis is also extended to MC-DS-CDMA system with Rake Receiver. The comparison for the Bit Error Rate (BER) for the above case is derived. The performance results are evaluated numerically in terms of SINR and BER considering several system parameters like number of users, processing gain, number of sub-carriers and number of rake fingers with and without CFO. The result shows that there are significant deterioration in SINR and BER performance due to fading and CFO. For a given performance level, optimum system design parameters are determined from the analytical results.

TABLE OF CONTENTS

Chapter-4 RESULTS AND DISCUSSIONS

LIST OF FIGURES

LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CFO	Carrier Frequency Offset
D-BPSK	Differential BPSK
DS/FH	Direct Sequence Frequency Hopping
DS/TH	Direct Sequence Time Hopping
DS-CDMA	Direct Sequence Code Division Multiple Access
EGC	Equal Gain Combining
FDMA	Frequency Division Multiple Access
GSM	Global System for Mobile
ICI	Inter Carrier Interference
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
LFSR	Linear Feedback Shift Register
LOS	Line of Sight
MAI	Multiple Access Interference
MC DS-CDMA	Multi Carrier Direct Sequence CDMA
MC-CDMA	Multi Carrier Code Division Multiple Access
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MLSD	Maximum Likelihood Sequence decoding
MRC	Maximal Ratio Combining
MSK	Minimum Shift Keying
MT-CDMA	Multi Tone Code Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Ratio

PN	Pseudo-random Noise
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SC-DS-CDMA	Single Carrier Direct Sequence CDMA
SIMO	Single Input Multiple Output
SINR	Signal to Interference and Noise Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SSMA	Spread Spectrum Multiple Access
STBC	Space Time Block Code
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunication System
WLAN	Wireless Local Area Network

CHAPTER-1

INTRODUCTION

1.1 Evolution of Communication Technology

Communication is a process of transferring information from one entry to another. It is commonly defined as "imparting or exchanging of thoughts, opinions or information by speech, writing or signs". Although there is such thing of one way communication, it can be perceived better as a two-way process in which there is an exchange and progression of thoughts, feelings or ideas towards a mutually accepted goal or direction. In technical terms, communication is a process whereby information is enclosed in a package and is channeled and imparted by a sender to a receiver via some medium. The receiver then decodes the message and gives the sender a feedback. Thus, all forms of communication require a sender, a message and a receiver. There are auditory means, such as speech, song and tone of voice and there are non-verbal means, such as pictures, graphics, sound and writings.

The requirement for communication is universal, but the means of communication has been updated time to time with the evolution to technology. Advancement in communication technology was initially centered to wired system. But with the advent of mobile technology, the communication perspective has been shifted. Today, mobile technology has got such wide-spread popularity that according to the survey of International Telecommunication Union (ITU) in 2009, nearly 4.1 Billion out of world's 6.7 Billion populations, have mobile subscription, whereas, it was only 1 Billion in the year 2002 [1]. Today, mobile phone and wireless network has become an essential part of human life. It is not remain bounded only within voice services, rather the demand for multimedia services through wireless means has increased many fold. This consequently raised the requirement of broadband wireless data facilities for mobile system. But, the wireless spectrum resources and their capacities are essentially limited. Thus, to meet the simultaneous demand of many users, there is a requirement of adopting means of sharing the resources. Here lies the basis of Multiple Access concept.

1.2 Multiple Access Schemes

Multiple access schemes enable the radio system elements to be used in the most appropriate combination to efficiently meet the demand of the users at any given situation. The choice of a multiple-access scheme is one of the crucial decisions made in the design of a radio communication system since it is closely related with the system capacity. Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) were the two major access techniques used in conventional mobile radio communication systems.

FDMA It assigns individual channels (frequency bands) to individual users. During the period of the call, no other user can share that frequency band. If an FDMA channel is not in use, it remains idle.

TDMA It divides the transmission time into time slots and in each slot, only one user is allowed to either transmit or receive. TDMA shares a single carrier frequency with several users, where each user makes use of non-overlapping time slots. Analogous to FDMA, if a channel is not in use, the corresponding time slots sit idle and cannot be used by other users.

1.3 General Weakness of FDMA and TDMA

a. They assume that all users transmit continuously. But actually, the percentage of a speaker remains active, ranges from 35% to 50%.

b. Low frequency reuse factor reduces the number of channels per cell.

c. Susceptible to fading, which is caused by interference between two or more versions of the transmitted signal that arrive at the receiver at slightly different time.

1.4 CDMA

A completely different approach is realized in CDMA systems in which all resources are being allocated to all the active users [2]. Here, each user is assigned with a unique code sequence to encode its information-bearing signal. The receiver, knowing the code sequences of the user, decodes a received signal after reception and recovers the original data. This is possible since the cross-correlations between the code of the desired user and the codes of the other users are small. Since, the bandwidth of the code signal is chosen to be much larger than the bandwidth of the information-bearing signal, the encoding process spreads the spectrum of the signal and is therefore also known as spread-spectrum modulation. That's why, CDMA is often denoted as spread-spectrum multiple access (SSMA) [3]. However, if the number of simultaneously transmitting users rises above a certain limit, the Multiple Access Interference (MAI) becomes too large for the desired signal to be extracted correctly and contention occurs. Therefore, CDMA system is essentially interference limited[4]. The ratio of code signal bandwidth B_c to information signal bandwidth B_b is called the processing gain G of the spread spectrum system, i.e. $G = B_c/B_b = T_b/T_c$.

1.5 Challenging Capabilities of CDMA

High data rate in multi-user wireless access is demanded by multimedia applications, which require very high bandwidth with mobility. CDMA is considered to be a strong candidate for next generation mobile systems to support multimedia services because it has the ability to cope with the asynchronous nature of multimedia traffic. There are number of properties that are behind the development of CDMA. Some of those are mentioned below [4]:

a. **Multiple access capability** The receivers will be able to distinguish between the users even if their signals overlap in both time and frequency.

b. **Inherent frequency diversity** Unlike narrow-band transmissions, broadband transmissions benefit from an inherent frequency diversity that significantly reduces the risk of destructive flat fading over the whole transmission bandwidth.

c. **Interference rejection and anti-jamming capability** CDMA has anti-jamming capability, where jamming refers to the particular case when the narrowband interferer voluntarily disturbs the system.

d. **Low probability of interception** Because of its low power spectral density and noise like codes, the spread spectrum signal is difficult to detect and intercept by a third party. This makes spread spectrum techniques attractive for military applications.

e. **Universal frequency reuse** In CDMA systems, all cells can use the total spectrum at the same time and, thus, a universal frequency reuse is possible. This highly increases the spectral efficiency and considerably simplifies frequency planning and system deployment.

f. **Soft handoff** Because of the universal frequency reuse, a mobile user can simultaneously communicate with several nearby base stations using the same frequency band and can establish a connection with the new base station before terminating the connection with the old base station. This improves handoff performance.

g. **Soft capacity** The maximum number of users that can be supported in each cell depends on the required quality of service (QoS) and is limited by MAI. As a result, there is no hard limit on the number of users in each cell. Thus by lowering QoS to a certain degree, the system can accommodate more number of users during heavy traffic.

1.6 CDMA Schemes

There are various schemes of CDMA system as shown in Fig. 1-1 [3].

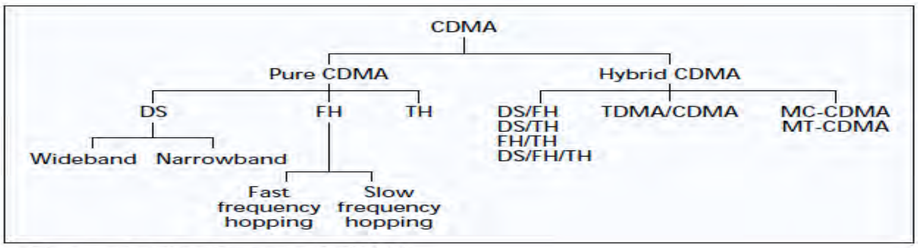


Figure 4. *Classification of CDMA.*

Fig. 1-1 Various CDMA schemes

There are number of coding and modulation techniques that generate spread spectrum signals. Some important schemes are briefly discussed below [3]:

a. **Direct Sequence CDMA (DS CDMA)** The information bearing signal is multiplied directly by a high chip rate code signal.

b. **Frequency Hopping CDMA (FH CDMA)** The carrier frequency at which the information-bearing signal is transmitted is rapidly changed according to the code signal.

c. **Time Hopping CDMA (TH CDMA)** The information-bearing signal is not transmitted continuously. Instead the signal is transmitted in short bursts where the times of the bursts are decided by the code signal.

d. **Multi Carrier CDMA (MC CDMA)** Two or more of the previously-mentioned modulation techniques can be used together to combine the advantages and to combat their disadvantages. In MC-CDMA, transmitter spreads the original data stream over different sub-carriers using a given spreading code in the frequency domain whereas, in MT-CDMA, spreading is done along the time-domain. However, in MC-DS-CDMA, spreading of signal is done in time-domain which is then modulated in diversified frequencies.

1.7 **Single Carrier Vs. Multi-Carrier CDMA Systems** [6]

The choice of a Single-carrier or Multi-carrier CDMA scheme is an important design consideration. Future mobile radio systems have to support a variety of services such as voice, video and high-rate data communications. Towards this goal, the system must be able to support variable and high bit-rate transmission, and with high bandwidth efficiency, bearing in mind the limited radio frequency spectrum. In mobile environments, high data-rate transmission will result in the channel delay exceeding the symbol duration. In this case, the single carrier DS-CDMA system is subject to a severe Inter Symbol Interference (ISI). MC modulation, a technique to reduce the symbol rate, is then essential, where the carrier frequencies are chosen to be orthogonal to one another [8]. Combination of MC modulation techniques with DS-CDMA forms the MC-CDMA system. In multi-carrier CDMA systems, frequency diversity may be achieved by repeating the transmitted signal in the frequency domain with the aid of several sub-carriers to increase the capacity of the multi-carrier CDMA systems. Additionally, it is also possible to use the spreading operation for multiple code transmissions to increase the data rate. As a result, a system operating with MC-CDMA technology can be flexibly changed from single-device transmission with high-data-rate transmission to multiple-device transmission with a low data rate for each device. But all these achievements are obtained with the expense of increased system complexity.

1.8 Merits of MC DS-CDMA

In comparison with the pure DS-CDMA using only time domain spreading and pure MC-CDMA using only frequency domain spreading, it has been demonstrated that the Multi-carrier DS-CDMA has the highest flexibility and the highest number of degrees-of-freedom for reconfigurations [9]. With a multi-carrier modulation technique, the entire bandwidth of a multi-carrier direct-sequence code-division multiple-access system (MC-DS-CDMA) system is subdivided into several narrow-band sub-channels operating at lower data rates. So, there is only flat fading, which has no Inter-chip Interference (ICI), in each sub-channel if the number of sub-carriers is chosen properly. These properties render the MC DS-CDMA a versatile multiple access scheme that is suitable for cognitive and software-defined radios.

1.9 Limiting Factors of Wireless Communication System

A radio signal transmitted through a mobile radio channel undergoes all the mechanisms that govern the propagation of electromagnetic waves. There are four basic mechanisms influence the propagation of electromagnetic waves which are described below [10]:

a. **Path loss** The path loss describes a deterministic average attenuation of the signal strength depending only on the distance between the transmitter and receiver.

b. **Shadowing** Shadowing is caused by landscape details obstructing line of sight, such as hills, forests, bushes, buildings and so forth. It also reflects the changes in the propagation paths due to movements of the mobile.

c. **Multi path fading** It is a result of the multiple propagation paths created by reflection, diffraction, and scattering mechanisms which leads to Inter-Symbol Interference (ISI). Multi path fading characteristics depend on whether the transmitter and receiver are in line of sight (LOS) or not. The latter is modeled as a Rayleigh Distribution, while the former case is modeled as a Rician distribution.

d. **Carrier frequency offset** It indicates the shift in frequency of the signal spectrum caused by the motion of the objects within the propagation environment.

1.10 **Diversity and Combining Techniques** [11]

To combat multi-path fading, diversity and linear combining techniques are used. Diversity improves transmission performance by making use of more than one independently faded version of the transmitted signal. If there are several replicas of the signal carrying the same information, the chances of all the signal components experience deep fading simultaneously are greatly reduced thereby improves transmission accuracy. Diversity can be applied in terms of frequency, time, space and angle. After obtaining diversified received signals, they are combined together. The methods for combining independently faded signal components are Maximal Ratio

Combining (MRC), Equal Gain Combing (EGC) and Selective Combining. Rake Receiver is used in the CDMA system for the implementation of different combining techniques.

1.11 Motivation of this Thesis

Multi-carrier DS-CDMA has been considered to be an attractive technique in achieving high data-rate transmission for future mobile communication system. Therefore this scheme is to be analyzed to evaluate it's capabilities for applicability in different aspects. It is a known fact that various multimedia services are characterized by the requirement of Bit Error Rate and information data-rate for specific Quality of Service (QoS). Thus, the capacity i.e. upper limit for the number of users of MC DS-CDMA in different setup is to be evaluated and correct tradeoffs are to be identified in varying circumstances. As the system performance is greatly influenced by the limiting factors like interference, fading and carrier frequency offset, the evaluation is also to be done at different extent of these effects. Again, as the use of rake receiver can greatly reduce the fading effects at the expense of receiver complexity, the extent of capacity improvement also needs to be evaluated.

In order to study the above-mentioned performance of the system, there are mainly two approaches, such as, computer simulation and analytical modeling. The computer simulation is an easy approach to get the result but its main drawback is that it cannot be used for further evaluation or evaluation of other similar systems. For this reason, in this thesis, the analytical approach has been chosen for the said study.

1.12 Review of Previous Works

A good number of studies have already been carried out by different scholars on the evaluation of capacity of MC DS-CDMA system. But, either they have used the computer simulation methods which have produced unique result for a particular setup only, or they have not addressed all the issues like fading, carrier frequency offsets and rake receiver together. The similar studies are briefly described below:

a. Essam Sourour,[12] analytically derived the model for evaluating the BER performance of the MC DS-CDMA system and compare the performance of the system with conventional code and with orthogonal code. He concluded that the system with orthogonal codes give best performance. But he did not evaluate the system performance for carrier frequency offset due to which even the orthogonal codes may not be able to maintain their orthogonal property.

b. Heng Yang, and Xian-Da Zhang focuses the MC-DS-CDMA system with frequency spread coding [13]. They found that due to exponential computation complexity of the Maximum Likelihood Sequence Decoding (MLSD), maximum number of sub-carrier in the MC DS-CDMA is 8. To cope with such a bottleneck, they have proposed a fast MLSD method and found that it causes low BER and steady BER performance relative to the change of the number of active users But the evaluation is done through computer simulation and the effect of Carrier Frequency Offset (CFO) on BER performance was not considered.

c. Shu-Ming Tseng and Hung-Chieh Yu have proposed a vector autoregressive model which accounts for correlation between different user/carrier fading channels [14]. The result was also evaluated through computer simulation. Though they have considered the Doppler frequency shift effect, but didn’t account for the use of rake receiver.

d. Xinsheng Wang, Wei Yang, Zhmhui Tan and Shixin Cheng have compared the performance of Space Time Block Coded (STBC) MC-DS-CDMA system with conventional MC DS-CDMA system [15]. They concluded that the capacity of the system with two receiving antenna is double to that of one receiving antenna. Their analysis was with both analytical and simulation, but they did not consider the effect of CFO and Rake receiver.

e. Yewen Cao, Tjeng Thiang Tjhung and Chi Chung Ko proposed premulticoded MC-DS-CDMA system [16]. In the proposal, the basic MC-DS-CDMA system is augmented with a precoder and a multicode encoder at the transmitter. The use of the precoder results in multicoded symbol streams of two levels, thus minimizing PAPR in the transmitted MC-DS-CDMA signal. After the simulation, they have shown that the BER performance of the proposed system was significantly better than that of both SC-DS-CDMA (with Rake receiver) and MC DS-CDMA system without pre-coding. They have used the rake receiver for the SC-DS-CDMA but didn’t consider the rake receiver for MC DS-CDMA. Moreover, they have not considered the effect of CFO and have not shown the performance change with the change of no of path (i.e. finger) of the rake receiver.

f. Y.-S. Kim and S.-H. Hwang have done a comprehensive analysis of the BER performance of MC DS-CDMA with rake receiver in a multipath fading environment [17]. They have identified the improvement of performance on applying space diversity by using multiple receiver antennas and also by varying the number of rake fingers. However, they were left with incorporation of Doppler frequency spread effect in their analysis.

g. Saimoon Ara Amin, Mahbubul Alam Rafel and S.P Majumder, describe the four systems of CDMA; DS-CDMA, MT-CDMA, MC-CDMA, MC-DS-CDMA [18]. They perceived the BER with respect of Number of Users for different CDMA schemes. They also evaluated the maximum number of users and required SNIR for different code lengths for all those schemes. But in their analysis, they have considered the medium as ideal and the propagation impairments like fading and CFO was not taken into account.

1.13 Objective of this Thesis Work

Followings are the objectives of this research work:

a. To evaluate the expression of MAI, ICI and Bit Error Rate (BER) of a MC-DS-CDMA wireless communication system with Quadrature Phase Shift Keying (QPSK) modulation and Rake receiver, considering the effect of Rayleigh fading.

b. To extend the analysis to include the effect of carrier frequency offset and to find out the expression of BER.

c. To evaluate the BER performance results based on the analytical approach.

d. To determine the effect of frequency offset and to find the optimum system design parameters.

1.14 Structure of this Thesis Paper

The outline of this thesis is organized as follows:

Chapter 2: It describes the basic concepts on Multi-carrier CDMA system which is required for better understanding of this work. It starts with the description of various schemes of CDMA and their comparison. It then explains various spreading codes which are being used in CDMA system. Thereafter it described the method of calculating the Bit Error Rate and lastly the methods of mitigating the propagation impairments.

Chapter 3: In this chapter, the analytical expression of an MC-DS-CDMA scheme has been obtained. Initially the expression is formulated without considering rake receiver. Then, it was modified for the system with rake receiver. Thereafter, the effect of Carrier frequency Offset has been incorporated.

Chapter 4: This chapter encompasses the performance results obtained from various calculations and plots. Basing on that, the optimum system parameters has been chosen.

Chapter 5: It includes the conclusions and the scopes of future works on this subject.

CHAPTER-2

FUNDAMENTAL CONCEPT OF MULTICARRIER CDMA SYSTEM

2.1 Introduction

Broadband wireless mobile system aims to provide wide range of services by employing techniques that can achieve better spectrum efficiency. CDMA is an attractive scheme in this regard. In the context of broadband wireless system with CDMA, the main options include DS-CDMA, MC-CDMA, MC-DS-CDMA and MT-CDMA. Since single-carrier CDMA suffers from increased Inter Symbol Interference (ISI), the multicarrier CDMA is more effective due employment of frequency diversity. The multi-carrier CDMA technique was proposed in 1993 based on a combination of orthogonal frequency division multiplexing (OFDM) and DS-CDMA. In this chapter, the behavior of different CDMA schemes and in particular the MC DS-CDMA are described. In addition, different types of spreading codes and technologies to mitigate wireless channel-impairments are highlighted.

2.2 DS-CDMA System

In DS-CDMA, the modulated information bearing signal (the data signal) is directly modulated by a digital, discrete-time, discrete-valued code signal. The data signal can be either analog or digital; in most cases it is digital. In the case of a digital signal the data modulation is often omitted and the data signal is directly multiplied by the code signal and the resulting signal modulates the wideband carrier. It is from this direct multiplication that the direct sequence CDMA gets its name. The basic functional block diagram of a DS-CDMA transmitter is given in Fig. 2-1 [3].

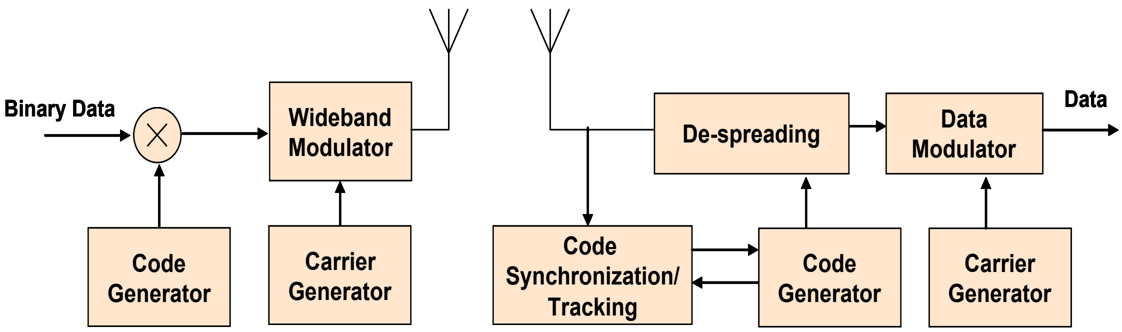


Fig. 2-1 Basic block diagram of DS-CDMA system

The binary data signal modulates a RF carrier. The modulated carrier is then modulated by the code signal. This code signal consists of a number of code bits called “chips” that can be either +1 or –1. To obtain the desired spreading of the signal, the chip rate of the code signal must be much higher than the data rate of the information signal. For the code modulation various modulation techniques can be used, but usually some form of Phase Shift Keying (PSK) like Binary Phase Shift Keying (BPSK), Differential Binary Phase Shift Keying (D-BPSK), Quadrature Phase Shift Keying (QPSK), or Minimum Shift Keying (MSK) are employed [6]. After transmission of the signal, the receiver uses coherent demodulation to de-spread the SS signal, using a locally generated code sequence. To be able to perform the dispreading operation, the receiver must not only know the code sequence used to spread the signal, but the codes of the received signal and the locally generated code must also be synchronized. After de-spreading a data modulated signal results, and after demodulation the original data can be recovered. Now, the transmitted signal after coding and modulation can be expressed as follows [20]:

$$\sum\sum \cos(2\ldots) \; C \; i \; j \; T \; f \; t \qquad \sqrt{\quad}$$

Where,

= No of User

= Transmitted Power

b_i = i-th transmitted bit (+1 or -1)

C_j = j-th chip of the spreading code

T_b = Bit period

T_c = Chip Period

f_c = Carrier Frequency

2.3 **MC CDMA System**

This scheme is used in OFDM-based telecommunication systems which can allow the system to support multiple users at the same time. In this system, each user symbol is carried over multiple parallel sub-carriers, but it is phase shifted (typically 0 or 180 degrees) according to a code value. The code values differ per sub-carrier and per user. The block diagram of Transmitter, power spectral density of transmission signal and

Receiver block diagram of MC-CDMA are shown in Figs 2-2 through 2-4 respectively [21].

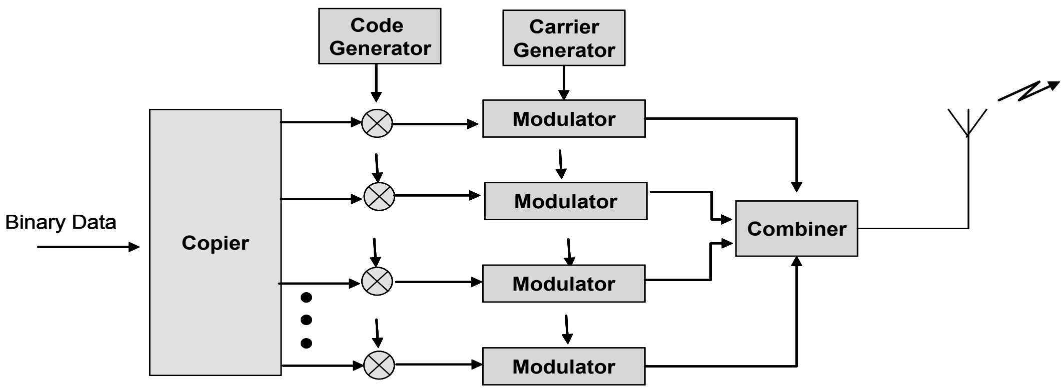


Fig. 2-2 Block diagram of MC-CDMA transmitter

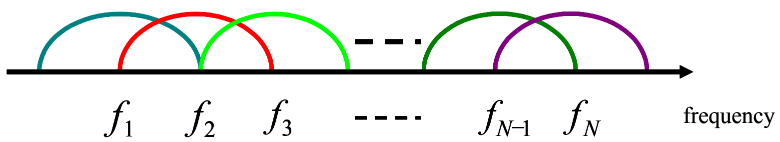


Fig. 2-3 Power spectral density of transmitted signal of MC CDMA

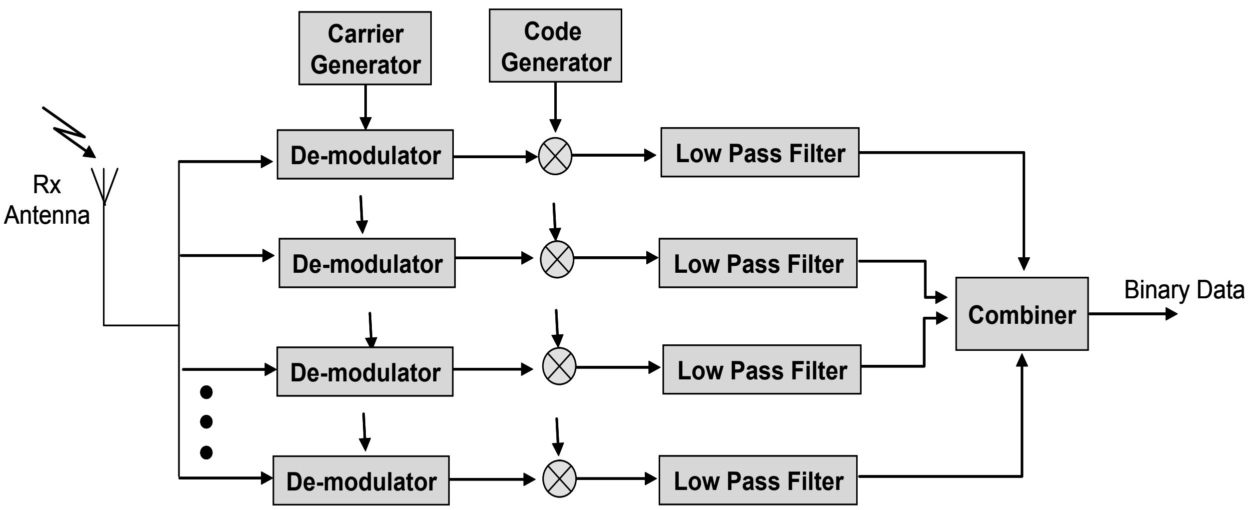


Fig. 2-4 Basic block diagram of MC CDMA receiver

The receiver combines all sub-carrier signals by weighing these to compensate varying signal strengths and undo the code shift. The receiver can separate the signals of different users, because these have different (e.g., orthogonal) code values. The spreading operation in MC-CDMA can be used for multiple access schemes as well as for exploiting frequency diversity gain. Additionally, it is also possible to use the spreading operation for multiple code transmissions to increase the data rate. As a result, a system operating with MC-CDMA technology can be flexibly changed from single-device transmission with high-data-rate transmission to multiple-device transmission with a low data rate for each device. From each transmission link's point of view, scalability in terms of the data rate can be easily achieved by changing the length and number of spreading codes assigned to the link's modulation and coding scheme. The number of users supported by the MC-CDMA system depends on both the processing gain (i.e. T_b/T_c) and the cross-correlation characteristics of the spreading codes.

2.4 MC DS-CDMA System

The principle of MC-DS-CDMA is to create multiple parallel DS-CDMA streams of long chip duration and of moderate bandwidth. Thus, analogous to DS-CDMA, MC-DS-CDMA performs spreading along the time domain on each individual stream. The parallel streams are transmitted on orthogonal sub-carriers, where orthogonality is achieved after spreading in order to avoid the ICI. The block diagram of the transmitter, receiver and the power spectral density of transmitted signal of this system are shown in Figs 2-5 through 2-7 respectively. It is clear from the diagram that the S/P converter reduces the sub-carrier data rate by mapping the serial data to a number of reduced-rate parallel streams. Thus, the T-domain spreading increases the achievable processing gain with each sub-carrier, while F-domain spreading further increases the total processing gain. For a given transmission bandwidth, small numbers of sub-carriers are generally be considered since the sub-carriers are disjoint and individually spread. This results in a lower Peak to Average Power Ration (PAPR) than in MC-CDMA for the same transmission bandwidth. The low PAPR property and the capability to handle asynchronous transmissions make MC-DS-CDMA suitable for the asynchronous uplink of mobile radio communication systems.

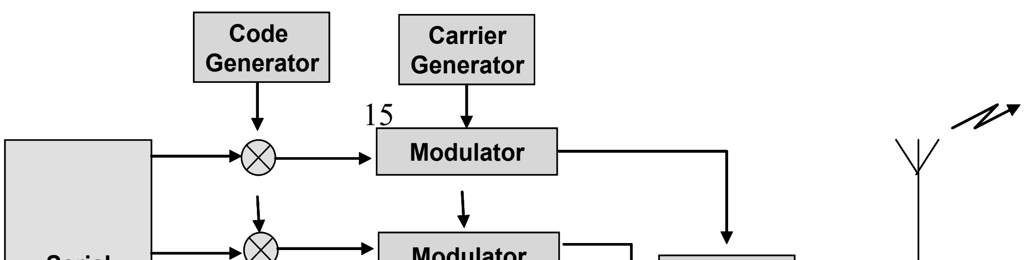


Fig. 2-5 Transmitter block diagram of MC DS-CDMA system [5]

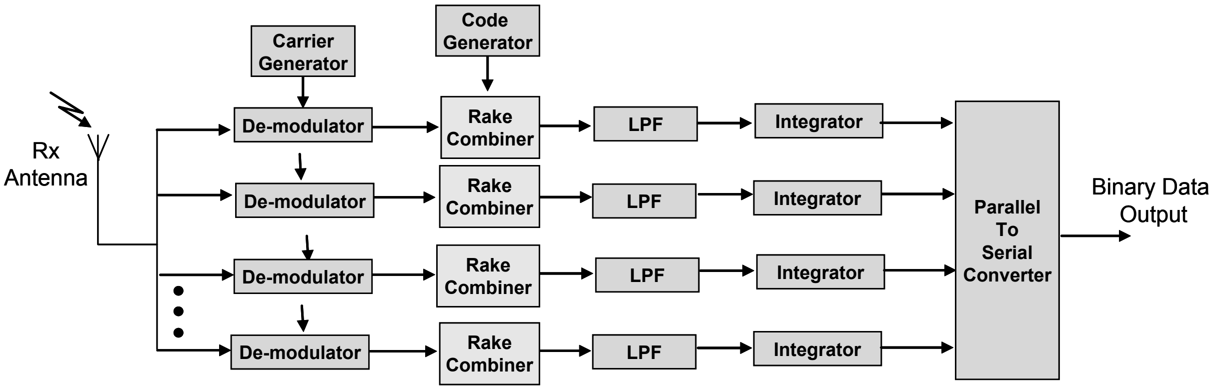


Fig. 2-6 Receiver block diagram of MC DS-CDMA (with rake)

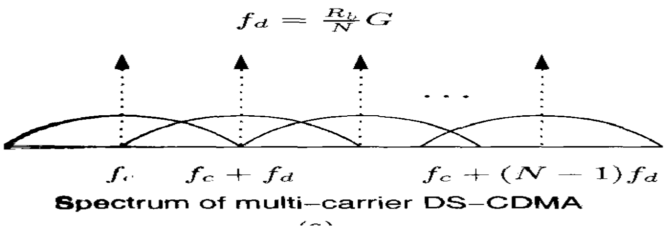


Fig. 2-7 Power spectral density of MC DS-CDMA transmission signal

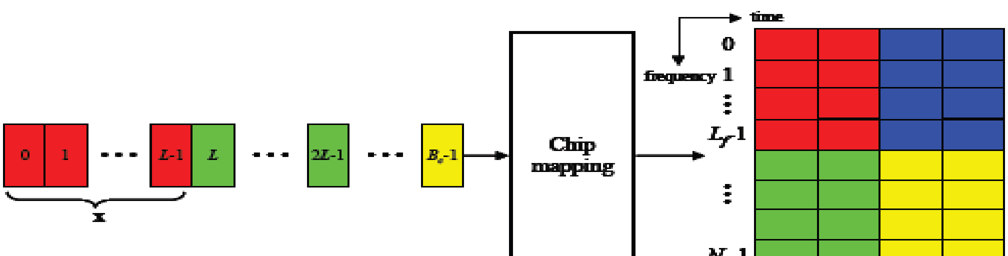


Fig. 2-8 Transmission concept of MC-DS-CDMA

2.5 MT CDMA System

The MT-CDMA system aims at combating the effects of multi-path propagation thanks to the longer symbol duration of multi-carrier modulation and the capability of DS-CDMA to reduce the multi-path interference. Fig. 2-9 indicates that MT-CDMA follows the same spreading approach as in MC-DS-CDMA so that spreading is done along the time domain. Here, the difference is that MT-CDMA chooses the sub-carriers orthogonal

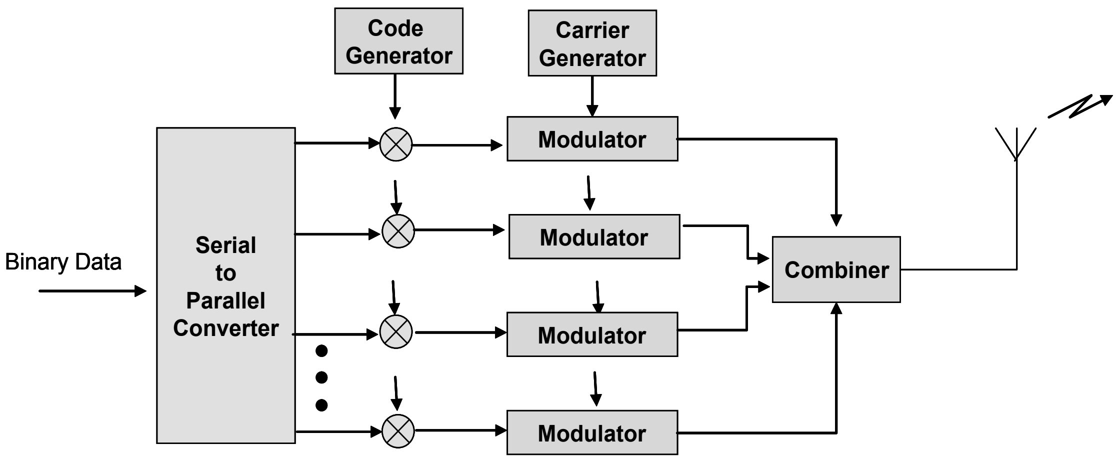


Fig. 2-9 Transmitter block diagram of MT-CDMA system

on the symbol duration T of the parallel streams with the minimum frequency spacing 1/T = 1/LTc, where L is the length of the spreading code. As each sub-carrier occupies a bandwidth close to 1/Tc, the spectra of the different sub-carriers are therefore strongly overlapping, which introduces ISI and ICI in multi-path propagation. The ISI and ICI effects have severe impact on the system performance, and high-complexity receivers are required to cancel them out. On the other hand, the tight sub-carrier spacing allows the use of more sub-carriers than in MC-DS-CDMA, which helps reduce the MAI and, thus, allows accommodating more users in the system.

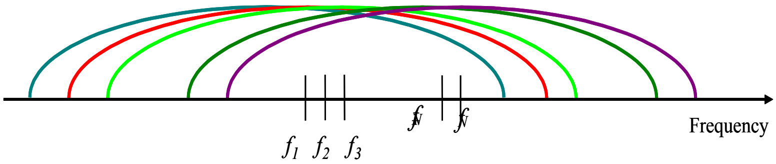


Fig. 2-10 psd of MT-CDMA transmission signal [5]

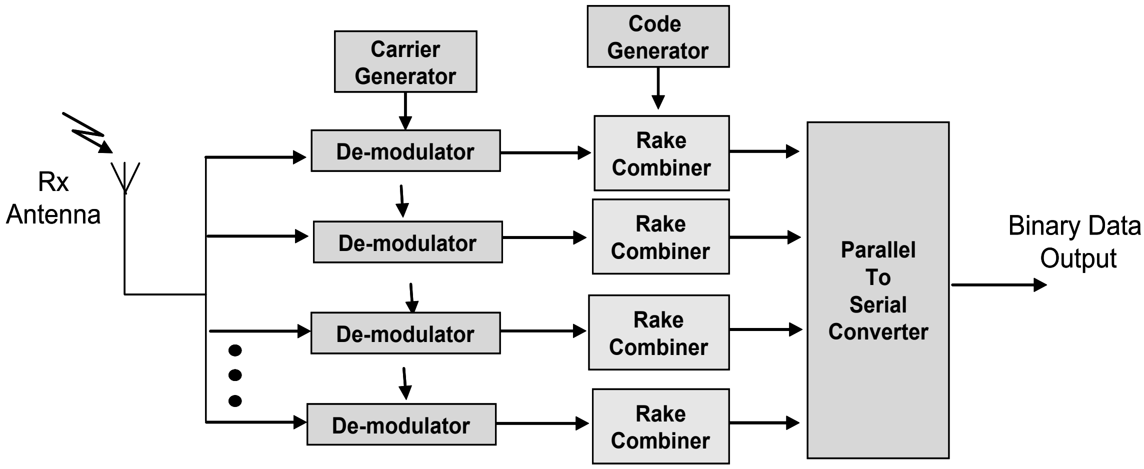


Fig.2-11 Receiver block diagram of MT-CDMA system [5]

2.6 Comparison between different CDMA schemes

Access Scheme	Symbol Duration at Subcarrier	The Number of Subcarrier	Processing Gain	Chip Duration	Subcarrier Separation	Required Bandwidth (Nyquist Filter roll-off factor 0)
DS-CDMA	T_s	(1)	G_{DS}	T_s / G_{DS}		[illegible]
MC-CDMA	T_s	N_{MC} [illegible]	G_{MC} [illegible]	[illegible]	$1/T_s$	[illegible]
Multicarrier DS-CDMA	$N_c T_s$	N_c	G_{MDS} [illegible]	[illegible]	[illegible]	[illegible]
MT-CDMA	$N_c T_s$	N_c	$G_{MT} = N_c G_{DS}$ [illegible]	[illegible]	$1/(N_c T_s)$	[illegible]

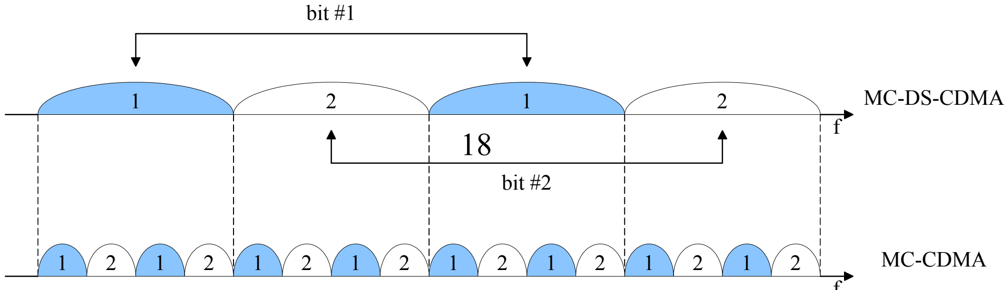


Fig. 2-12 Difference between MC-CDMA and MC-DS-CDMA

2.7 Summary of CDMA schemes

In light of the current discussions, the basic properties of different CDMA schemes is summarized below in light of their applicability [3]:

- DS-CDMA — a) Robustness to multi-path fading capability

- TDD-CDMA — a) Asymmetric communications capability
  b) Requirements for long-overhead for synchronization

- MC-CDMA — a) Suitable for frequency-selective fading channel
  b) Requirement for highly linear amplification

- MC-DS-CDMA — a) Advantages of both MC and DS CDMA
  b) High data transmission under severe fading channel

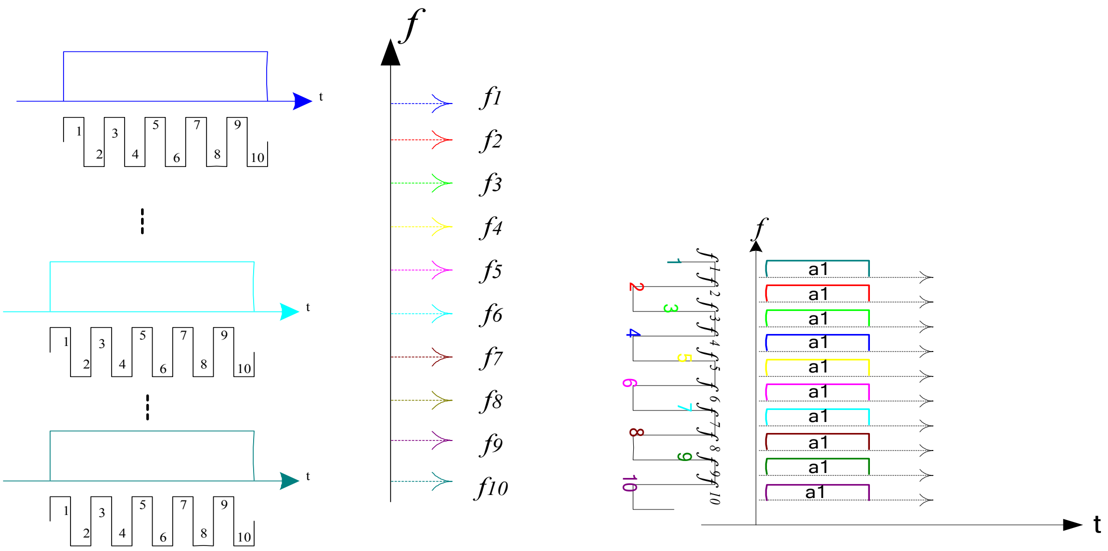


Fig. 2-13 Graphical representation of series to parallel and vice versa

2.8 Spreading Codes [21]

In CDMA, modulation is done twice, first with a binary sequence and then by a carrier. The binary sequence modulation ahead of the carrier modulation accomplishes following two functions, (a) it spreads the signal and (b) it introduces a form of encryption because the same sequence is needed at the receiver to demodulate the signal. Multiplication of the base-band information signal with the higher-rate code sequence results a much wider spectrum. The ratio of the code rate to the information bit rate is called the spreading factor or the processing gain of the CDMA system.

2.8.1 **Properties of spread sequences**

For CDMA spreading code, we need a random sequence that passes certain 'quality' criterion for randomness. These criterions are as follows [22]:

a. The number of runs of 0's and 1's is equal. We want equal number of two 0's and 1's, a length of three 0's and 1's and four 0's and 1's etc. This property gives a perfectly random sequence.

b. There are equal number of runs of 0's and 1's. This ensures that the sequence is balanced.

c. The periodic autocorrelation function is nearly two valued with peaks at 0-shift and is zero elsewhere. This allows encrypting the signal effectively.

2.8.2 **Different sequences**

Binary sequences that can meet these properties are called Pseudo-random Noise (PN) Sequences. Popular PN sequences used in spread-spectrum transmission are described below:

a. **Maximum-Length (M) sequence** M–sequences are created by using Linear Feedback Shift Registers (LFSR). Fig. 2-12 shows a three register LFSR with two different tap connection arrangements. The tap connections are based on primitive polynomials on the order of the number of registers. Unless the polynomial is irreducible, the sequence will not be an m-sequence and will not have the desired properties.

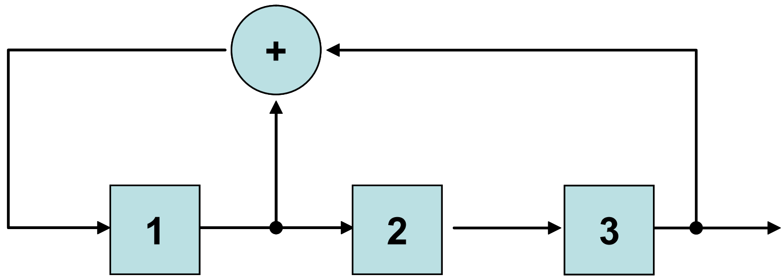


Fig. 2-12 Three stages LFSR generating m-sequence of period 7

Each configuration of N registers produces one sequence of length 2^N. If taps are changed, a new sequence is produced of the same length. There are only a limited number of m-sequences of a particular size. The cross correlation between an m-sequences and noise is low which is very useful in filtering out noise at the receiver. The cross correlation between any two different m-sequences is also low and is useful in providing both encryption and spreading. The low amount of cross-correlation is used by the receiver to discriminate among user signals generated by different m-sequences.

b. **Gold sequences** Gold sequences are important class of sequences that allow construction of long sequences with three valued Auto Correlation Function. Gold sequences are constructed from pairs of preferred m-sequences by modulo-2 addition of two maximal sequences of the same length. Given a preferred pair of sequences of period n = (2^m - 1), say and , we can construct a new family of sequences by taking the modulo-2 sum of s with the n cyclically shifted versions of r or vice versa. Thus, we obtain n new periodic sequences with period n. If we include also the original sequences s and r we obtain a family of n + 2 sequences. The resulting sequences are the Gold Sequences. Fig. 2-14 (in the next page) shows the shift registers for generating a preferred pair of sequences corresponding the polynomials.

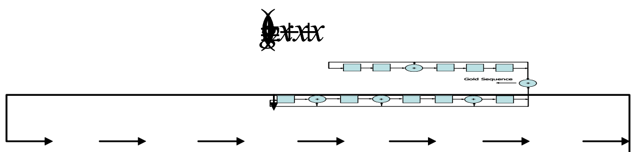


Fig. 2-14 Generation of gold code sequence of length 31

Gold sequences are useful in non-orthogonal CDMA and they have only three cross-correlation peaks which tend to get less important as the length of the code increases. They also have a single auto-correlation peak at zero, just like ordinary PN sequences. The use of Gold sequences permits the transmission to be asynchronous.

c. **Kasami sequences** A similar procedure used in the generation of Gold sequences can be used to generate a smaller set of $M = 2^{m/2}$ binary sequences of period $n = 2^m - 1$, where m is even. In this procedure, we begin with an m-sequence s and we form a binary sequence r by taking every $2^{m/2}+1$ bit of s. In other words, the sequence r is formed by decimating s by $2^{m/2}+1$. It can be verified that the resulting r is periodic with period $2^{m/2}-1$. Now, by taking $2^{m/2}-1$ bits of the sequences s and r, we form a new set of sequences by adding, modulo-2, the bits from s and all $2^{m/2}-2$ cyclic shifts of the bits from r. By including s in the set, we obtain a set of $2^{m/2}$ binary sequences of length $n = 2^m - 1$. These are called the (small set of) Kasami sequences. Kasami sequences have optimal cross-correlation values. The lower bound on the cross-correlation between any pair of binary sequences of period n in a set of m-sequence is:

$$\theta_{max} \geq n\sqrt{\frac{M-1}{Mn-1}}$$

2.9 **Rake Receiver** [11]

After the spread spectrum modulation using any of the discussed codes, the transmitted signal normally has much larger bandwidth than that of a wireless channel. Thus the channel exhibit frequency-selective fading at the chip level. To recover the transmitted information sequence, the receiver needs to generate the same PN sequence and synchronize the locally generated sequence with the incoming one. By making use of the autocorrelation property of the PN sequence, the receiver can use multiple correlators to separate the received signal components of different propagation delays to a chip interval. Then, by estimating the channel gain experienced by each signal component, the receiver can combine all the components coherently by properly compensating for the propagation delay and carrier phase distortion. With the ability to separate and then constructively combine the signal components with different propagation paths and therefore overcome the transmission performance degradation due to delay dispersion. Rake receivers are the effective receiver elements which are used for combination of diversified received signals. The representation of it's principle is shown in the Fig. 2-14 below [3]:

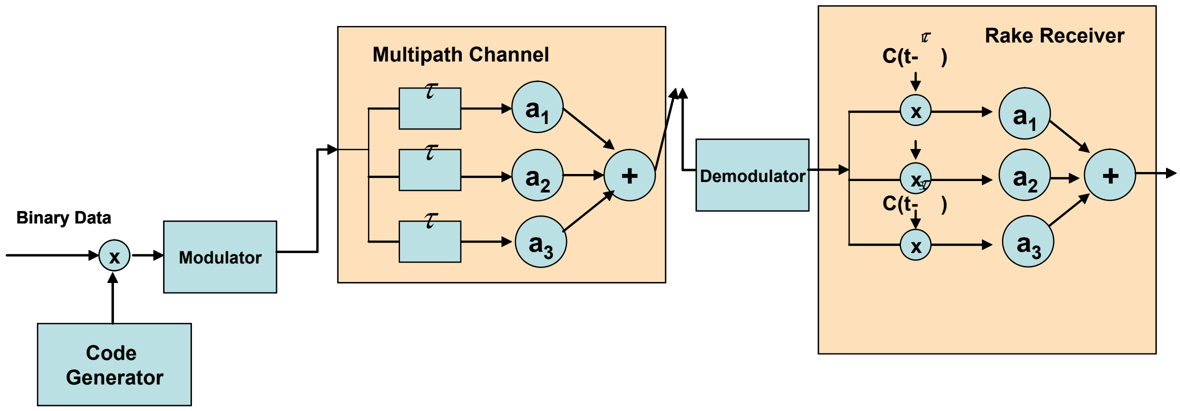


Fig. 2-15 Principle of rake receiver

2.10 Probability of Reception Error

The term "error" arises in two ways. Firstly, it arises in the context of decision making, where the probability of error may be considered as being the probability of making a wrong decision and which would have a different value for each type of error. Secondly, it arises in the context of statistical modeling, where the model's predicted value may be in error regarding the observed outcome and where the term probability of error may refer to the probabilities of various amounts of error occurring. In communication system, error may occur both during transmission and reception. However, error in reception is more severe since the expected signal while traveling through the medium are subject to fading. The next subsection will discuss the method of estimating reception error for both BPSK and QPSK modulation.

2.10.1 **Reception in AWGN channel (for BPSK)** Suppose we are transmitting digital information using two-level pulses each with period *T*. The wave shape of the base band signal and the signal while being transmitted through noisy environment are shown in the Fig. 2-16(a) and (b) respectively. The binary digit '0' is represented by a signal of level '0' for the duration T of the transmission, and the digit '1' is represented by the signal level A_t.

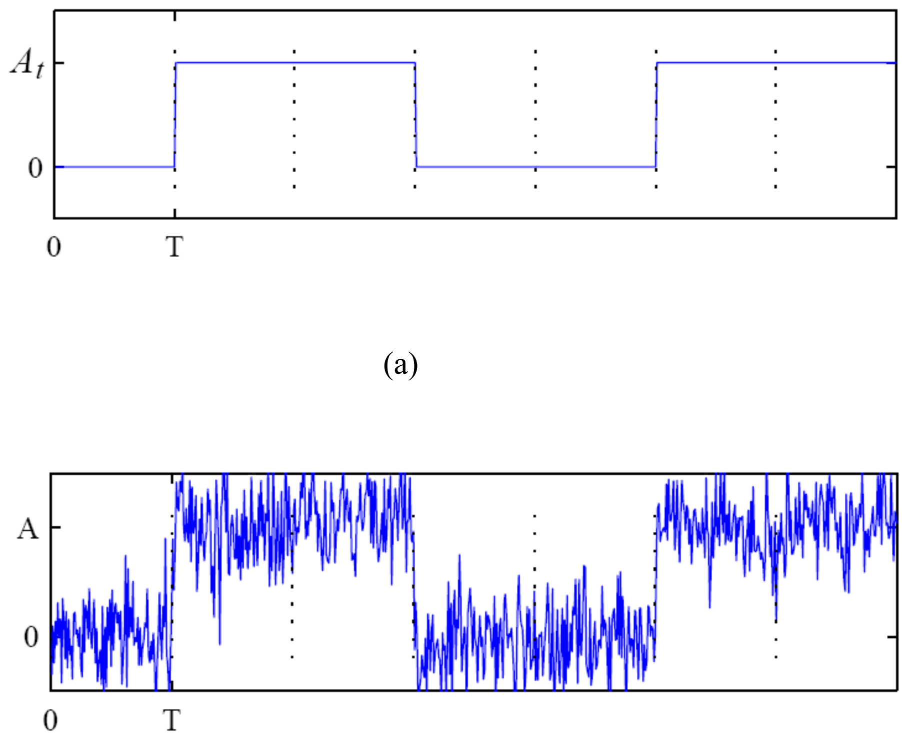


Fig. 2-16 Binary transmitted (a) and received (b) signal in a noisy gaussian channel

The function of the receiver is to distinguish the digit '0' from the digit '1'. The most important performance characteristic of the receiver is the probability that an error will be made in such a determination. Let us now consider a coherent BPSK receiver model over an AWGN channel which is as shown in Figure-2.17 below [11]:

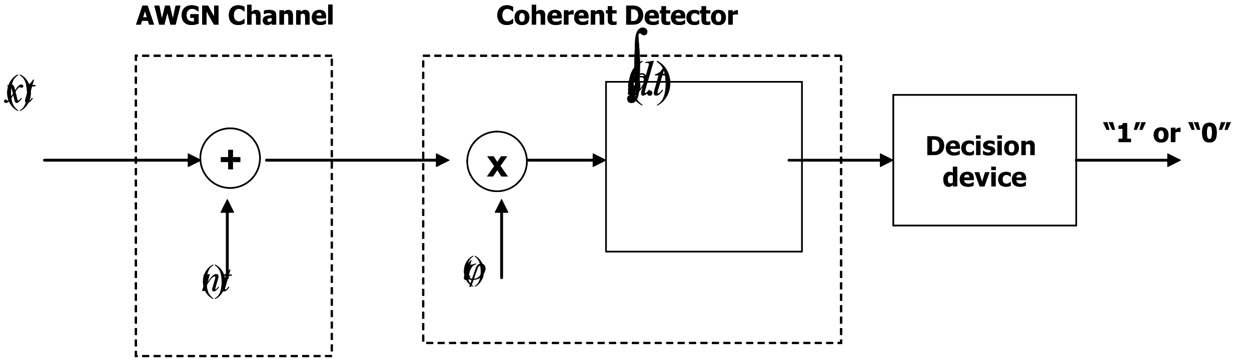


Fig. 2-17 Coherent Reception in an AWGN Channel

If the detection of a symbol transmitted over the time interval is considered [0, Tb]. The transmitted signal is

$x(t)$

$\sqrt{\ }$, For symbol “1”

$\sqrt{\ }$, For symbol “0”

Now, in an AWGN channel, the received signal is then expressed as follows:

$$r(t) = x(t) + n(t) \qquad (2.1)$$

where $n(t)$ represents the white Gaussian noise process with zero mean and two-sided psd $N_o/2$. The output of the correlator (or the matched filter at $t = T_b$) is as follows:

$$\int r(t)\, dt \qquad (2.2)$$

In equation 2.2, r is a Gaussian random variable with variance $N_0/2$ and it’s probability density function (pdf) with mean $\sqrt{E}$ is given as follows:

$$f(r) = \frac{1}{\sqrt{\ }} e^{\ /\ } \qquad (2.3)$$

With equally likely symbols “1” and “0”, the probability of symbol (i.e. bit) error, or Bit Error Rate (BER) is given as:

(Probability of detecting ‘1’ when symbol ‘0’ was sent)(Probability of sending symbol ‘0’) + (Probability of detecting ‘0’ when ‘1’ was sent)(Probability of sending ‘1’)

$$P(e) = P(1|'0').P('0') + P(0|'1').P('1') \qquad (2.4)$$

Here, since ‘1’ and ‘0’ are equally probable,

$$P(0) = P(1) = \frac{1}{2}$$

So,

(2.5)

If we assume the following:

Putting these values in Eq 2-5, we get,

(2.6)

$$ \tag{2.7} $$

2.10.2 For QPSK modulation

Since QPSK is two BPSK in quadrature, the two BPSK signal components are orthogonal. Over an AWGN channel, the signal detections at the two branches are thus independent. The probability of detection error for the odd-numbered digits is the same as that of even-numbered digits and is equal to the BPSK. Thus, the probability of bit error for coherent QPSK is the same as that for BPSK and is mentioned below [11]:

$$ P_e = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_o}}\right) = Q\left(\sqrt{\frac{2E_b}{N_o}}\right) \tag{2.8} $$

2.10.3 Reception in a flat Rayleigh fading channel

If a stationary flat and slow fading channel is considered, following facts are assumed [11]:

a. The delay spread introduced by the multi-path propagation environment is negligible compared with the symbol interval (hence, the channel does not introduce inter-symbol interference)

b. Channel fading status does not change much over a number of symbol intervals.

Let us consider that a signal *x(t)*, with symbol interval T_S, is transmitted and the received signal is as follows:

$$ r(t) = \alpha(t) \exp[j\theta(t)]\, x(t) + n(t) \tag{2.9} $$

Here, $n(t)$ = white gaussian noise with zero mean and two-sided power spectral density No/2.

According to the assumption (b), it is possible for the receiver to estimate [illegible] and remove it. As a result, in the following BER performance analysis, we assume [illegible] = 0.

Now let’s consider the following:

a) Bit Energy of Transmitted signal = E (constant)

b) Amplitude Fading Parameter = [illegible]

c) Instantaneous bit energy of Received signal = E [illegible]

Now the average SNR without fading, [illegible]

But, when fading is considered, then

Conditional SNR = [illegible] (2.10)

Here, [illegible]

So, the pdf of [illegible] ,

[illegible] when [illegible] ; 0 else

So the conditional BER, [illegible] (2.11)

Now, the average BER for coherent PSK is given as:

[illegible] (2.12)

Let, Putting these values in Eq. 2.11, we get the following:

(2.13)

2.11 Mitigation of Propagation Impairments

In the wireless mobile communication system, transmitted signals often experience channel fading and time dispersion due to user mobility and multi-path propagation. Channel gain fluctuations can be decomposed into long-term fading and short-term fading. Long term fading is mainly due to shadowing and variations in the distance between the mobile and base station. Short-term fading is mainly due to multi-path propagation. It changes with time at a much faster rate compared with that of long-term fading. To combat multi-path fading, diversity and linear combining techniques are used [22].

2.11.1 Diversity mechanisms

The short-term multi-path fading can severely reduce transmission accuracy. Diversity improves transmission performance by making use of more than one independently faded version of the transmitted signal. If several replicas of the signal, carrying the same information, are received over multiple channels that exhibit independent fading with comparable strengths, the chances that all the independently faded signal components experience deep fading simultaneously are greatly reduced. This significantly improves transmission accuracy as transmission errors are most likely to happen when the instantaneous SNR is low during a deep fading period. Few diversity techniques are described in the subsequent sub-paragraphs.

a. **Frequency diversity** The desired message is transmitted simultaneously over several frequency slots. The separation between adjacent frequency slots should be larger than the channel coherence bandwidth such that channel fading over each slot is independent of that in any other slot.

b. **Time diversity** The desired message is transmitted repeatedly over several time periods. The time separation between adjacent transmissions should be larger than the channel coherence time such that the channel fading experienced by each transmission is independent of the channel fading experienced by all of the other transmissions.

c. **Space diversity** The desired message is transmitted by using multiple transmitting antennas and/or receiving antennas. Space diversity implies creating several independent propagation paths at the expense of involving multiple antennas, which explains the other popular name for this technique *Antenna Diversity*. Duplicating antennas may be used at the receiving side as well as at the transmitting side. Being spaced from each other by a distance of 7–10 wavelengths or more, they provide practical independence of parallel interference patterns at the receiver input.

d. **Angle diversity** The desired message is received simultaneously by several directive antennas pointing in widely different directions. The received signal consists of scattering waves coming from all directions. It has been observed that the scattered signals associated with the different (non-overlapping) directions are uncorrelated. Angle diversity can be viewed as a special case of space diversity since it also requires multiple antennas.

2.11.2 **Linear combining techniques** After obtaining diversified received signals of different instantaneous SNR, the signals are combined together. There are various methods for combining independently faded signal components, and the tradeoff among these methods is the receiver complexity versus transmission performance improvement. These techniques are explained below:

a. **Maximal Ratio Combining (MRC)** In this technique, the receiver coherently demodulates the received signal from each branch and the phase distortion of the received signal is removed. The detected signal is then weighted by the corresponding amplitude gain. The weighted received signals from all the branches are then summed together and applied to the decision device. Maximal ratio combining achieves the best performance

b. **Equal Gain Combining (EGC)** The maximal ratio combining approach requires an accurate estimate of the channel amplitude gain, which increases the receiver complexity. An alternative approach is to weight all the signals equally after coherent detection. Then the detected signals from all the branches are simply added and applied to the decision device. As the receiver does not need to estimate the amplitude fading, its complexity is reduced as compared with that of maximal ratio combining.

c. **Selective Combining** In this scheme, the receiver monitors the SNR value of each diversity channel and chooses the one with the maximum SNR value for signal detection. Compared with the preceding two schemes, selective diversity is much easier to implement without much performance degradation.

2.12 **Summary**

In this chapter, the principles and major characteristics of CDMA technique has been presented. CDMA is an efficient and flexible technique that allows a universal frequency reuse in a cellular system. Therefore the general concepts of the four basic multi-carrier CDMA techniques, namely, DS-CDMA, MC-CDMA, MC-DS-CDMA and MT-CDMA has been described here. In addition, different code sequences which are used in CDMA and the effect of fading on CDMA channels has been explained. At the end, various diversity techniques for mitigation of the effect of fading have been briefly introduced. The next chapter will make the effort to formulate the analytical expression of MC-DS-CDMA scheme for it's onward performance evaluation, which is the main object of this work.

CHAPTER-3

ANALYTICAL MODEL OF MC-DS-CDMA SYSTEM

3.1 Introduction

In this chapter, a model of MC DS-CDMA operating in a multi-path fading environment is presented and an analytical expression of the system has been formulated. During the analysis, the input high speed random data bit stream to the system has been divided into a number of parallel low-speed data streams which is used to modulate a number of orthogonal sub-carriers after correlation with a PN Sequence code for each parallel branch. The modulation considered is QPSK. The output of the transmitter, which is a MC-DS-CDMA signal, has been considered to pass through a Rayleigh fading channel and is received by the receiver. Initially a normal receiver is considered and then the analysis has been done for the rake receiver. The expression of the output of the Rake receiver has been derived considering the effect of fading and carrier frequency offset due to Doppler frequency shift. The analytical approach has been carried out for determining the expression of ICI and MAI and the expression of the carrier to interference ratio has been found. The expression for the BER has been derived for a given value of ICI and MAI and given number of sub-carrier and code length.

3.2 Basic Model of MC DS-CDMA

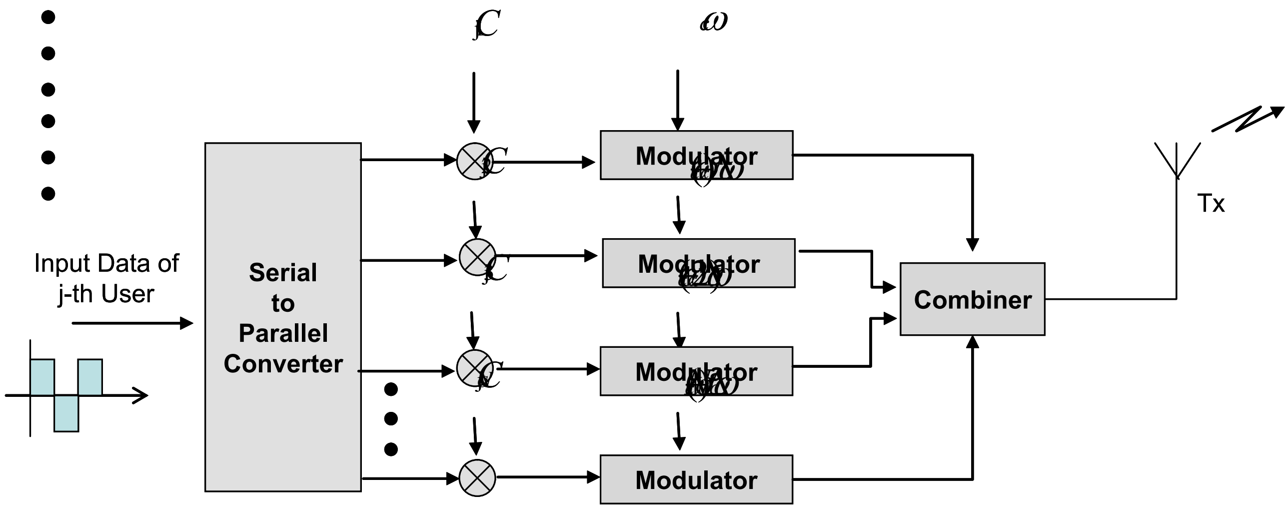


Fig. 3-1 Block diagram of MC DS-CDMA transmitter

Let us consider an MC-DS-CDMA transmitter, the block diagrams of which are as shown in the Fig. 3-1. In a specific cell, let for any period of time, there are j number of users and j-th user is the reference.

Now, to have a system model, following assumptions has been made:

a. All the users are active at any time

b. All the users' transmitter power levels are equal

c. All the transmitted signals are suffering equal amount of fading (i.e. flat fading) at any time

d. The bit-rate is much larger than chip-rate of the coding PN sequences

Now, let us consider the following terms for this system:

j = Total no of user

P = Chip power of each user

N_c = Number of sub-carriers

N = Length of spreading codes per bit

C_j = Code of j-th user

R_b = Bit-rate

$m_j(t)$ = Input data stream of the j-th user

b_j = n-th bit of $m_j(t)$

Thus, $m_j(t) = \sum b$; where 1

Now, the input data of the j-th user are converted into N_c parallel data streams and each of the parallel data is coded by the channel-respective code of the j-th user. Thus each data bit is speeded in time domain and then is modulated by the respective sub-carrier. To write the general expression of the sub-carriers, let us consider the following:

[illegible] = Freq of the reference channel

[illegible] = Freq spacing between two successive channels

[illegible] = Instantaneous phase angle of the k-th sub-carrier

So the general expression of the sub-carrier is:

(3.1)

Thus, the expression of the transmitted signal of the j-th user is as follows:

(3.2)

Here,

b_{jk}^{n} = n-th bit of the j-th user, which is being modulated by the k-th channel

C_{jk}^{x} = x-th chip of the k-th section of the j-th user's code

3.3 MC-DS-CDMA Receiver without Rake

3.3.1 Expression of received signal

The Functional Block Diagram of the MC DS-CDMA Receiver is shown in Fig. 3-2.

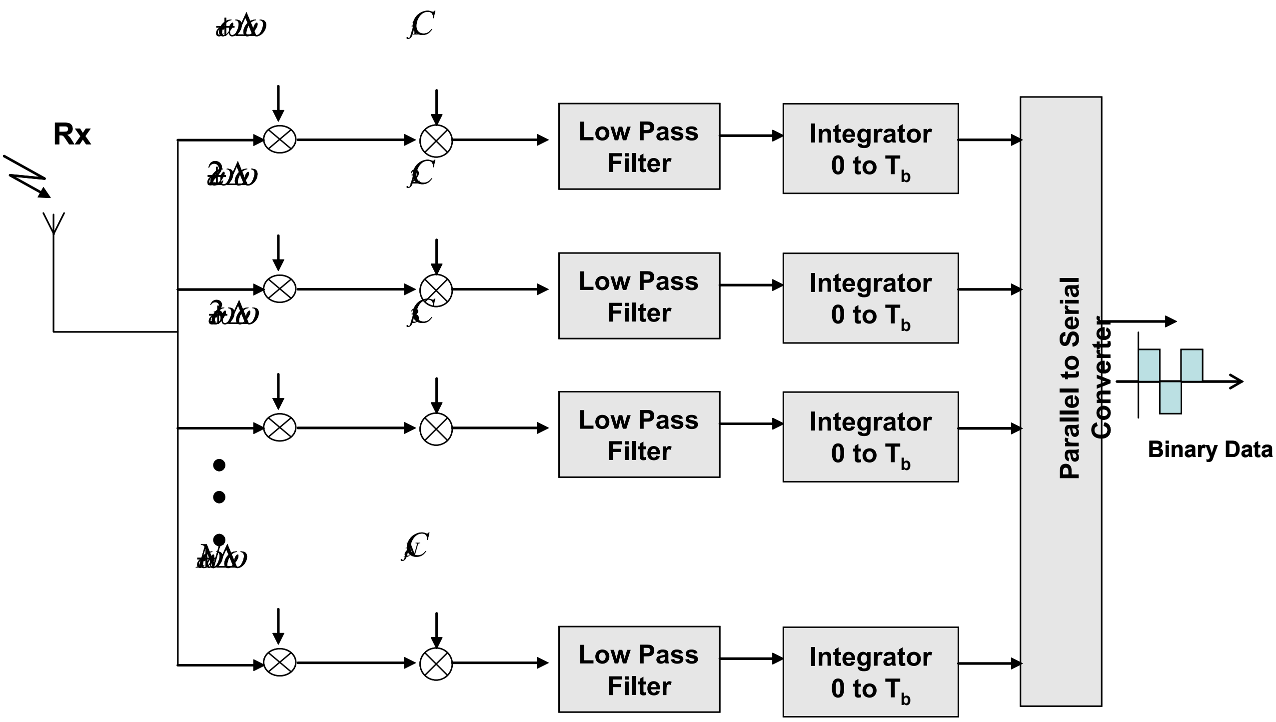


Fig. 3-2 Block diagram of MC DS-CDMA receiver (without rake)

The receiver of the j-th user receives signals transmitted by all the j number of users. Thus, the expression of the received signal is:

(3.3)

Here, $()$ term is the AWGN noise, whose spectral density is around $2N$ $/$. This signal, while propagating through the medium, suffers frequency-selective multi-path Rayleigh fading. To account the fading, consider that be the instantaneous amplitude distortion and be the instantaneous phase distortion due fading. So, at the receiver end, the expression of the received signal is as follows:

But, due to the Doppler Effect, there will be offset in carrier frequency. If be the amount of such frequency offset, then,

(3.4)

This signal is then coherently de-modulated by the respective carriers and the output becomes y(t), which takes the following form:

(3.5)

It is then de-coded and takes the following form:

(3.6)

Now, separating the j-th user's term and assuming   as the cross-correlation among the codes of the j-th user and all other users, we get:

(3.7)

The value of   is '1' when maximum interference occurs whereas, it is '0' when there is no interference. Now, after passing through the low-pass filter, the high frequency components will be eliminated. Thus, Eq. 3.7 becomes as follows:

(3.8)

Now, after integrating over 0 to T_b, we get the following:

(3.9)

Now, for the time being, we ignore the carrier frequency offset by setting =0. Then, Eq. 3.9 takes the following form:

(3.10)

(3.11)

Here,

- Desired signal of j-th user
- Multiple Access Interference
- Noise

3.3.2 Desired signal of receiver

The desired signal of the j-th user is which is given as follows:

(3.12)

Since, , . Thus, the above term becomes:

Thus, for the j-th user, the desired signal power, P_s is given as:

(3.13)

3.3.3 **Multiple access interference (MAI)**

So the interference power is given as,

(3.14)

3.3.4 **Noise**

Now, it can be evaluated that, the noise power is:

, where, (3.15)

3.3.5 **Signal to Interference and Noise Ratio (SINR)**

(3.16)

(3.17)

3.3.6 **BER of the receiver without rake**

Now, this is a function of . So, for an instantaneous value of , the instantaneous Bit Error Rate is

Thus,

(3.18)

Now, the average bit error rate of the system without rake can be obtained as follows:

(3.19)

Here,

= Instantaneous BER

= pdf of amplitude distortion coefficient for Rayleigh Fading,

Or, (3.20)

3.4 MC-DS-CDMA Receiver with Rake

The functional block diagram of the MC-DS-CDMA receiver rake is shown in Fig. 3-3 below:

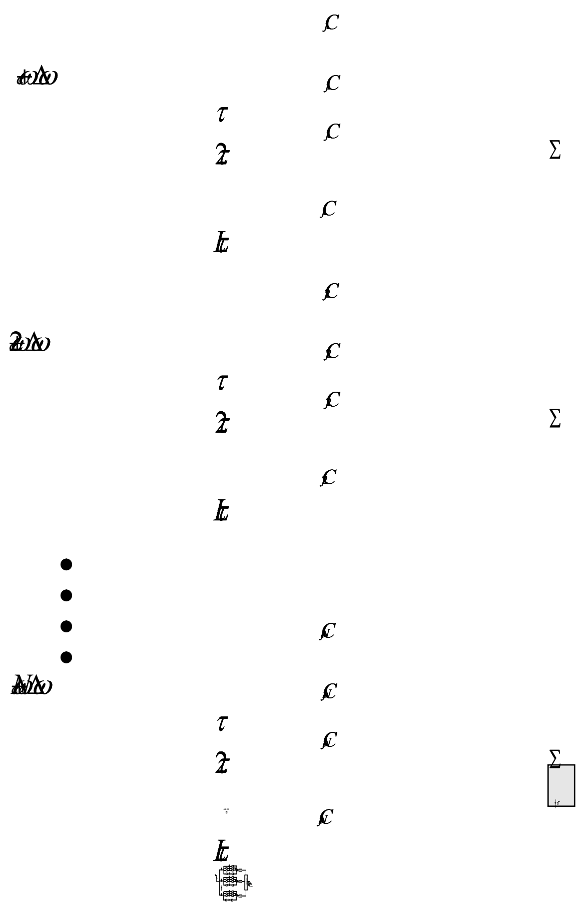


Fig. 3-3. Functional block diagram of MC-DS-CDMA receiver with rake

Let us consider there are rake receivers in each sub-carrier channel which have L no of fingers and they are considered for Maximal Ratio Combining. If $\bar{\ }_{1}$ ….. $\bar{\ }_{L}$ be the instantaneous bit SNIR for different branches, then the probability of bit error rate at the output of an SSDR is given as follows:

(3.21)

Where,

So, the average bit error probability is:

(3.22)

Now, the pdf of can be obtained by differentiating the following cdf of F( ):

(3.23)

Where,

Thus, pdf of is given as:

(3.24)

Substituting these values of Eq 3.22 and 3.23 in Eq 3.21, the Average Bit Error Probability is given as:

(3.25)

3.5 Effect of Carrier Frequency Offset

Carrier Frequency Offset is the difference between transmitter and receiver oscillator. It results from the Doppler shift of the signal due to mobility. It introduces interference in the down-converted signal. In this situation, the SINR of the system with CFO is explained in [23] and is mentioned below:

(3.25)

Where,

is the normalized CFO of the channel which is given as:

CFO is modeled by Gaussian distributed process with zero mean and unit variance, which can be expressed as follows:

$$f(\varepsilon)=\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{\varepsilon^2}{2\sigma^2}\right);\quad \text{where, } \sigma^2 \text{ is the variance of } \varepsilon.$$

CHAPTER-4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter represents the results obtained from computation following the theoretical analysis of an MC-DS-CDMA system described in chapter-3. Results have been evaluated numerically and degradation of system performance due to channel impairments has been determined in terms of power penalty at a given BER without and with Rake receiver. Optimum design parameters, like number of sub-carriers, optimum length of the PN sequence code and optimum number of branches in the Rake receiver etc, has been determined from the BER performance curves at various bit rates and other system parameters.

4.2 Performance without Considering Rake Receiver

Following the analysis presented in sections 3.2 to 3.3, we evaluated the BER performance of the MC-DS-CDMA system without Rake receiver and the results are presented in Figs 4-1 to Fig. 4-7. Here, the aim of the analysis was to evaluate the BER performance of the system at certain values of following different design/system/medium parameters:

j = Number of users at any instant

N_c = Number of sub-carriers

N = Length of spreading code (i.e. number of chips per bit)

[illegible] = Fading variance

[illegible] = Cross-correlation

R_b = Bitrate

E_b/N_0 = SNR

4.2.1 BER Vs SNR for different number of users

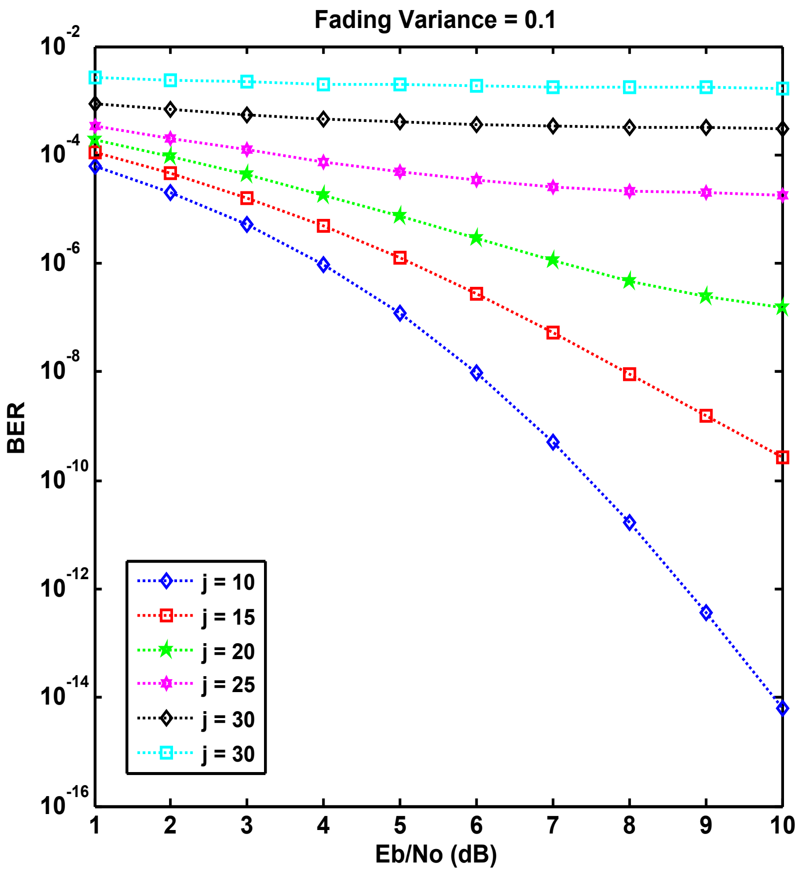


Fig. 4-1 Plots of BER Vs E_b/N_0 (dB) with number of users j as parameter, considering fading variance =0.1, for the MC-DS-CDMA system without rake receiver and without considering the effect of CFO

The plots of BER versus E_b/N_0 (dB) are shown in the Fig 4-1 with Rayleigh Fading (at a fading variance =0.1) and without Rake Receiver for different number of users j without CFO. It is clear from the figure that the user number at any instant has significant effects on the BER performance. This is mainly due to the increase of multiple access interference originated from the users' transmissions. Now for satisfactory system performance, if the required standard SNR be considered as 6dB and maximum BER to be 10^{-4}, then according to the figure, the optimum number of user at any instant should be around 25. For evaluation of above plots, the values of different other parameters have been chosen as follows:

- Bitrate = 50 kbps,
- Cross-correlation=10% (i.e. 0.1),
- Spreading Code Length =16

4.2.2 Effect of fading on BER performance

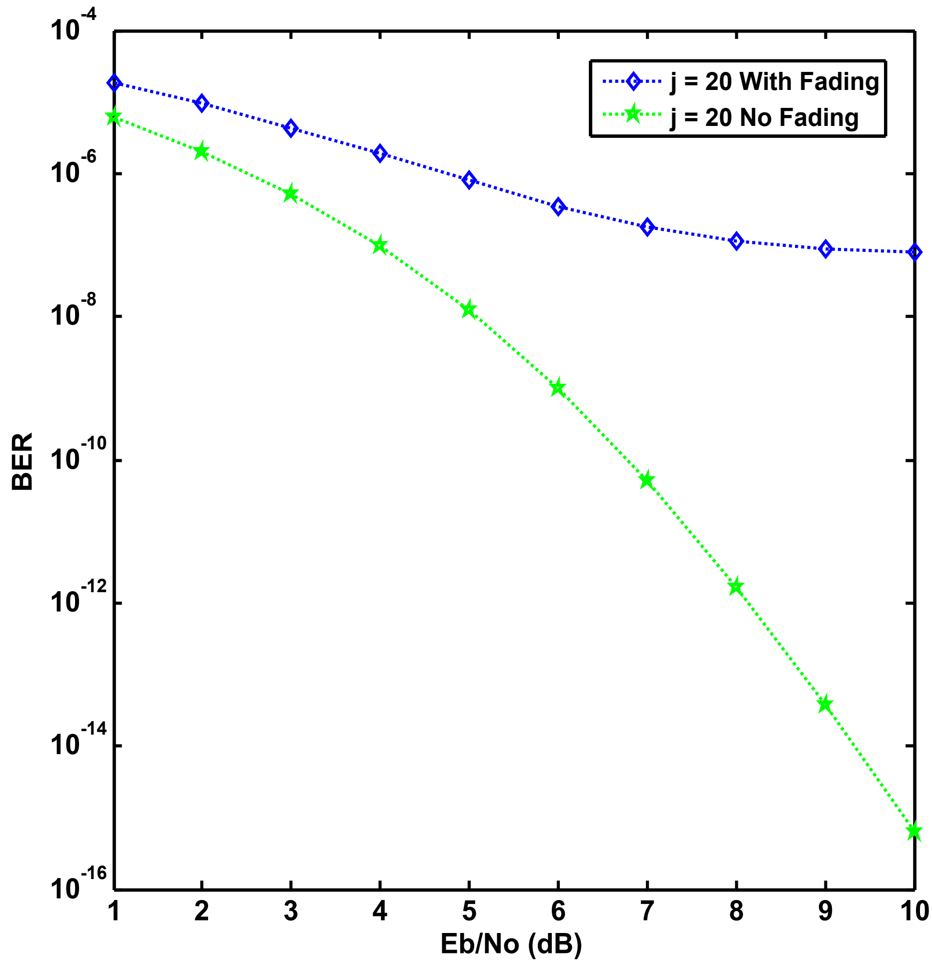


Fig. 4-2 Plots of BER Vs E_b/N_0 (dB) with and without considering fading taking number of user j=20, for the MC-DS-CDMA system without rake receiver and the effect of CFO is not considered

The Fig. 4-2 shows the difference of BER performance with and without considering fading. The figure indicates that due to fading, performance degradation occurs.

4.2.3 BER Vs SNR for different no of sub-carriers

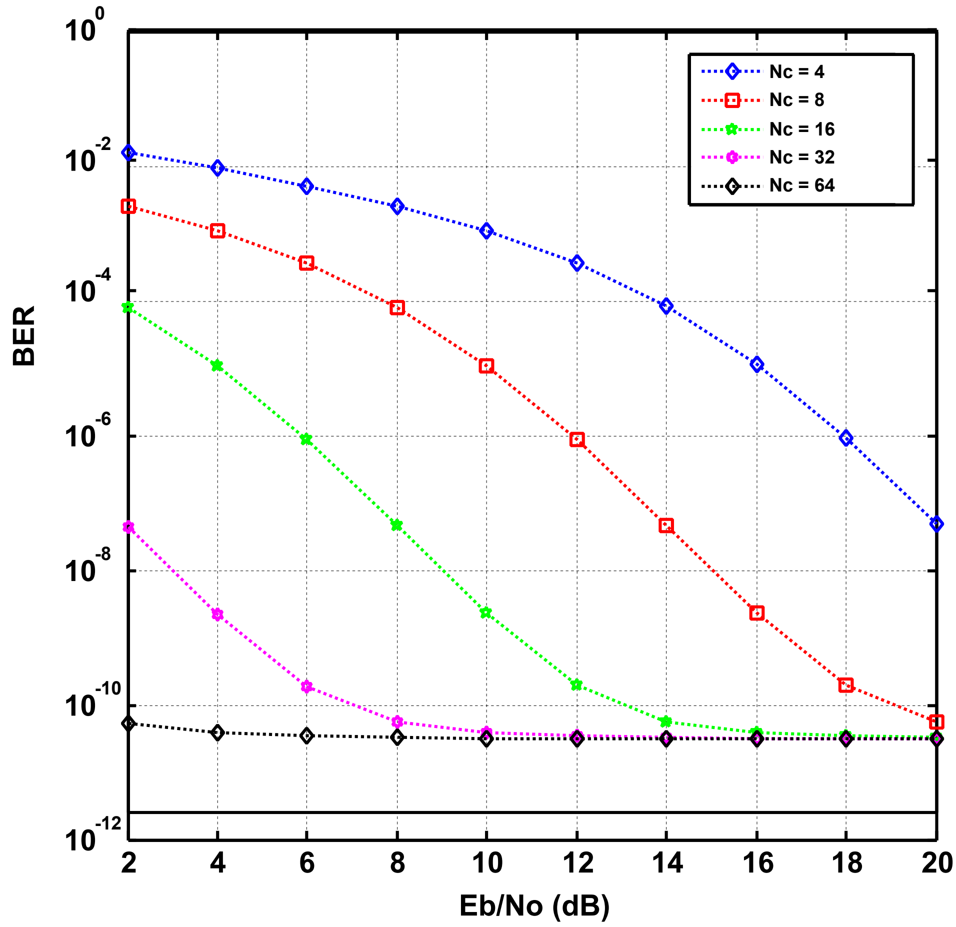


Fig. 4-3 Plots of BER Vs E_b/N_0 (dB) with Number of Sub-carriers N_c as parameter, considering fading variance =0.1, j=16, for the MC-DS-CDMA system without rake receiver and the effect of CFO is not considered

The plots of BER versus E_b/N_0 (dB) are shown in the Fig 4-2 with Rayleigh Fading (at a fading variance =0.1) and without Rake Receiver for different number of sub-carriers without CFO. The quantitative variation of sub-carriers has significant effect on the system performance which is reflected in the above Fig. 4-3. But again, the maximum number of sub-carriers is limited by the minimum inter-carrier spacing requirement of the system. As per this figure, at SNR=6dB and maximum BER=10^{-4}, the minimum number of sub-carrier should be 8.

4.2.4 BER Vs user at a particular SNR for different number of sub-carriers

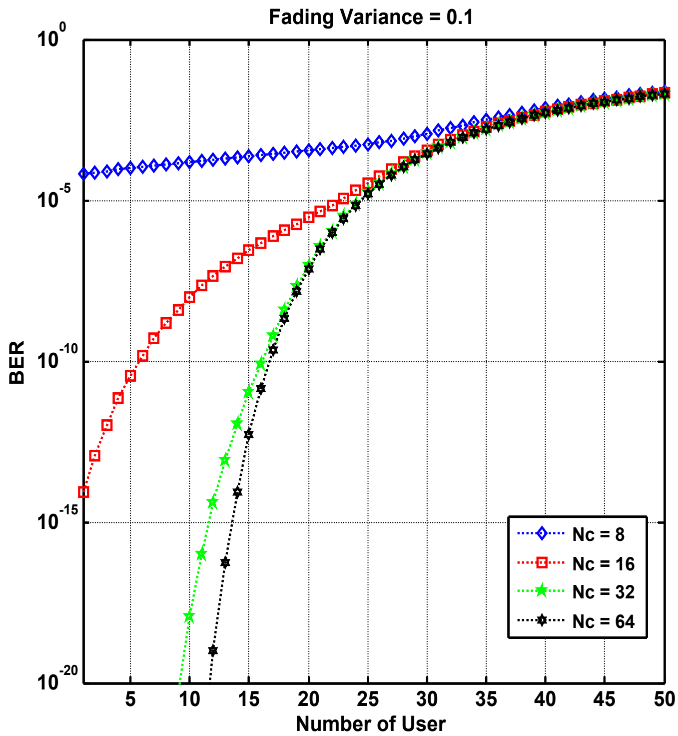


Fig. 4-4 Plots of BER Vs number of users with number of sub-carriers N_c as parameter, considering fading variance σ^2=0.1, SNR=6dB, N=16, for the MC-DS-CDMA system without rake receiver and effect of CFO is not considered

The plots of BER versus number of user at 6 dB SNR are shown in the Fig 4-4 with Rayleigh Fading (at a fading variance σ^2=0.1) and without Rake Receiver for different number of sub-carriers without CFO. From the plot of Fig 4-4, we can see that more number of users can be served by increasing the number of sub-carriers. Again, that too also limited up to a certain value, as, according to the figure, the increment rate gradually reduces at higher number of sub-carriers. It is mainly due to the fact that at higher number of sub-carriers, the ICI increases significantly. Furthermore, the data symbol length, which should be limited in fading environments, is also dependent on the number of sub-carriers. However, this plot justifies the previous requirements of minimum 8 sub-carriers to provide service to a maximum 25 users at any instant. For the evaluation of the above plots, other parameters have been chosen as follows:

- Bitrate = 50Kbps
- Cross Correlation = 0.1
- Length of Code = 16 chips per bit

4.2.5 BER Vs No of user at a particular SNR for different code lengths

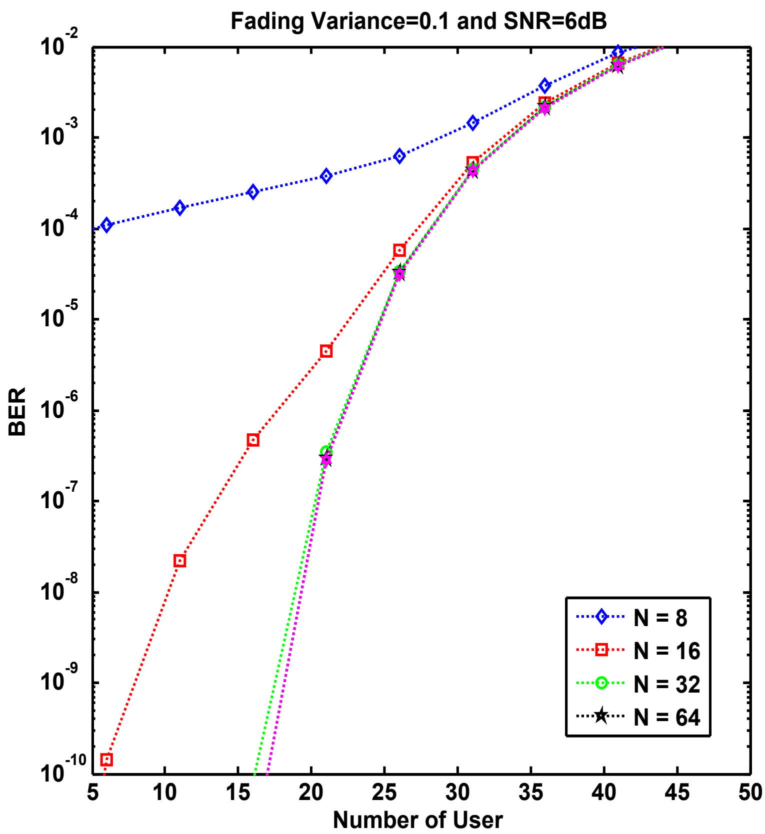


Fig. 4-5 Plots of BER Vs number of users with code lengths N as parameter, considering fading variance σ^2 =0.1, SNR=6dB, N_c=16, for the MC-DS-CDMA system without rake receiver and without considering the effect of CFO

The plots of BER versus number of user at 6 dB SNR are shown in the Fig. 4-4 with Rayleigh Fading (at a fading variance σ^2 =0.1) and without Rake Receiver for different lengths of spreading codes without CFO. It indicates that the length of the spreading code has also effects on the BER performance of the system significantly. From the Fig. 4-5, it can be concluded that the maximum code-length should be 32 chips/bit, since values beyond 32 does not cause any significant increase in user capacity of the system. This plot also justifies the upper limit of number of users at any instant to be 25, which is the same as evaluated by the previous plots. The above performance curve has been evaluated taking the SNR = 6 dB and number of sub-carrier is 8.

4.2.6 BER Vs Number of user for different values of fading variance

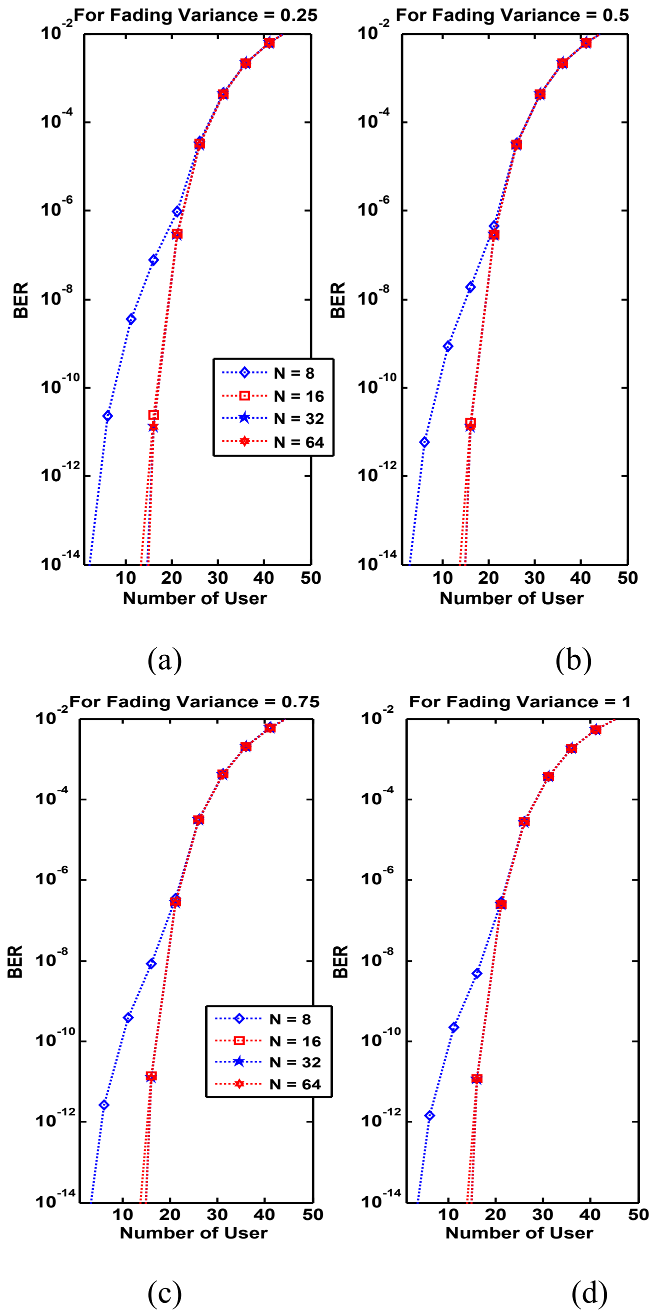
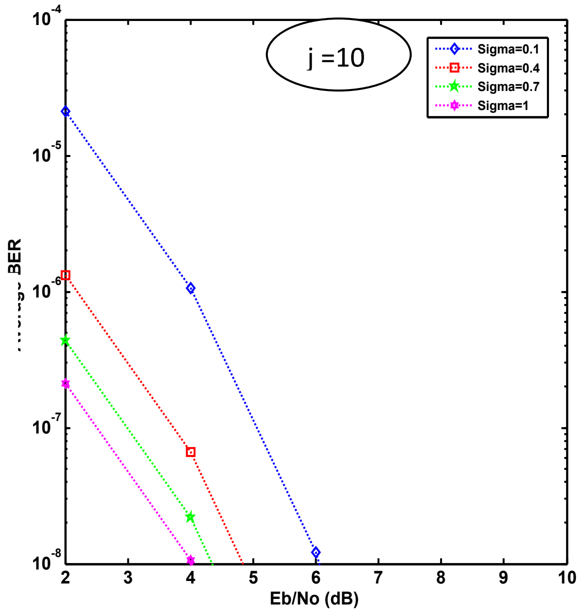


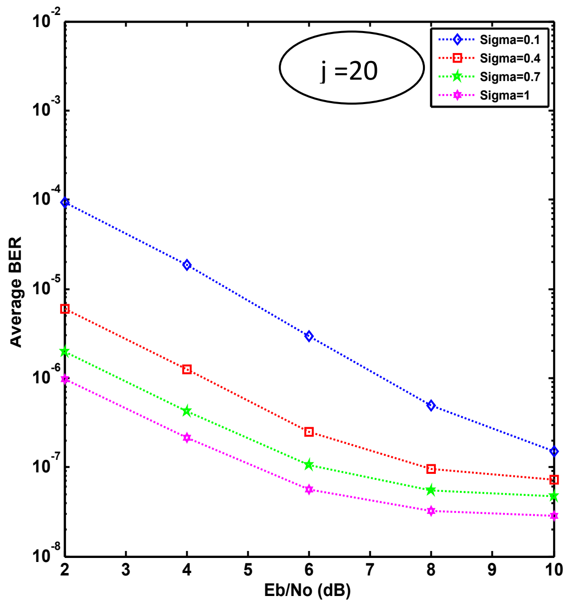
Fig. 4-6 Plots of BER Vs number of users with code length and fading variance as parameters, considering number of sub-carriers N_c=16, SNR=6dB, for the MC-DS-CDMA system without rake receiver and not considering the effect of CFO

The plots of BER versus number of user at different values of fading variance ^{2} and code lengths N, at 6 dB SNR are shown in the Fig. 4-6 (a through d) without considering Rake Receiver and CFO. The plots show that the fading variances of 0.5 or more do not cause significant effect on the system capacity in terms of user number.

4.2.6 **BER Vs SNR at different fading variances**



(a) For 10 users



(b) For 20 users

Fig: 4-7 Plots of BER Vs E_b/N_0 (dB) with different fading variance as parameter considering j=10 and 20 for the MC-DS-CDMA system without rake receiver and without considering the effect of CFO

Fig. 4-7 depicts the plots of BER Vs E_b/N_0 (dB) at different values of fading variances for number of users j = 10 and 20. These figures show that at higher values of σ^2, the performance of the system improves and results BER flows when number of users is 20 and E_b/N_0 is greater than 10 dB.

4.2.8 BER Vs SNR for different values of cross-correlation

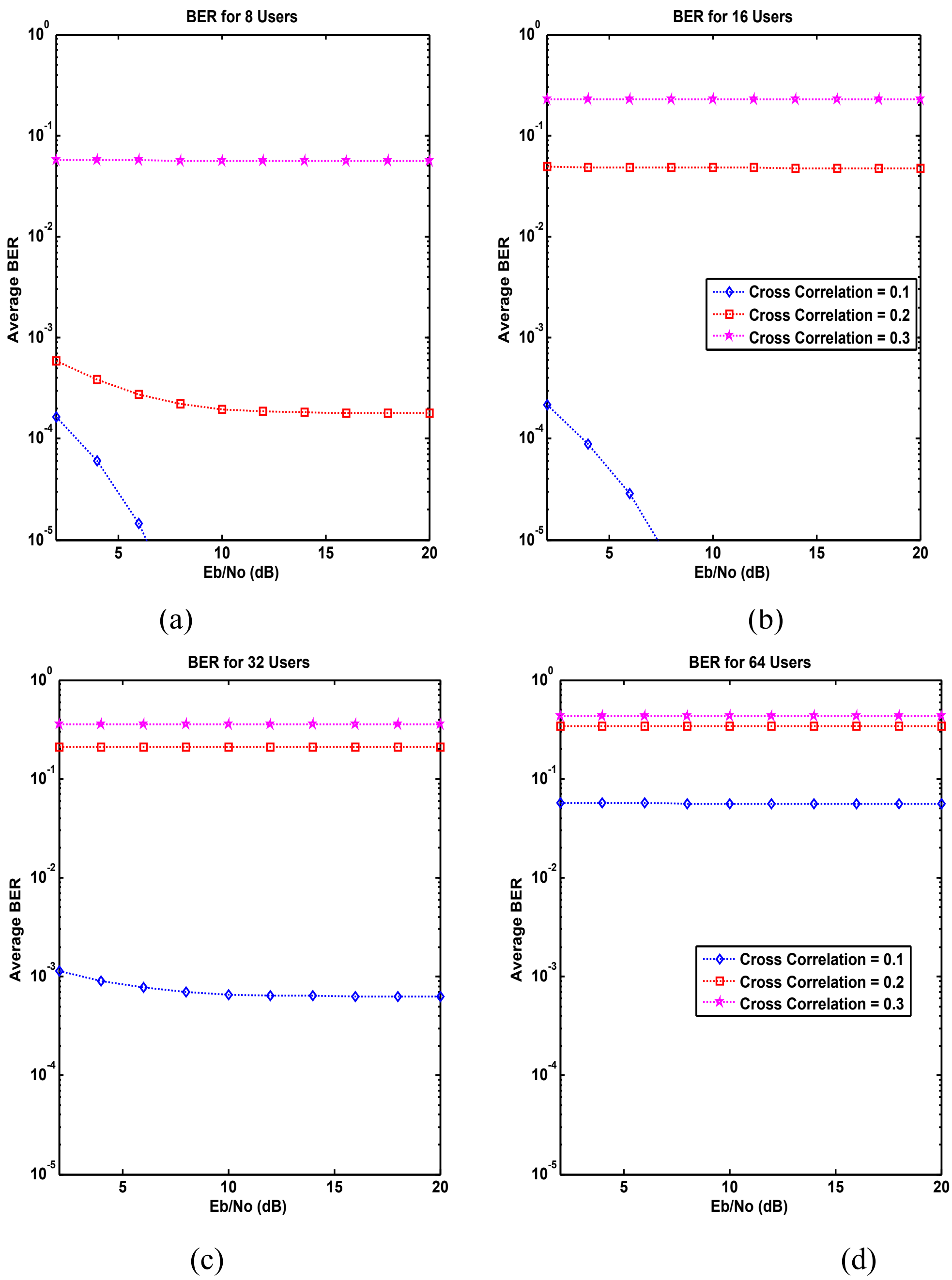


Fig. 4-8 Plots of BER Vs E_b/N_0 (dB) with cross correlation as parameter considering j= 8(a), 16(b), 32(c) and 64(d) for the MC-DS-CDMA system without rake receiver and without considering the effect of CFO

The Fig. 4-8 depicts the plots of BER Vs E_b/N_0 (dB) for different values of cross-correlation among the user codes, taking number of user j = 8, 16, 32 and 64. From the figures, it is clear that the system performance is greatly affected by the cross-correlation. At values of cross-correlation higher than 10%, there occur BER floors which cannot be lowered by increasing the value of E_b/N_0. Thus for this CDMA scheme, the cross-correlation value should be limited to 10%.

4.3 Performance Results Considering Rake Receiver

Based on the analysis mentioned in section 3.4 of the previous chapter, we evaluate the BER performance of the MC-DS-CDMA system with Rake Receiver but without CFO and the results are presented in Fig-4.8 through Fig-4.14. The additional system design parameter for this system with rake receiver is the number of rake finger L.

4.3.1 BER Vs SNR for different no of users

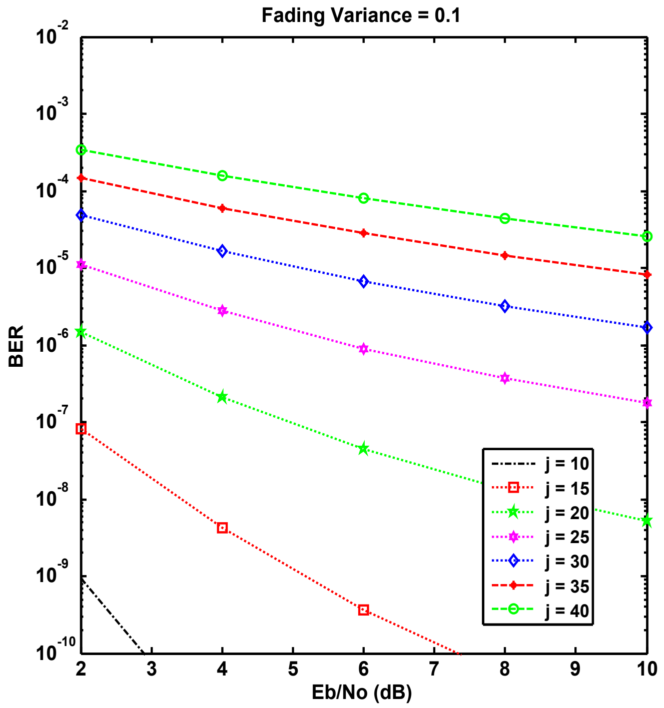


Fig: 4-9 Plots of BER Vs E_b/N_0 (dB) with user number as parameter, taking fading variance =0.1, length of code N=16, number of sub-carrier N_c=16 and considering the MC-DS-CDMA system with rake receiver of L=3 and not considering CFO

The Fig 4-9 depicts the plot of BER vs E_b/N_0 at different value of j, considering rake receiver but without considering CFO. The Fig. 4-9 shows that there is significant reduction of BER when the system uses the rake receiver. For satisfactory performance of the system, if the maximum BER to be 10^{-4} at E_b/N_0 = 6 dB, the maximum number of simultaneous users could be up to 40. It is to be noted that it was 25 for the system without rake receiver. For the purpose of this evaluation, the other design parameters have been as follows:

- Bitrate, R_b = 50 Kbps
- Number of Sub-Carrier, N_c = 16
- Length of Spreading Code, N = 16
- Cross Correlation, = 0.1
- Fading Variance, = 0.1
- No of Rake Finger, L = 3

4.3.2 BER Vs SNR for system with and without rake receiver

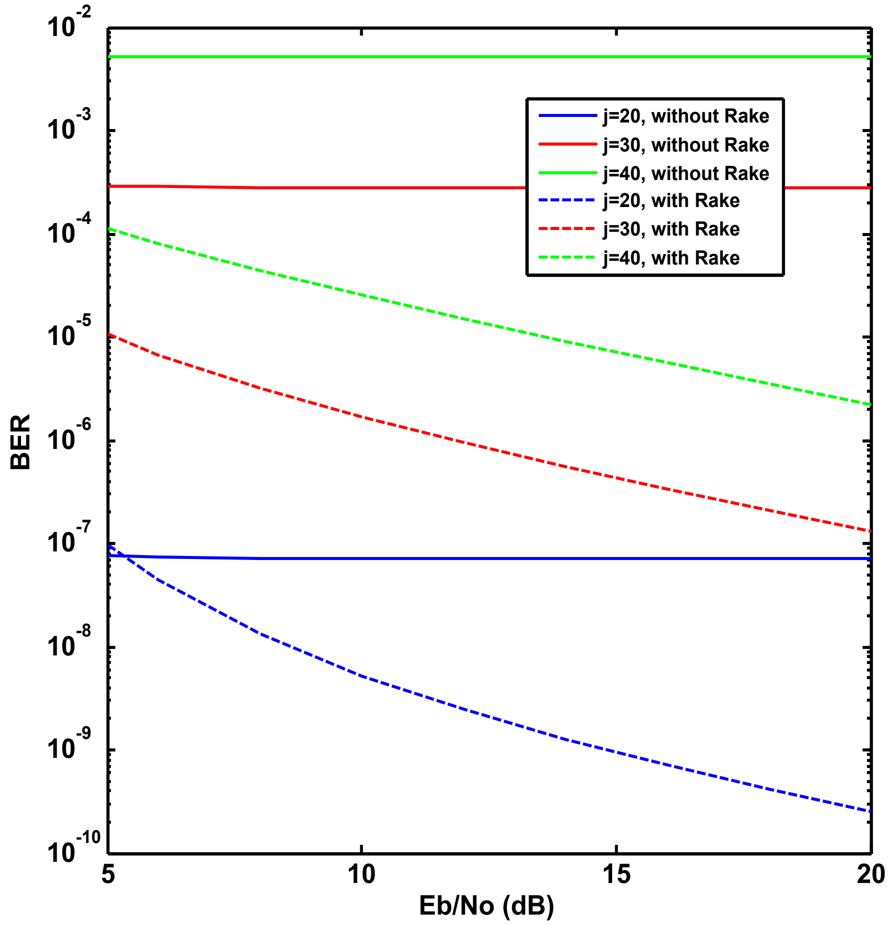
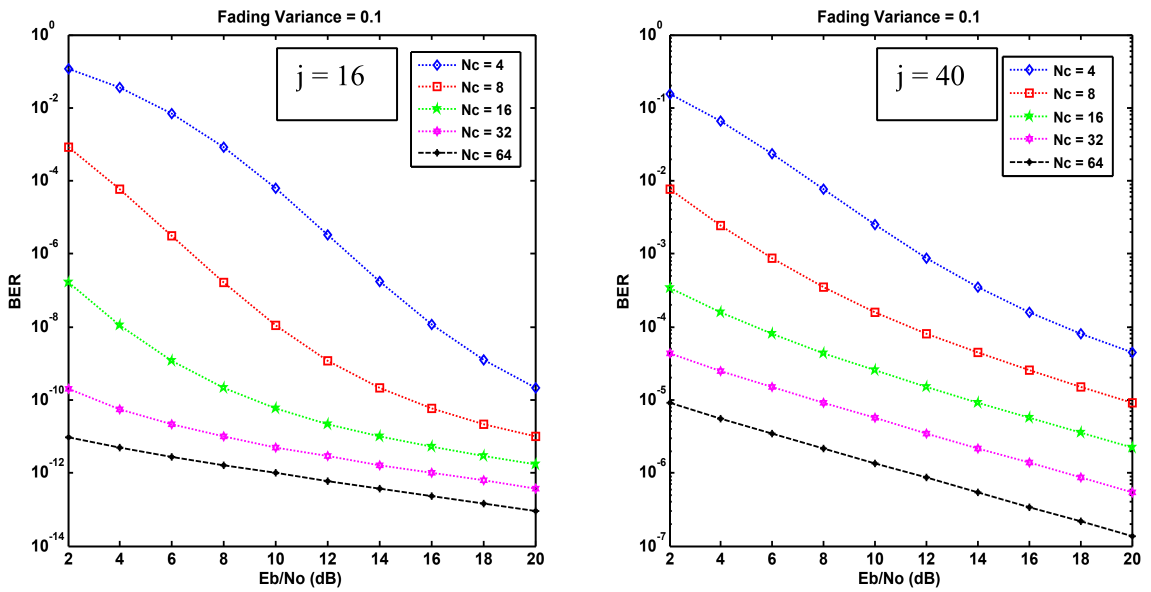


Fig. 4-10 Plots of BER Vs E_b/N_0 (dB) with user number as parameter, considering the MC-DS-CDMA system with and without rake receiver of L=3 and not considering CFO

Fig 4-10 depicts the plots of BER performances at different number of users with and without rake receiver. The plots indicate that there are distinct improvements in performance when using rake receiver. It may be noted here that with number of users 20 and above where system without rake receiver gets floor, the system with rake receiver still shows satisfactory performance.

4.3.3 BER Vs SNR for different number of sub-carriers



(a) (b)

Fig: 4-11 Plots of BER Vs E_b/N_0 (dB) with number of sub-carrier as parameter, taking fading variance =0.1, number of user j = 16 (a) and 40 (b), considering the MC-DS-CDMA system with rake receiver having L=3 and not considering CFO

The above Fig. 4-11 shows the plots of BER Vs E_b/N_0 (dB) at different values of N_c , taking number of users as 16 and 40, considering rake receiver but without considering CFO. The above BER curves allow us to select the number of Sub-Carriers to be used for the system when operating with rake receiver configuration. To have max^m BER 10^{-4} at SNR = 6dB, the minimum number of sub-carriers should be 8 when the number of simultaneous users is limited to 16. But for higher number of users, say 40 as prescribed in previous sub-section, the number of sub-carriers should be increased to minimum 16. Now, the more number of sub-carriers are used, the better performance will be achieved. However, the maximum usable sub-carrier number is limited by the bandwidth, minimum sub-carrier spacing requirement and the tolerance of CFO.

4.3.4 BER Vs user at a particular SNR for different no of sub-carriers

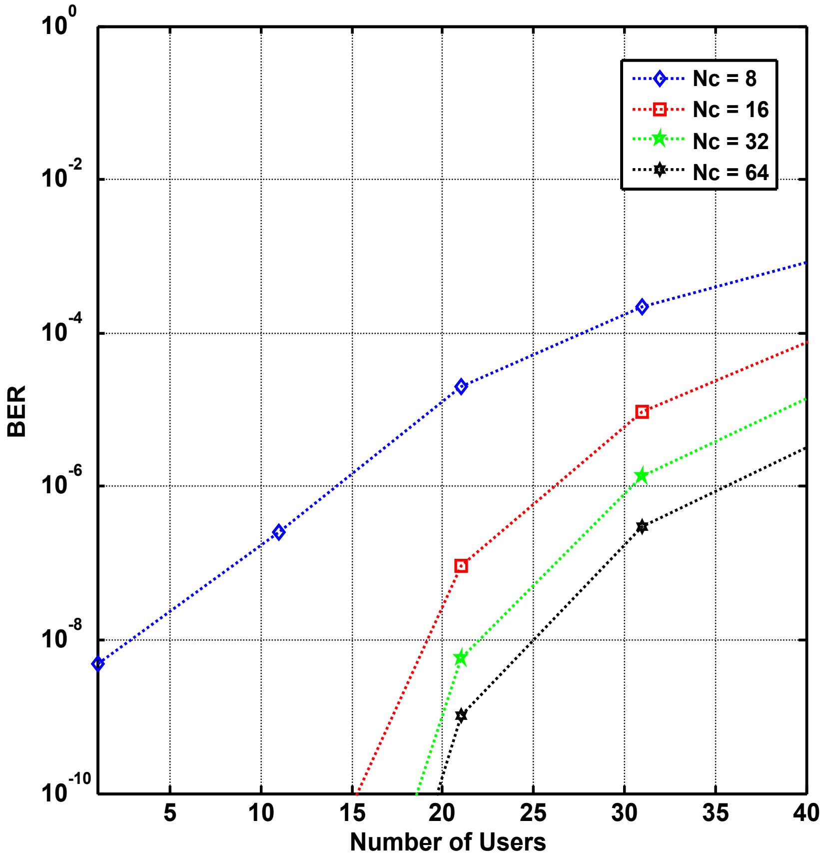


Fig. 4-12 Plots of BER Vs number of users with number of sub-carrier as parameter, taking fading variance =0.1, E_b/N_0 = 6 dB, N=16, considering the MC-DS-CDMA system is with rake receiver of L=3 and not considering the effects of CFO

Fig 4-12 depicts the plots of BER Vs number of users at different values of N_c, considering rake receiver but without considering CFO. The result emphasizes the requirement of having minimum 16 sub-carriers to accommodate 40 simultaneous users at maximum BER = 10^{-4} when SNR = 6 dB.

4.3.5 BER Vs number of user at a particular SNR for different code lengths

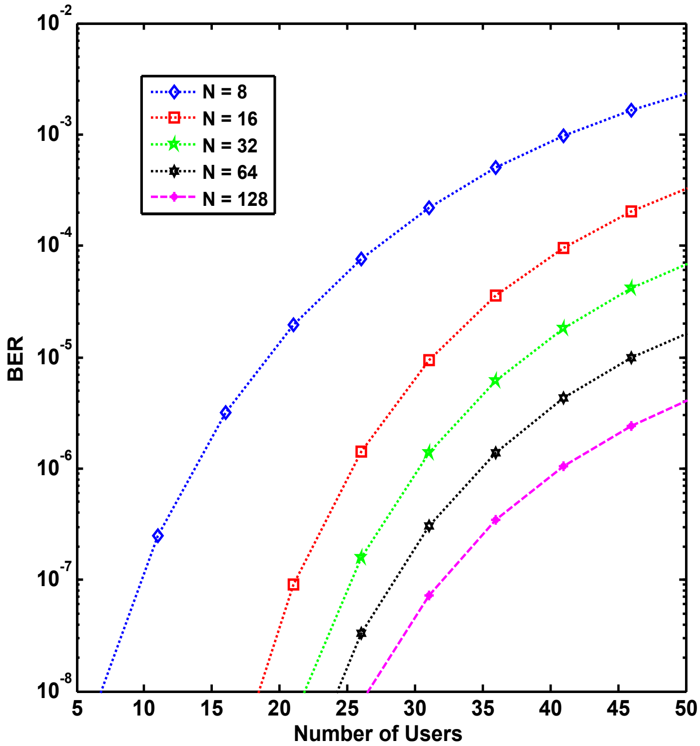
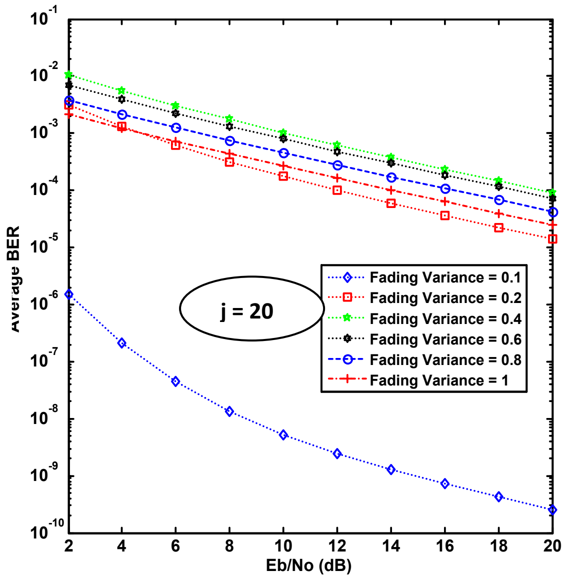


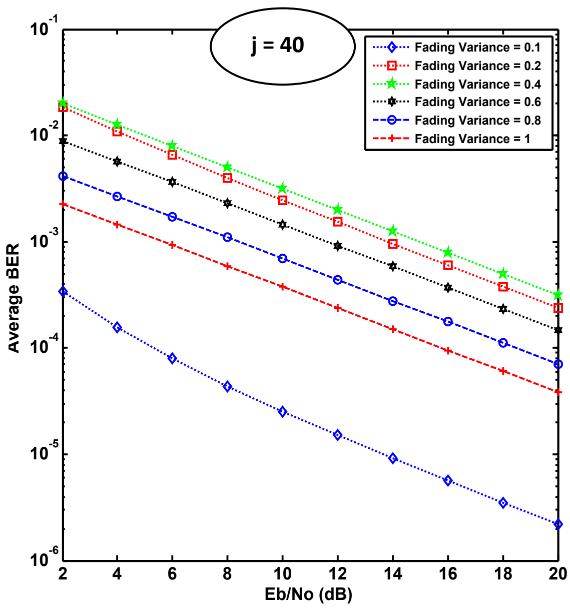
Fig. 4-13 Plots of BER Vs number of users with code length as parameter, taking fading variance =0.1, $E_b/N_0 = 6$ dB, number of sub-carrier N_c =16, considering the MC-DS-CDMA system is with rake receiver of L=3 and not considering the effects of CFO

Fig. 4-13 shows the plots of BER Vs Number of Users at different lengths of the spreading code with 3-fingered rake receiver and not considering CFO. In order to achieve BER less than 10^{-4}, the minimum code length is found to be 8 to support 16 simultaneous users. But, if higher number of users is intended, for example 40 as prescribed in the earlier paragraphs, the minimum code length is to be 16. The figure shows that the longer the code length, the better will be the system performance, though the improvement margin reduces gradually. Here the calculation has been done for up to 128 chips/bit, however, the maximum code length is limited by various other factors like bit period (i.e. 1/Bitrate), noise margin, processing delay of the system etc.

4.3.6 BER Vs SNR for different values of fading variance



(a)

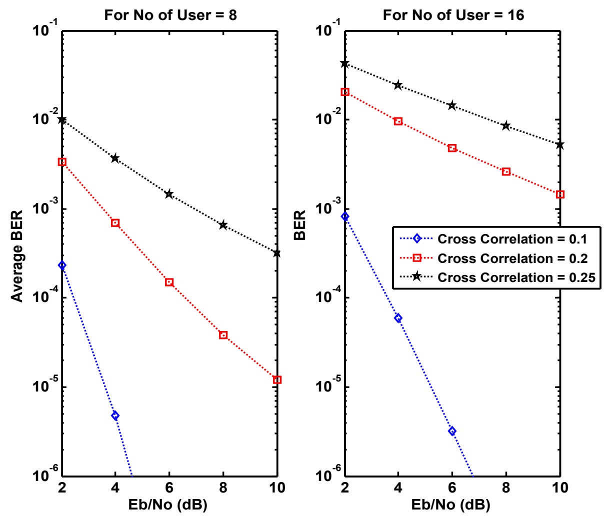


(b)

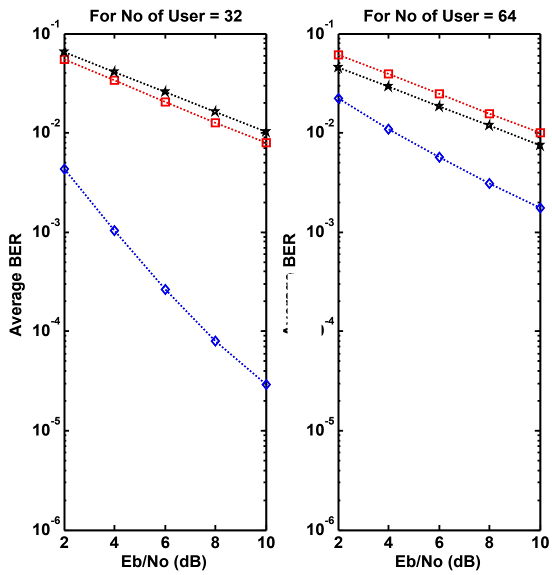
Fig. 4-14 Plot of BER Vs E_b/N_0 with fading variance as the parameter for number of user j = 20 and 40 considering the MC-DS-CDMA system is with rake receiver of 3 fingers and ignoring the effects of CFO

Plots of BER Vs E_b/N_0 for the system with 3-fingered Rake Receiver without CFO are shown in Fig. 4-14. In the figure, it is noticed that there are changes in performance of the system with the change of fading variance. Here we can see that up to a certain value of fading variance (0.4 for 20 users and 0.3 for 40 users), the performance of the system little improves as the fading variance increases further.

4.3.7 BER Vs SNR for different values of cross-correlation



(a) (b)



(c) (d)

Fig. 4-15 Plot of BER Vs E_b/N_0 (dB) with cross correlation among the codes of the users as the parameter, for number of users j = 8, 16, 32 and 64, considering the MC-DS-CDMA with rake receiver of 3 fingers and ignoring the effects of CFO

Fig. 4-15 shows the plots of BER Vs SNR at various cross-correlations of the user codes for different number of simultaneous users with rake receiver without considering CFO. These plots indicate the importance of lower cross correlation for satisfactory system performance. However, in comparison to the similar plot for system without rake receiver (Fig 4-8), it is clear that system with rake receiver have greater tolerance against higher cross-correlations. As per this figure, if the cross-correlation is 0.1, more than 32 users can get simultaneously and acceptable quality of service.

4.4 Performance of the System Considering CFO

All the calculations and BER response plots, so far has been done, are with the assumption that the receiver oscillator frequency has a perfect match with that of transmitter sub-carriers. But, as also explained in chapter-3, practically there exist some mis-match between them giving rise to the phenomenon of CFO. This is mainly due to the Doppler effect of received frequency of the moving users. To take this effect into account, expression for SINR has been mentioned in section 3.5 of the previous chapter. Now, it will be used to calculate the BER for both the configurations of the proposed MC-DS-CDMA systems (i.e. without and with Rake Receiver). The subsequent paragraphs will state the same.

4.4.1 System without rake receiver - BER Vs SNR for different number of users (considering CFO)

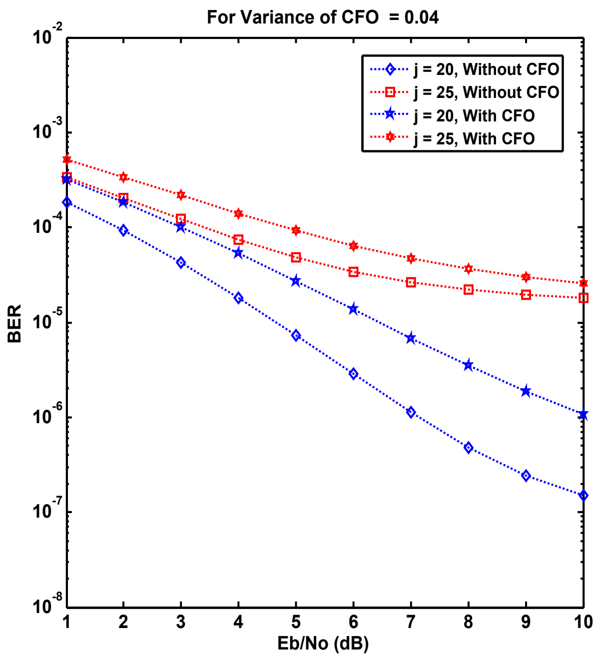


Fig. 4-16 Plots of BER Vs E_b/N_0 (dB) with number of user j as parameter showing the difference of performance with and without the consideration of CFO

The Fig 4-16 depicts the plots of BER Vs E_b/N_0 at two different numbers of user while considering and not-considering CFO for an MC-DS-CDMA system without Rake Receiver. From the figure, it is noticed that CFO cause reduction of system capacity. However, at higher value of SNR, it is gradually minimized, but not eliminated.

4.4.2 Without Rake - BER Vs. SNR for different no of sub-carrier (considering CFO)

CFO variance ^{2} =0.04

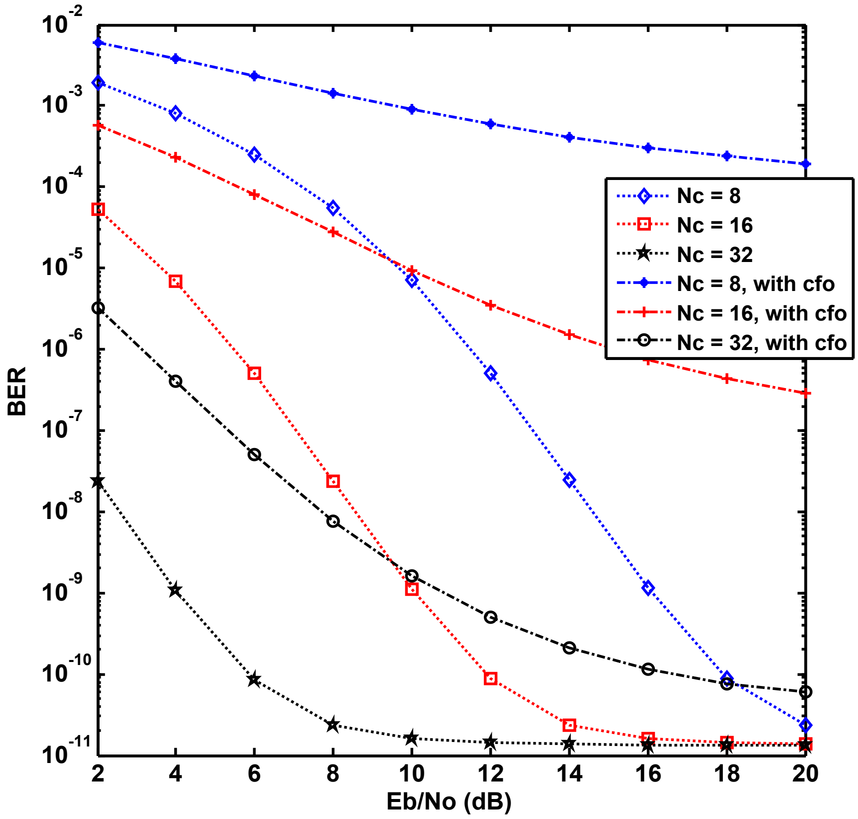


Fig. 4-17 Plots of BER Vs E_b/N_0 with number of sub-carrier N_c as a parameter for the MC-DS-CDMA system without rake receiver and showing the difference in responses plotted considering and not-considering CFO

Fig 4-17 depicts the plots of BER Vs E_b/N_0 at different number of sub-carriers to evaluate the effect of CFO, when the MC-DS-CDMA system is without Rake Receiver and simultaneous number of user (j) is 16. The BER response curves indicate that in practical situation where CFO happens, the minimum number of sub-carrier have to be 16, whereas it is 8 when CFO was not considered.

4.4.3 Without Rake – BER Vs user at different code lengths (considering CFO)

CFO variance σ^2 =0.02

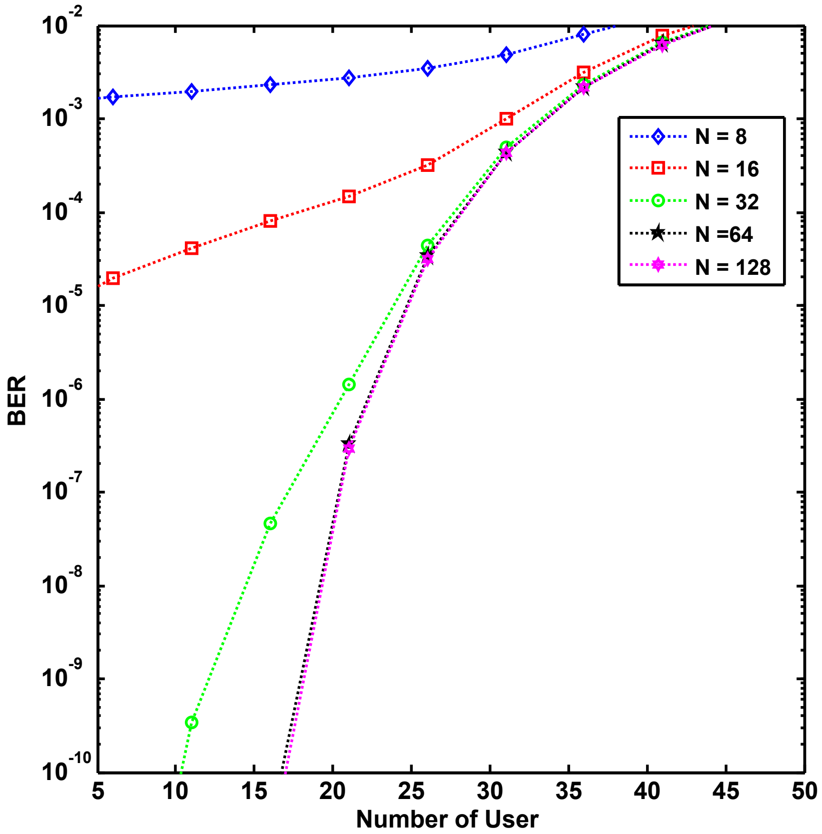


Fig 4-18 Plots of BER Vs E_b/N_0 with length of spreading code N as a parameter for the MC-DS-CDMA system without rake receiver plotted considering the effect of CFO with CFO variance σ^2 =0.02

Fig. 4-18 depicts the plots of BER Vs user numbers with different lengths of spreading code considering the effect of CFO with a CFO variance σ^2 =0.02. This plots show that, if the effect of CFO is not ignored and the code length is taken as 16, then maximum 20 subscribers can be served at a time. The value was 25 when CFO was not considered. However, to increase up to such capacity, the code length should be 32. Here, the E_b/N_0 has been considered 6 dB and maximum BER is considered as 10^{-4}, as in few previous cases.

4.4.4 System having rake receiver - BER Vs SNR for different number of users (considering CFO)

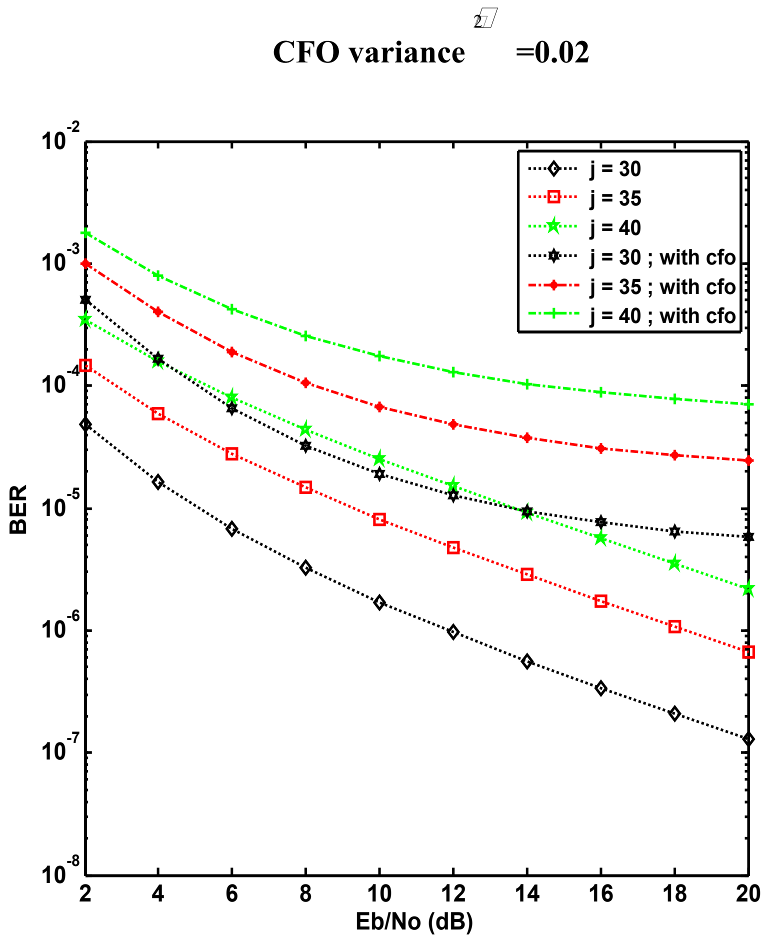


Fig. 4-19 Plots of BER Vs E_b/N_0 (dB) with j as the parameter, showing the difference of performance with and without the consideration of CFO for the system having rake receivers

The Fig. 4-19 is the plots of BER Vs E_b/N_0 (dB) for different number of users showing the difference between the performance of MC-DS-CDMA with Rake Receiver considering and not-considering CFO. The figure indicates that the system with rake receivers is highly affected by the CFO and causes BER floors at higher values of SNR. At standard SNR and BER, the maximum number of simultaneous user will be 30 instead of 40. In these calculations, the values of other parameters are chosen as follows:

- Bit rate, R_b = 50 kbps
- No of Sub-carrier, N_c = 16
- Length of code, N = 16 chips/bit
- Variance of Fading, = 0.1
- Variance of CFO, = 0.01 to 0.02

4.4.5 System having rake receiver - BER Vs SNR for different number of sub-carriers (considering CFO)

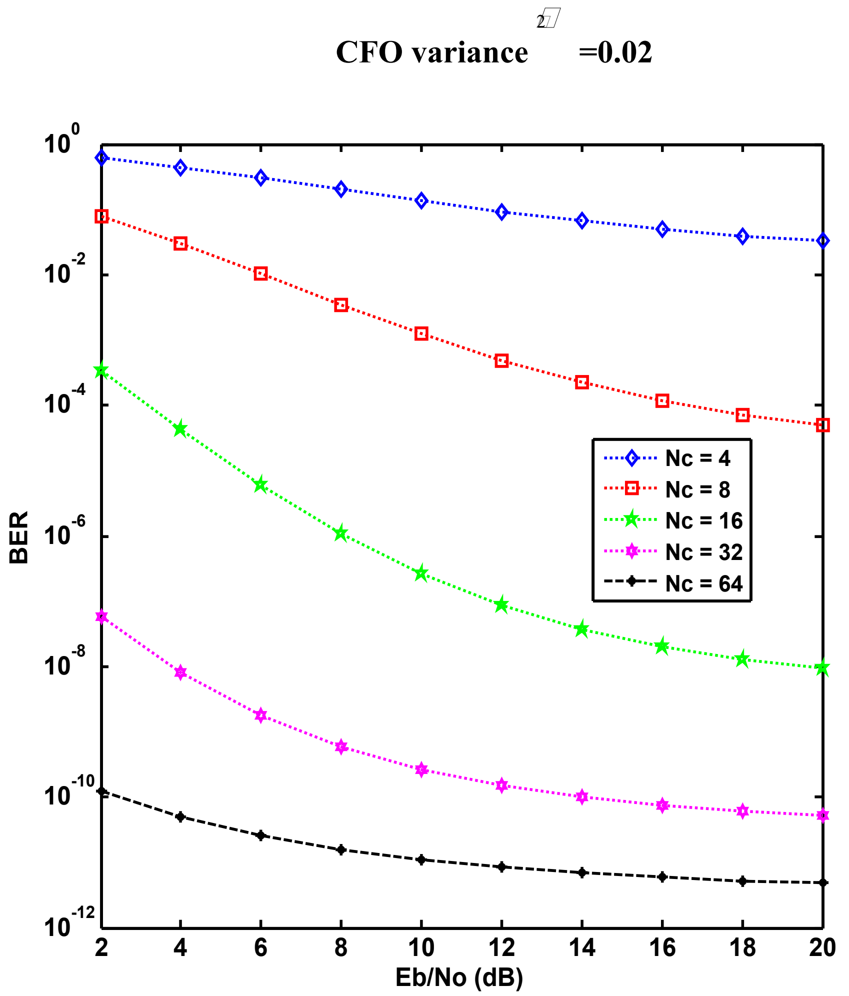


Fig. 4-20 Plots of BER Vs E_b/N_0 (dB) with number of sub-carrier N_c as the parameter, with consideration of CFO of variance σ^2 =0.02 for the MC-DS-CDMA system having 3-finger rake receivers

The Fig. 4-20 depicts the plots of BER Vs E_b/N_0 (dB) with different number of sub-carriers showing the difference between the performance of MC-DS-CDMA with Rake Receiver considering and not-considering CFO. The Fig. 4-21 indicates that for 6dB SNR and maximum BER=10^{-4}, there should be at least 16 Sub-carriers. Number of sub-carrier required was 8 when CFO was not considered.

4.4.6 System having rake receiver - BER Vs number of user for different code lengths (considering CFO)

CFO Variance σ^2 =0.02

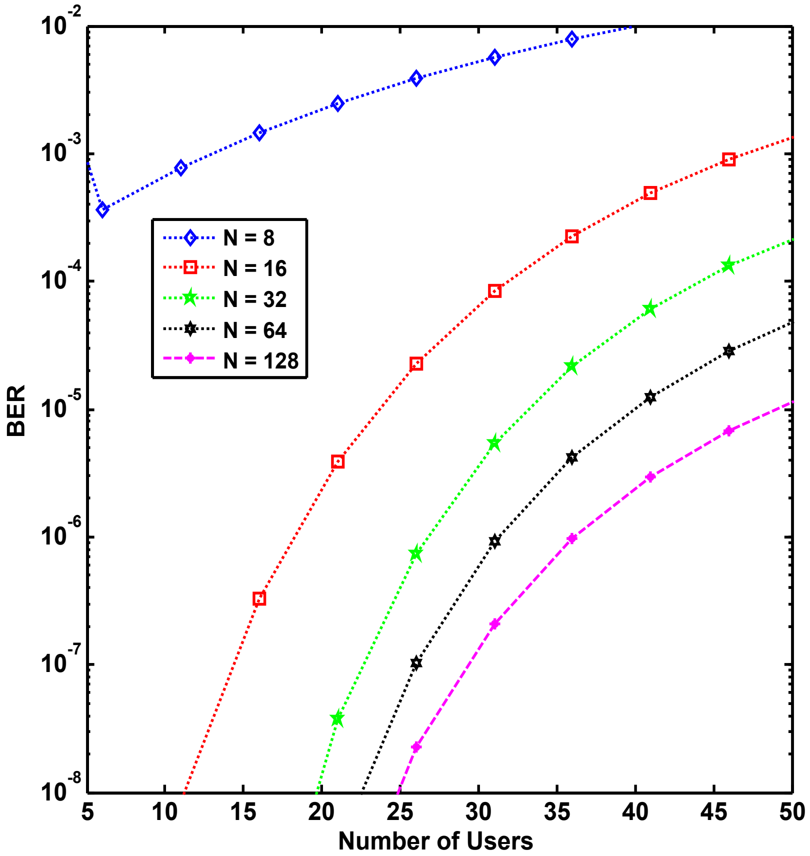


Fig. 4-21 Plots of BER Vs E_b/N_0 (dB) with code length N as the parameter, with consideration of CFO of variance σ^2 =0.02 for the system having 3-finger rake receivers

Fig. 4-21 depicts the plots of BER Vs number of user for different lengths of spreading codes of the users for the system having rake receiver and CFO is considered with CFO variance σ^2 =0.02. Here, it is clear that, when CFO is considered, 16 chips/bit code length is not sufficient to provide simultaneous support to 40 users. Rather it can support maximum 30 users. However, in order to increase the capacity up to 40, the user's code length should be minimum 32 chips/bit.

4.5 Optimum Design Parameters

After analyzing all the numerical results as mentioned in paragraphs 4.3, 4.4 and 4.5, we now prescribe the optimum design parameters for the MC-DS-CDMA scheme with and without rake receiver. Following paragraphs will state the same.

4.5.1 MC-DS-CDMA without rake receiver considering CFO

Number of Simultaneous User, j	= 25
Number of Sub Carriers, N_c	= 32
Length of Spreading Code, N	= 32 chips/bit
Fading Variance, $\square^2$	= 0.2
CFO Variance, $\square^2$	= 0.02
Cross Correlation, $\square$	= 0.1
Bitrate, R_b	= 50 Kbps
SNR, E_b/N_0	= 6 ~ 10 dB
Maximum Allowable BER	= 10^{-4}
Minimum Bit Power, P	= 10

With the above parameters, the BER performance of the system is as shown in Fig 4-22.

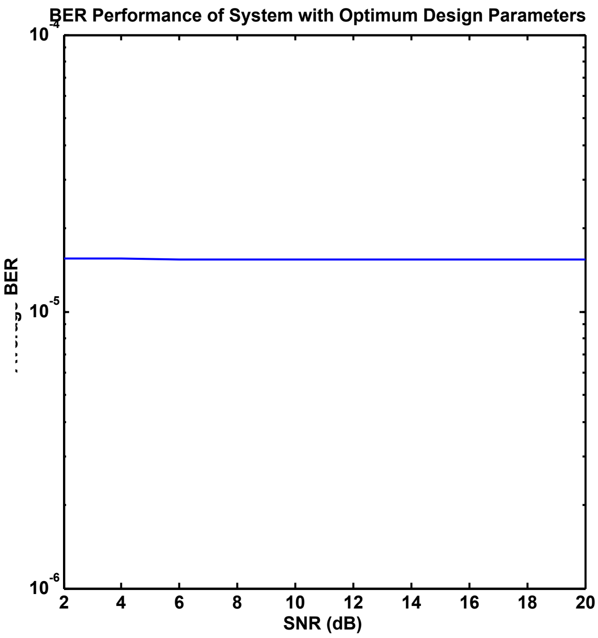


Fig. 4-22 Plots of BER Vs E_b/N_0 of the MC-DS-CDMA system without rake receiver having optimum design parameters and the evaluation is done considering CFO

4.5.2 MC-DS-CDMA with rake receiver considering CFO

Number of Simultaneous User, j	= 38
Number of Sub Carriers, N_c	= 32
Length of Spreading Code, N	= 32 chips/bit
Fading Variance,	= 0.15
CFO Variance,	= 0.02
Cross Correlation,	= 0.1
Bitrate, R_b	= 50 Kbps
SNR, E_b/N_0	= 6 ~ 10 dB
Maximum Allowable BER	= 10^{-4}
Minimum Bit Power, P	= 10

With the above parameters, the BER performance of the system at different number of rake fingers is as shown in Fig. 4-23 below.

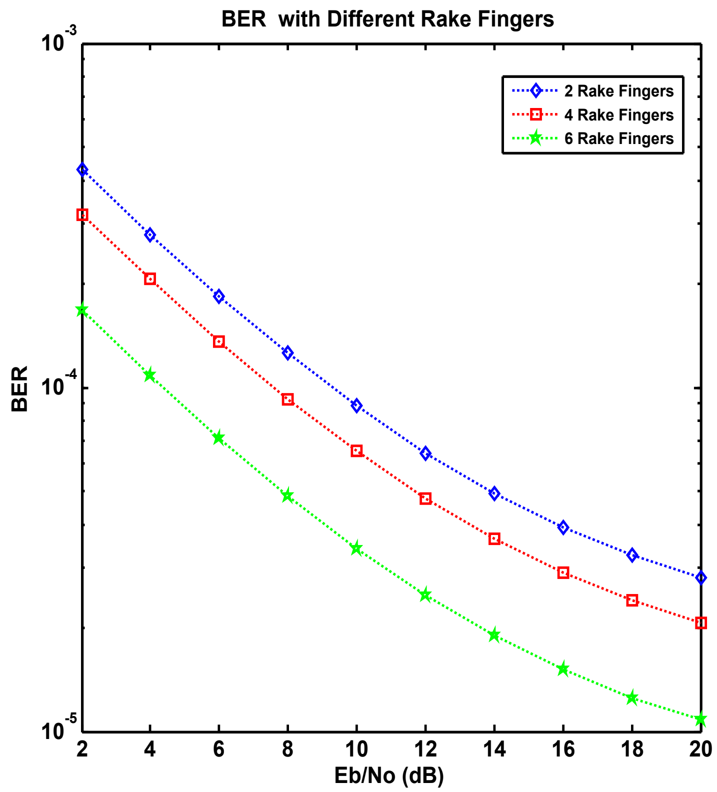


Fig. 4-23 Plot of BER Vs E_b/N_0 (dB) at different number of rake fingers of the MC-DS-CDMA system having rake receiver and optimum design parameters and the performance is evaluated considering CFO

CHAPTER-5

CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

A novel theoretical analysis is carried out for an MC-DS-CDMA system over a wireless faded channel without and with Rake receiver. The analysis also includes the effects of Carrier Frequency Offset and the effect of Rayleigh fading. The analysis results in the development of an analysis expression for the SNIR at the output of an MC-DS-CDMA receiver without and with a Rake receiver. The results are evaluated in terms of Bit Error Rate (BER) performance considering various system parameters to optimize the number of sub-carriers, the code length and number of rake fingers.

The computed results show that there is deterioration in BER performance due to fading. The results also show that performance can be improved by increasing the number of sub-carriers in the MC-DS-CDMA system. There are also significant improvements in terms of number of users at increased number of sub-carriers at a given BER. For example, at a BER of 10^{-4}, number of users that can be supported over Rayleigh fading channel is 8 with number of sub-carrier is 8, where as it can be increased to 25 by using 16 sub-carriers. Further, the BER corresponding to a number of users of 20 is 10^{-6} when number of sub-carriers is 16. By increasing the number of sub-carriers to 64, the BER can be reduced to 10^{-8}.

It is also noticed that there are an optimum number of sub-carriers corresponding to a given BER and number of users in a MC-DS-CDMA system without a Rake receiver. Thus, the performance results in the presence of CFO are also evaluated. It is noticed that the system suffers power penalty due to increase in the variance of CFO. For example the required E_b/N_0 to achieve BER = 10^{-4} is 2 dB corresponding to σ^2 =0, when number of sub-carrier is 8. It is found to be 3.5 dB when σ^2 is increased to 0.04. For higher values of σ^2, the penalty is found to be more significant and allows less number of users for a given number of sub-carriers.

It is noticed that the performances of MC-DS-CDMA system can be highly improved by incorporating a Rake receiver. The results with Rake receiver indicate that there is significant improvement in BER performance with increase in the number of rake fingers. For example, when number of sub-carriers is 8, the number of user is 7 to get the BER at $E_b/N_0 = 6$ dB is 10^{-4} without a Rake receiver whereas it is found to be 26 with a rake receiver of 3-fingers. Increasing the number of rake fingers allows more number of users at a given level of BER for a given number of sub-carriers. The optimum values of system parameters are also evaluated for a given system BER.

5.2 Scope for Future Works

Further works can be carried out to find the performance of multi carrier CDMA (MC CDMA) and multi-tone CDMA (MT-CDMA) system considering Rayleigh fading channels. The performance analysis can be extended to find the performance with a rake receiver. Further works can be initiated to find the performance of MC-CDMA system with space and time diversity with Maximum Input Maximum Output (MIMO) and Space Time Block Code (STBC) with a rake receiver and multi-carrier detection scheme.

Further investigation can be carried out for an MC-CDMA system with OFDM and forward error correction coding like convolution coding and turbo coding with spatial diversity schemes.

REFERENCES

[1] The Guardian, http://www.guardian.co.uk/technology /2009/mar/03/mobile-phones1, 03 March 2009.

[2] Kamil H Zigangirov, “Theory of Code Division Multiple Access Communication”, John Wiley & Sons Inc, IEEE Press, NJ, 2004, pp 07.

[3] R Prasad and T Ojanperä, “An Overview of CDMA Evolution Towards Wideband CDMA” a paper published in IEEE Communications Surveys, http://www.comsoc.org/pubs/surveys , Fourth Quarter, Vol. 1 No. 1 of 1998.

[4] Kiseon Kim and Insoo Koo, “CDMA System Capacity Engineering”, Artech House Mobile Communication series, Norwood, MA 02062, 2005.

[5] R. Prasad, "CDMA for Wireless Personal Communications," Artech House Publishers, 1996.

[6] Albena Mihovska and R Prasad, “New Horizons in Mobile and Wireless Communication”, Vol-1, Radio Interfaces, Artech House, Norwood, MA, 2009.

[7] Shinsuke Hara and R Prasad, “Overview of Multicarrier CDMA” a paper published in IEEE Communications Magazine, December 1997.

[8] J. A. C. Bingham, “Multicarrier modulation for data transmission: An idea whose time has come,” an article published in IEEE Commun. Mag., vol. 28, no. 5, pp. 5–14, May 1990.

[9] Webpage www.hindaw.com/journals/wcn/2008/541410.html#B15

[10] Mourad, Abdel-Majid, “On the System Level Performance of MC-CDMA Systems in the Dopwnlink”, Paper published in tel-00089123, version 1 – 10, Aug 2006

[11] John W Mark and Weihua Zhuang, "Wireless Communications and Networking", Prentice-Hall Inc, New Delhi, 2005.

[12] Essam Sourour, "Effect of Carrier Separation With Bandwidth Limitation on The Performance of Multi-Carrier DS-CDMA Systems in Multi-Path Fading Channels", paper published in IEEE Communication Journal, 2001

[13] Heng Yang, and Xian-Da Zhang, "A Fast Maximum Likelihood Sequence Decoding Method for Multicarrier DS-CDMA Using Frequency Spread Coding", an article published in IEEE Transactions on Wireless Communications, Vol. 3, No. 3, May 2004.

[14] Shu-Ming Tseng and Hung-Chieh Yu, "Vector Channel Estimation and Multi-user Detection for Multi-carrier DS CDMA in Time and Frequency Selective Fading Channels", paper submitted in WCNC of IEEE Communications Society, 2004.

[15] Xinsheng Wang, Wei Yang, Zhmhui Tan and Shixin Cheng , "Performance of Space-Time Block-Coded Multicarrier DS-CDMA System in a Multipath Fading Channel", a paper presented in IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications Proceedings, 2005.

[16] Yewen Cao, Tjeng Thiang Tjhung and Chi Chung Ko, "Performance of a New Premulticoded Multicarrier DS-CDMA System in Nakagami Fading", IEEE Transactions on Communications, Vol. 55, No. 7, July 2007.

[17] Y S Kim and S H Hwang, "Analysis of the Antenna Array-aided multi-carrier DS-CDMA Rake System with Synchronous Uplink transmission", published in IEEE Communication Publication, Vol. 3, Issue 10, pp 1597-1605, 2009.

[18] Saimoon Ara Amin, Mahbubul Alam Rafel and S.P Majumder, "Performance Analysis of Multi-carrier DS-CDMA wireless Communication System", Third UK European Symposium on Computer Modeling and Simulation, 2009.

[19] R Prasad and T Ojanperä, "An Overview of CDMA Evolution Towards Wideband CDMA" a paper published in IEEE Communications Surveys, http://www.comsoc.org/pubs/surveys Vol. 1 No. 1 of 1998

[20] Lie-Liang and Lajos Hanzo, “Multicarrier DS-CDMA: A Multiple Access Scheme for Ubiquitous Broadband Wireless Communication”, a paper published in IEEE Communication Magazine, October 2003.

[21] L. Hanzo, M Munster, B. J. Choi and T. Keller, “OFDM and MC-CDMA For Broadband Multi-user Communication”, article published in IEEE Press, 2003.

[22] Kamil SH. Zigangzirov, ‘Theory of Code Division Multiple Access Communication’, article published in IEEE Press Series, John Wiley & Sons, Inc Publication, 2004.

[23] S. Mallick and S. P. Majumder, “Performance analysis of an OFDM system in the presence of carrier frequency offset, phase noise and timing jitter over Rayleigh fading channels,” ICECE 2008, pp. 205–210, Dec. 2008.