PERFORMANCE ANALYSIS OF A MC-CDMA SYSTEM WITH SPATIAL DIVERSITY OVER NAKAGAMI FADING CHANNEL

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APPROVAL CERTIFICATE

This thesis titled "PERFORMANCE ANALYSIS OF A MC-CDMA SYSTEM WITH SPATIAL DIVERSITY OVER NAKAGAMI FADING CHANNEL" submitted by Taposh Kumar Biswas, Roll No.-040506206P has been accepted as satisfactory in Partial Fulfillment of the Requirements for the Degree of **Master of Science in Electrical and Electronic Engineering**

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It is hereby declared that this thesis or nay part of it has not been submitted elsewhere for the award of any degree or diploma.

Taposh Kumar Biswas
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Counter Signed by

Dr. Satya Prasad Majumder
The Supervisor

Dedicated to

My beloved parents

And

Honorable teachers,

Who brought me to this enlightened stage of life

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ABSTRACT

The new information age is paving its way forward with high demand of wireless communication systems. New services such as data and video require achieving reliable high-speed transmissions even in high mobility scenarios. Multicarrier code-division multiple access (MC-CDMA) is a transmission technique which combines advantages of both code-division multiple access (CDMA) and orthogonal frequency-division multiplexing (OFDM). In this thesis, we consider a wireless system with MC-CDMA with orthogonal subcarrier multiplying with OFDM after converting the high data bit stream to low data parallel streams. Spatial diversity is considered in the receiving end with multiple antenna and Rake receiver. Analysis is carried out to find out the expression of the receiver output with Maximal Ratio Combining (MRC) technique considering a Nakagami-m fading channel. Performance analysis includes the effect of Multiple Access Interferences (MAI), Inter Carrier Interferences (ICI) and in presence of Additive White Gaussian Noise (AWGN). The expression of the Signal to Interference and Noise Ratio (SINR) is derived for a MC-CDMA system considering the above limitations. Analysis is also carried out to find the expression for the MAI and instantaneous SINR and the probability density function of the SINR at the output of maximal ratio combiner. The analysis is then extended to MC-CDMA system with Rake Receiver. The performance results are evaluated numerically in terms of SINR and BER considering several parameters like number users, number of subcarriers, code length of a sub-channel, bit rate, number of rake fingers and number of receiving antennas. The results show that there is a significant improvement in SINR and BER performance considering rake receiver and number antennas at the receiver. For a given performance level and a given system BER, optimum system design parameters are determined from the analytical results.

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LIST OF ABBREVIATIONS

4G	The fourth generation of mobile communication
AWGN	Additive White Gaussian Noise
BER	Bit error rate
bps	Bits per second
BPSK	Binary phase shift keying
BS	Base station
CDMA	Code division multiple access
DS-CDMA	Direct-sequence CDMA
EGC	Equal gain combining
FDMA	Frequency division multiple access
FFT	Fast Fourier transforms
GSM	Global System for Mobile communication
ICI	Inter-channel interference
ISI	Inter-symbol interference
ITU	International Telecommunication Union
LFSR	Linear Feedback Shift Register
MAI	Multiple access interference
MC-CDMA	Multicarrier CDMA
MC-DS-CDMA	Multicarrier DS-CDMA
MIMO	Multiple Inpout Multiple Output
MRC	Maximal ratio combining
MS	Mobile subscriber
MT-CDMA	Multi Tone CDMA
MUD	Multiuser detection
OFDM	Orthogonal frequency division multiplexing
PDF	Probability density function
PAPR	Peak to Average Power Ratio
PN	Pseudo random Noise
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying

SINR	Signal to Interference plus Noise Ratio
SNR	Signal-to-noise ratio
STBC	Space Time Block Code
TDMA	Time division multiple access

CHAPTER 1

INTRODUCTION

1.1 Overview of Wireless Communications

The need to communicate with others has always existed. In 1837 Samuel Morse invented the telegraph and by the end of the 19th century Gugliemo Marconi established what is considered the first successful and practical radio system. Nevertheless, it was not until the 1940s when commercial mobile telephony began and then the point where we can establish the first roots of cellular communications [1]. It is a process to transfer information from one entry to another. Wireless communication is the transfer of information without the use of wires. The medium for wireless communications is the open space, and information is transferred via electromagnetic waves. The technical terms, mobile wireless communication is a process in where information is encoded in a package and is channeled and imparted by a sender to a receiver via some medium. Then the receiver decodes the information and gives the sender a feedback. Communication resources refer to the time and frequency bandwidth that is available in a given system. With multiple users on a system, resources need to be shared among the users in order to establish communication links between the mobile subscriber (MS) and the base station (BS). Nowadays wireless communication is used widely in many communication systems: mobile telephony, satellite networks, digital radio, television broadcasting, fixed wireless local loops, etc. but the means of mobile communication has been updated time to time with the evaluation to technology. Today mobile phone has become a vital part of human life. It is not remain bounded only within voice services, rather than the demand for multimedia communication like high speed data and video services through wireless medium has increased many folds. However, the available resources are often limited for any given user as the total bandwidth on a system is restricted. In order to improve the efficiency of the resource allocations, multiple access techniques have been introduced. These techniques ensure the following qualities:

- Available resources are fully utilized
- All resources are shared equally among users
- Interference is not introduced between users i.e. no multiple access interference (MAI), and
- The capacity of the system is maximized.

1.2 Multiple Access Techniques

A multiuser communication system is a multiple access channel where a large number of users share a common communication channel to transmit information to a receiver. The main task of the communication system designer is to make the best use of the system resources. The challenge is to make the most efficient use of the RF bandwidth. Frequency division multiple access (FDMA), Time division multiple access (TDMA) and Code division multiple access (CDMA) are the three major access techniques [1], used to share the available bandwidth in a mobile communication system to provide group of users in one RF channel.

1.2.1 Frequency division multiple access (FDMA)

The first multiple access technique implemented in cellular radio environment is known as frequency division multiple access (FDMA) [1]. With FDMA, the total frequency bandwidth is divided into frequency channels that are assigned to each user permanently, resulting in multiple user signals that are both spectrally separated and simultaneously transmitted and received. This has been graphically represented in Fig. 1.1.

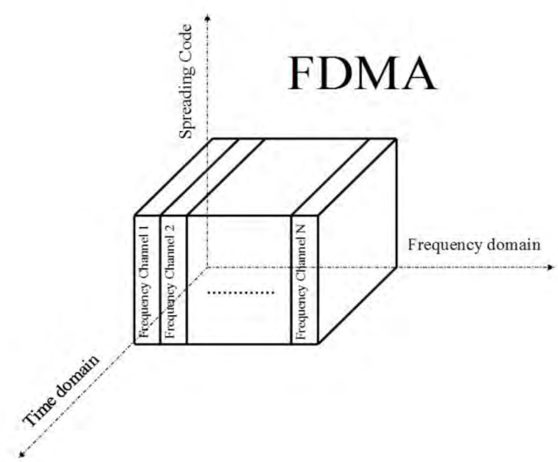


Fig. 1.1 Frequency division multiple access (FDMA)

1.2.2 Time division multiple access (TDMA)

Time division multiple access (TDMA) has been developed with a similar concept to FDMA, but with TDMA, multiple user signals are separated in the time domain rather than in the frequency domain. Fig. 1.2 shows a TDMA system with the transmission time divided into a number of cyclically repeating time slots that can be assigned to individual users, allowing all users access to all of the available bandwidth.

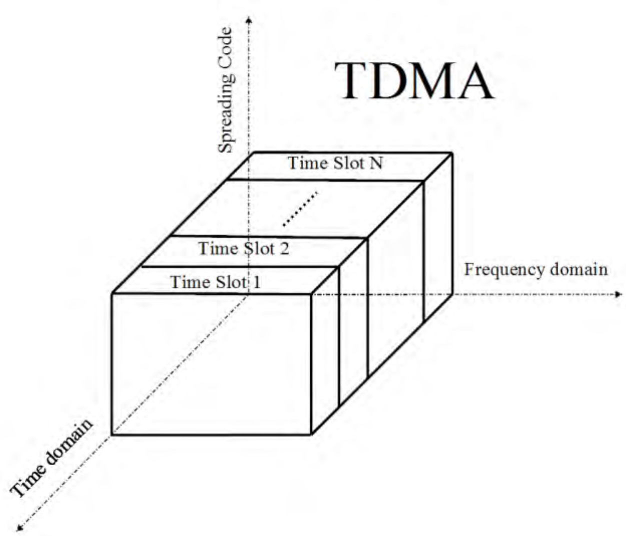


Fig. 1.2 Time division multiple access (TDMA)

1.2.3 Code division multiple access (CDMA)

Another multiple access technology which was designed to increase both the system capacity and the service quality is called code-division multiple access (CDMA). Over the last decade, CDMA has been developed to overcome the disadvantages of other multiple access techniques such as TDMA and FDMA [2]. Fig. 1.3 demonstrates multiple CDMA users' signals that are separated by spreading sequences. In particular, each user signal is spread using a pseudo-random sequence which is orthogonal to the sequence of other users. As a result, only the intended user receiver can de-spread and receive the information correctly; other users on the system perceive the signal as noise, resulting in multiple user signals that can be transmitted within the same bandwidth simultaneously. That's why CDMA is often denoted as spread- spectrum multiple access (SSMA).

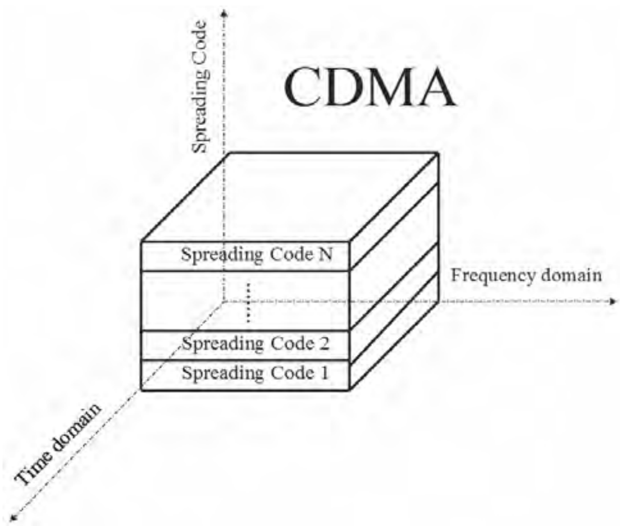


Fig. 1.3 Code division multiple access (CDMA)

The main advantage with CDMA is that the system capacity is limited only by the amount of interference; with a lower level of interference the system can support a higher number of users [1]. CDMA systems are also robust to narrow band jamming as the receiver signal can spread the jamming signals' energy over the entire bandwidth making it insignificant in comparison to the signal itself. If the spreading sequence is perfectly orthogonal, it is possible to transmit multiple CDMA signals without introducing multiple access interference (MAI) during synchronous transmission [2]. The ratio of the code signal bandwidth B_c to information signal bandwidth B_b is called the processing gain G of the spread spectrum system, i.e. $G= B_c/B_b=T_b/T_c$.

1.2.4 Orthogonal frequency division multiplexing (OFDM)

Orthogonal frequency division multiplexing (OFDM) has the ability to support higher data rate transmission [3]. When using OFDM, the channel bandwidth is divided into a number of equal bandwidth subchannels, with each subchannel utilizing a subcarrier to transmit a data symbol. The frequency separation of adjacent subcarriers ia chosen to equal the inverse of the symbol duration, resulting in all the subcarriers being orthogonal to one another over one symbol interval. Hence, OFDM technique can transmit a large number of different data symbol over multiple subcarriers simultaneously, enabling this technique to support a higher data rate transmission, In addition the bandwidth of each sub channel is designed to be so narrow that the frequency characteristics of each subchannel are constant, making OFDM signals robust to frequency selective fading. The other advantage of OFDM is that the signal can be easily and efficiently modulated and demodulated using Fast Fourier transform (FFT) devices. As FFT can be easily implemented, the receiver complexity does not increase substantially while transmission rate can be largely increased.

Despite all this advantages, OFDM still have some drawback due to its implementation of multicarrier modulation. OFDM suffers a high peak to average power ratio that occurs when all the signals in the subcarriers are added constructively. This results in the saturation of the power amplification at the transmitter, causing inter-modulation distortion. OFDM is very sensitive to frequency offset, as the spectrums of the subcarriers are overlapping. Any frequency offset can lead to ICI, which suggests that OFDM requires a high degree of synchronization of subcarriers. Besides, the conventional OFDM systems can support only a single user, raising the need for multicarrier code divitson multiple access (MC-CDMA).

1.3 Limitations of FDMA and TDMA over CDMA

There are several limitations of FDMA and TDMA which are listed below [2]:

- Unused channels cannot be utilized by other users, resulting in wasted communication resources.
- Nonlinearities in the power amplifier can cause signal spreading in the frequency domain, causing inter-channel interference (ICI) in other FDMA channels.
- Low frequency reuse factor reduces the number of channels per cell.
- Susceptible to fading, which caused by interference between two or more versions of the transmitted signal that arrive at the receiver at slightly different time.

1.4 Capabilities of CDMA Schemes

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 system 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]:

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

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

iii. **Interference rejection and anti-jamming capability** CDMA has anti-jamming capability, where jamming refers to the particular case when the narrowband interference voluntarily disturb the system.

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

v. **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.

vi. **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.

vii. **Soft capacity** The maximum number of user 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.

1.5 Spread spectrum communications

Spread-spectrum (SS) is based on spreading the transmitted signal over a frequency band much wider than the one required to transmit the information being sent. At the receiver, synchronizing the received signal is necessary for de-spreading and, thus, recovers the data signal. Even though the initial applications of spread-spectrum systems mainly exploited the anti-jamming and low probability of interception characteristics for military communications, robustness to multipath and multiple access suggested that spread-spectrum was used in commercial systems. CDMA is a form of Direct Sequence Spread Spectrum communications. There are three ways to spread the bandwidth of the signal [3]:

- **Frequency hopping CDMA (FH-CDMA)** The signal is rapidly switched between different frequencies within the hopping bandwidth pseudo-randomly, and the receiver knows beforehand where to find the signal at any given time.

- **Time hopping CDMA (TH-CDMA)** The signal is transmitted in short bursts pseudo-randomly, and the receiver knows beforehand when to expect the burst.

- **Direct sequence CDMA (DS-CDMA)** The digital data is directly coded at a much higher frequency. The code is generated pseudo-randomly, the receiver knows how to generate the same code, and correlates the received signal with that code to extract the data.

1.6 Single Carrier Vs. Multi-Carrier CDMA systems

Various types of CDMA such as direct-sequence CDMA (DS-CDMA) and wideband CDMA (W-CDMA), have been developed and utilized in both 2G and 3G systems. These techniques are considered to be single-carrier CDMA systems. Further mobile communication have to support a verity of services such as voice, video high data rates Unfortunately when moving into the fourth generation of wireless communication systems (4G), in which data is transmitted at a rate as high as 1 Giga bits-per-second (bps), single-carrier CDMA systems are not suitable [4]. This is because:

- With high data rates the symbol duration will become shortened, resulting in the channel delay spread exceeding the symbol duration causing ISI.

- When data rate goes beyond a hundred Mega bps, it becomes difficult to synchronize, as the data is sequenced at high speeds.
- Due to multipath propagation, signal energy is scattered in the time domain.

In single-carrier CDMA systems such as DS-CDMA, RAKE receivers are often used to combine the multipath signals. However, not all paths of signals can be successfully received. If the number of fingers in the RAKE receiver is less than the number of resolvable paths, some of the received signal energy cannot be combined, thus a portion of the signal energy is lost. But if the number of fingers in the RAKE receiver is more than the number of resolvable paths, noise will be enhanced. A conventional single-carrier CDMA such as DS-CDMA is not practical for 4G systems where a high data rate is required. MC modulation, a technique to reduce the symbol rate, is then essential, where the carrier frequencies are chosen to be orthogonal to one another. Combination of MC modulation (OFDM) techniques with DS-CDMA forms the MC-CDMA system. In multicarrier CDMA systems, frequency diversity may be achieved by repeating the transmitting 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 operation with MC-CDMA technology can be flexibly changed from single-device transmission with high-data-rate transmission to multiple-device transmission with low data rate for each device.

1.7 Need for MC-CDMA

Narrowband communications is immune to Inter Symbol Interference (ISI) but susceptible to attenuation caused by fading. CDMA is characterized by resistance to fading by spreading the signal over the entire bandwidth. However, this is affected by delay spreads and thus inter-chip interference is seen as a major drawback. OFDM is extremely popular in mobile communications over hostile radio environments. They use a large number of orthogonal parallel subcarriers for transmission. The biggest advantage of OFDM is the performance against inter symbol interference at the receiver and frequency selective fading. A large peak to average ratio and sensitivity to frequency offsets are seen as major drawbacks to OFDM. MC-CDMA takes the advantages of both OFDM and CDMA and makes an efficient transmission system by spreading the input data symbols with spreading codes in the frequency domain. It uses a number of narrowband orthogonal subcarriers with symbol duration longer than the delay spread. This makes it unlikely for all the subcarriers to be affected by the same deep fades of the channel at the same time thereby improving performance. Synchronization during transmission becomes easier with longer symbol durations.

1.8 Merits of MC-CDMA

Based on the combination of OFDM and DS-CDMA, multicarrier code division multiple access (MC-CDMA) is proposed. Unlike DS-CDMA, which spreads the orthogonal data stream into the time domain, MC-CDMA spreads the orthogonal data stream into the frequency domain by initially converting the input data stream into serial to parallel then multiplying this stream by the spreading chips in different OFDM subcarriers, resulting in a MC-CDMA signal which takes on the advantages of both DS-CDAM and OFDM. The advantages of MC-CDMA are [5]:

- The capacity is interference limited and any technique that reduce interference is capable of increasing the capacity of MC-CDMA.
- The signal is robust to frequency selective fading and can support high data rate transmission.
- Bandwidth is used more efficiently as the spectra of subcarrier overlap
- Since the received signal is combined in the frequency domain, a MC-CDMA receiver can employ all the received signal energy scattered in the frequency domain. This is a significant advantage over DS-CDMA, where part of the signal energy can be lost due to insufficient number of fingers in the RAKE receiver.
- The transmitter and receiver signals can be implemented using FFT, which does not increase the degree of complexity.

1.9 Transmission Limitations in a Wireless Communication System

Many problems may occur during the transmission of a radio signal in the wireless communication channel such as the thermal noise often modeled as Additive White Gaussian Noise (AWGN), the path loss, the shadowing and the fading etc. Upon the signal transmission, different signal copies undergo different attenuation, distortion, delays and phase shifts. Due to this problem, the overall system performance can be severely degraded. Some of the most common problems are described below [2]:

i. **Path Loss** Path loss occurs when the received signal becomes weaker and weaker due to increasing distance between MS and BTS, even if there are no obstacles between the transmitting (Tx) and receiving (Rx) antenna. The path loss problem seldom leads to a dropped call because before the problem becomes extreme, a new transmission path is established via another BTS.

ii. **Shadowing** Shadowing occurs when there are physical obstacles including hills and buildings between the BTS and the MS. The obstacles create a shadowing effect which can decrease the received signal strength. When the MS moves, the signal strength fluctuates depending on the obstacles between the MS and BTS. A signal influenced by fading varies in signal strength. Drops in strength are called fading dips.

iii. **Multipath fading** Multipath fading occurs when there is more than one transmission path to the MS or BTS, and therefore more than one signal is arriving at the receiver. This may be due to buildings or mountains, either close to or far from the receiving device. Rayleigh fading and time dispersion are forms of multipath fading.

iv. **Rayleigh fading** This occurs when a signal takes more than one path between the MS and BTS antennas. In this case, the signal is not received on a line of sight path directly from the Tx antenna. Rather, it is reflected off buildings, for example, and is received from several different indirect paths. Rayleigh fading occurs when the obstacles are close to the receiving antenna.

v. **Time dispersion** Time dispersion is another problem relating to multiple paths to the Rx antenna of either an MS or BTS. However, in contrast to

Rayleigh fading, the reflected signal comes from an object far away from the Rx antenna. Time dispersion causes Inter-Symbol Interference (ISI) where consecutive symbols (bits) interfere with each other making it difficult for the receiver to determine which symbol is the correct one.

1.10 Diversity in Wireless Communication [6]

1.10.1 Transmit Diversity

The basic concept of diversity is that the receiver has more than on version of the transmitted signal available and each version of transmitted signal is received through a distinct channel. When several versions of the signal, carrying the same information, are received over multiple channels that exhibits independent fading with comparable strengths, the chances that all the independently faded signal components experiences the same fading simultaneously are greatly reduced. This significantly improves the transmission accuracy as transmission errors are most likely to happen when the instantaneous SNR is low during a deep fading period. Some diversity techniques are described as follows:

(i.) **Space diversity** Two antennas separated physically by a short distance can be provided two signals with low correlation between their fades. The separation in general varies with antenna height and with the frequency. Typically, a separation of a few wavelengths is enough to obtain uncorrelated signals. Taking into account the shadowing effect usually a separation of at least 10 carrier wavelengths is required between two adjacent antennas. This diversity does not require extra system capacity; however, the cost is the extra antennas needed.

(ii.) **Frequency diversity** Signals received on two frequencies, separated by coherence bandwidth are uncorrelated. To use frequency diversity in an urban or suburban environment for cellular communications, the frequency separation must be 300kHz or more. This diversity improves link transmission quality at the cost of extra frequency bandwidth.

(iii.) **Time diversity** If the identical signals are transmitted in different time slots, the received signals will be uncorrelated, provided the time difference between time slots is more than the channel coherence time. This system will work for an environment where the fading occur independent of the movement of the receiver.

(iv.) **Polarization diversity** The horizontal and vertical polarization components transmitted by two polarized antennas at the base station and received by two polarized antennas at the mobile station can provide two uncorrelated fading signals. Polarization diversity results in 3dB power reduction at the transmitting site since the power must be split into two different polarized antennas.

(v.) **Angle diversity** The desired signal 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 directions are uncorrelated. Angle diversity can be viewed as a special case of space diversity since it also requires multiple antennas.

1.10. 2 Receive Diversity

The goal of a combiner is to improve the noise performance of the system. After obtaining the diversified received signals, they are combined together. The analysis of combiners is generally performed in terms of SNR. The methods for combining independently faded signal components are Maximal Ratio Combining (MRC), Equal Gain Combining (EGC) and Selective Combining. Rake receiver is used in the CDMA system for the improvement of different combining techniques. Discussion of each of these techniques follows:

(i.) **Selection Combining** With selection combining, the system simply selects the diversity branch output with the largest signal-to-noise ratio (SNR) and discards the output into other branches. Such branch selection can increase the average SNR of the system and thus offers a better performance. The advantage of selection combining is its simple implementation, as it requires only a side monitoring station and an antenna switch at the receiver. However, this technique is not optimal because it does not fully utilize the signals available in all possible diversity branches.

(ii.) **Maximal Ratio Combining (MRC)** Maximal ratio combining (MRC) overcomes the limitations of selection combining: it combines the input signals in all diversity branches. 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. MRC has been considered as the optimal combining technique in the presence of additive white Gaussian noise (AWGN) due to its ability to maximize the instantaneous output SNR. MRC can produce an output SNR equal to the sum of the individual SNRs in each diversity branch. It follows that MRC can offer the advantage of producing an acceptable output SNR even when none of the SNR in individual branches is acceptable.

(iii.) Equal Gain Combining (EGC) Although MRC has the ability to maximize the instantaneous output SNR, in certain cases it is difficult to track the magnitude and phase of the received signal in order to produce a time varying combining weight. Equal gain combining (EGC) provides a more convenient solution whereby the combining weights in all branches are equal to a constant. Then the detected signals from all the branches are simply added and applied to decision device. As the receiver does not need to estimate the amplitude fading, its complexity is reduced as compared with maximal ratio combining.

1.11 Review of Previous Research Works

A significant number of research works has been carried out regarding evaluation of capacity of MC-CDMA wireless communication system. Some of these similar studies are briefly described below:

Yee, N., Linnartz, J.-P., and Fettweis, G., [7] introduced a new spread spectrum technique called multicarrier CDMA (MC-CDMA). They also analyzed its BER performance for Rayleigh fading dispersive channel. In this paper they compared the performance of two reception diversity techniques, MRC and EGC and shown MRC has better performance than EGC in the uplink but less effective in downlink. Comparing the performance of

EGC in the uplink to downlink at a BER 10^{-3}, there is increase in capacity from 8 users to 20 users in the downlink.

Joy Ion-Zong Chen [8] focuses the performance analysis for MC-CDMA system works in uncorrelated and correlated Nakagami-m fading channel. The results show that the phenomena of channel correlation do degrade the performance of MC-CDMA communication system. So it is important to pay attention to correlation coefficient for channel fading while designing the MC-CDMA system.

Author review the Multicarrier based CDMA schemes such as MC-CDMA, Multicarrier DS-CDMA and Multi-tone CDMA [9]. They compared their advantages and disadvantages with a normal DS-CDMA scheme. The MC-CDMA scheme with MMSEC is a promising protocol in a 2-path frequency selective slow Rayleigh fading channel. But, more analysis are required using different multipath delay profiles.

Koichi Adachi, Fumiyuki Adachi and Masao Nakagawa compared the channel capacity of MC-CDMA MIMO with perfect ICIC to that of OFDM MIMO by using the *Jensen's* inequality and showed that the channel capacity of MC-CDMA MIMO with perfect ICIC is always larger than or equal to that of OFDM MIMO [10]. They also showed that MC-CDMA MIMO can approach the capacity of multiple SIMO while OFDM MIMO cannot.

Jean-Paul M. G. Linnartz,, [11] modeled the Doppler spread and computes its effect on the bit error rate (BER) for multicarrier code division multiple access (MC-CDMA) transmission and compares it to orthogonal frequency division multiplexing (OFDM). Also evaluated the transmission capacity per subcarrier to quantify the potential of MC-CDMA and (coded-) OFDM. He focuses on linear receivers, in particular those using the minimum mean-square error (MMSE) criterion.

Adachi, K.; Adachi, F. and Nakagawa, M., have shown that Multiple-input multiple-output (MIMO) space division multiplexing (SDM) can increase the transmission rate without bandwidth expansion [12]. They derived the channel capacity formula for MC-CDMA MIMO taking into account the ICI and co-channel interference (CCI) in a cellular environment. The cellular channel capacity of MC-CDMA MIMO with perfect ICI cancellation is numerically evaluated and is compared to that of OFDM MIMO in a cellular environment. The numerical computation results show that the cellular channel capacity of MC-CDMA is larger than that of OFDM.

Taeyoung Kim, Younsun Kim, Joonhyun Park, Kyunbyoung Ko, Sooyong Choi, Changeon Kang and Daesik Hong, mathematically analyzed the performance of an MC-CDMA system with carrier frequency offsets in correlated multipath fading [13]. The derived results show that the performance degradation of the MC-CDMA system is caused by both carrier frequency offset and correlation among subcarriers. From the derived results, however, the performance degradation due to correlation among subcarriers is more severe than effect of frequency offset.

Zexian Li and Latva-aho, M. [14] presented the bit-error rate (BER) of equal gain combining (EGC) receivers for multicarrier code-division multiple-access (MC-CDMA) systems. This new method is based on an alternative Gaussian approximation (AGA) and it applies to the system with multiple active users in frequency selective Nakagami-m fading channels. The AGA method has the advantage of simplicity in expression and computational efficiency.

Moreover, high data rate MC-CDMA systems can additionally employ MIMO techniques, e.g., Alamouti codes and STBC [15]. Currently, Multiple-Input Multiple-Output (MIMO) systems, where array antennas are equipped at both the transmitter and receiver, have emerged as significant break-through in wireless communication systems [16]. It can provide high-bit-rate transmission and increase system performance over multipath fading channels and interference. The system performance of MC-CDMA system with MIMO OFDM is reported in literature [17] with space time diversity scheme. It is important to evaluate the deterioration in system performance due to different type of channel fading mechanisms.

1.12 Motivation of the Thesis

The number of mobile and Internet subscribers is growing rapidly on a global scale, and with this growth comes new and improved wireless services and increased quality of service (QoS) demands. 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). The emerging need for high data rate wireless services has raised considerable interest in MC-CDMA systems. MC-CDMA is capable of offering a low BER for the single user system. However, when two or more users exist in the system, MAI is introduced, and the BER is increased, indicating performance degradation. Therefore MAI is one of the major factors that limit the performance of asynchronous MC-CDMA. As the system performance is greatly influence 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 and spatial diversity can greatly reduce the fading effects and improve the BER performance at the expense of receiver complexity, the extent of capacity improvement also needs to be evaluated.

1.13 Objectives of the Thesis

The main objectives of this research work are:

a) To carry out the bit error rate (BER) performance analysis of a MC-CDMA system with space diversity over Nakagami-m fading channel.
b) To evaluate the perform results with various degrees of fading.
c) To determine the deterioration in system performances due to fading and improvement with space diversity.

1.14 Organization of this Thesis

After the introductory chapter, the outline of this thesis is organized as follows:

Basic concepts on Multi-carrier CDMA system is discussed in chapter 2. 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.

In chapter 3, the analytical expression of MC-CDMA schemes has been obtained considering without and with fading. Initially the expression is formulated without considering Rake receiver and then it was modified for the system with Rake receiver. Thereafter, the spatial diversity has been incorporated to improve the system performance.

Chapter 4 describes the performance results obtained from various calculations and plots. The optimum system parameter has been chosen based on the numerical calculation.

Conclusions and the scope of the further works on this subject are provided in chapter 5.

CHAPTER-2

MULTICARRIER CDMA (MC-CDMA) SYSTEM

2.1 Introduction

Future wireless systems such as a fourth-generation (4G) system will need flexibility to provide subscribers with a variety of services such as voice, data, images and video. Because these services have widely differing data rates and traffic profiles, future generation systems will have to accommodate a wide variety of data rates. DS-CDMA has proven very successful for large scale cellular voice systems, but there are concerns whether DS-CDMA will be well suited to non-voice traffic. The DS-CDMA system suffers inter-symbol interference (ISI) and multi-user interference (MUI) caused by multipath propagation, leading to a high loss of performance.

With OFDM, the time dispersive channel is seen in the frequency domain as a set of parallel independent flat subchannels and can be equalized at a low complexity. There are potential benefits to combining OFDM and DS-CDMA. Basically the frequency-selective channel is first equalized in the frequency domain using the OFDM modulation technique. DS-CDMA is applied on top of the equalized channel, keeping the orthogonality properties of spreading codes. The combination of OFDM and DS-CDMA is used in MC-CDMA. MC-CDMA marries the best of the OFDM and DS-CDMA world and, consequently, it can ensure good performance in severe multipath conditions. MC-CDMA can achieve very large average throughput. To further enhance the spectral efficiency of the system, some form of adaptive modulation can be used. Based on code division multiple access (CDMA) and OFDM techniques there are three different types of new multiple access schemes are proposed in 1993, such as Multicarrier (MC-) CDMA, Multicarrier DS CDMA and Multi-tone (MT-CDMA). In this chapter, the behavior of single carrier and multicarrier CDMA schemes is described. In addition, different types of spreading codes and Rake Receiver model are highlighted. Finally, this chapter is summarized.

2.2 Direct-Sequence Code Division Multiple Access (DS-CDMA)

DS-CDMA is often referred to as spread-spectrum multiple access (SSMA). In direct sequence code division multiple access (DS-CDMA), the narrowband message is multiplied by a large bandwidth signal, which is called the spreading signal [18]. The spreading signal is generated by convolving a pseudo-noise (PN) code with a chip waveform whose duration is much smaller than the symbol duration. By assigning different code sequences to each user, it is possible to allow many users to share the same channel and frequency simultaneously. The basic functional block diagram of a DS-CDMA transmitter and receiver is given in Fig. 2.1

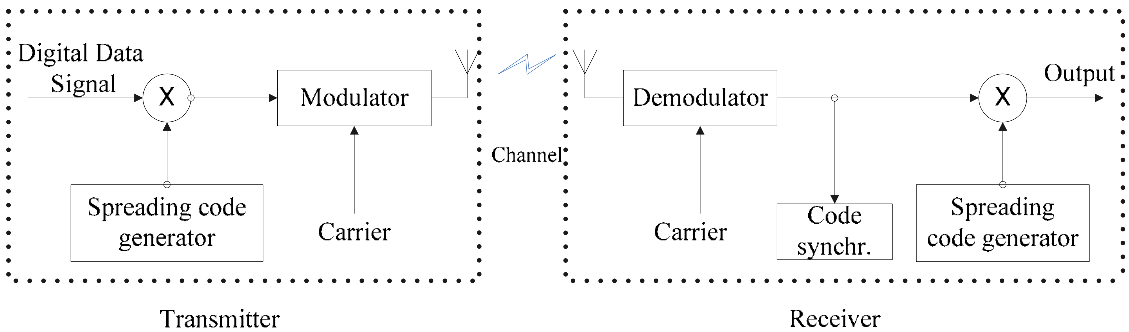


Fig. 2.1 Block diagram of a DS-CDMA System

Serial data is first spread by the appropriate code called chip that can be either +1 or -1. To obtain the desired spreading of the signal, the chip rate of a PN code must be much higher than the bit rate. There are various types of modulation techniques such as Binary Phase Shift Keying (BPSK), Differential Binary Phase Shift Keying (D-BPSK), Quadrature Phase Shift Keying (QPSK) or Minimum Shift Keying (MSK) are deployed at the transmitter before transmitting the signals. At the receiver reverse operation (despreading) is performed upon reception. To able to perform the despreading operation, the receiver must know the code sequence used to spread the signal. The despreaded signal is then demodulated and passed through a matched filter adapted to the rectangular shape of the data. Finally, a decision device is applied yielding the final estimate of the desired information signal. The transmitted signal (spread spectrum signal) of the k^{th} user can be expressed as [19]

$$x_{DS}(t) = \sqrt{2P}\sum_{i=-\infty}^{\infty}\sum_{j=0}^{K-1} b_i C_j \prod(t - iT_b - jT_c)\cos(2\pi f_c t)$$

where,

K = No of User

P = Transmitted Power

$T_b =$ Bit duration

$T_c =$ Chip duration

$f_c =$ Carrier frequency

Processing gain $= \frac{T_b}{T_c}$

2.3 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a multicarrier transmission technique which divides the available spectrum channel into several independent sub-carriers. This is achieved by making all the sub-carriers orthogonal to one another, preventing interference between the closely spaced sub-carriers [12]. In an OFDM signal, all the orthogonal sub-carriers are transmitted simultaneously. Orthogonality is achieved by making the peak of each sub-carrier signal coincide with the nulls of other signals where the result is a perfectly aligned and spaced sub-carrier signal. See Figure 2.2 and 2.3 below:

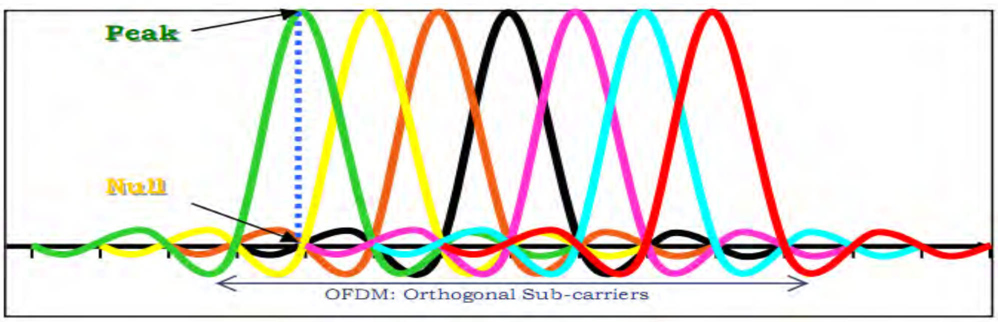


Fig. 2.2 OFDM Orthogonal Subcarrier

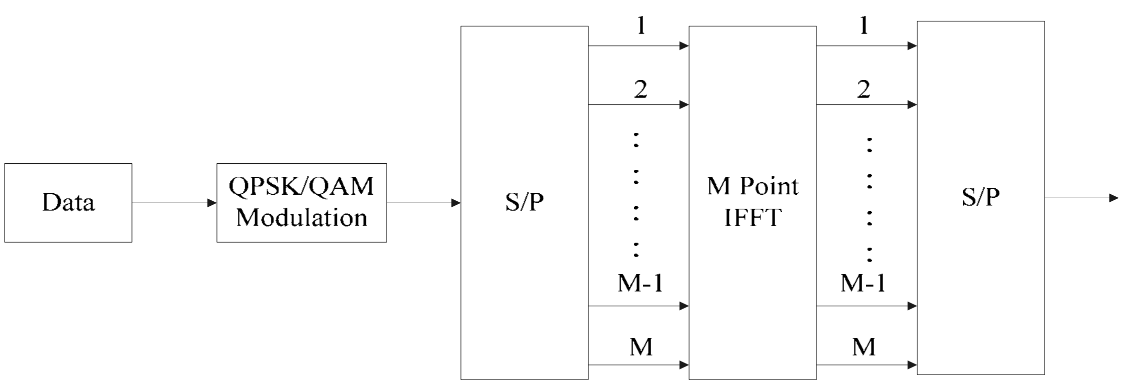


Fig. 2.3 A sample OFDM transmitter

The signals in the independent sub-carriers are individually modulated and demodulated. If one or two sub-carriers are degraded or impacted by frequency selective fading (signals at different frequencies travel at different energy propagation and velocity), the impact is minimal since the information is spread across the remaining sub-carriers. The simultaneous transmission of several parallel sub-carriers delivers high data rates.

2.4 MC-CDMA

MC-CDMA systems combined with orthogonal frequency division multiplexing (OFDM) are categorized into two types. One is a “copy type” system and the other is a “serial to parallel(S/P) type” system. The transmitter of the system is shown in Fig.2.1, where the bit stream with bit duration T_b is serial-to-parallel converted into ρ parallel streams, The new bit duration on each stream is $T= \rho T_b$. Each stream feeds G_{MC} parallel streams such that the same data stream exists on the G_{MC} branches. The G_{MC} branches carrying the same data stream are denoted as identical-bit branches, and after modulation, the frequencies carrying the same data stream are denoted as identical bit carriers. The data bits at each data stream are coded by a PN code. The processing gain of MC-CDMA is $N_c = \rho G_{MC}$ [9]. Power spectral density of the transmitted signal and the Receiver block diagram of MC-CDMA system are shown in Fig.2.4 through Fig.2.6 respectively.

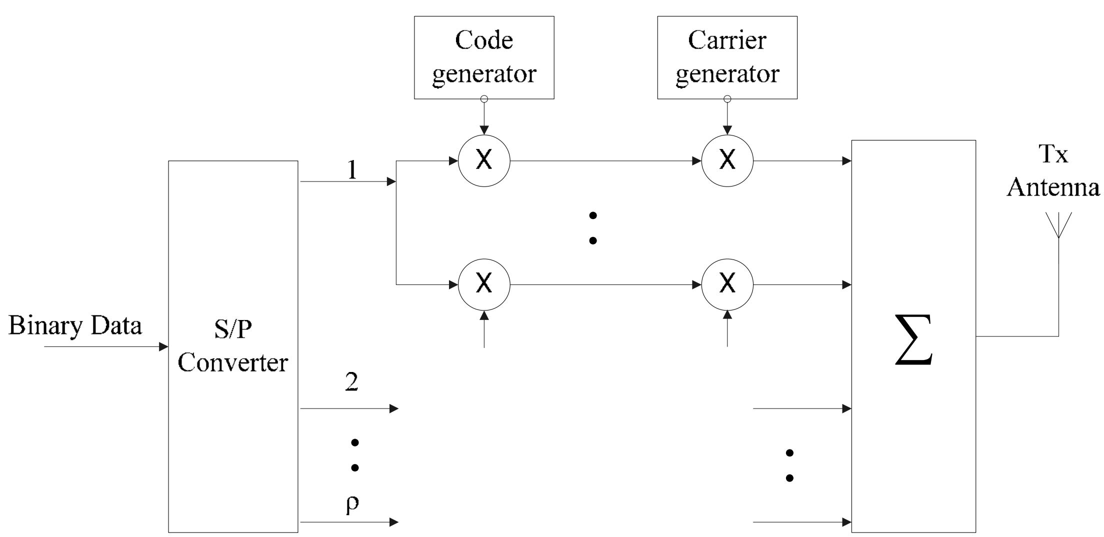


Fig. 2.4 Block diagram of Multicarrier CDMA transmitter

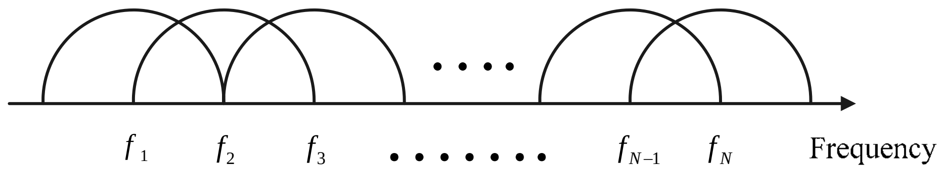


Fig. 2.5 Transmitted psd for orthogonal for MC system with 12 sub-carrier: M=4 and S=3

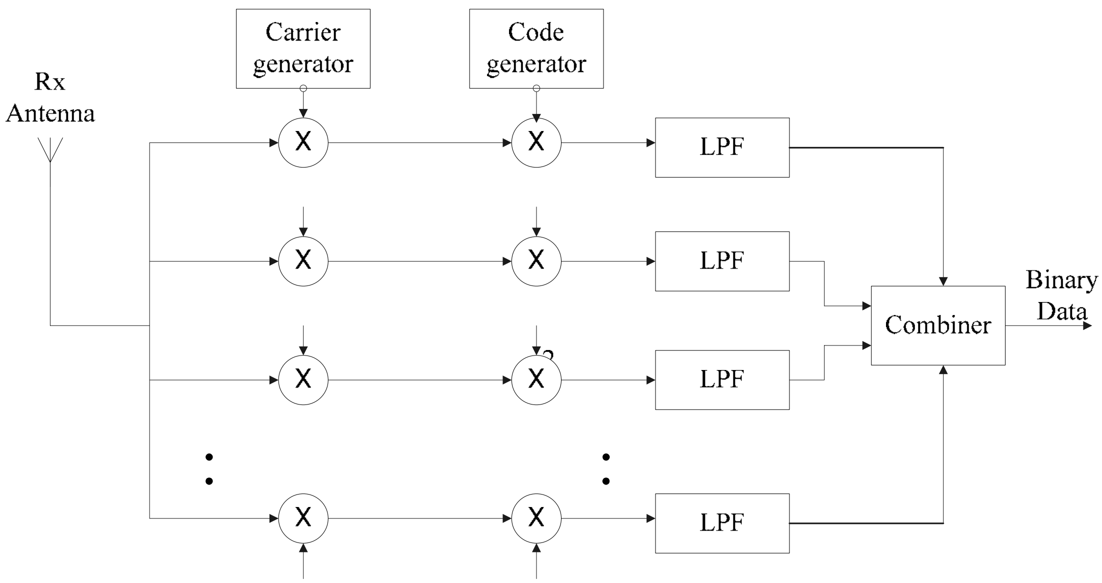


Fig. 2.6 Block diagram of Multicarrier CDMA receiver

After combining all sub-carriers signals, the dispreading operation in MC-CDMA receiver, simply involves the multiplication by a single chip. Because the PN code values are orthogonal in nature. The spreading operation in MC-CDMA can be used for multiple access schemes and 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. It is easy to achieve the scalability by changing the code length and the number of spreading code used to the link's modulation and coding scheme. The system capacity of MC-CDMA depends on the both processing gain and the cross correlation characteristics of the spreading codes.

2.5 MC-DS-CDMA

The family of orthogonal MC-DS-CDMA systems is shown in Fig.2.7 to 2.9, where the transmitter spreads the serial-to-parallel (SP) converted data streams using a time-domain spreading code [20], so that the resultant spectrum of each subcarrier remains orthogonal while maintaining the minimum required frequency separation. DS signals are transmitted in parallel on different subcarriers. Such a system has two main advantages:

1) It may suppress the MAI since zero cross-correlated orthogonal codes are used and
2) It may combat the effect of ICI via MC modulation

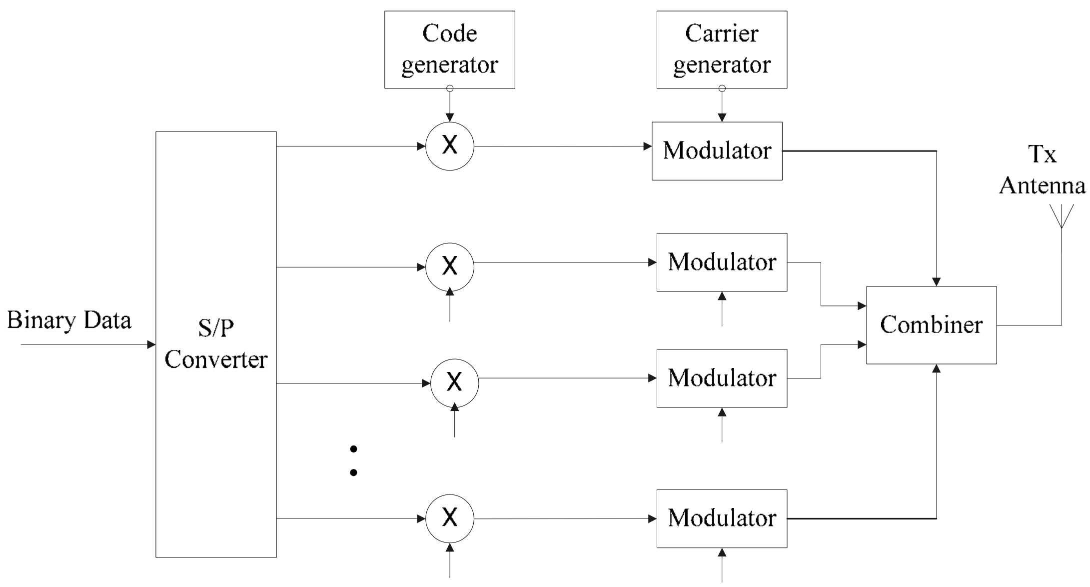


Fig. 2.7 Block diagram of MC-DS- CDMA Transmitter

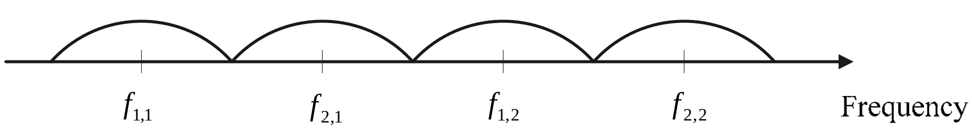


Fig. 2.8 Power spectral density of MC-DS- CDMA Transmition signal

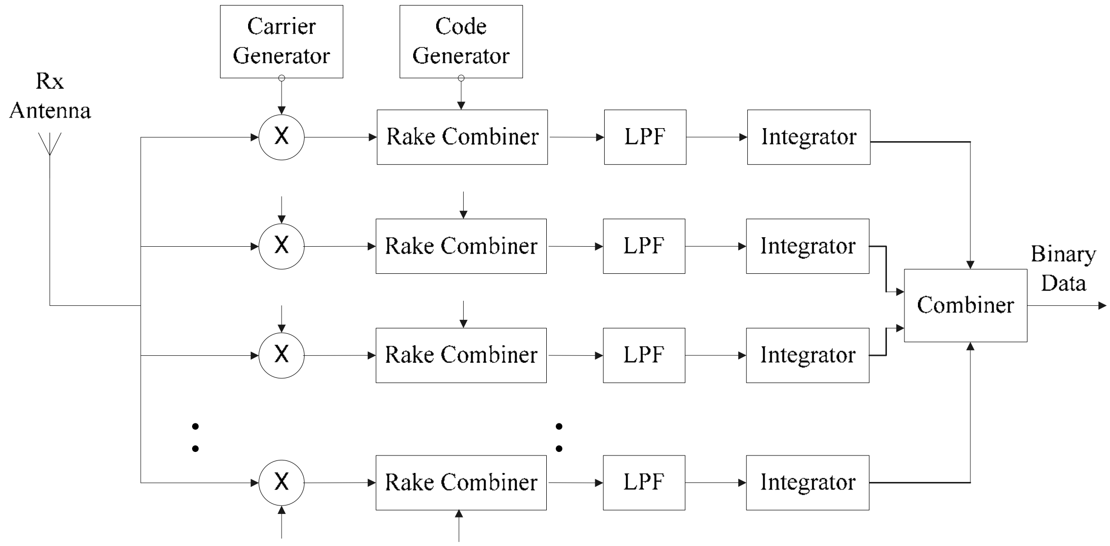


Fig. 2.9 Block diagram of MC-DS- CDMA receiver

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 Time domain spreading increase the achievable processing gain with each sub-carrier, while the frequency domain spreading further increase the total frequency gain. Small numbers of sub-carrier are generally considered since sub-carrier are disjoint and individually spread. This result lowers the peak to average power ratio (PAPR) in MC-DS-CDMA than in MC-CDMA for a same transmission bandwidth. MC-DS-CDMA is of special interest for the asynchronous uplink of mobile radio systems, due to its close relation to asynchronous single-carrier DS-CDMA systems.

2.6 MT-CDMA

A special case of MC-DS-CDMA systems is obtained when the sub-carrier spacing is equal to $1/(N_cT_s)$. The tight sub-carrier spacing allows the use of longer spreading codes to reduce multiple access interference; however, it results in an overlap of the signal spectra of the sub-carriers and introduces ICI. This special case of MC-DS-CDMA is referred to as multi-tone CDMA (MT-CDMA). An MT-CDMA signal is generated by first modulating a block of N_c data symbols on N_c sub-carriers applying OFDM before spreading the resulting signal with a code of length N_cL, where L is the spreading code length of conventional MC-DS-CDMA. Due to the N_c times increased sub-channel bandwidth with MT-CDMA, each sub-channel is broadband and more complex receivers are required. The ISI and ICI effects have severe impact on the system performance and high-complexity receivers are required to cancel them out. Fig. 2.10 to 2.12 shows the transmitter, power spectral density and receiver block diagram which are follows [9]:

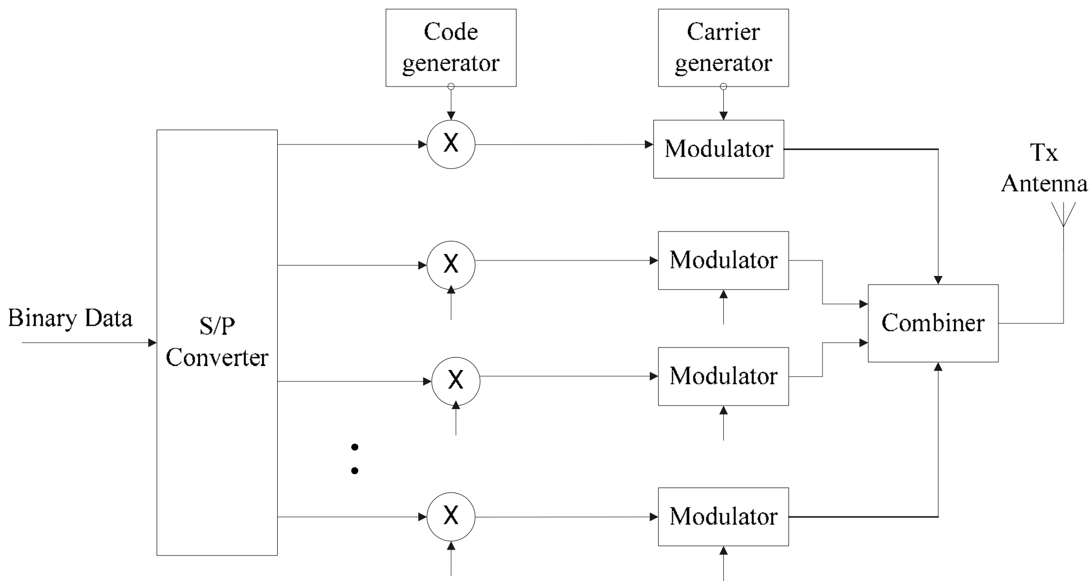


Fig. 2.10 Block diagram of MT- CDMA Transmitter

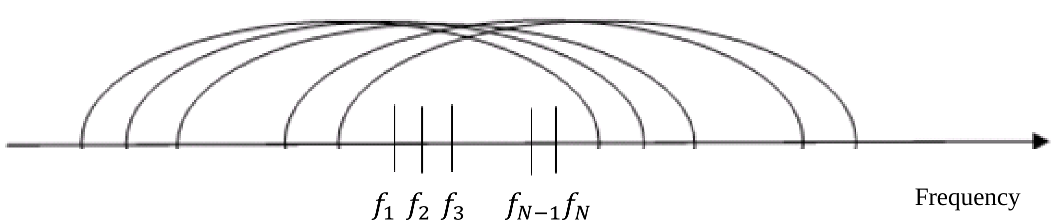


Fig. 2.11 Power spectral density of of MT- CDMA Transmitter

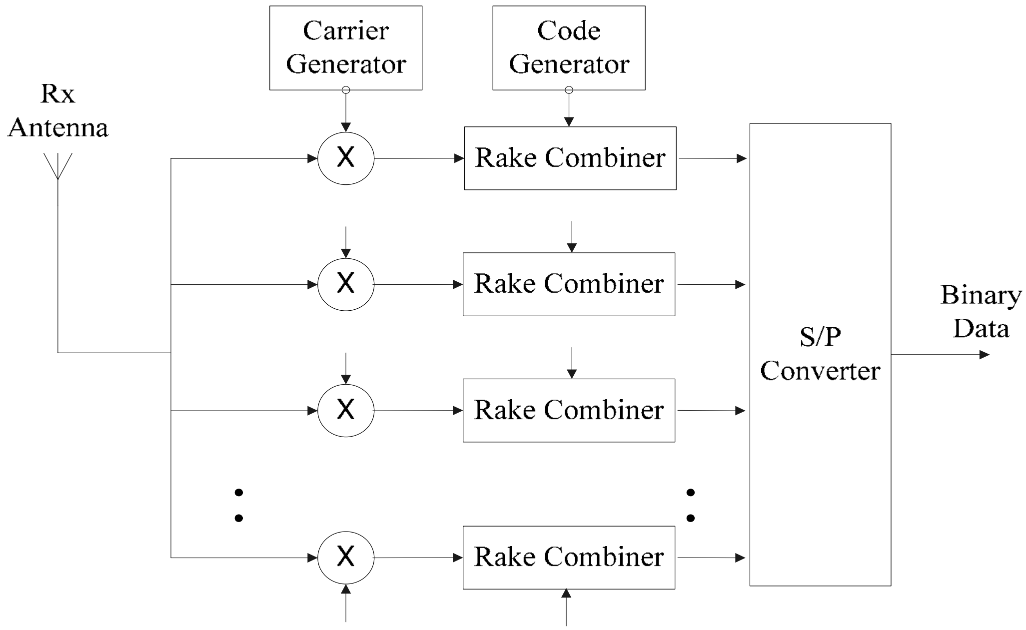


Fig. 2.12 Block diagram of MT- CDMA Receiver

2.7 Different CDMA schemes comparison [9]

Access Schemes	Symbol duration at subcarrier	The no. of Subcarreir	Processing Gain	Chip Duration	Subcarrier separeation	Required Bandwidth
DS-CDMA	T_s	(1)	G_{DS}	T_s/G_{DS}	-	G_{DS}/T_s
MC-CDMA	T_s	$N_c(=G_{MC})$	$G_{MC} \approx G_{DS}$	-	$1/T_s$	$(G_{MC}+1)/T_s$
MC-DS-CDMA	N_cT_s	N_c	$G_{MD} = G_{DS}$	N_cT_s/G_{DS}	G_{DS}/N_cT_s	$(N_c+1)G_{DS}/N_cT_s$
MT-CDMA	N_cT_s	N_c	$G_{MT} = N_cG_{DS}$	T_s/G_{DS}	$1/N_cT_s$	$(N_c-1)\frac{1}{N_cT_s} + 2G_{DS}/T_s$

Table: 2.1 Comparison among the different CDMA schemes

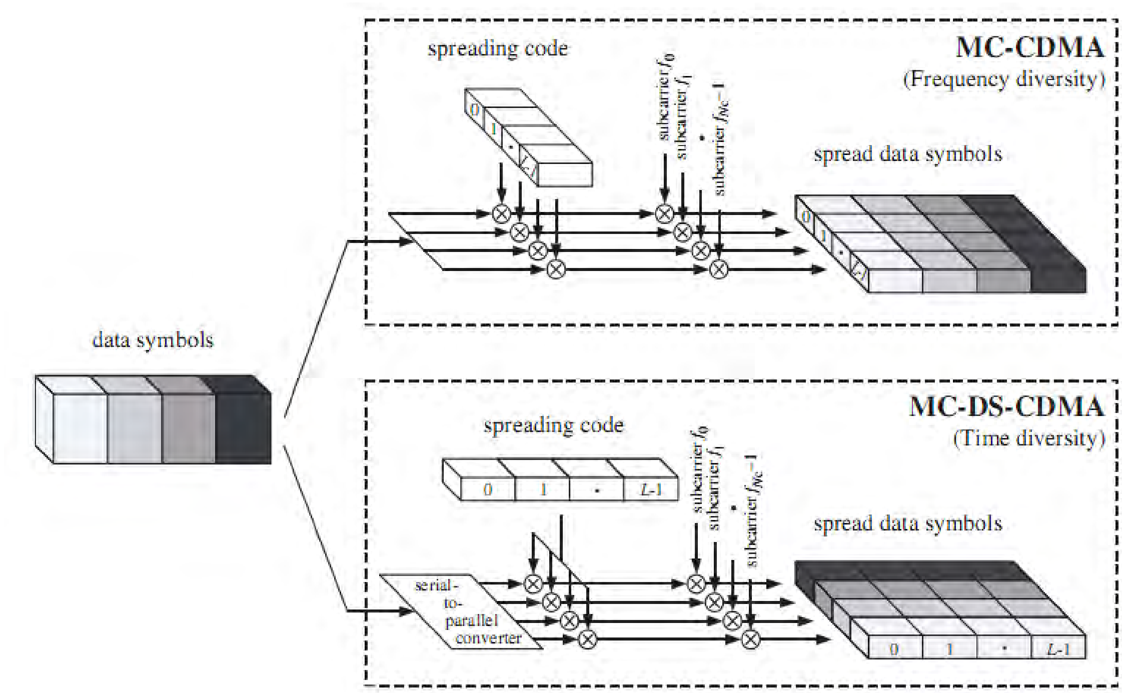


Fig. 2.13 General principle of MC-CDMA and MC-DS-CDMA system

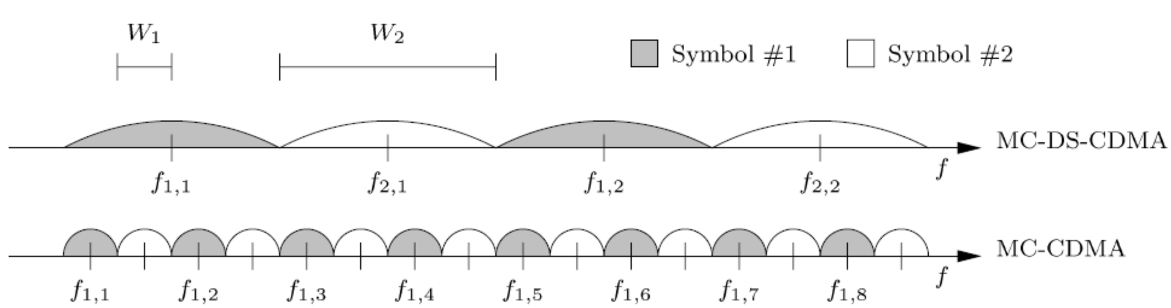


Fig. 2.14 Difference between MC-CDMA and MC-DS-CDMA

2.8 Spreading codes

The CDMA orthogonal spreading codes are one of the major elements within the whole CDMA system. The CDMA orthogonal spreading codes are combined with the data stream to be transmitted in such a way that the bandwidth required is increased and the benefits of the spread spectrum system can be gained [21]. The concept of CDMA is based around the fact that a data sequence is multiplied by a spreading code or sequence which increases the bandwidth of the signal. Then within the receiver the same spreading code or sequence is used to extract the required data. Only when the required code is used, does the required data appear from the signal.

2.8.1 Spreading code properties

In order to spread the data sequence (Direct Sequence Spread Spectrum), the code sequence must be [21]:

- Much faster than the data sequence.
- Exhibit some Randomness properties.
- The correlation of two different codes (cross- correlation)should be small
- The correlation of a code with a time-delay version of itself (auto-correltaion) should equal 0 for any time delay other than zero in order to reject multi-path interference.
- The code must have a long period.

2.8.2 Description of different code sequences

The binary sequences which can meet the above properties are called Pseudo-random (PN) code. Some popular PN code sequences used in spread spectrum transmission are described below:

i. **Maximum-Length (M) sequences** M-sequence codes are widely used in communication applications. They have certain properties such as:
    - A sequence has 2n-1 ones and 2n-1 -1 zeros.
    - Statistical distribution of ‘1’s and ‘0’s is well defined and same.
    - There is 2n-3 runs of ‘1’s and 2n-3 runs of ‘0’s of length one
    - Periodic autocorrelation of a m-sequence is 1 or -1/N.
    - N=2n-1, n= number of registers
    - Modulo-2 addition of a sequence with phase shifted replica of itself results in another replica of itself with phase-shift.
    - Every possible state of the n-stage generator exist at sometime during generation of complete code cycle and for one clock interval only.

M-sequences are created by using Linear Feedback Shift Registers (LFSR). Fig. 2.12 shows a three register LFSR with two different tap connecting arrangements.

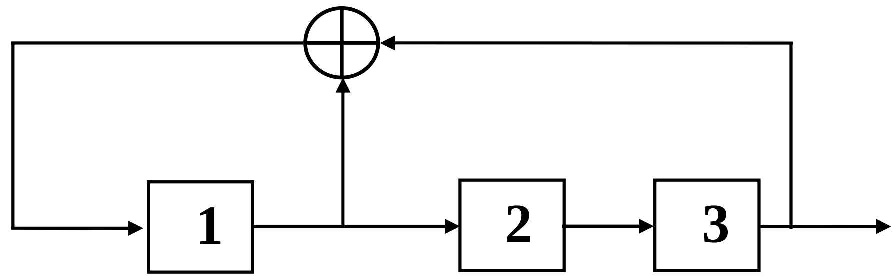


Fig. 2.15 Three stage LFSR generating m-sequence of period 7

ii. **Gold sequences** Gold sequences are constructed by the XOR of a preferred pair of m-sequences with the same clocking. They have well-defined cross correlation properties and only simple circuitry is needed to generate large number of unique codes. Fig.2.13 shows the shift registers for generating a preferred pair of sequences correlated the polynomials.

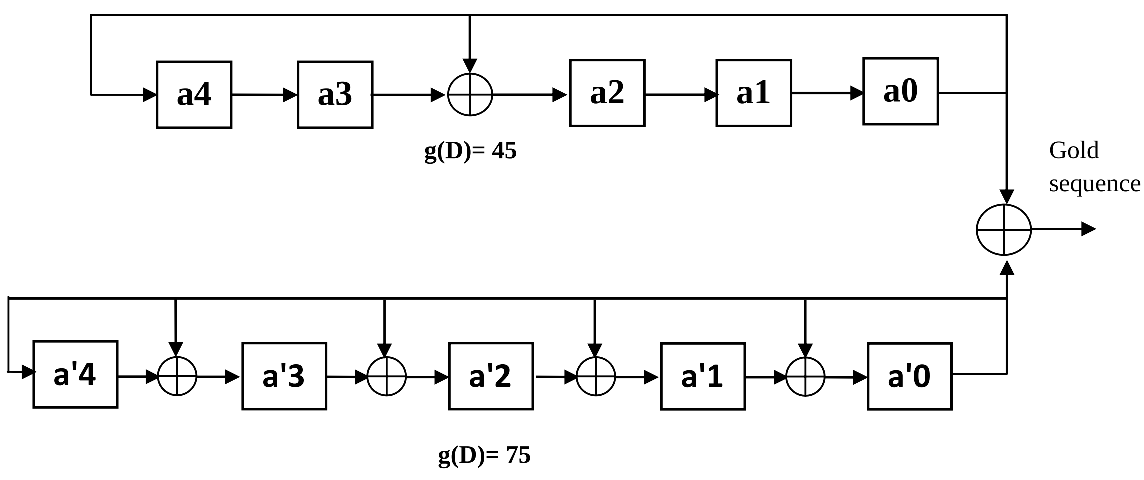


Fig.2.16 Generation of gold code sequence

Gold sequence are useful in non-orthogonal CDMA and they have only three cross-correlation peaks which tends to get less important as the length of the code increase. They also have a single auto-correlation peal at zero, just like ordinary PN sequences.

iii. **Kasami sequences** Kasami codes have popular use in 3G wireless schemes. They can classified as (1) large Kasami set or (2) small Kasami set. Small Kasami set has family size (M) = $2^{n/2}$ and period = N = 2^n-1. Their maximum cross-correlation is 2^n-1. Large Kasami set contains both gold sequence and small set of Kasami sequence as subset. Its period is N=2^n-1. Maximum cross-correlation is $2^{(n+2)/2}$.

2.9 Rake Receiver [6]

CDMA systems use the spread spectrum technique with spreading codes designed to provide very low correlation between successive chips. Due to the signal propagation characteristics of the wireless communications channel, the receiver may receive one direct line-of-sight (LOS) wave and many multiple versions of the transmitted signal at a spread of arrival times. If these multipath signals are delayed in time by more than one chip interval, the despreading process will make the uncorrelated noise appear as negligible at the receiver. This leads to the implementation of a RAKE receiver within a CDMA system, as it is able to recover each multipath signal and combine them with the correct delays to achieve a significant improvement in the SNR of the output signal. The RAKE receiver however, works only on the basis that these multipath components are practically uncorrelated from one another when their relative propagation delays exceed a chip period. 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 receiver is the effective receiver elements which are used for combination of diversified received signals. The representation of it’s principal is shown in the Fig.2.17 below:

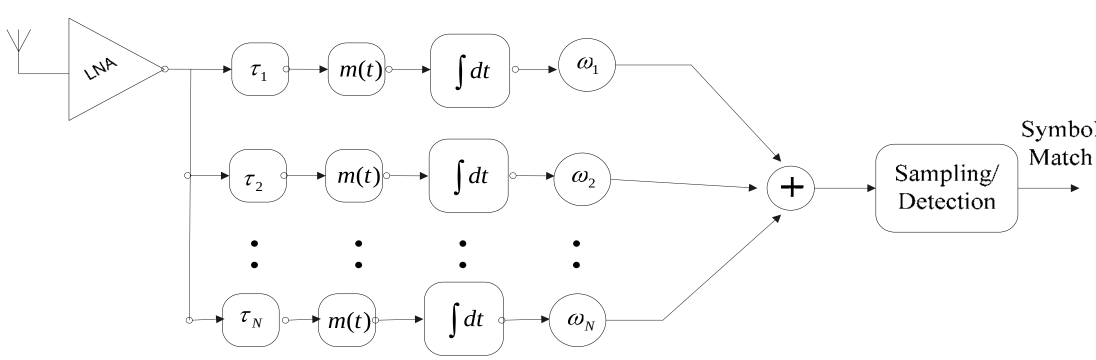


Fig.2.17 Rake receiver with N parallel correlators

2.10 Error Probability of Transmission Channel

In wireless communication system, error may occur both during transmission and reception. When the signal travelling through the medium with fading the amount of error in reception is more severe than transmission. The term probability of error may refer to the probabilities of various amounts of error occurring. The method of estimating reception error will be described for both BPSK and QPSK modulation in the next subsection.

2.10.1 Coherent reception in AWGN channel for BPSK

In the most basic form, transmitted digital signal sequences are represented in a binary format, with symbol drawn from the set {0, 1}. Consider an additive white Gaussian noise (AWGN) channel, where the received signal is the transmitted signal plus a white Gaussian noise component with zero mean and two sided power spectral density $N_0/2$. Also, consider coherent BPSK reception over an AWGN channel, as shown in Fig.2.8

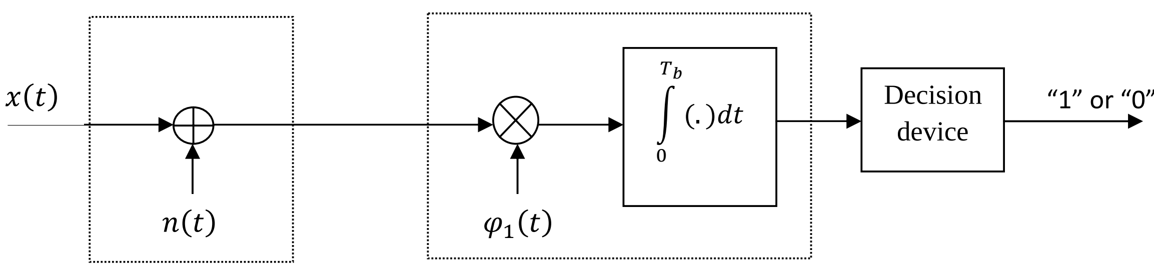


Fig. 2.18 Coherent reception in AWGN channel with BPSK

where the detection of a symbol transmitted over the time interval {0, T_b}. Without loss of generality, the transmitted signal is given by [6]

$$x(t)=\begin{cases}\sqrt{E_b}\,\varphi_1(t), & for\ symbol\ "1"\\ -\sqrt{E_b},\ \varphi_1(t), & for\ symbol\ "0"\end{cases} \tag{2.1}$$

where, $\varphi_1(t)$ is basis function. Now, in an AWGN channel, the received signal is

$$r(t) = x(t) + n(t) \tag{2.2}$$

where $n(t)$ denotes the white Gaussian noise. The output of the matched filter at t = T_b is given by

$$r_1 = \int_0^{T_b} r(t)\,\varphi_1(t)dt \tag{2.3}$$

In (2.3), r_1 is a Gaussian random variable with variance σ_n^2=$N_0/2$ and it's conditional probability density function (pdf) with mean ± $\sqrt{E_b}$ is given by

$$f_{r_1}(r_1) = \frac{1}{\sqrt{2\pi}\varphi_n}\, e^{-(r_1-\mu_1)^2/\,2\sigma_n^2} \tag{2.4}$$

With equally likely symbols "1" and "0", the probability of bit error rate (BER) is expressed as

P_b = (Probability of sending symbol '1')(probability of detecting '0' when symbol '1' was sent) + (Probability of sending symbol '0')(probability of detecting '1' when symbol '0' was sent)

$$P_b = P_r(1).\, P_r(r_1 > 0|\text{'1'}) + P_r(0).\, P_r(r_1 > 0|\text{'0'}) \tag{2.5}$$

Assuming that '1' and '0' are equally probable, one gets

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

$$P_r(r_1 > 0|\text{'0'}) = \int_0^{\infty} f_{r_1}(\mu_1, \sigma_n^2)d\,r_1$$

$$P_r(r_1 > 0|\text{'1'}) = \int_{-\infty}^{0} f_{r_1}(\mu_1, \sigma_n^2)d\,r_1$$

thus,

$$P_b = \frac{1}{2}\left[\int_0^{\infty} \frac{1}{\sqrt{2\pi}\varphi_n}\, e^{-(r_1-\mu_0)^2/\,2\sigma_n^2} + \int_{-\infty}^{0} \frac{1}{\sqrt{2\pi}\varphi_n}\, e^{-(r_1-\mu_1)^2/\,2\sigma_n^2}\right] \tag{2.6}$$

If we assume the following:

$$x = \frac{-r_1+\mu_0}{\sqrt{2}\varphi_n} \qquad y = \frac{r_1-\mu_1}{\sqrt{2}\varphi_n}$$

$$dx = \frac{-dr_1}{\sqrt{2}\varphi_n} \qquad dy = \frac{dr_1}{\sqrt{2}\varphi_n}$$

Putting these values in (2.5), one gets

$$P_b = \frac{1}{2}\left[\int_{\frac{-\mu_0}{\sqrt{2}\varphi_n}}^{\infty} \frac{1}{\sqrt{\pi}}\, e^{-x^2}dx + \int_{-\infty}^{\frac{-\mu_1}{\sqrt{2}\varphi_n}} \frac{1}{\sqrt{\pi}}\, e^{-y^2}dy\right]$$

$$= \frac{1}{\sqrt{\pi}} \int_{\frac{\mu_0}{\sqrt{2}\varphi_n}}^{\infty} e^{-x^2}dx$$

$$= \frac{1}{2}\; erfc\,[\frac{\mu_0}{\sqrt{2}\varphi_n}] \tag{2.7}$$

or, $P_b = \frac{1}{2}\ erfc\ [\frac{\sqrt{E_b}}{\sqrt{2}\sqrt{\sigma_n^2}}]$ as $\sigma_n^2 = \frac{N_0}{2}$

$$= \frac{1}{2}\ erfc\ [\frac{\sqrt{E_b}}{\sqrt{N_0}}]$$

$$= Q[\frac{\sqrt{2E_b}}{\sqrt{N_0}}] \quad (2.8)$$

2.10.2 Coherent reception in AWGN channel for QPSK

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 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 of BPSK and given by

$$P_b = \frac{1}{2}\ erfc\ [\frac{\sqrt{E_b}}{\sqrt{N_0}}] = Q[\frac{\sqrt{2E_b}}{\sqrt{N_0}}] \quad (2.9)$$

2.10.3 Coherent reception in flat Rayleigh Fading channel [6]

For a stationary flat and slow fading channel, the following facts are assumed:

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

ii. 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. The received signal is then given by

$$r(t) = \alpha(t) \exp[j\theta(t)]\, x(t) + n(t) \quad (2.10)$$

where, $n(t)$ is white Gaussian noise component with zero mean and two sided power spectral density N_0 /2, $\alpha(t)$, the amplitude fading and $\theta(t)$ phase distortion. According to the second assumption, it is possible for the receiver to estimate $\theta(t)$ and remove it. As a result, in the following BER performance analysis, $\theta(t)$ is assumed to be zero.

Let, E_b (constant) is bit error of transmitted signal, α is amplitude fading parameter. Then instantaneous bit energy of received signal is defined as $\alpha^2 E_b$.

Now the average SNR without fading, $\gamma_b(\alpha) = \gamma_b|\overline{\alpha 2}| = \gamma_b E(a^2)$ (2.11)

where, $E(a^2) = 2\sigma_\alpha^2$

thus, the pdf of α is

$$P_b(\alpha\ ) = \frac{\alpha}{\sigma_\alpha^2} e^{-\alpha^2/2\sigma_\alpha^2}; \quad when\ \alpha \geq 0$$

$$= 0; \quad \text{else}$$

So the conditional BER, $P_b(\gamma_b|\alpha\ ) = Q(\sqrt{2\gamma_b\alpha^2})$ (2.12)

Now the average BER for coherent PSK is given as:

$$P_b(\overline{\gamma_b}) = \int_{-\infty}^{\infty} P_b(\gamma_b|\alpha) P_b(\alpha)\, d\alpha$$

$$= \int_{-\infty}^{\infty} Q(\sqrt{2\gamma_b\alpha^2}) \frac{\alpha}{\sigma_\alpha^2} e^{-\alpha^2/2\sigma_\alpha^2}\, d\alpha \qquad (2.13)$$

Let, $a^2 = x$, $\therefore 2\alpha d\alpha = dx$ Putting these values in (2.12), one obtains

$$P_b(\overline{\gamma_b}) = \frac{1}{2}\int_{-\infty}^{\infty} Q(\sqrt{2\gamma_b x}) \frac{\alpha}{\sigma_\alpha^2} e^{-x/2\sigma_\alpha^2}\, dx$$

$$= \frac{1}{2\sigma_\alpha^2}\int_{-\infty}^{\infty} [\{\frac{1}{\sqrt{\pi}} \int_{\sqrt{2\gamma_b x}}^{\infty} e^{-x^2/2}\, dx]. e^{-x/2\sigma_\alpha^2}\, dx$$

$$= \frac{1}{2}[1 - \sqrt{\frac{\overline{\gamma_b}}{1+\overline{\gamma_b}}}\ ] \qquad (2.14)$$

2.12 Summary

The major characteristics of single carrier and multicarrier CDMA techniques and multicarrier modulation OFDM are presented in this chapter. CDMA technique allows a universal frequency reuse in a cellular system in efficient and flexible manner. The general concept of OFDM is described here briefly due to its combination with CDMA produced multicarrier CDMA. Therefore, the basic four multicarrier CDMA techniques such as DS-CDMA, MC-CDMA, MC-DS-CDMA and MT-CDMA are explained. Moreover, the effect of fading on CDMA channel and the different types of code sequences in CDMA are introduced. At the end of this chapter, error probability of transmission channel is described for both BPSK and QPSK modulation considering the fading effect on CDMA channel. In the next chapter, the analytical expression of MC-CDMA system and its performance evaluation will be formulated, which is the main objective of this thesis work.

CHAPTER-3

PERFORMANCE ANALYSIS OF MC-CDMA SYSTEM

3.1 Introduction

In this chapter, a MC-CDMA wireless communication system is considered using multi-carrier QPSK modulation with orthogonal subcarriers after converting the high data rate bit stream to low data rate parallel streams. At the receiver, multiple receivers' individual correlators for each subcarrier channel is considered. The output of each receiver is combined using a maximal ratio combiner. A novel analytical approach is developed to find the analytical expressions for the signal, interference and noise at the output of the MRC considering a Nakagami-m fading channel. Analysis is also be carried out to find the expression for the MAI and instantaneous SINR and the probability density function of the SINR at the output of maximal ratio combiner is derived. The expression for the conditional BER conditioned on a given value of SINR is derived. The average BER is found by averaging the conditional BER over the PDF of instantaneous SINR. The performance results is evaluated numerically for different system parameters like number of subcarriers, code length of a sub-channel, bit rate and number of receiving antennas. For a given BER (10^{-3}), the optimum values of the parameters are determined from the BER performance results.

3.2 MC-CDMA System Model

3.2.1 MC-CDMA Transmitter Model

Fig. 3.1 shows the transmitter structure of MC-CDMA system. In a specific cell, consider for any period of time, there are k number of users and k-th user is the reference.

Assume the following to get a system model of MC-CDMA:

i. All the users are active at any time

ii. All the transmitter power level of user are equal

iii. The number of sub-carrier are larger than the spreading factor i.e. $G_{MC}>N_c$.

iv. The bit rate is much larger than the chip rate of spreading sequence.

v. All the transmitted signals power is suffering equal amount of fading at any time.

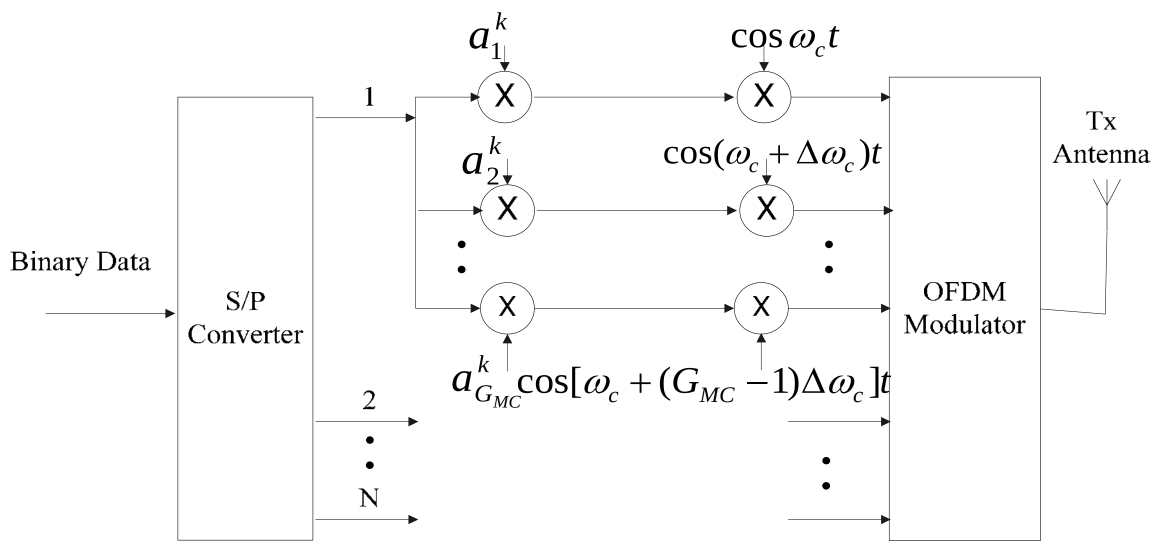


Fig.3.1 A MC-CDMA Transmitter model

In the above system, the data stream (symbol duration T_s) is first serial to parallel converted, onto N parallel arms. This serial-to-parallel conversion is performed to ensure frequency nonselective fading over the subcarrier, which is vital in multicarrier transmission. The new symbol duration is expected to $T_p = NT_s$, keeping the data rate fixed at

$$R = \frac{1}{T_s}$$

Spreading sequence is then applied to each of the N parallel paths, modulating single chip on each of the G_{MC} subcarrier, making $T_c = NT_s$. The total number of subcarrier is therefore equal to the product $= N * G_{MC}$.

Let, k = Total no of users (simultaneously),

P = Chip power of each user

N_c = No. of chip in spreading codes per bit

G_{MC} = No. of sub-carriers

N = No. of parallel paths

$m_k(t)$ = Input data steam of the k-th user

3.2.2 MC-CDMA Receiver Model

The structure of a MC-CDMA receiver is shown in Fig.3.2:

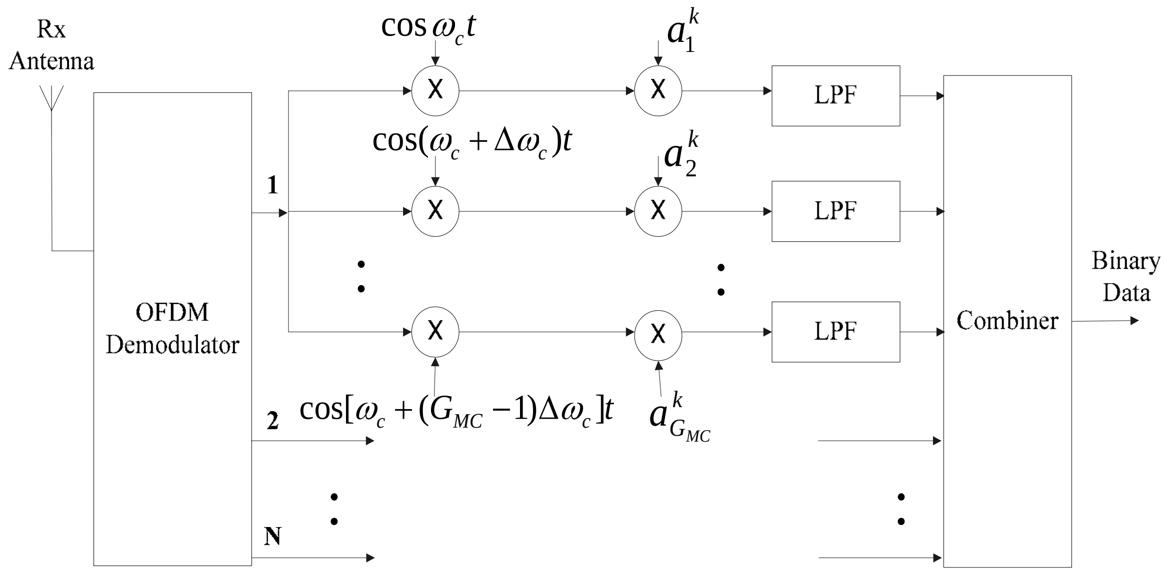


Fig.3.2 A MC-CDMA Receiver model

In the above receiver model, the received signal of k active users is combined in frequency domain. The signal is then demodulated and despreaded by respective subcarrier and PN code. Maximal Ratio Combining (MRC) is applied to the despreaded signals. However, through a Nakagami-m fading channel, all the subcarriers have different amplitude levels and different phase shifts, which results in the distortion of the orthogonality among users.

3.3 Analysis of MC-CDMA System without Rake Receiver

PN sequence no k-th user for $1 \leq j \leq N$ is given by,

$$c_k(t) = \sum_{j=0}^{N-1} a_k(t - jT_c) \quad ; \quad [a = \pm 1]$$

The data symbol of k-th users is given by,

$$m_k(t) = \sum_{n=-\infty}^{\infty} b_n^{(k)} \quad ; \quad [b = \pm 1]$$

The expression for modulated signal is given by

$$\sum_{j=1}^{G_{MC}} \sqrt{2P}\ \ b_{n,j}^{(k)} \cos[\{\omega_c + (j-1)\Delta\omega_c\}t + \varphi_j] \tag{3.1}$$

Hance, the k-th user transmitted signal can be expressed as

$$S_k(t) = \sum_{i=1}^{N} \sum_{j=1}^{G_{MC}} \sqrt{2P}\ \ b_{n,j,i}^{(k)} \left(\sum_{x=1}^{N_c} a_{x,j}^{k}\right) \cos[\{\omega_c + (j-1)\Delta\omega_c + (i-1)\ \Delta\omega\}t + \varphi j] \tag{3.2}$$

where

$b_{n,j,i}^{(k)}$ = n-th bit of k-th user, which is modulated by j-th channel in i-th branch

N = no. of parallel branch

G_{MC} = no. of sub carrier

P = transmitted power per carrier

ω_c = carrier frequency

φ_j = random phase for each carrier $[0, 2\pi]$

$a_{x,j}^{(k)}$ = periodic train of chip, $a_1, a_2 \ldots\ldots a_N$

$= \pm 1$

$\Delta\omega = \Delta\omega_c \times G_{MC}$

When there are k active users, the received signal is given by

$$r(t) = \sum_{m=1}^{k} \left[\sqrt{2P} \sum_{i=1}^{N} \sum_{j=1}^{G_{MC}} \{b_{n,j,i}^{(k)} \left(\sum_{x=1}^{N_c} a_{x,j}^{k}\right) \cos[\{\omega_c + (j-1)\Delta\omega_c + i-1\ \Delta\omega\}t + \varphi j] + \eta(t) \tag{3.3}$$

where, k is the total no. of users and $\eta(t)$ is the AWGN noise with two sided spectral density $N_0/2$. This signal while propagating through the medium and suffering Nakagami-m fading. Here, $\alpha(t)$ represents the instantaneous amplitude of distortion and θ be the instantaneous phase distribution due to fading.

So, the received signal is given by:

$$r(t) = \sum_{m=1}^{k}\left[\alpha(t)\sqrt{2\mathrm{P}}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}} \mathrm{b}_{\mathrm{n,j,i}}^{\mathrm{m}} \left(\sum_{x=1}^{N_c} a_{x,j}^{k}\right) \cos[\{\omega_c + (j-1)\Delta\omega_c + (i-1)\Delta\omega\}t + \varphi j+\theta] + \eta(t) \quad (3.4)$$

This signal is then coherently demodulated by the respective carrier and the output becomes $y(t)$, given by

$$y(t)= \sum_{m=1}^{k}\left[\alpha(t)\sqrt{2\mathrm{P}}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}} \mathrm{b}_{\mathrm{n,j,i}}^{\mathrm{m}} \left(\sum_{x=1}^{N_c} a_{x,j}^{k}\right) \cos[\{\omega_c + (j-1)\Delta\omega_c + (i-1)\Delta\omega\}t + \varphi j+\theta] \times \cos\{\omega c+j-1\Delta\omega c\}t + i=1Nj=1GMC\eta t \times \cos\{\omega c+j-1\Delta\omega c\}t \quad (3.5)$$

The demodulated signal is then despreaded and expressed as

$$y(t)= \sum_{m=1}^{k}\left[\frac{\alpha(t)\sqrt{2\mathrm{P}}}{2}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}} \mathrm{b}_{\mathrm{n,j,i}}^{\mathrm{m}} \sum_{x=1}^{N_c}(a_{x,j}^{m} \times a_{x,j}^{k}) \{\cos[\{2\omega_c + 2(j-1)\Delta\omega_c + i-1\ \Delta\omega\}t+\varphi j+\theta] + \cos\{i-1\ \Delta\omega t+\varphi j+\theta\}\}$$

$$+ \sum_{i=1}^{S}\sum_{j=1}^{G_{MC}} \eta(t) \times \sum_{x=1}^{N_c} a_{x,j}^{k} \cos\{\omega_c + (j-1)\Delta\omega_c\}t \quad (3.6)$$

Now separating the k-th user term and assuming μ as the cross-correlation among the codes of the k-th user and all other users, one obtains

$$y(t)=\frac{\alpha(t)\sqrt{2P}}{2}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\Big[b_{n,j,i}^{k}\sum_{x=1}^{N_c}(1)\{\cos[\{2\omega_c+2(j-1)\Delta\omega_c+(i-1)\,\Delta\omega\}t+\varphi_j+\theta]+\cos\{i-1\,\Delta\omega t+\varphi j+\theta\}\}$$

$$+\sum_{m=1}^{k-1}\left[\frac{\alpha(t)\sqrt{2P}}{2}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}b_{n,j,i}^{m}\sum_{x=1}^{N_c}(\mu)\{\cos[\{2\omega_c+2(j-1)\Delta\omega_c+(i-1)\,\Delta\omega\}t+\varphi_j+\theta]+\cos\{(i-1)\,\Delta\omega t+\varphi_j+\theta\}\}\right]$$

$$+\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\eta(t)\times\sum_{x=1}^{N_c}a_{x,j}^{k}\cos\{\omega_c+(j-1)\Delta\omega_c\}t \qquad (3.7)$$

The value of μ is ‘1’ when maximum interference occurs and is ‘0’ with no interference. After passing through the low-pass filter, the high frequency components are eliminated, thus (3.7) becomes

$$y(t)=\frac{N_c\alpha(t)\sqrt{2P}}{2}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}b_{n,j,i}^{k}\cos\left(\varphi_j+\theta\right)$$

$$+\sum_{m=1}^{k-1}\left[\frac{\alpha(t)\sqrt{2P}}{2}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\left\{b_{n,j,i}^{m}\,N_c\mu\;\cos\left(\varphi_j+\theta\right)\right\}\right]$$

$$+\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\eta(t)\times\sum_{x=1}^{N_c}a_{x,j}^{k}\cos\{\omega_c+(j-1)\Delta\omega_c\}t \qquad (3.8)$$

After integrating over 0 to T_b , we get the following:

$$y(t)= \frac{N_c\alpha(t)\sqrt{2P}}{2T_b}\int_0^{T_b}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}} b_{n,j,i}^{k}\cos\left(\varphi_j+\theta\right) dt$$
$$+\sum_{m=1}^{k-1}\left[\frac{\alpha(t)\sqrt{2P}}{2T_b}\int_0^{T_b}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\left\{ b_{n,j,i}^{m} N_c\mu \ \cos\left(\varphi_j+\theta\right)\right\} dt\right]$$
$$+\frac{1}{T_b}\int_0^{T_b}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\eta(t) \times\sum_{x=1}^{N_c} a_{x,j}^{k}\cos\{\omega_c+(j-1)\Delta\omega_c\}t\, dt \tag{3.9}$$

or

$$y(t)= \frac{N_c\alpha(t)\sqrt{2P}}{2T_b}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}} b_{n,j,i}^{k}\cos\left(\varphi_j+\theta\right)\int_0^{T_b} dt$$
$$+\sum_{m=1}^{k-1}\left[\frac{\alpha(t)\sqrt{2P}}{2T_b}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\left\{ b_{n,j,i}^{m} N_c\mu \ \cos\left(\varphi_j+\theta\right)\right\}\int_0^{T_b} dt\right]$$
$$+\frac{1}{T_b}\int_0^{T_b}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\eta(t) \times\sum_{x=1}^{N_c} a_{x,j}^{k}\cos\{\omega_c+(j-1)\Delta\omega_c\}t\, dt \tag{3.10}$$

or

$$y(t)= \frac{N_c\alpha(t)\sqrt{2P}}{2}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}} b_{n,j,i}^{k}\cos\left(\varphi_j+\theta\right)$$
$$+\sum_{m=1}^{k-1}\left[\frac{\alpha(t)\sqrt{2P}}{2}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\left\{ b_{n,j,i}^{m} N_c\mu \ \cos\left(\varphi_j+\theta\right)\right\}\right]$$
$$+\frac{1}{T_b}\int_0^{T_b}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\eta(t) \times\sum_{x=1}^{N_c} a_{x,j}^{k}\cos\{\omega_c+(j-1)\Delta\omega_c\}t\, dt \tag{3.11}$$

or

$$y(t) = y_k(t) + y_{MAI}(t) + \eta(t) \tag{3.12}$$

here,

$y_k(t)$ = Desired signal of k-th user

$y_{MAI}(t)$ = Multiple Access Interference

$\eta(t)$ = Noise

Desired received signal

Received signal of k-th user at receiver output is $y_k(t)$ is given by

$$y_k(t) = \frac{N_c \alpha(t)\sqrt{2\mathrm{P}}}{2} \sum_{i=1}^{N} \sum_{j=1}^{G_{MC}} \mathrm{b}_{\mathrm{n,j,i}}^{\mathrm{k}} \cos\left(\varphi_{\mathrm{j}} + \theta\right)$$

$$y_k(t) = N_c \alpha(t) \sqrt{2\mathrm{P}/2} \sum_{i=1}^{N} \sum_{j=1}^{G_{MC}} \mathrm{b}_{\mathrm{n,j,i}}^{\mathrm{k}} \cos\left(\varphi_{\mathrm{j}} + \theta\right) \tag{3.13}$$

Since $\mathrm{b}_{\mathrm{n}}^{\mathrm{k}} = \pm 1$, $\sum_{i=1}^{N} \sum_{j=1}^{G_{MC}} \mathrm{b}_{\mathrm{n,j,i}}^{\mathrm{k}} = \mathrm{N\ G_{MC}}$, Thus the above term becomes,

$$y_k(t) = \mathrm{N\ G_{MC}} N_c \alpha \sqrt{2\mathrm{P}/2} \sum_{i=1}^{N} \sum_{j=1}^{G_{MC}} \cos\left(\varphi_{\mathrm{j}} + \theta\right)$$

Thus, for the k-th user, the desired signal power, P_s is given by

$$P_s = \frac{1}{2}\, \alpha^2 (\mathrm{N\ G_{MC}} N_c \sqrt{2\mathrm{P}/2})^2$$

$$= \frac{1}{4}\, (\alpha^2 N^2 N_c{}^2 \mathrm{G_{MC}}{}^2 \mathrm{P}) \tag{3.14}$$

Multiple Access Interference (MAI)

$$y_{MAI}(t) = \sum_{m=1}^{k-1}\left[\frac{\alpha(t)\sqrt{2\mathrm{P}}}{2}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\left\{ \mathrm{b}_{\mathrm{n,j,i}}^{\mathrm{m}}\, N_c\mu \;\cos\left(\varphi_{\mathrm{j}}+\theta\right)\right\}\right]$$

$$= \sum_{m=1}^{k-1}\left[\frac{\alpha(t)\, N_c\,\mu\,\sqrt{2\mathrm{P}}}{2}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\left\{ \mathrm{b}_{\mathrm{n,j,i}}^{\mathrm{m}} \;\cos\left(\varphi_{\mathrm{j}}+\theta\right)\right\}\right]$$

Thus the interference power is given by

$$P_{MAI} = \sum_{m=1}^{k-1}\left[\frac{1}{2}\,(\alpha\, N_c\, G_{MC}\, N\,\mu\,\sqrt{2\mathrm{P}/2})^2\right]$$

$$= \sum_{m=1}^{k-1}\left[\frac{1}{4}\,(\alpha^2\mu^2N^2{N_c}^2{\mathrm{G_{MC}}}^2\,\mathrm{P}\right]$$

$$= \frac{1}{4}\,(\alpha^2\mu^2N^2{N_c}^2{\mathrm{G_{MC}}}^2\,\mathrm{P}\,(k-1) \tag{3.15}$$

Noise

$$\eta(t) = \frac{1}{T_b}\int_0^{T_b}\sum_{i=1}^{N}\sum_{j=1}^{G_{MC}}\eta(t)\;\times\sum_{x=1}^{N_c} a_{x,j}^{k}\cos\{\omega_{\mathrm{c}}+(\mathrm{j}-1)\Delta\omega_{\mathrm{c}}\}\mathrm{t}\,\mathrm{dt}$$

Now, it can be evaluated that, the noise power is [19],

$$\sigma_n^2 = \frac{N_0}{4T_b} \qquad \text{where, } N_0 = KTR_b \tag{3.16}$$

Signal to interference and noise ratio (SINR)

$$\mathrm{SINR} = \frac{P_S}{P_{MAI}+\sigma_n^2} \tag{3.17}$$

or, $$\gamma = \frac{\frac{1}{4}\,(\alpha^2N^2{N_c}^2{\mathrm{G_{MC}}}^2\mathrm{P})}{\frac{1}{4}\,(\alpha^2\mu^2N^2{N_c}^2{\mathrm{G_{MC}}}^2\,\mathrm{P}\,(k-1)+\frac{\mathrm{N_0}}{4\mathrm{T_b}}}$$

$$= \frac{\alpha^2N^2{N_c}^2{\mathrm{G_{MC}}}^2\mathrm{P}\;\;\mathrm{T_b}}{\alpha^2\mu^2N^2{N_c}^2{\mathrm{G_{MC}}}^2\,\mathrm{P}\,(k-1)\mathrm{T_b}+\;\mathrm{N_0}}$$

$$= \frac{\alpha^2 N^2 {N_c}^2 {\mathrm{G_{MC}}}^2 \ \mathrm{E_b}}{\alpha^2 \mu^2 N^2 {N_c}^2 {\mathrm{G_{MC}}}^2 \ (k-1) + \left(\frac{\mathrm{E_b}}{\mathrm{N_0}}\right)^{-1}} \quad (3.18)$$

BER without Rake Receiver

Now this γ is a function of α. So, for instantaneous value of α, the instantaneous bit error rate is,

$$P_b(\alpha) = f(\gamma) = \frac{1}{2}\ erfc[\frac{\gamma}{\sqrt{2}}]$$

Thus, $P_b(\alpha) = \frac{1}{2}\ erfc[\frac{\alpha^2 N^2 {N_c}^2 G_{MC}^2 E_b}{\alpha^2 \mu^2 N^2 {N_c}^2 G_{MC}^2 (k-1) + (\frac{E_b}{N_0})^{-1}} \times \frac{1}{\sqrt{2}}]$ (3.19)

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

$$P_b(\alpha) = \int_0^\infty P_b(\alpha) \, . \, f(\alpha) d\alpha \quad (3.20)$$

here,

$P_b(\alpha)$= Instantaneous BER

$f(\alpha)$= pdf of amplitude distortion co-efficient for Nakagami-m fading

or, $f_\alpha(x) = \left(\frac{m}{\Omega}\right)^m \frac{x^{m-1}}{\Gamma(m)} e^{-\left(\frac{m}{\Omega}\right)x}$ (3.21)

where *m* is the Nakagami fading parameter and $\Gamma(m)$ is gamma function defined as

$$\Gamma(m) \triangleq \int_0^\infty t^{m-1} e^t dt \qquad m > 0$$

and $\Omega = E[\alpha^2]$ where, Ω = average fading power

$$m = \frac{(E[\alpha^2])^2}{\sigma_\alpha^2}$$

3.4 Model of MC-CDMA system with multiple received antennas

Consider there are M received antennas at the receiver and each antennas have L Rake fingers. The output of m-th antennas are combined with Maximal Ratio Combining (MRC). Functional diagram of MC-CDMA with M received antenna is shown in Fig.3.3:

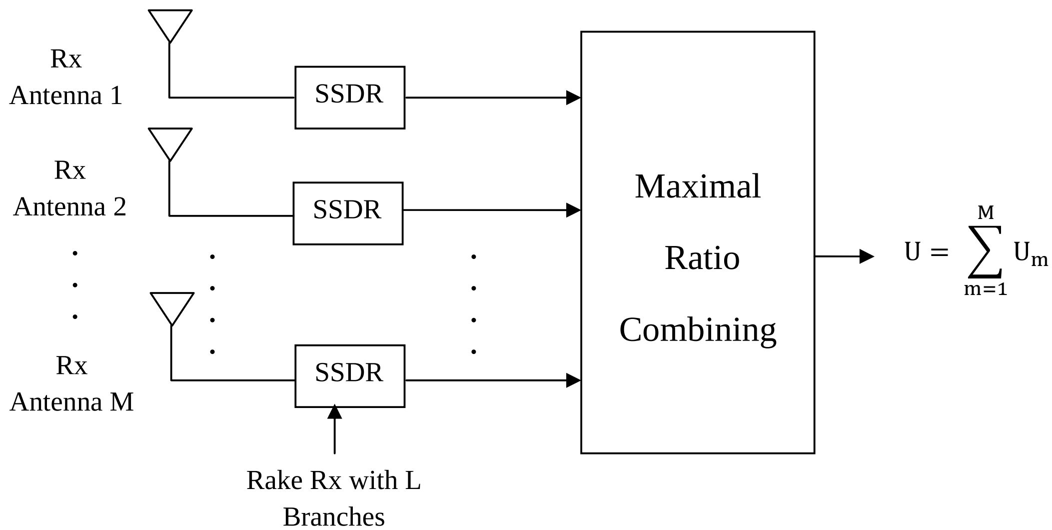


Fig.3.3 Functional block diagram of spatial diversity with Maximal Ratio Combining (MRC)

3.5 Analysis of MC-CDMA System with a Rake Receiver

Let us consider there are rake receiver in each subcarrier channel that have L number of fingers with Equal gain combining. Figure.3.4 shows the MC-CDMA system with Rake receiver.

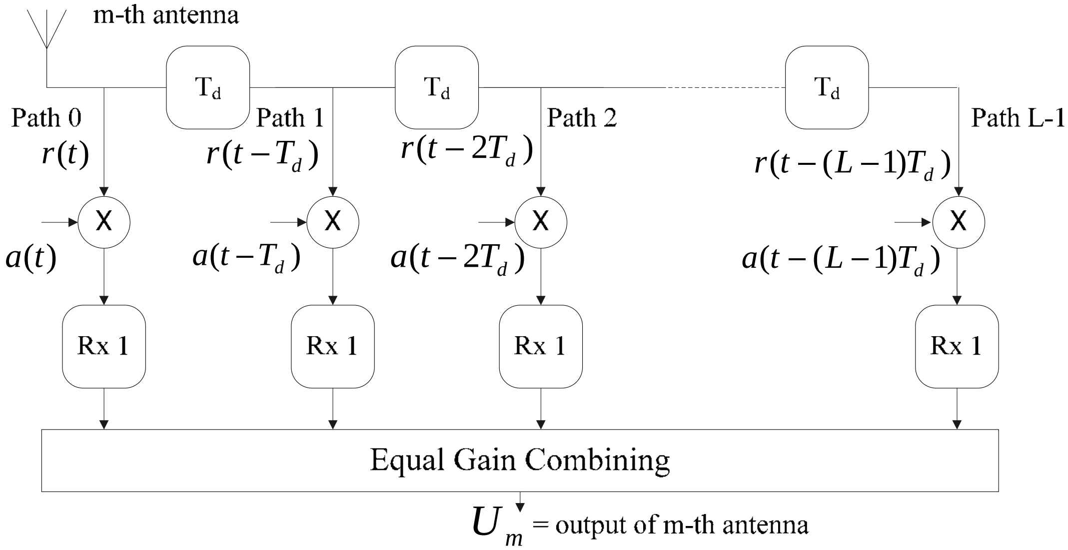


Fig.3.4 MC-CDMA receiver with Rake

The composite signal received by the m-th antenna is

$$r_m(t) = \sum_{k=0}^{L-1} r_{m,k}(t) + n_j(t) + n(t) \tag{3.22}$$

The de-spreaded signal of k-th path of the m-th antenna is

$$S_{m,k}(\mathrm{t}) = r_m(\mathrm{t} - (\mathrm{L} - 1 - \mathrm{k})\, T_c)\;\; d_{nN+l-(L-1)} \quad ; \text{ for } nT_s + lT_c \le \mathrm{t} \le nT_s + (l+1)T_c$$

$$\& \;\; 0 \le \mathrm{k} \le \mathrm{L-1}$$

Each of these L components are processed with separate detectors and the output are assumed to form,

$\{U_m\}$ for $1 \le m \le M$.

Let,

$\lambda_{m,k}$= instantaneous received bit SNR for Antenna m & path k

$\lambda_m = \sum_{k=0}^{L-1} \lambda_{m,k}$ = instantaneous processed bit SNR for Antenna m

$\lambda = \sum_{m=1}^{M} \lambda_m$ = Total instantaneous processed bit SNR

Thus, $\Lambda_k = E[\lambda_{m,k}]\ \forall_m$

$\Lambda = \Lambda_m == \sum_{k=0}^{l-1} \Lambda_k$ = Total average bit SNR for m antenna,

$$\therefore E(\lambda) = \sum_{m=1}^{M} \Lambda_m = M\Lambda. \tag{3.23}$$

If $\gamma_1, \gamma_2 \ldots\ldots\ldots \gamma_L$ be the instantaneous bit SINR for different L branches, then the conditional probability of bit error rate at the output of an SSDR with post detection Maximal ratio combining is given by

$$P_b(\gamma) = \frac{1}{2^{2L-1}}\ e^{-\gamma} \sum_{k=0}^{L-1} b_k\, \gamma^k \tag{3.24}$$

where,

$$b_k = \frac{1}{K!} \sum_{n=0}^{L-1-k} \binom{2L-1}{n}$$

So, the average bit error probability is as follows:

$$P_b = \int_0^{\infty} P_b(\gamma).\, f(\gamma)\, d\gamma \tag{3.25}$$

The probability density function (pdf) of γ can be obtained by differentiating the cdf $F(\gamma)$, where

$$F(\gamma) = \left[\sum_{k=0}^{L-1} \Pi_k \left(1 - e^{-\frac{\gamma}{\Lambda_k}}\right)\right]^M \tag{3.26}$$

and,

$$\Pi_k = \prod_{\substack{i=1 \\ i \neq k}}^{L} \frac{\Lambda_k}{\Lambda_k - \Lambda_i}$$

The pdf of γ is given by

$$f(\gamma) = \frac{d}{d\gamma} F(\gamma)$$

$$= M\left[\sum_{k=0}^{L-1} \Pi_k \left(1 - e^{-\gamma/\Lambda_k}\right)\right]^{M-1} \times \sum_{k=0}^{L-1} \frac{\Pi_k}{\Lambda_k} e^{-\gamma/\Lambda_k} \tag{3.27}$$

where the average SINR for the k-th channel path can be expressed as:

$$\Lambda_k = E[|A_k|^2] \times \frac{NPT_c}{N_0} = 2\sigma_k^2 \times \frac{NPT_c}{N_0} \quad (3.28)$$

here,

PT_c = Transmitted PN chip energy

A_k = Channel fading gain

σ_k^2 = Fading variance = $=\rho\sigma^2 e^{-k\beta}$

where, $\beta = \frac{T_c}{T_m}$ = Relative Delay spread

Thus, $\Lambda_k = \frac{2\sigma^2 NPT_c}{N_0} \times \beta e^{-k\beta}$; $0 \le k \le L-1$

Since Λ_k form a geometric series, thus

$$\Lambda = \sum_{k=0}^{\infty} \Lambda_k = \frac{2\sigma^2 NPT_c}{N_0} \times \frac{\beta}{1-e^{-\beta}} \quad (3.29)$$

Therefore Λ_k can be expressed as

$$\Lambda_k = \Lambda\, (1 - e^{-\beta}) e^{-k\beta} \quad (3.30)$$

Submitting these values of (3.24) and (3.27) in (3.25), the average bit error probability is given by

$$P_b = \int_0^{\infty} P_b(\gamma).f(\gamma)d\gamma$$

$$= \int_0^{\infty} \left(\frac{1}{2^{2L-1}} e^{-\gamma} \sum_{k=0}^{L-1} b_k \gamma^k\right).\left(M\left[\sum_{k=0}^{L-1} \Pi_k (1 - e^{-\gamma/\Lambda_k})\right]^{M-1} \times \sum_{k=0}^{L-1} \frac{\Pi_k}{\Lambda_k} e^{-\gamma/\Lambda_k}\right) d\gamma$$

$$= \frac{M}{2^{2L-1}} \sum_{k=0}^{L-1} b_k \sum_{k=0}^{L-1} \frac{\Pi_k}{\Lambda_k} \int_0^{\infty} \left[\sum_{k=0}^{L-1} \Pi_k \left(1 - e^{-\frac{\gamma}{\Lambda_k}}\right)\right]^{M-1} \times e^{-\frac{(1+\Lambda_k)}{\Lambda_k}\gamma} \gamma^k d\gamma \quad (3.31)$$

3.6 Summary

In this chapter, a novel theoretical analysis is derived for and MC-CDMA system considering Nakagami-m fading channel without rake receiver. Analysis is carried out to find out the expression of the receiver output with Maximal Ratio Combining (MRC) technique. Performance analysis includes the effect of Multiple Access Interferences (MAI), Inter Carrier Interferences (ICI) and in presence of Additive White Gaussian Noise (AWGN). The expression of the Signal to Interference and Noise Ratio (SINR) is derived for a MC-CDMA system considering the above limitations. Analysis is also carried out to find the expression for the MAI and instantaneous SINR and the probability density function of the SINR at the output of maximal ratio combiner. Initially the expression is formulated without considering Rake receiver and then it was modified for the system with Rake receiver. The analysis is evaluated in terms of Bit Error Rate (BER) performance considering various system design parameters. Furthermore, the spatial diversity has been incorporated to improve the system performance.

CHAPTER-4

RESULTS AND DISCUSSION

4.1 Results and Discussion

In this chapter, the performance results are evaluated numerically based on the analysis of the MC-CDMA system described in chapter-3. Performance results are evaluated in terms of SINR and BER without and with Rake receiver considering multipath fading channel. Optimum design parameters of MC-CDMA receiver such as optimum number of PN code length, number of subcarriers, optimum number of Rake receiver finger, the number of received antennas etc. has been determined from the BER performance curves at various system parameters.

4.1.1 Performance without Rake receiver

The BER performance is evaluated for MC-CDMA system without Rake receiver and the results are shown in figs 4.1 to 4.7. List of the parameters are given below:

k = No. simultaneous users at any time
G_{MC} = No. of subcarriers
N = No. of parallel paths
N_c = No. of chip per bit
σ_α^2 = Fading variance
μ = Cross-correlation
R_b = Bit rate
E_b/N_0 = SNR

Fig.4.1 shows that the plots of BER versus E_b/N_0 (dB) for different number of users k considering Rayleigh fading at a fading variance σ_α^2 = 0.1 without rake receiver for SISO configuration. It is clear from the plots that the number of users at any instant has significant effects on BER performance. This is mainly due to the increase of Multiple Access Interferences (MAI) originated from user transmissions. Now for a satisfactory system performance with standard SNR 6dB and maximum BER to be 10^{-4}, according to the plots the optimum number of user at any instant should be around 25. For the evaluation of above plots, the values of different other parameters have been chosen as follows:

- Bit rate, R_b = 50 kbps
- Cross-correlation, μ = 10%
- Spreading code length, N_c = 16

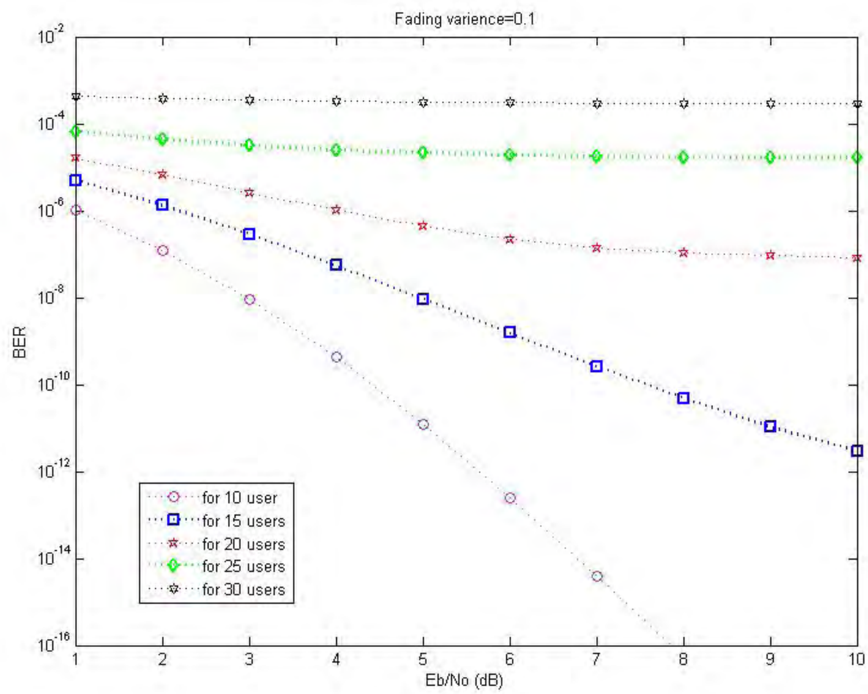


Fig.4.1 Plots of BER Vs E_b/N_0 (dB) with number of users k as parameter, considering fading variances σ_α^2 = 0.1, for the MC-CDMA system without rake receiver and spatial diversity**.**

Fig.4.2 shows that the plots of BER versus E_b/N_0 (dB) for different number of subcarriers G_{MC} considering Rayleigh fading at a fading variance σ_α^2 = 0.1 without rake receiver as well as without considering multiple received antenna. The quantitative variation of sub-carriers has significant effect on the system performance which is reflected in above fig.4.2. 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^{-8}, the minimum number of subcarrier should be 4.

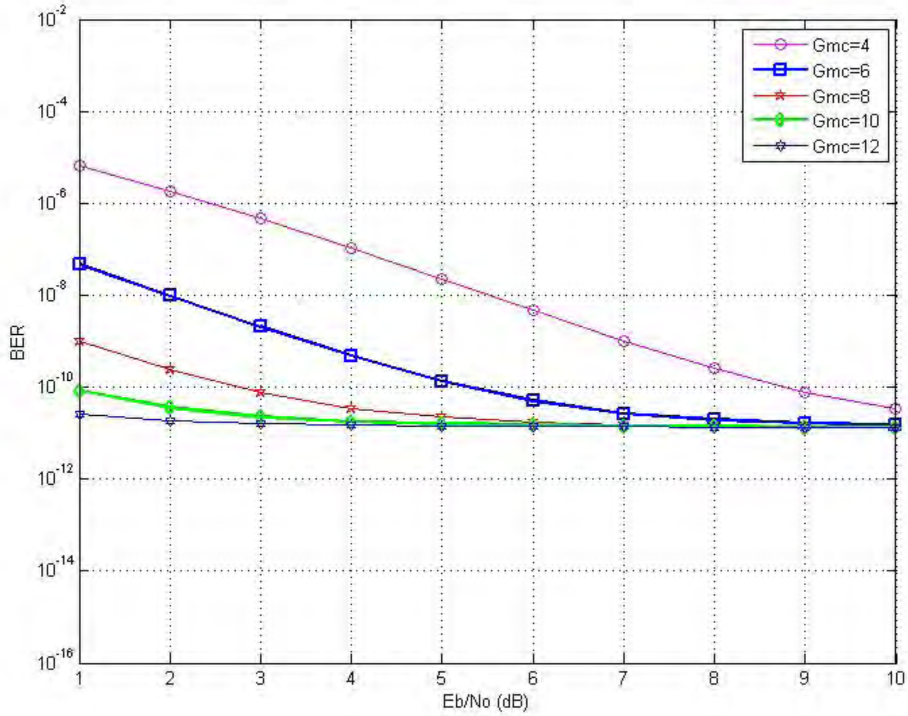


Fig.4.2 Plots of BER Vs E_b/N_0 (dB) with number of Subcarrier G_{MC} as parameter, considering fading variances σ_α^2 = 0.1, N=3 and k=16 for the MC-CDMA system without rake receiver and spatial diversity.

The plots of BER Versus number of users at 6dB SNR are shown in the fig.4.3 considering Rayleigh fading at a fading variance σ_α^2 = 0.1 without rake receiver as well as without considering multiple received antenna. From the plot of fig.4.3, we can see that more numbers of users can be served by increasing the number of subcarriers. Again, this is limited up to certain value, as according to the figure, the increment rate is gradually reduces at higher number of subcarriers. It is mainly due to the fact that at higher number of subcarriers, the ICI increases significantly. Furthermore, the data symbol length, which should be limited in fading environments, is also dependent on the number of subcarriers. However, this plot justifies the previous requirements of minimum 4 subcarriers to provide to maximum 25 users at any instant.

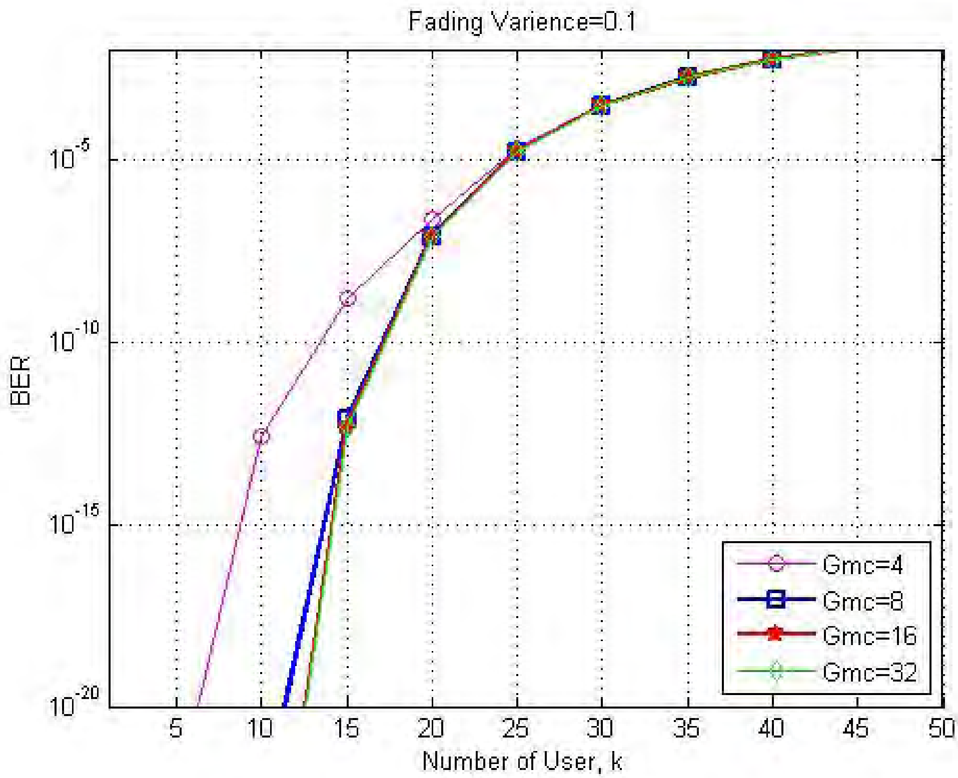


Fig.4.3 Plots of BER Vs number of users with number of Subcarrier G_{MC} as parameter, considering fading variances σ_{α}^{2} = 0.1, N=3, SNR=6dB and N_c=16 for the MC-CDMA system without rake receiver and spatial diversity.

The plots of BER versus number of user at 6dB SNR are shown in fig.4.4 considering Rayleigh fading at a fading variance σ_{α}^{2} = 0.1 without rake receiver for SISO configuration. It indicates that the length of the spreading code has also effects on the BER performance of the system significantly. The maximum code length should be 32 chips/bit, since the values beyond 32 does not cause any significant increase in user capacity of the system. This plot also shows the maximum number of users is approximately 5, 22 and 23 corresponding to N_c = 8, 16 and 32 respectively.

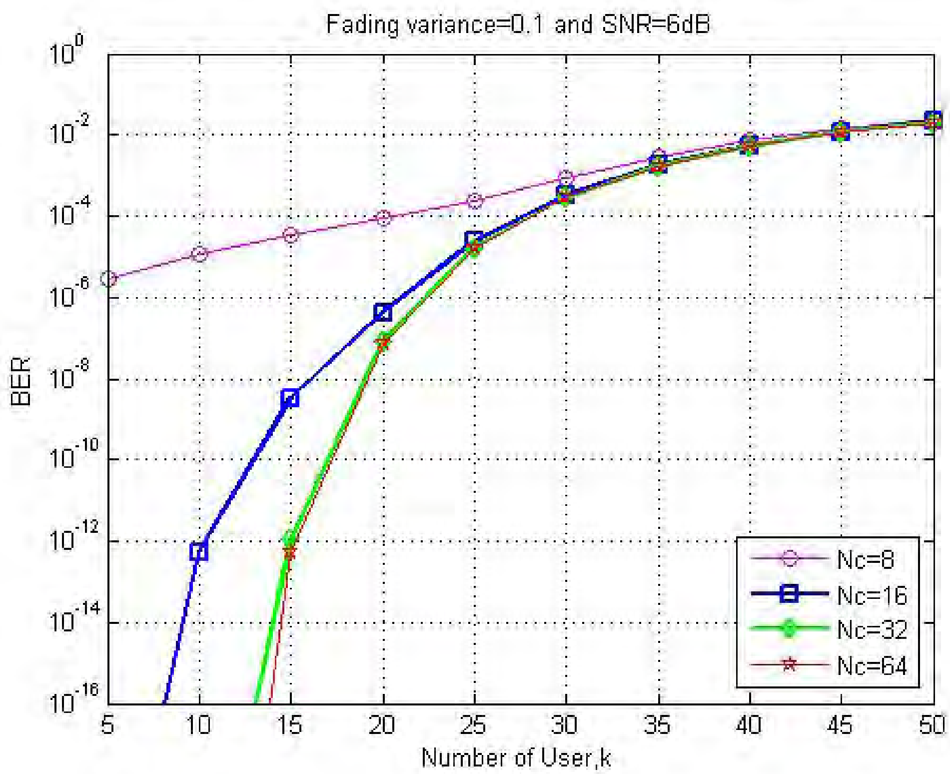
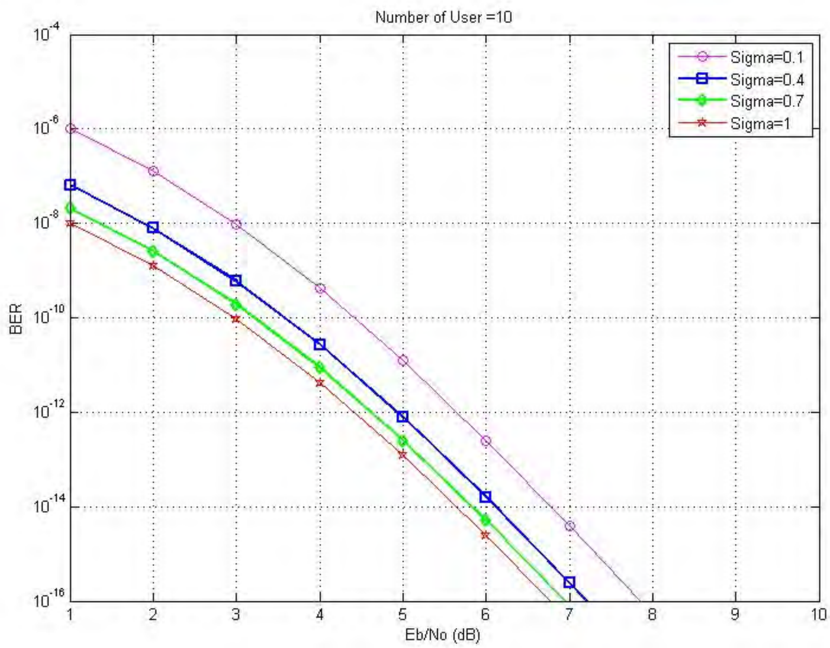
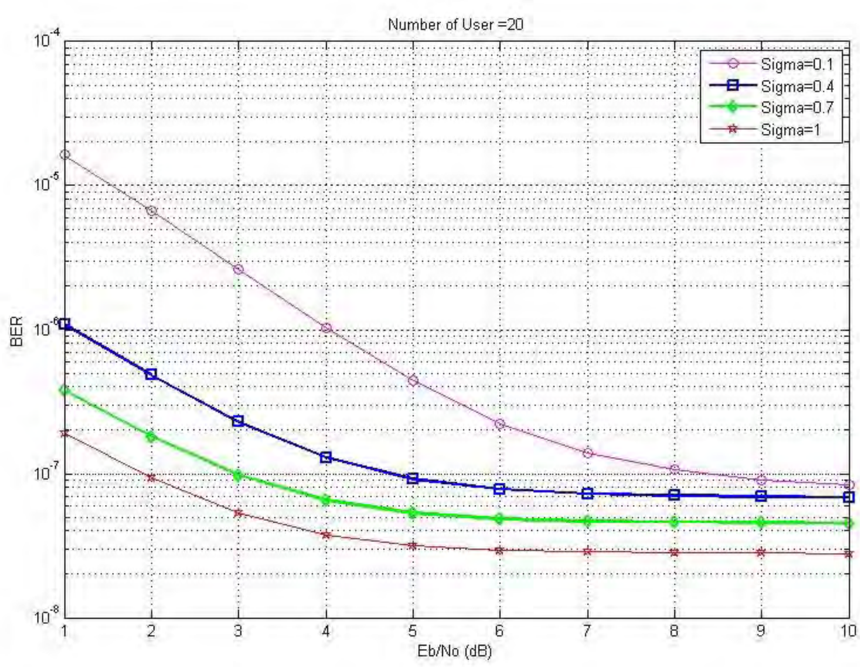


Fig.4.4 Plots of BER Vs number of users with code length N_c as parameter, considering fading variances σ_α^2 = 0.1, N=3, SNR=6dB and G_{MC} =4 for the MC-CDMA system without rake receiver and spatial diversity.

The plots of BER versus E_b/N_0 (dB) with fading variance as a parameter for number of users k= 10 and 20 are shown in fig.4.5a and 4.5b. These figures shows at higher values of σ_α^2, the performance of the system improves and results BER floor when number of user is 20 and E_b/N_0 greater than 10 dB.



(a) For 10 Users



(b) For 20 Users

Fig. 4.5 Plots of BER Vs E_b/N_0 (dB) with fading variance as a parameter, considering number of user, k= 10 and 20 for the MC-CDMA system without rake receiver and spatial diversity.

The fig.4.6 depicts the plots BER Vs E_b/N_0 (dB) for different values of cross-correlation among the user codes, taking number of user k = 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 the value of E_b/N_0. Thus for this CDMA scheme, the cross-correlation value should be limited to 10%.

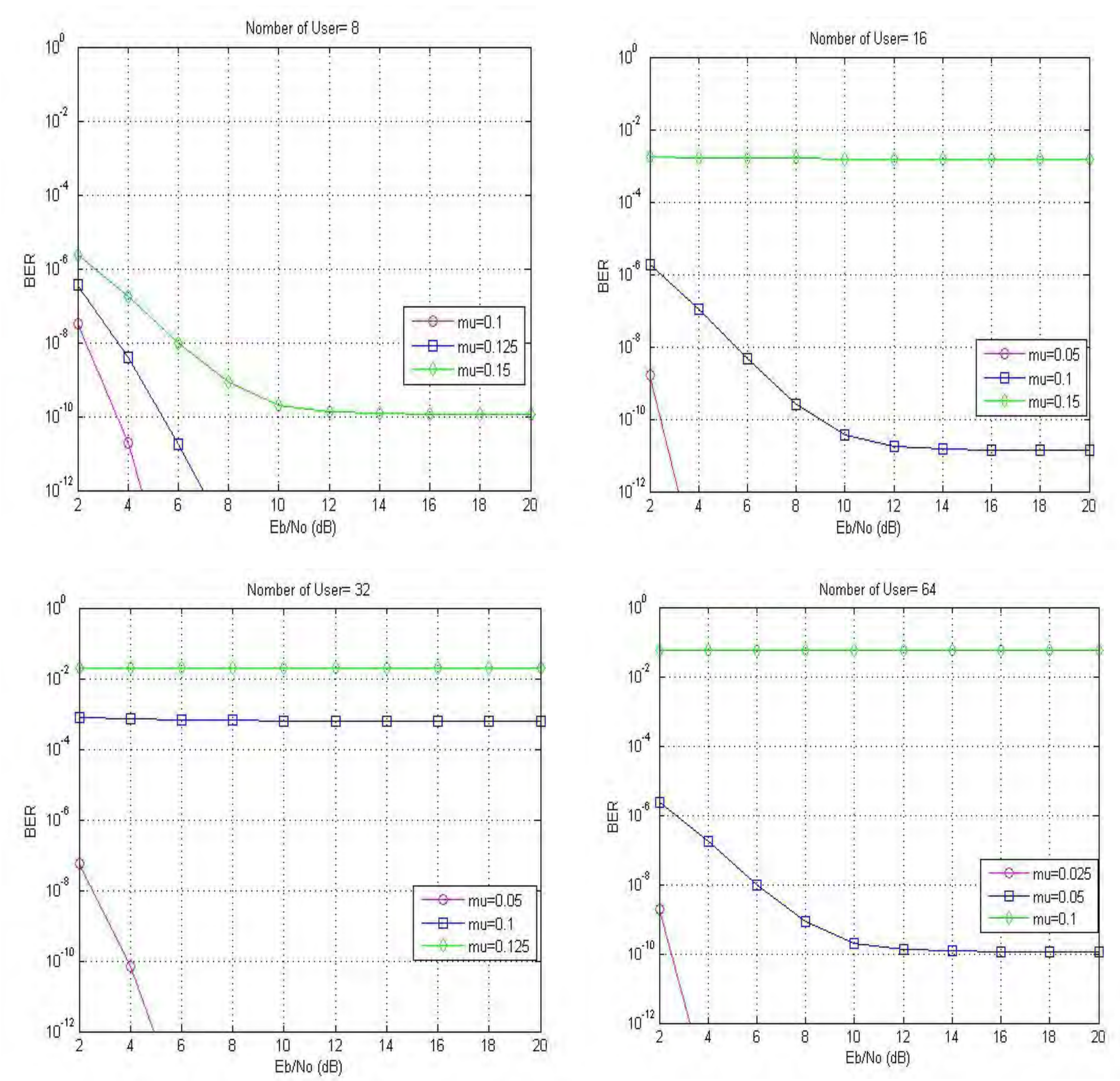


Fig.4.6 Plots of BER Vs E_b/N_0 (dB) with cross correlation as parameter considering k = 8, 16, 32 and 64 for the MC-DS-CDMA system without rake receiver and spatial diversity**.**

4.1.2 Performance with Rake receiver

Considering the Rake receiver, the performance results are now presented. The plots BER versus E_b/N_0 at different numbers of k are presented in fig.4.7 considering rake receiver for SISO configuration. In this plots, there is significant reduction in BER when the system uses the rake receiver. For the satisfactory performance of the system with BER $\leq 10^{-4}$, E_b/N_0= 6dB, the number of simultaneous users could be up to 35. It is to be noted that without rake receiver the system capacity was 25. The design parameters are: Bit Rate = 50 Kbps and cross-correlation μ = 0.1.

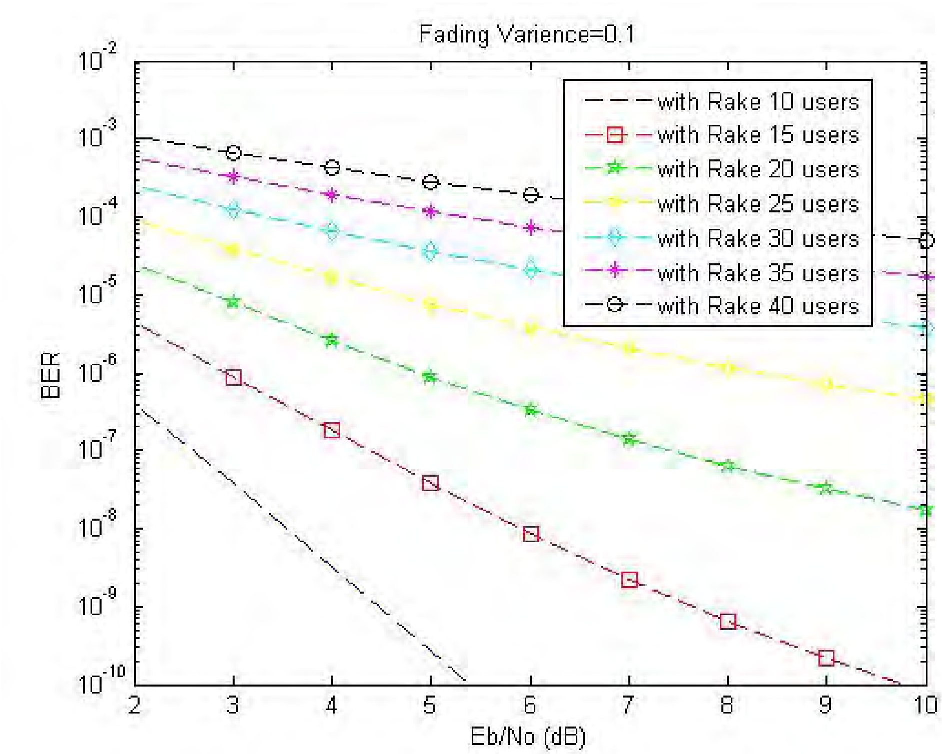


Fig.4.7 Plots of BER Vs E_b/N_0 (dB) with number of users k as parameter, considering fading variances σ_α^2 = 0.1, code length N_c=16, number of subcarrier G_{MC}=4 for the MC-CDMA system with rake receiver of L=3 without spatial diversity

The plots BER versus E_b/N_0 at different numbers of k are presented in fig.4.8 considering with and without rake receiver for SISO configuration. There is significant improvement in BER performance when using rake receiver. It is noted that the system without rake receiver

BER floor occur with the number of user 20 but with rake receiver the system shows satisfactory performance for the same number of users.

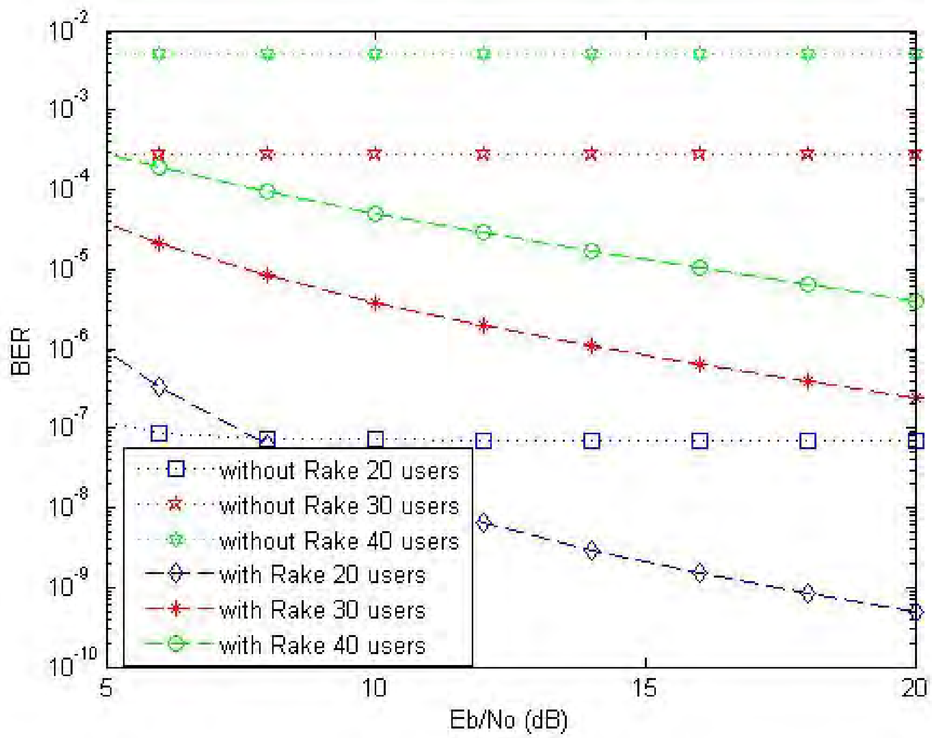


Fig.4.8 Plots of BER Vs E_b/N_0 (dB) with number of users k as parameter, considering MC-CDMA system with and without rake receiver of L=3 without spatial diversity

The plots BER versus E_b/N_0 at different numbers of subcarrier G_{MC} are presented in fig.4.9 taking number of users 16 and 40, considering rake receiver for SISO configuration. To have maximum BER= 10^{-4} at E_b/N_0= 6dB, the minimum number of subcarrier should be 2 when the number of simultaneous users is limited to 16. But the higher number of users, say 40, the minimum number of subcarrier should be 8. Now the more subcarriers are used, the better performance will be achieved.

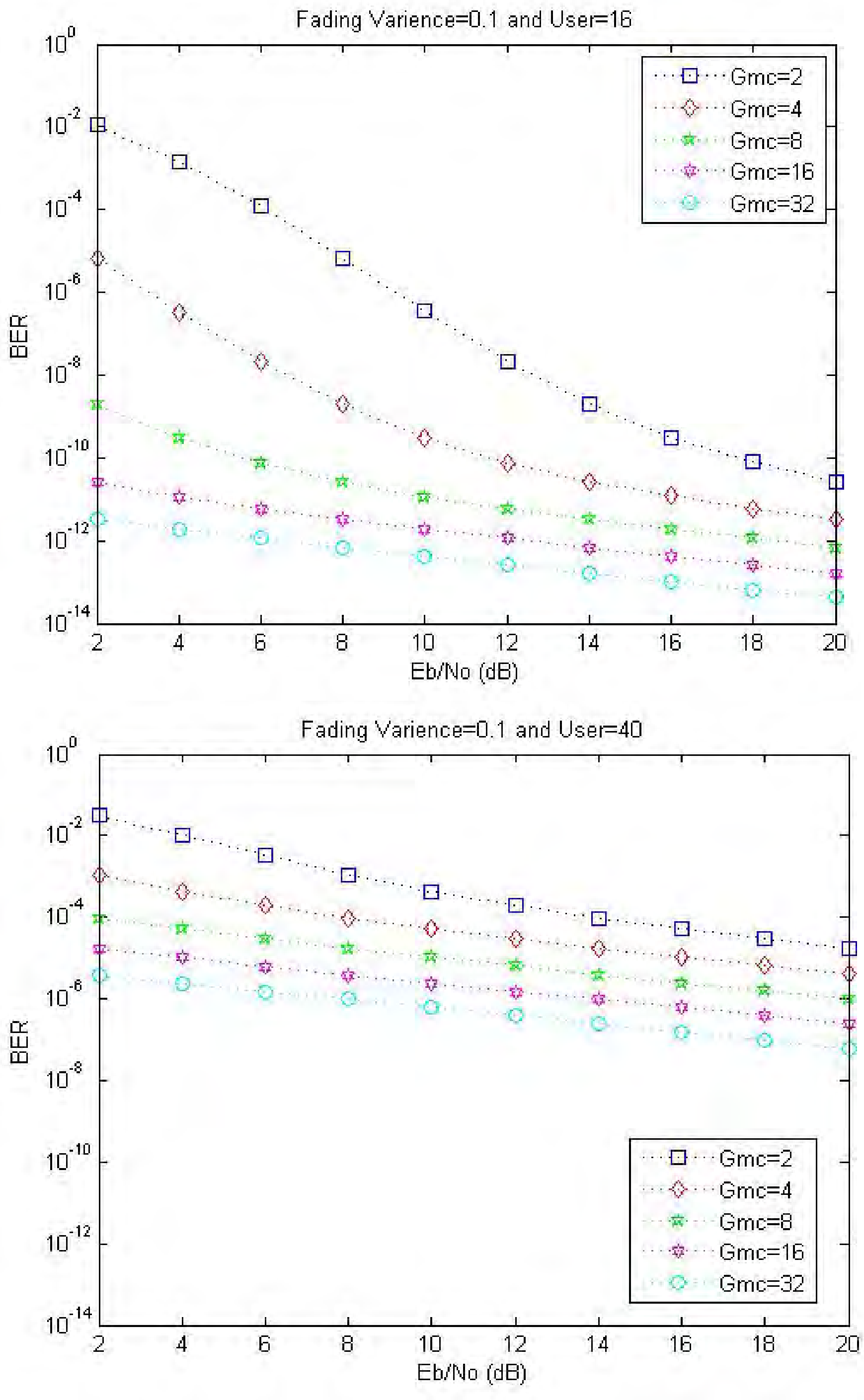


Fig.4.9 Plots of BER Vs E_b/N_0 (dB) with number of subcarrier as parameter, considering fading variances σ_α^2 = 0.1, code length N_c=16, number of users k=16 and 40 for the MC-CDMA system with rake receiver of L=3 without spatial diversity.

The plots BER versus numbers of users at different number of subcarriers G_{MC} are presented in fig.4.10 considering rake receiver for SISO configuration. The result emphasize the requirements of having minimum 8 subcarriers to accommodate 45 simultaneous users with maximum BER= 10^{-4} at E_b/N_0= 6dB.

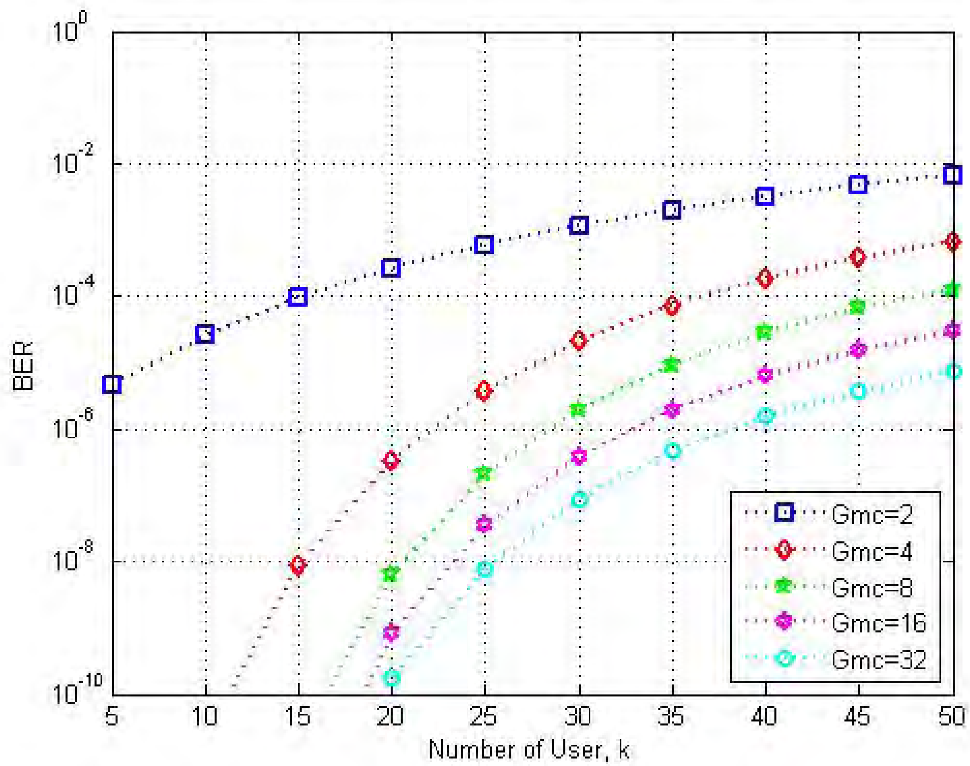


Fig.4.10 Plots of BER Vs number of users with number of subcarrier as parameter, considering fading variances σ_{α}^{2} = 0.1, code length N_c=16, E_b/N_0=6 (dB) for the MC-CDMA system with rake receiver of L=3 without spatial diversity

The plots BER versus numbers of users at different number of code length N_c are presented in fig.4.11 considering rake receiver for SISO configuration. The figure shows that in order to achieve BER less than 10^{-4} to support 16 simultaneous users, the minimum code length is 8 whereas code length 16 is needed to support 37 users. The figure also shows that the longer the code length, the better will be the system performance, though the system performance reduce gradually. However the maximum code length is limited by various factors like bit period, noise margin, processing delay of the system etc.

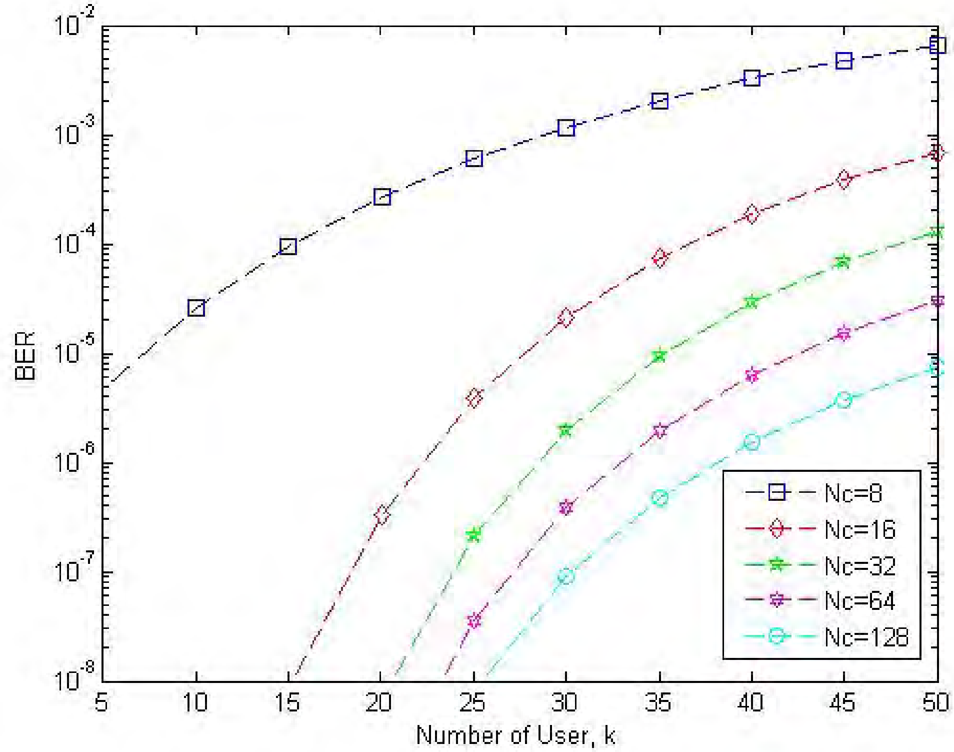
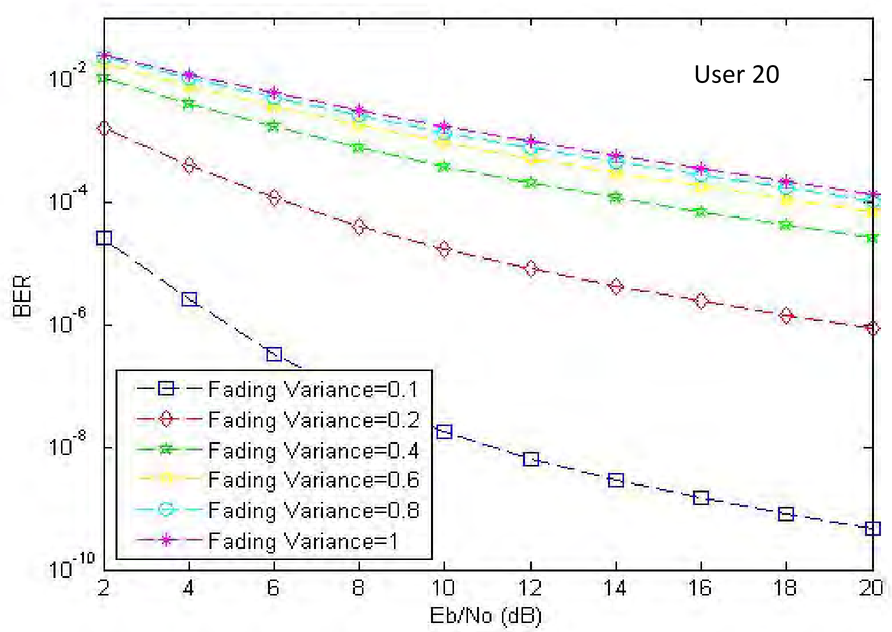


Fig.4.11 Plots of BER Vs number of users with different number of code length N_c as parameter, considering fading variances σ_{α}^{2} = 0.1, G_{MC}=4, E_b/N_0=6 (dB) for the MC-CDMA system with rake receiver of L=3 without spatial diversity

The plots BER versus E_b/N_0 (dB) at different number of fading variance are presented in fig.4.12 considering rake receiver for SISO configuration. Figure shows that with the change in fading variance the performance of the system is changed. After a certain values (0.4) of fading variance, the performance of the system are improved a little when further increase in fading variance.



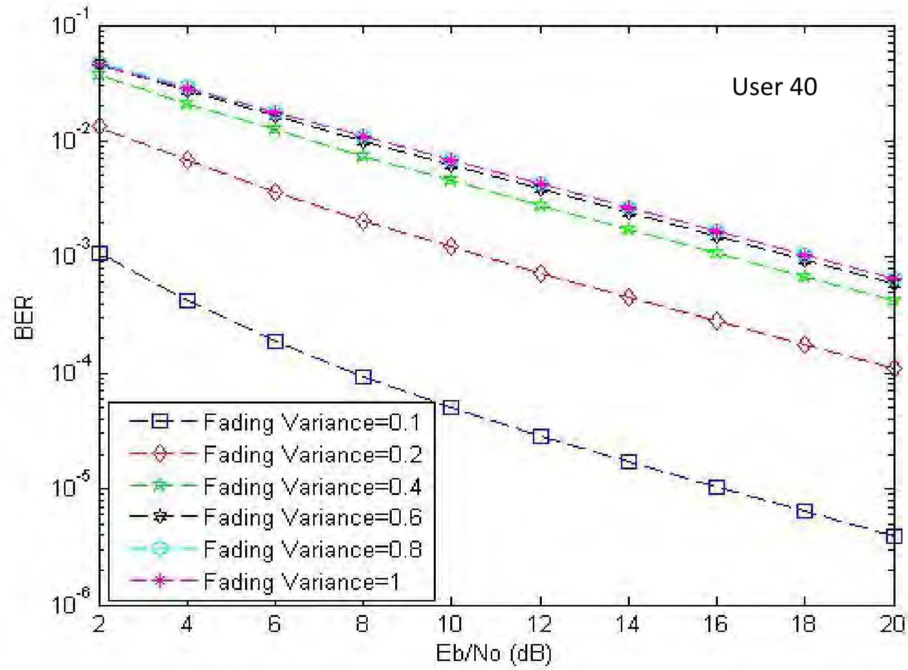


Fig.4.12 Plots of BER Vs E_b/N_0 with different fading variance as parameter, considering number of user= 20 and 40 for the MC-CDMA system with rake receiver of L=3 without spatial diversity

The plots E_b/N_0 (dB) versus fading variance at different number user are presented in fig.4.13 considering rake receiver for SISO configuration at fixed BER=10^{-3}. Figure shows that to accommodate higher number of user it is needed higher values of SNR and Fading variance. This figure justifies the results of fig.4.12.

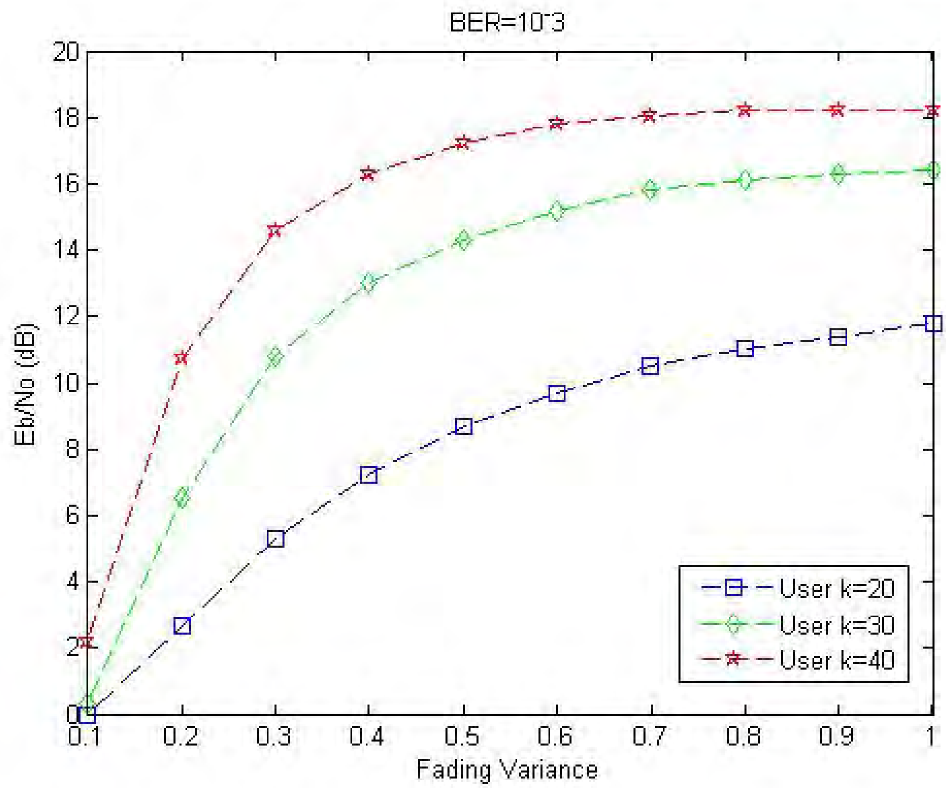


Fig.4.13 Plots of E_b/N_0 Vs Fading Variance with different number of user as parameter, considering BER=10^{-3} for the MC-CDMA system with rake receiver of L=3 without spatial diversity

The plots BER versus E_b/N_0 (dB) at different number of cross-correlation among the codes are presented in fig.4.14 for different number of simultaneous users considering rake receiver for SISO configuration. Plots show that lower the cross-correlation, the better the system performance. However, in comparison to the similar plots for system without rake receiver in fig.4.6, it is clear that the system with rake receiver have greater tolerance against higher cross-correlation.

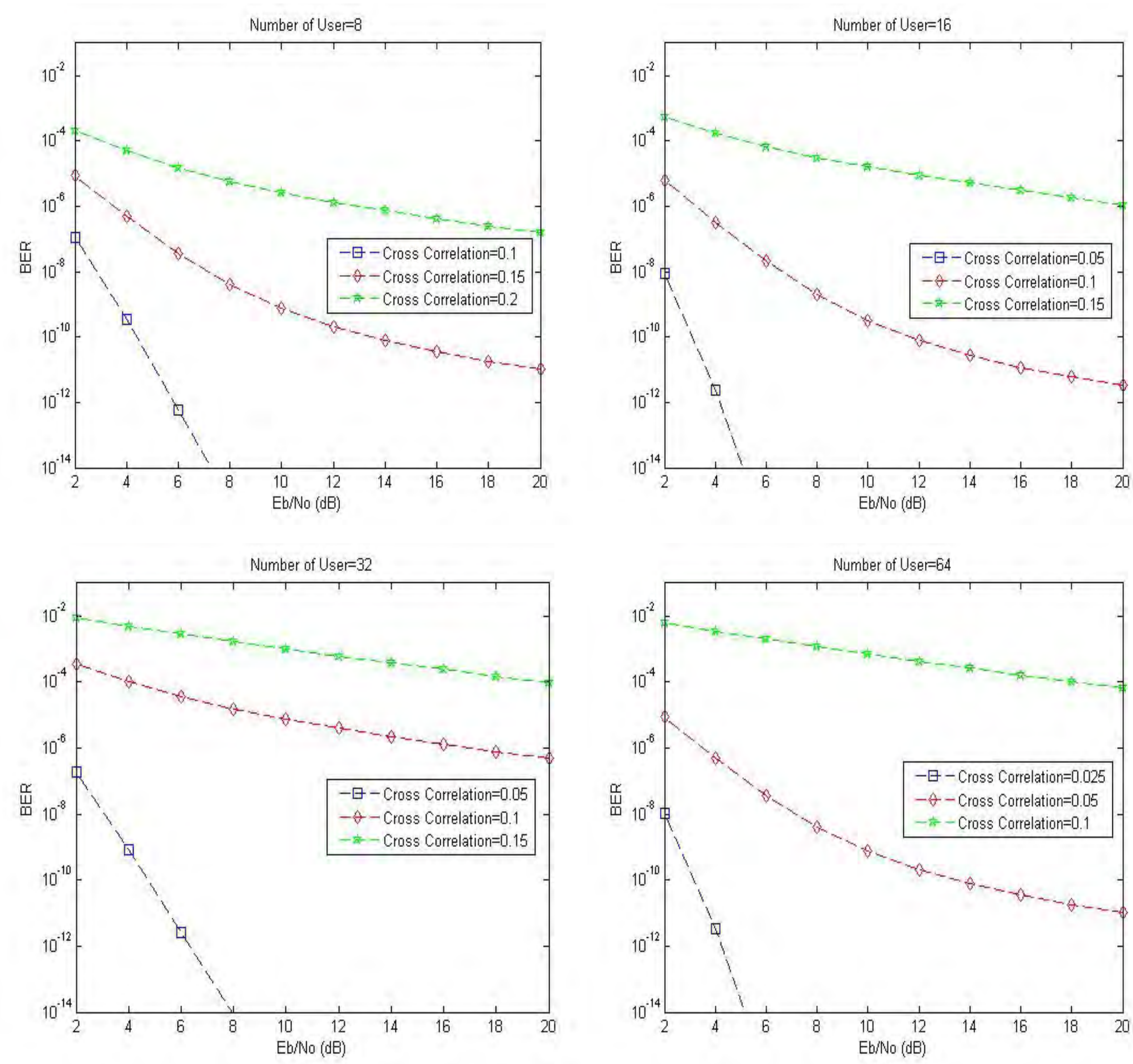


Fig.4.14 Plots of BER Vs E_b/N_0 with different cross-correlation μ as parameter, considering number of user k= 8, 16, 32 and 64 for the MC-CDMA system with rake receiver of L=3 without spatial diversity

The plots E_b/N_0 (dB) versus cross-correlation among the codes with different number of user are presented with in fig.4.15 for SISO configuration at fixed BER=10^{-6}. Plots show that to accommodate higher number of user in the system, the cross-correlation should be lower. This figure justifies the results of fig.4.14.

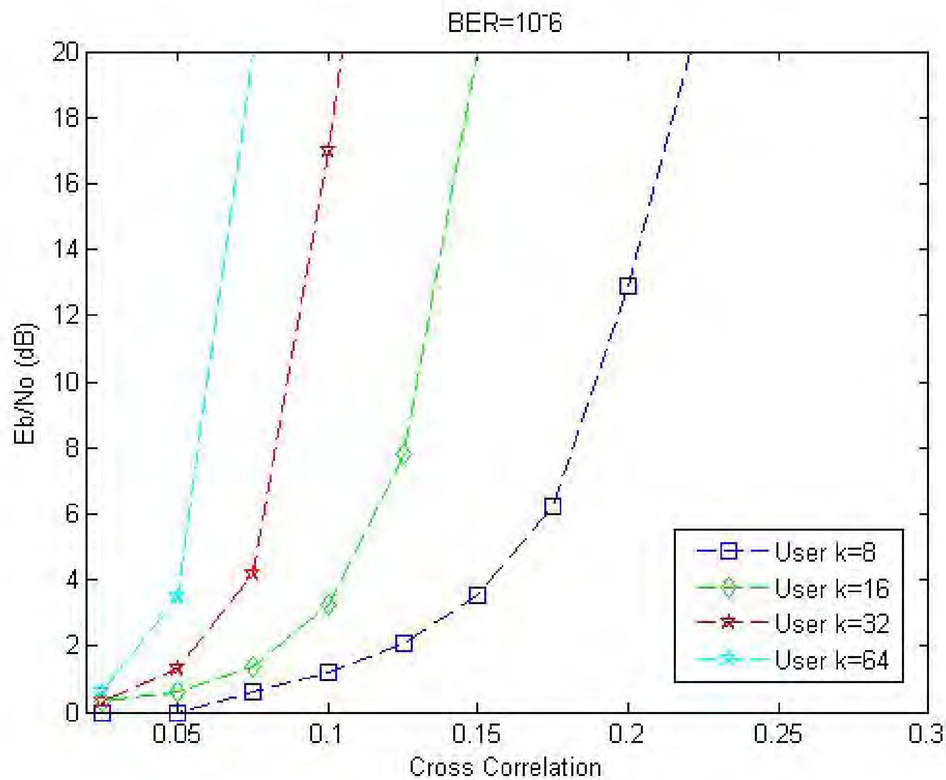


Fig.4.15 Plots of E_b/N_0 Vs cross-correlation μ with different number of user as parameter, considering BER=10^{-6} for the MC-CDMA system with rake receiver of L=3 without spatial diversity

The plots number of user versus number of subcarriers with different number of rake finger L are presented with in fig.4.16 for SISO configuration at fixed BER=10^{-6}. Plots show that higher the Rake finger, better the system performance. But after the certain values of subcarriers G_{MC} (16), the system performance is improved a little if rake finger is further increased.

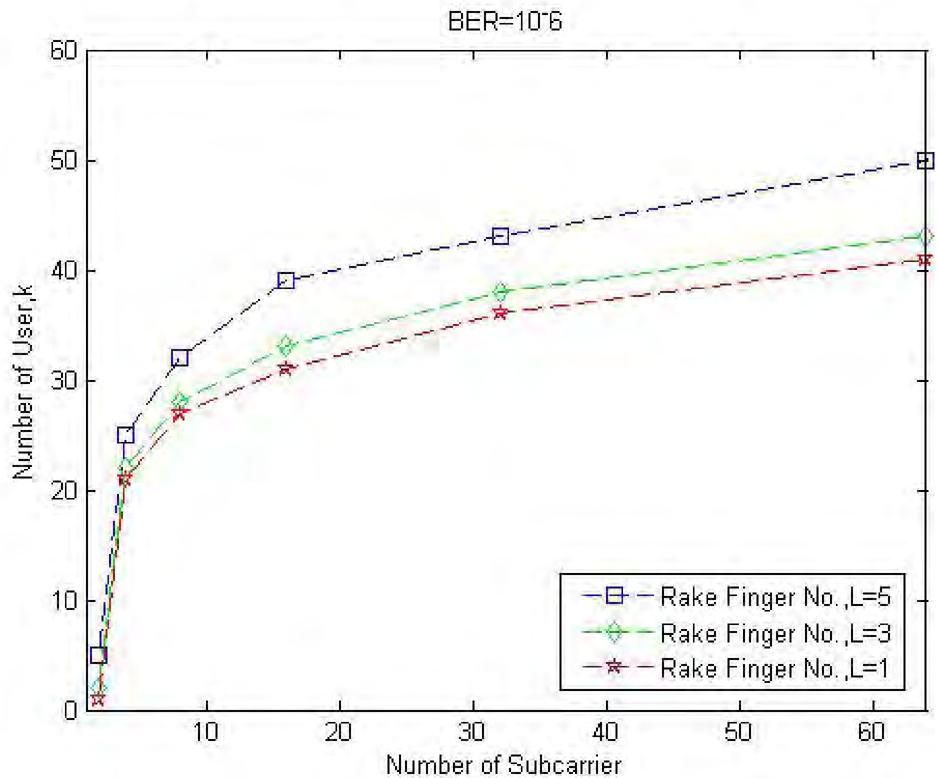


Fig.4.16 Plots of Number of User Vs Number of Subcarriers with different number of Rake finger L as parameter, considering BER=10^{-6} for the MC-CDMA system without spatial diversity

4.1.3 Performance with Rake receiver and Diversity

Considering the Rake receiver with diversity, the performance results are now presented. The plots BER versus E_b/N_0 at different numbers of k are presented in fig.4.17 considering with and without rake receiver for SIMO configuration. There is significant improvement in BER performance when using rake receiver finger L=3 and number of received antenna M=3. It is noted that the system without rake receiver BER floor occurs with the number of user 30 but with rake receiver still shows satisfactory performance.

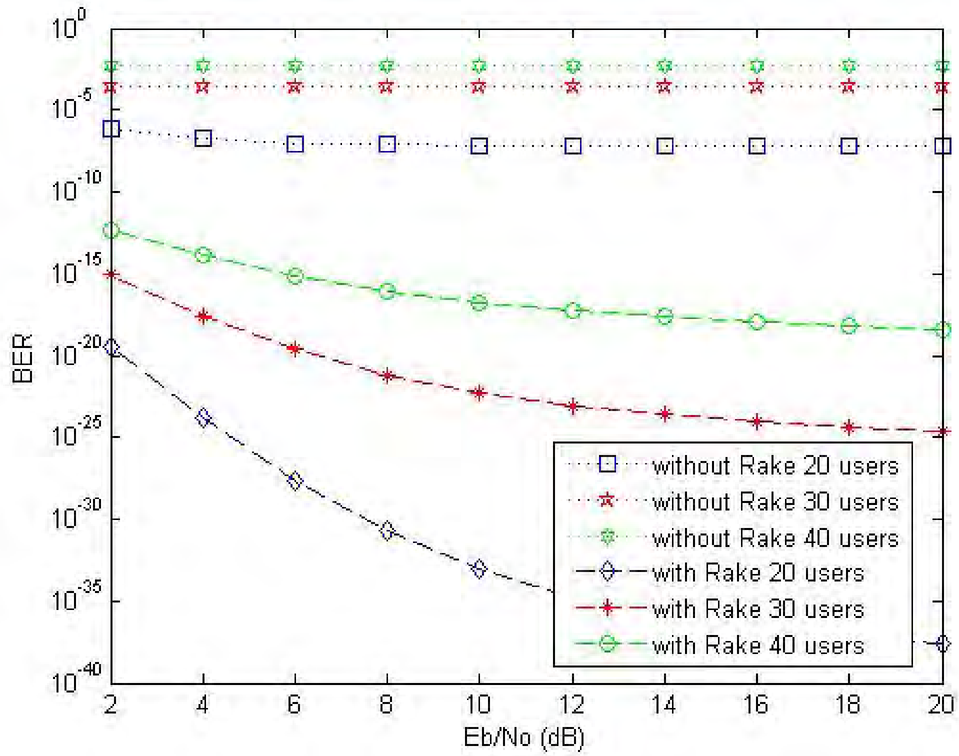
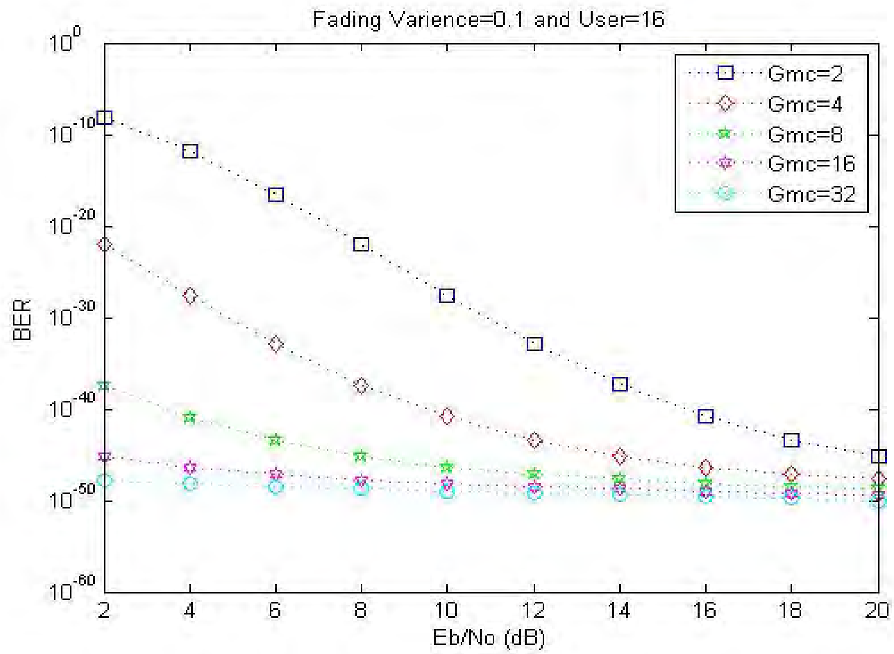


Fig.4.17 Plots of BER Vs E_b/N_0 (dB) with number of users k as a parameter, considering MC-CDMA system with and without rake receiver of L=3 and M=3

The plots BER versus E_b/N_0 at different numbers of subcarrier G_{MC} are presented in fig.4.18 taking number of users 16 and 40, considering rake receiver for SIMO configuration with received antennas M=3. BER performance is significantly increased when using rake receiver with multiple received antennas. But the higher number of users should have higher number of subcarrier to get better performance. Now the more subcarriers are used, the better performance will be achieved.



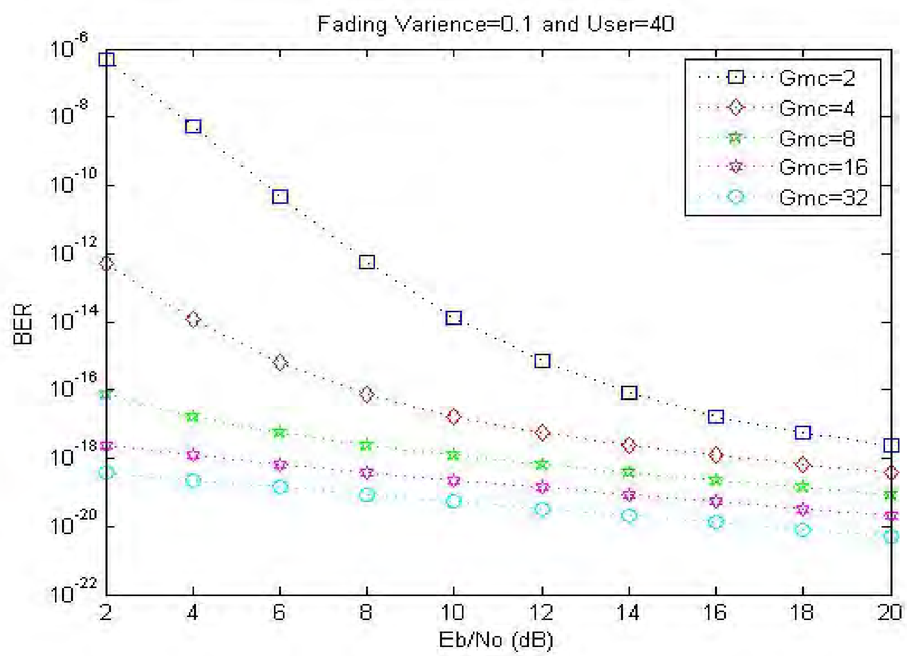


Fig.4.18 Plots of BER Vs E_b/N_0 (dB) with number of subcarrier as parameter, considering fading variances σ_α^2 = 0.1, code length N_c=16, number of users k=16 and 40 for the MC-CDMA system with rake receiver of L=3 and M=3.

The plots BER versus numbers of users at different number of subcarriers G_{MC} are presented in fig.4.19 considering rake receiver and multiple received antennas. The result emphasize the requirements of having minimum 2 subcarriers to accommodate 50 simultaneous users with maximum BER= 10^{-10} at E_b/N_0= 6dB.

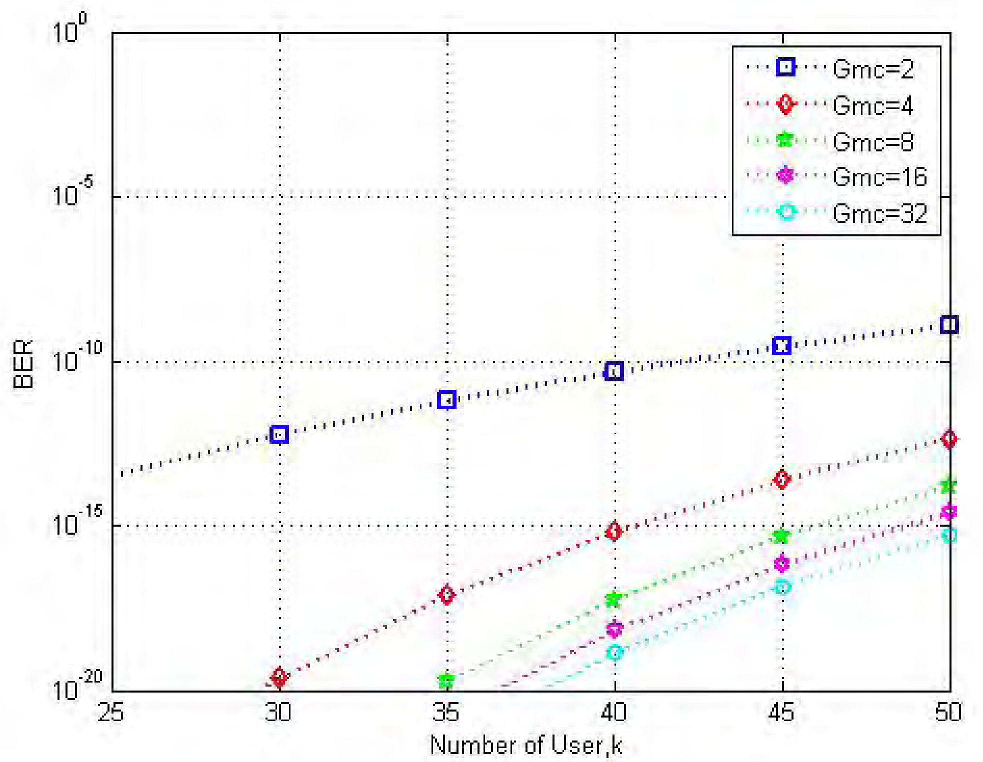


Fig.4.19 Plots of BER Vs number of users with number of subcarrier as parameter, considering fading variances σ_{α}^{2} = 0.1, code length N_c=16, E_b/N_0=6 (dB) for the MC-CDMA system with rake receiver of L=3 and M=3

The plots BER versus numbers of users at different number of code length N_c are presented in fig.4.20 considering rake receiver for SIMO configuration. The figure shows the remarkable improvement than that in achieved in Fig.4.11. The figure also shows that the longer the code length, the better will be the system performance, though the system performance reduce gradually. However the maximum code length is limited by various factors like bit period, noise margin, processing delay of the system etc.

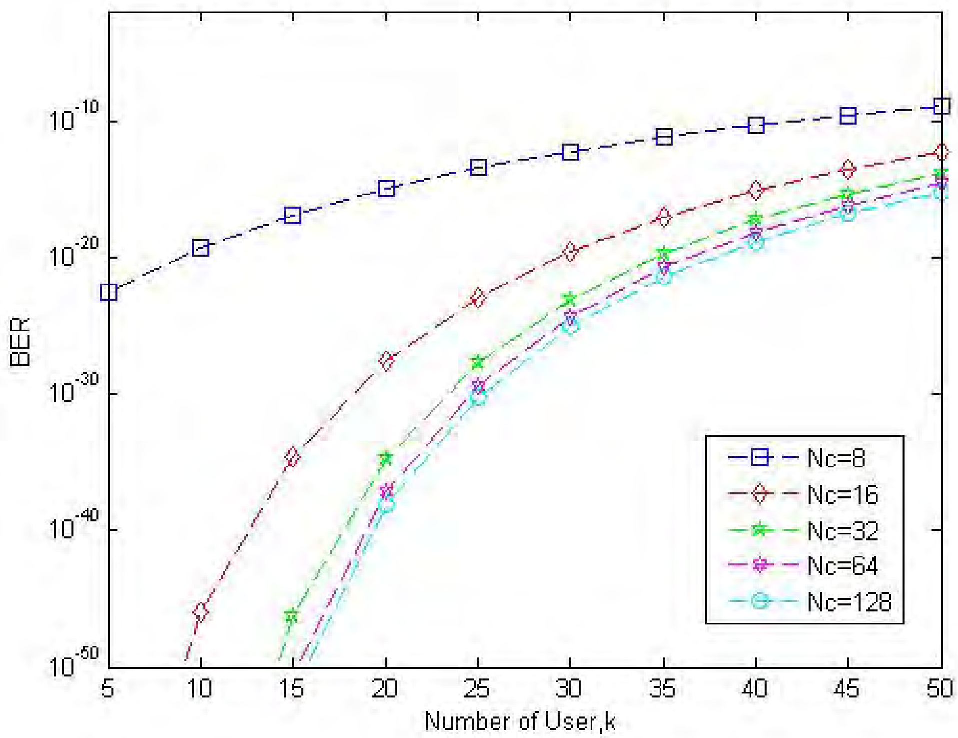


Fig.4.20 Plots of BER Vs number of users with different number of code length N_c as parameter, considering fading variances σ_α^2 = 0.1, G_{MC}=4, E_b/N_0=6 (dB) for the MC-CDMA system with rake receiver of L=3 and M=3.

The plots BER versus E_b/N_0 (dB) at different number of fading variance are presented in fig.4.21 considering rake receiver for SIMO configuration. Figure shows that with the change in fading variance the performance of the system is changed. After a certain values (0.2) of fading variance, the performance of the system are improved a little when further increase in fading variance.

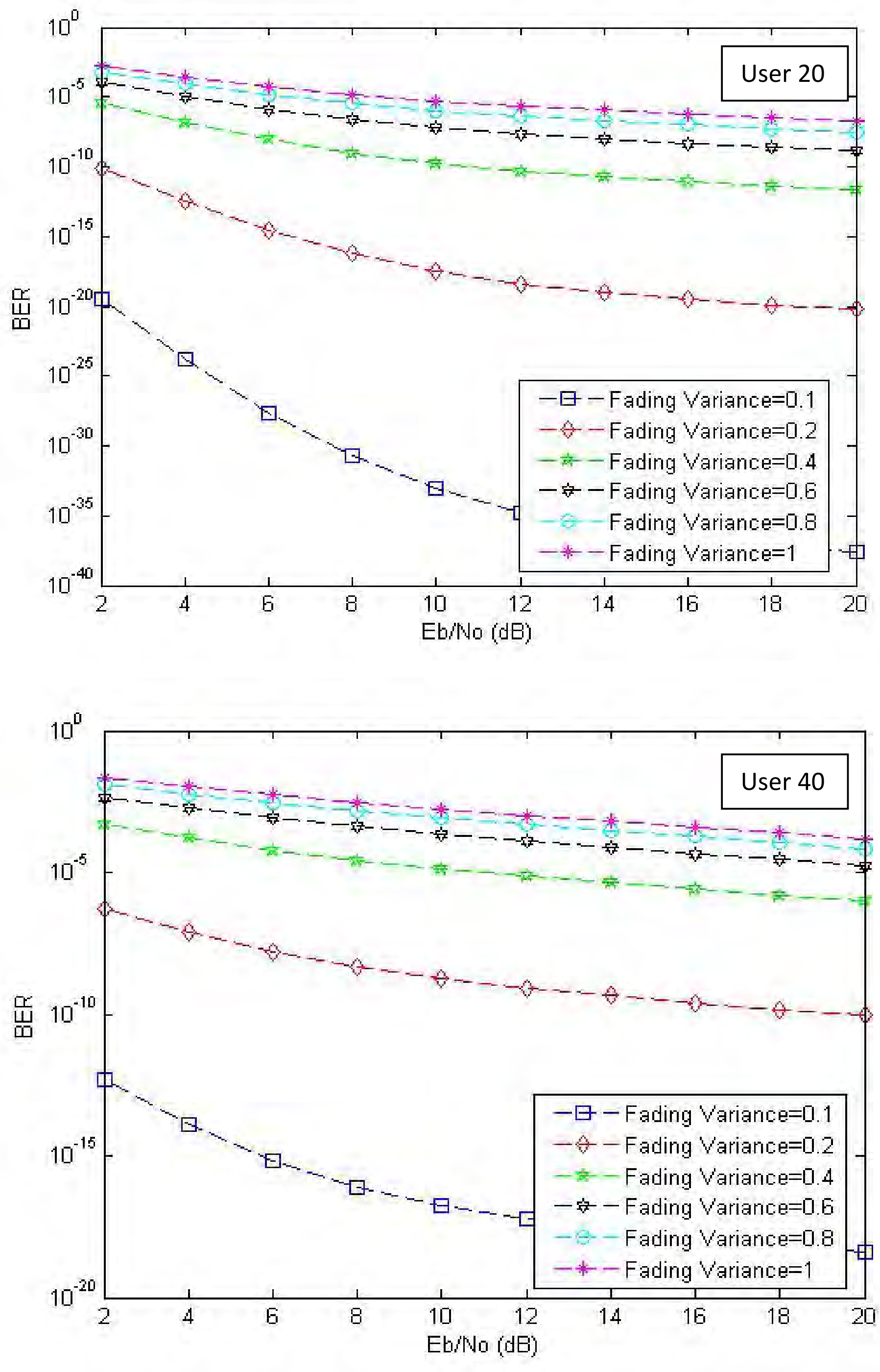


Fig.4.21 Plots of BER Vs E_b/N_0 with fading variance as a parameter, considering number of user k = 20 and 40 for the MC-CDMA system with rake receiver of L=3 and M=3.

The plots E_b/N_0 (dB) versus fading variance at different number user are presented in fig.4.22 considering rake receiver for SIMO configuration at fixed BER=10^{-6}. Figure shows that to accommodate higher number of user it is needed higher values of SNR and Fading variance. Compare with the fig.4.13 in SISO configuration, SIMO configuration show significant better performance.

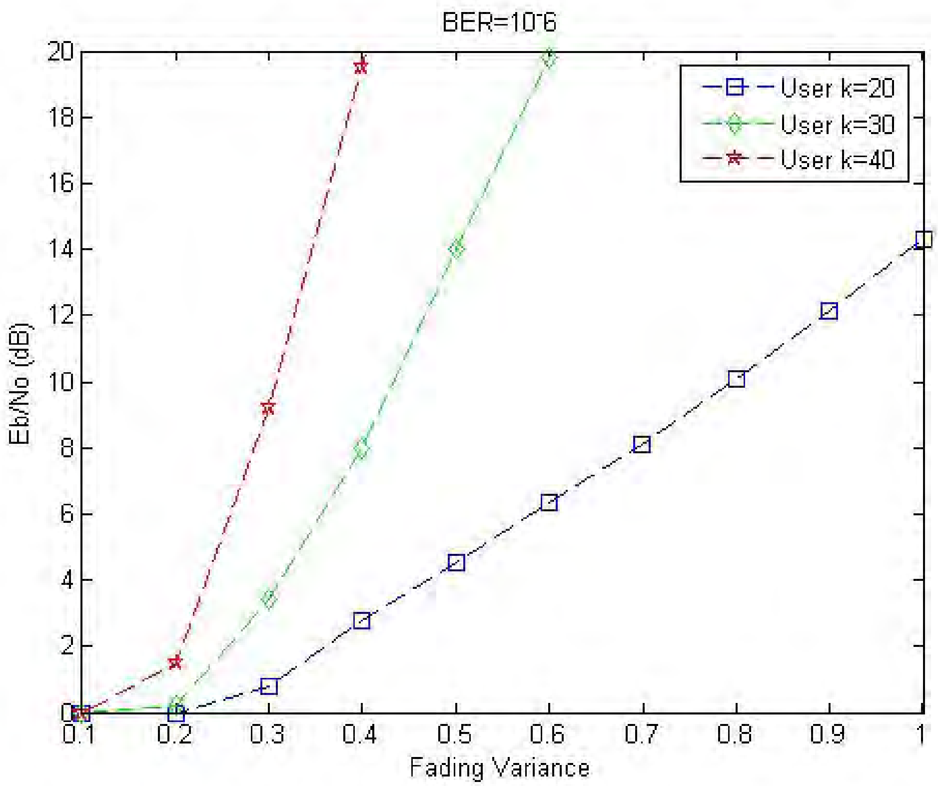


Fig.4.22 Plots of E_b/N_0 Vs Fading Variance with different number of user as parameter, considering BER=10^{-6} for the MC-CDMA system with rake receiver of L=3 and M=3

The plots BER versus E_b/N_0 (dB) at different number of cross-correlation among the codes are presented in fig.4.23 for different number of simultaneous users considering rake receiver for SIMO configuration. Plots show that lower the cross-correlation, the better the system performance. However, in comparison to the similar plots for system without rake receiver in fig.4.6 and fig.4.14, it is clear that the system with rake receiver and multiple received antennas have greater tolerance against higher cross-correlation.

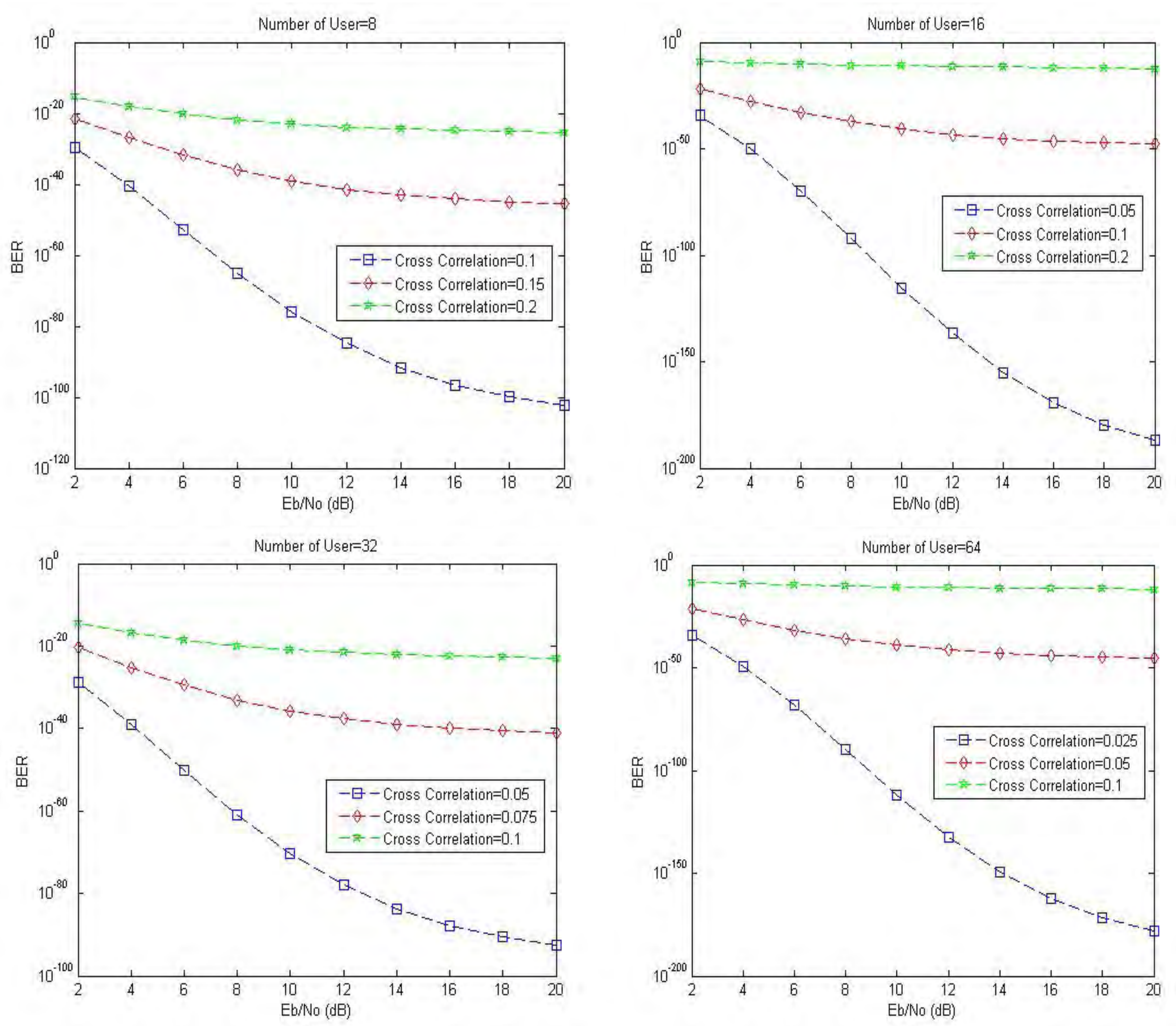


Fig.4.23 Plots of BER Vs E_b/N_0 with cross-correlation μ as a parameter, considering number of user k= 8, 16, 32 and 64 for the MC-CDMA system with rake receiver of L=3 and M=3.

The plots number of user versus number of subcarriers with different number of rake finger L are presented with in fig.4.24 for SIMO configuration at fixed BER=10^{-6}. Plots show that higher the Rake finger, better the system performance. Compare with the fig.4.16 in SISO configuration, SIMO configuration show significant better performance in system capacity.

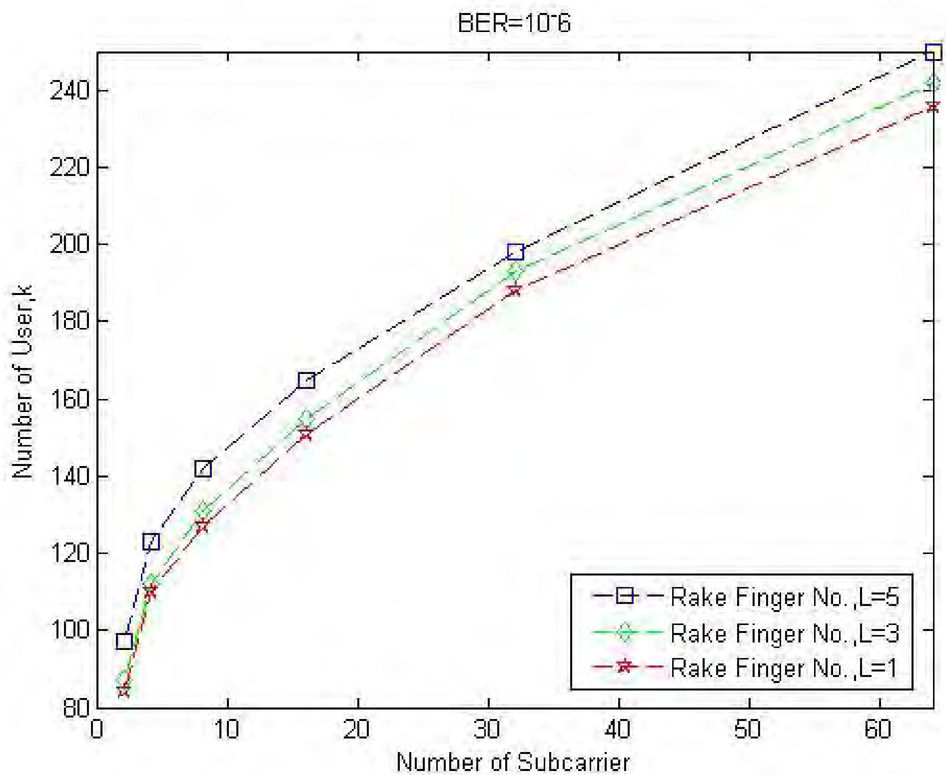


Fig.4.24 Plots of Number of User Vs Number of Subcarriers with different number of Rake finger L as parameter, considering BER=10^{-6} for the MC-CDMA system with spatial diversity, M=3

The plots BER versus SNR (E_b/N_0) with different number of received antennas M are presented in Fig.4.25 for SIMO configuration. Figure shows that spatial diversity can rapidly improve the system performance. As M increases, the BER performance is improved. But after a certain value of the number of receiving antenna, M=4, the improvement in SNR is less pronounced. When M >= 10, the improvement in SNR remains almost constant.

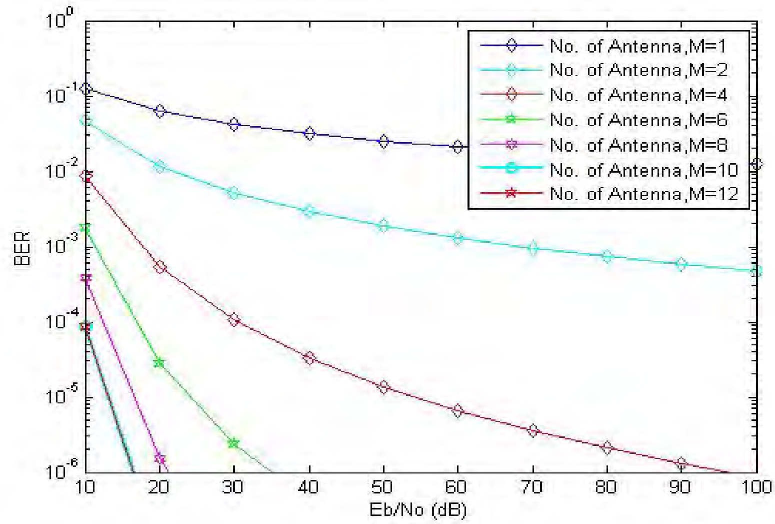


Fig.4.25 Plots of BER Vs E_b/N_0 (dB) with number of received antenna M as parameter, considering fading variances σ_α^2 = 0.1, code length N_c =16, number of users k=32 and subcarrier=4 for the MC-CDMA system with rake receiver of L=3 and diversity.

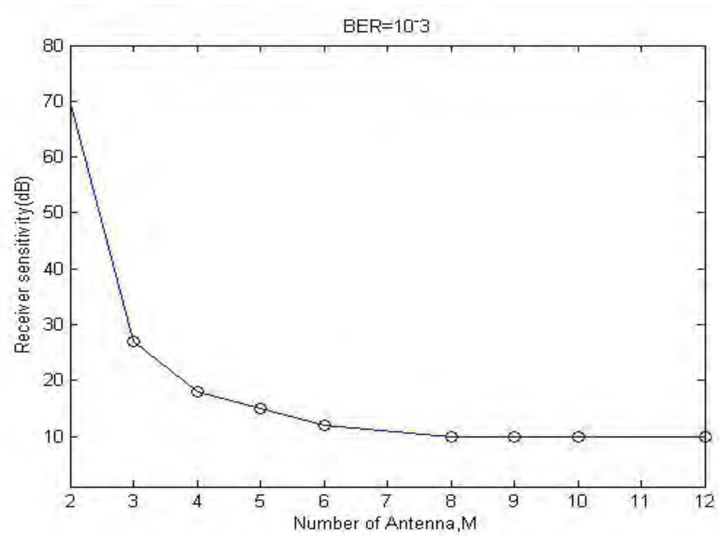


Fig.4.26 Plots of SNR Vs no. of antenna at fixed BER=10^{-3} considering fading variances σ_α^2 = 0.1, code length N_c =16, number of users k=32 and subcarrier=4 for the MC-CDMA system with rake receiver of L=3 and diversity.

CHAPTER-5

CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

Multicarrier code division multiple access (MC-CDMA) is a promising multiplexing technique supporting the high data rate requirement in the fourth generation of wireless communication systems. A novel theoretical analysis is derived for and MC-CDMA system considering Nakagami-m fading channel without and with rake receiver. The analytical expression for the SINR at the output of an MC-CDMA receiver is developed without and with rake receiver. The analysis is evaluated in terms of Bit Error Rate (BER) performance considering various system design parameters. Furthermore for a given BER, the optimum values of the code length, the number of subcarriers and the number of rake fingers are evaluated analytically. It is found that more number of users can be served by increasing the number of subcarriers. The results show that the longer the code length, the better will be the system performance. For example, in order to achieve BER less than 10^{-4} to support 16 simultaneous users, the minimum code length is 8 whereas code length 16 is needed to support 37 users. After analyzing the analytical results, it is shows that the BER performance is degraded due to fading. In that situation the BER performance can be enhanced by adding the rake receiver and multiple antennas at receiver end in the MC-CDMA system. It is also evaluated that the performance of the system is improved at higher fading variance. It is also found that the system performance is greatly affected by the cross-correlation among the code. At values of cross-correlation higher than 10%, it cannot lower the value of E_b/N_0. Thus the cross-correlation value should be limited to 10% in the system without rake receiver but the system with rake receiver has greater tolerance against higher cross-correlation. Moreover, it is found that higher number of rake finger (L) increased the BER performance but after the certain values of subcarriers (G_{MC}=16), the system performance is improved a little if rake finger is further increased. There is significant improvement in terms of number of users at SIMO configuration compared with that of SISO configuration at a given BER.

5.2 Future Works

Future research can be carried out to find the performance of multicarrier DS-CDMA and multi-tone CDMA (MT-CDMA) system with space and time diversity with Multiple Input and Multiple Output (MIMO) and Space Time Block Code (STBC) with a rake receiver. The performance of multi-tone CDMA (MT-CDMA) system over Nakagami fading channel can be the scope of further works. Further works 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.

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