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Multi-User Detection for the Optical Code Division Multiple Access (OCDMA): Optical Parallel Interference Cancellation (OPIC)

I, NAGI ELFADEL MASAD MOHAMED

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Date: ____________________

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Multi-User Detection for the Optical Code Division Multiple Access (OCDMA): Optical Parallel Interference Cancellation (OPIC)

submitted by

Nagi Elfadel Masad Mohamed

for the fulfilment of the requirements for the degree of

Masters of Science in Electrical and Electronic Engineering

____
Date

Signature : ______________

Main Supervisor : *Dr.Mohamad Naufal Mohamad Saad*

Date : ______________

Co-Supervisor : ______________

UNIVERSITI TEKNOLOGI PETRONAS

Multi-User Detection for the Optical Code Division Multiple Access (OCDMA): Optical Parallel Interference Cancellation (OPIC)

By
Nagi Elfadel Masad Mohamed

A THESIS

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BANDAR SERI ISKANDAR,
PERAK

September, 2007

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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Name : *Nagi Elfadel Masad Mohamed*

Date : ________________

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ABSTRACT

Optical Code Division Multiple Access (OCDMA) has recently been proposed as an alternative to frequency and time based multiple access methods for the next generation high-speed optical fiber networks. This is because such system offers a large bandwidth. Based on the vast amount of bandwidth available in optical line, OCDMA system has received much attention in fiber optic Local Area Network (LAN) where the traffic is typically bursty. However, Multiple Access Interference (MAI), which is originated from other simultaneous users, severely limits the capacity of the system. In addition, the need for dynamic threshold in the Conventional Correlation Receiver (CCR) is a very demanding requirement particularly in the high speed LANs.

To overcome the stated problems, Optical Parallel Interference Cancellation is used throughout this thesis. Optical Hard Limiter (OHL) has been placed at the front of the OPIC receiver to reduce the effect of MAI and fixed threshold is used to overcome the problem of dynamic threshold. The study carried out using theoretical and simulation. The results reveal that, OPIC system is attractive technology for next generation optical networks. The drawback of OPIC is the increases in the demand for hardware in each receiver. As a result, it requires more complex hardware, higher processing time and cost. To overcome these difficulties, an efficient method is proposed called, One Stage Optical Parallel Interference Cancellation (OS-OPIC) which is based mainly on the OPIC. Performance analysis of the proposed design is done using Optical Orthogonal Code (OOC) as a signature sequence and a new expression for error probability is demonstrated. It is shown that, the proposed method is effective to reduce the hardware complexity, processing time and cost while maintaining the same BER at the cost of increasing threshold value.

ABSTRAK

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ABBREVIATIONS AND SYMBOLES

BER	Bit Error Rate
CCR	Conventional Correlation Receiver
CDMA	Code Division Multiple Access
CW	Continuous Wave
DD	Direct Detection
DS-OCDMA	Direct Sequence Optical Code Division Multiple Access
FDMA	Frequency Division Multiple Access
FO-CDMA	Fiber Optic Code Division Multiple Access
LAN	Local Area Network
MAI	Multiple Access Interference
MAN	Metropolitan Area Network
NRZ	Non Return to Zero
OCDMA	Optical Code Division Multiple Access
OHL	Optical Hard Limiter
OHL+OPIC	Region of Interest
OOC	Optical Orthogonal Code
OOK	On-Off Keying
OPIC	Optical Parallel Interference Cancellation
OSIC	Optical Serial Interference Cancellation
OS-OPIC	One Stage OPIC
PIC	Parallel Interference Cancellation
PRBS	Pseudo Random Binary Sequence
RF	Radio Frequency
S-OCDMA	Synchronous OCDMA
TDMA	Time Division Multiple Access
Th	Threshold
WAN	Wide Area Network
WDMA	Wavelength Division Multiple Access

$b_i^{(j)}$	Bit number i for user #j.
$\hat{b}_i^{(j)}$	Extracted bit for user #j.
$b_k(t)$	Bits of user #k.
$c_k(t)$	Signature sequence for user #k.
$d_{k,j}$	The periodic sequence of user #k.
$g(x)$	The signal at the position x.
H	The detected data of non-desired user by the OS-OPIC.
I	Interference.
k^{th}	User #k.
L	OOC length (number of chips).
N	Number of users.
P_0	The probability of error when the desired user sends data “0”.
$P_{0(H=-1)}$	The probability of error if the user #k is interfering user.
$P_{0(H=0)}$	The probability of error if the user #k is not interfering user.
P_1	The probability of error when the desired user sends data “1”.
P_e	The probability of error.
$P(k)$	Probability density function.
P_T	$P_0 + P_1$.
$P(t)$	Unit rectangular pulse.
Q	The probability of error if the non-desired sends “0”.
Q^*	The probability of error for user #k to be interfering user.
$r(t)$	The received signal.
S_d	The threshold level of the desired user of the OS-OPIC.
S_F	The threshold level of the desired user of the OPIC.
S_n	The threshold level of user #k of the OPIC.
S_T	The threshold level of the non-desired user of the OPIC.

$S(t)$	The signal applied to the entry of the desired user of the OPIC.
T_c	The duration of the rectangular pulse.
w	OOC weight (number of marks).
$Z_i^{(1)}$	Signal of user #1 after the integration process.
λ_a	Auto-correlation.
λ_c	Cross-correlation.
τ_k	Time delay associated with user #k.

CHAPTER 1

1. INTRODUCTION

1.1 Background

In the information age, we are seeing increasing demand for networks with higher capabilities at lower cost. This demand is fueled by many different factors. The tremendous growth of the internet has brought more and more users online, consuming large amounts of bandwidth due to data transfers involving video and image. At the same time, businesses are relying increasingly on internet for day to day operations. Moreover, the ultimate vision of the information age is that information can be located anywhere but is accessible from everywhere as if it were located locally. Networks of enormous capacity will be required to provide the infrastructure to realize this vision. All these factors are deriving the need for more bandwidth for networks as well as new network services.

To fulfill the demands for bandwidth and to deploy new services, new technology must be deployed, and fiber optic is one such key technology.

The advanced developments in fiber optics over the past 20 years have made possible the use of optical fiber as transmission media in modern communication systems. Optical fiber offers several advantages over the traditional media (e.g. twisted wire pair and coaxial cable) [1-2]. It offers virtually unlimited bandwidth and is considered as the ultimate solution to deliver broadband access to the last mile. It also offers a much lower attenuation factor where optical signals can be transmitted over very long distances without signal regeneration or amplification. In addition, many channels can be multiplexed to share the same fiber optic medium, thus reducing the number of links required and the cost to end users. Due to this, fiber optic has been widely deployed in the long haul communication systems as a backbone to support the transmission of very high bandwidth while avoiding the bottleneck problem.

The success of fiber optic in long-haul communication systems has shifted the focus of optical networking to the shorter-haul metropolitan and local-area domains. Local Area Network (LAN) may well comprise hundreds of users, each user may well require individual data rates in gigabits per second, leading to aggregate data rates reaching hundreds of gigabits per second. Fortunately, fiber optic offers huge bandwidth and can be implemented to meet the requirement of high bandwidth.

To share the available bandwidth offered by fiber optic among all the users in a manner which is fair and fast, three multiple access approaches are often considered to make the system bandwidth available to the individual user [3]: Time Division Multiple Access (TDMA), Wavelength Division Multiple Access (WDMA) and Code Division Multiple Access (CDMA).

1.2 Multiple Access Schemes

Whenever some resources is used and thus accessed by more than one independent user, the need for a multiple access schemes arises. In the absence of such schemes, conflicts can occur if more than one user tries to access the resources at the same time. Therefore, the multiple access schemes should avoid or at least resolve these conflicts. Optical fiber provides huge bandwidth for multiple access operations, permitting many users to simultaneously communicate over the same medium. Three multiple access approaches are often considered to make the system bandwidth available to the individual user: Time Division Multiple Access (TDMA), Wavelength Division Multiple Access (WDMA) and Code Division Multiple Access (CDMA). In a TDMA system, each channel occupies a time slot, which interleaves with time slots of other channels. In a WDMA system, each channel occupies a narrow bandwidth around a center wavelength or frequency. In CDMA, each user is identified by different codes or addresses.

Traditional fiber optic communication systems use either TDMA or WDMA schemes to allocate bandwidth among multiple users. Unfortunately, both present significant drawbacks in local area systems requiring large number of users [3].

1.2.1 Time Division Multiple Access (TDMA):

In TDMA scheme [3-4], the bandwidth is divided into frames of equal duration, and each frame is divided into the same number of time slots. All time slots have equal duration. Each slot position within frame is allocated to a different user. This means, a particular user transmits in specific time slot in each transmitting frame. The length of the transmission frame is determined by the data bit period and is subdivided into a number of time slots according to the width of optical pulse. In TDMA the total system throughput is limited by the product of the number of users and their respective transmission rates since only one user can transmit at a time. For instance, if 100 users wish to transmit at 1 gigabit per second, at a minimum the communication hardware would need to be capable of sustaining a throughput of 100 gigabits per second, which is very hard to achieve this requirement at the present time. In addition, TDMA systems require strong centralized control to allocate time slots and maintain synchronous operation [3].

1.2.2 Wavelength Division Multiple Access (WDMA):

Unlike TDMA, a WDMA system allows each user to transmit at the peak speed of the network hardware since each channel is transmitted on a single wavelength of light [5-7]. WDMA systems allocate the available optical bandwidth into distinct wavelength channels that are sent simultaneously by different users to permit multiple access. A WDMA system could easily support a bandwidth of one terabit per second, ideal for the needs of a local area network. The problem with using WDMA in LANs is the need for a significant amount of dynamic coordination between nodes [3]. A dedicated control channel can be used for pretransmission coordination. However, this wastes bandwidth that could otherwise be used for data transmission and introduces latency as nodes attempt to negotiate a connection [3].

1.2.3 Code Division Multiple Access (CDMA):

CDMA is a spread-spectrum multiplexing technique by which the users access a common channel simultaneously and asynchronously [8-10]. CDMA schemes do not achieve their multiple access property by division of the transmission of different users in either time or frequency, but instead make a division by assigning each user a different code.

A CDMA user inserts its code or address in each data bit and asynchronously initiates transmission. Thus, this modifies its spectrum appearance in a way recognizable only by the intended receiver. Otherwise, only noise-like bursts are observed.

Recently, there has been growing interest in applying CDMA technique in optical domain [11-28] to support the increasing bandwidth demands of multimedia applications, such as video conferencing and World Wide Web browsing. By utilizing CDMA in optical networks, we can achieve link capacities on the order of multi THz ideal for the local area networks requirements. In fact, CDMA is particularly attractive for optical communication channels because CDMA offers the flexibility needed in the bursty LAN environment. Therefore, the additional bandwidth required by spread spectrum can be accommodated by using a fiber-optic channel and incoherent optical signal processing [12]. The primary difficulty in obtaining maximum throughput from a fiber network is the limit imposed by the electronic bandwidth.

For the optical bandwidth to be fully exploited, the system must be designed so that the electronic medium required for extracting and distributing the information does not restrict the spreading gain of the CDMA system. This requires that all the broadband processing such as the CDMA encoding and decoding is performed in the optical domain. It is believed that [13] optical components, once fully developed and integrated, will offer much higher speeds for optical signal processing than electrical one. Therefore, a desirable feature of Optical CDMA (OCDMA) [11-28] systems would be the ability to perform signal processing functions optically so that the signal conversion from optical to electrical would be done only when desired (Figure.1.1) [13]. In this thesis the all optical network will be considered to achieve better performance. To use all optical networks the obvious choice is the incoherent detection as we will see later in chapter 2.

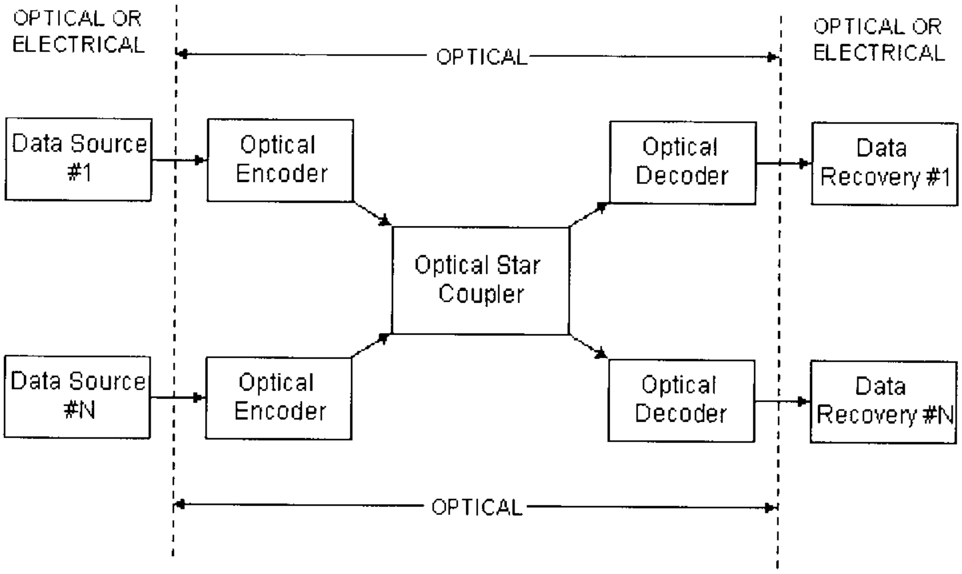


Figure 1.1: Schematic diagram of an optical code division multiple access communication system with an all optical encoder and decoder.

OCDMA offers several advantages over TDMA and WDMA. It is considered an interesting alternative for LANs because neither time management nor frequency management of nodes is necessary. OCDMA can operate asynchronously, without centralized control, and it does not suffer from packet collisions. As a result, OCDMA systems have lower latencies than TDMA or WDMA. On the other hand, since time and frequency (or wavelength) slots do not need to be allocated to each individual user, significant performance gains can be achieved through multiplexing [14]. TDMA and WDMA systems are limited by hardware because of the slot allocation requirements. In contrast, OCDMA systems are mainly limited by the Multiple Access Interference (MAI) or crosstalk from other users [15].

To summarize the advantages and disadvantages of the multiple access schemes, Table1.1 is considered [2] and more details will be given in Chapter 2.

Table 1.1: Comparison of Common Optical Multiple Access Schemes

Multiple Access Schemes	Advantages	Disadvantages
1. TDMA	a. Dedicated channels provided b. High throughput	• Accurate synchronization needed • Not efficient in bursty traffic • Bandwidth wastage • Channel not efficiently used • Performance degrades with the number of simultaneous users
2. CDMA	a. Simultaneous users allowed b. Asynchronous access c. No delay or scheduling d. High bandwidth efficiency e. Efficient for bursty traffic. f. Dedicated channels provided	a. Performance degrades due to the MAI.
3. WDMA	a. Dedicated channels provided	a. Channel crosstalk b. Channel idle most of the time c. Low bandwidth efficiency

1.3 Classification of networks

It is customary to classify networks into three categories with respect to the physical size:

- Local Area Networks (LAN): which span local geographical area up to two kilometers such as Ethernet.
- Metropolitan Area Networks (MAN): which span up to 100 kilometer such as the cable television distributing systems.
- Wide Area Networks (WAN): span up to thousands of kilometers such as internet.

1.3.1 Local Area Network (LAN):

While Ethernet continue to play a dominant role in LAN environments, the scalability of these networks is presently limited by the electronic technology in the hubs and switching nodes used to actively resolve contention on the LAN. Ultimately, the electronic bottleneck at switching nodes presently limits the scalability, flexibility of the overall LAN network [14]. These limitations have motivated the telecommunication community to investigate the potential of OCDMA in local area networks where the traffic is typically bursty [11-28]. Many proposed and demonstrated OCDMA systems have targeted high bandwidth, multiuser LANs as a key driving application and use for the technology [14].

OCDMA has the potential to scale and adapt gracefully to dynamic service needs and unpredictable network loading conditions. While OCDMA has the potential to provide scalability beyond the limits of today's LAN environments that are still dominated by electronic switching technologies, it is also an attractive approach when compared to other multiple access optical networking technologies that have been proposed over the last two decades.

The star topology (Figure 1.1) has been adopted to describe the OCDMA system. Star network is the topology that attracts the most research group due to its potential to accommodate large number of users. Beside this, no disruptions to the network when connecting or removing devices. In addition, by using star topology it is easy to detect faults and to remove parts [29].

Star network is used to describe the OCDMA networks (Chapter 2). A star network is a general class of interconnectivity among many nodes with a centralized node that broadcasts all network transmissions to all receivers. Each user is assigned a unique address on the network that enables it to distinguish traffic destined for its receiver from the traffic on the rest of the network. The implementation of star networks in the optical domain is particularly attractive for LAN environments and short distance interconnection networks. This is because star networks can provide transparent, bidirectional, full-duplex communications among many optical nodes [14].

To enable optical traffic from individual input optical fibers to be optically combined and broadcast to many output fibers optical, star couplers are used. Furthermore, individual nodes can be upgraded gracefully to support new services or higher data rates without replacing the fiber interconnection network. The star network is especially important for applications that require high bandwidth communications among many users such as a distributed computer interconnect, where each destination node has approximately the same expected network demand.

1.4 Problem Statement

All OCDMA systems are primarily limited in their performance by Multiple Access Interference (MAI) [15]. This is a direct result of the nonzero cross-correlation between different codes. MAI increases with the number of simultaneous users, resulting in deterioration in the Bit Error Rate (BER), performance and eventually limits the maximum number of simultaneous users. Analysis shows that, MAI is the main reason for the system degradation if other types of noise are neglected [15]. Research efforts [15], [20], [22] to reduce MAI in these systems have taken many directions including development of various coding techniques and detection techniques. However, since the early stage of OCDMA, it was quickly became clear that there were some fundamental differences in applying Spread Spectrum and CDMA in optical networks when compared to the more standard radio Spread Spectrum applications. For example optical reception is based on power rather than amplitude detection and therefore the use of radio CDMA codes which are designed for amplitude-based receivers is not straightforward in incoherent optical systems. New codes had to be invented. Research on OCDMA codes led to the invention of a few families of codes such as Optical Orthogonal Code (OOC) [30-38] and Prime Code [39-42]. However, all the codes that have been developed for the time domain up to date are not completely orthogonal. This means, interference between different users is originated because of the non-orthogonally of the code. Due to this, it is clear that an OCDMA system cannot be designed by considering the properties of the code only. The detection technique plays an important role and should be addressed as well.

In addition, the Conventional Correlation Receiver (CCR) [13] (see Chapter 3) requires dynamic estimation of the threshold which depends on the number of active users [43-44]. The need for dynamic threshold value in the CCR to recover the data is very demanding requirement particularly in the high speed LANs. Moreover, the performance of the CCR is very sensitive to the threshold. Unfortunately, this requirement is very difficult to achieve [44].

In this thesis, we focus on the detection technique that either reduce the effect of MAI or improve the performance even in the presence of MAI while overcomes the need for the dynamic threshold. In particular, Parallel Interference Cancellation (PIC) has been widely investigated in the area of wireless communication system to mitigate the effect of MAI [45]. In the recent years, the use of PIC in optical domain also has been investigated to reduce the dominant source of interference in the OCDMA system i.e. MAI [46]. In this thesis, Optical Parallel Interference Cancellation (OPIC) will be considered. To reduce the power of MAI, Optical Hard Limiter (OHL) is placed in front of the receiver side because of its ability to exclude some combinations of interference patterns from becoming heavily localized in a smaller part of non-zero positions of signature codes and fixed threshold value "1" is used for the desired user of OPIC in order to overcome the need for the dynamic threshold value. The study on this thesis carried out using theoretical and simulation. The results show that, OCDMA using the OPIC has the advantage of fixed threshold value "1", which is not the case with the CCR.

OPIC with OHL is complicated comparing to the conventional methods in term of hardware complexity but it is more efficient in term of MAI mitigation. To reduce the hardware complexity of the OPIC system, a new method has been proposed. This method will be discussed later in Chapter 3.

1.5 Objectives

The main goal of this research is to improve the performance of OCDMA systems using OPIC receiver. Optical Hard Limiter (OHL) is used in front of the OPIC for further improvement. The objectives of this research include:-

a) To compare the results of previous techniques used to mitigate the effect of MAI, in particular, we will consider in details the performance of the CCR with and without optical hard limiter.

b) OPIC has the potential of solving the problem of the dynamic threshold by using fixed threshold value. Due to this, one of the objectives of this research is to overcome the need for the dynamic threshold in the receiver side.

c) To reduce the hardware used in the OPIC receiver and thus reducing the hardware complexity and processing time by introducing a new method referred as One Stage OPIC.

1.6 Scope of Works

This research focus on the receiver side of the OCDMA system. In particular, Optical Parallel Interference Cancellation (OPIC) receiver is investigated and its performance is compared to other schemes used to improve the BER. Beside analytical study, extensive studies also performed through software simulations. The software is used to validate the theoretical analysis. The following work is carried out to meet the objectives of the study:

The most important technique used to mitigate the effect of MAI is discussed and the results are obtained and compared to the OPIC. Fixed threshold is used to overcome the dynamic threshold. Eventually, a new method is presented to reduce the hardware complexity of the OPIC.

In general, the OPIC is the main topic of this thesis and it will be discussed in details throughout this thesis.

1.7 Methodology

In general, this research can be divided into three stages as it illustrated in Figure 1.2:

In the first stage, the performance of the Conventional Correlation Receiver (CCR) with and without Optical Hard Limiter (OHL) has been studied. It is shown that, CCR is effective for small number of users but has poor performance for large number of simulations users [64].

In the second stage, Optical Parallel Interference Cancellation (OPIC) [46] has been considered to overcome the problem of MAI and improve the performance of OCDMA system. Optical Hard Limiter (OHL) is placed in front of the receiver because of its ability to remove some combination of the interference. Another study has been conducted on the code length. We found that, by increasing the length of the code sequence we managed to improve the throughput of the OPIC system.

Moreover, the need for the dynamic threshold value is addressed in this stage and optimum threshold has been proposed as a permanents solution for this problem. In addition, the hardware complexity has been reduced and new method has been introduced based mainly on the OPIC system namely, One Stage OPIC (OS-OPIC).

Finally, in the third stage the simulation is used to validate the theoretical models and the results are compared to each other.

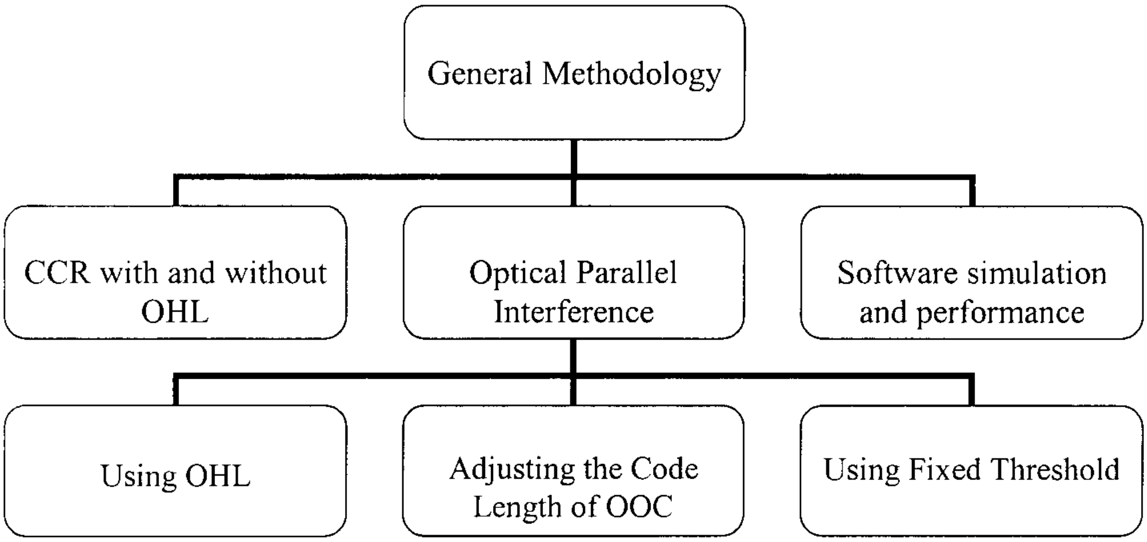


Figure 1.2: General Methodology

1.8 Thesis Overview

This thesis is organized into five chapters. Chapter one, an introduction chapter discusses the need for high speed networks and the main reasons of using fiber optic in these networks. The main problem faced in the implementation of the OCDMA system; the objectives and scope of study are also outlined.

Being an asynchronous multiple access scheme, OCDMA is especially well suited for local area applications with its bursty kind of traffic. OCDMA enables every user to access the transmission medium at any given time without waiting time. The main concept of the OCDMA system is given in chapter two, but this chapter starts with the details about the multiplexing and multiple access technologies used to allocate the available bandwidth offered by fiber optic line. Then, details are provided in this chapter including the classification of OCDMA system, the most studied code and the advantages of OCDMA in LAN.

MAI is the main problem hampers the implementation of the OCDMA. It was shown that, in non-coherent direct detection OCDMA, the use of unipolar pseudo-orthogonal code that have good correlation properties (i.e. high autocorrelation peaks and low cross-correlation) are needed to reduce the effect of MAI. Researches on the OCDMA systems have led to the invention of a few families of code such as Optical Orthogonal Codes (OOC) and Prime Sequence Codes. However, recent studies show that, an OCDMA system cannot be designed by considering the properties of the code only, the detection technique also plays an important role and should be addressed [46]. Due to this, several detection schemes appeared in the literature aiming at minimizing the effect of MAI. In particular, OPIC has been used in OCDMA system to reduce the effect of MAI. The concept of OPIC, the main advantages and disadvantages, the role of OPIC in reducing the MAI and solving the dynamic threshold problem will be discussed in chapter three. Different methods are proposed by the author to improve the performance of the OPIC will be discussed in this chapter as well. Both, the hardware and coding techniques are highlighted in this chapter. In particular, the use of OHL, OS-OPIC, optimum threshold value and adjusting the code length have been discussed in this chapter.

Chapter 4 presents simulation results. The software that used to evaluate the performance including: Matlab, C language and VPI Transmission Maker. Different families of OOC are considered for various numbers of users to ensure the results.

Finally, conclusions and future work are given in Chapter five.

CHAPTER 2

2. FIBER OPTIC CODE DIVISION MULTIPLE ACCESS TECHNOLOY FOR LOCAL AREA NETWORKS

2.1 Introduction

In the last two decades, interest in optical communication systems has been rapidly growing due to the large bandwidth offered by the fiber optic. A single mode optical fiber can support transmission capacity in the range of Terabits per second [14]. Optical multiplexing techniques have to be employed to exploit full system transmission capacity. Traditional ways of separating signals in time (i.e. TDMA) or in frequency (i.e. FDMA) or in wavelength (WDMA) are simple to make sure that the signals are orthogonal and non-interfering. However, in CDMA, different users occupy the same bandwidth at the same time, but they are separated from each other by the use of a set of orthogonal waveforms, sequences, or codes.

In this chapter, the use of CDMA in optical domain will be discussed. The classification of the OCDMA system, the most studied codes for the OCDMA i.e. Optical Orthogonal Code (OOC) and the advantages of OCDMA in local area networks. It starts with a discussion on various existing multiplexing and multiple-access techniques that used in the telecommunication systems up to date.

2.2 Multiplexing and Multiple Access Techniques

There is no big difference between multiple access and multiplexing techniques. Multiple access techniques are often used to allow a communication medium to be shared between different users. The basic multiple access techniques that mainly used in communication systems are: Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA).

Multiplexing technique which makes possible to cram a number of logical channels (each capable of supporting an independent connection) into the same physical channel or line. The objective of multiplexing should be obvious: to reduce costs by better utilizing the capacity of a line. The main multiplexing techniques used in the telecommunication systems are: Time Division Multiplexing (TDM) and Frequency Division Multiple (FDM). In optical communications, FDM is referred to as Wavelength Division Multiplexing (WDM).

According to the definition of the multiple access and multiplexing techniques, multiplexing are more suitable for metropolitan and long haul communication systems, while multiple access techniques are more suitable for shorter distance access networks. Due to this, our study will deal more with multiple access techniques since we are focusing on local area networks.

2.3 Optical CDMA Technology

2.3.1 Introduction

Traditional fiber optic communication systems use either TDMA or WDMA schemes to allocate bandwidth among multiple users. Unfortunately, both present significant drawbacks in local area systems requiring large number of users [19].

OCDMA [11-28] takes advantages of excess bandwidth in single mode fibers to map the low information rate of electrical or optical data into high rate optical pulse sequences followed by a laser beam to obtain random, asynchronous communications free of network control among many users. An additional advantage is that some processing can be moved into the optical domain, which is important since certain operations can be implemented with very low complexity using optical components. Even though it is possible to implement advanced receivers for radio CDMA systems it has to be taken into account that the bit rates are several orders of magnitude higher for optical systems. It is important that simple optical implementations are possible rather than the digital electronic signal processing at the rates common for radio systems. As a result, OCDMA has received substantial attention for local area networks. Since the traffic in LAN's is typically bursty, asynchronous multiplexing schemes which allow multiple users to share the entire channel, are more suitable than synchronous multiplexing schemes which dedicate a portion of the channel to each bursty user.

OCDMA offers an interesting alternative for LANs because neither time management nor frequency management of all nodes is necessary. OCDMA systems have lower latencies than TDMA or WDMA.

Furthermore, since time and frequency (or wavelength) slots do not need to be allocated to each individual user, significant performance gains can be achieved through multiplexing.

2.3.2 Synchronous and Asynchronous OCDMA:

The OCDMA system may be Synchronous (S-OCDMA) or Asynchronous. In a Synchronous system, the bits and chips are synchronized. In the Asynchronous system the bits are not synchronized but the chips may be transmitted synchronously.

Both Asynchronous and Synchronous OCDMA techniques have been examined in the literature [48-53]. Each of these has its strengths and limitations. In general, since synchronous accessing schemes follow rigorous transmission schedules, they produce more successful transmissions (higher throughputs) than asynchronous methods where network access is random and collision between users can occur [51].

In application that requires real time transmission, such as voice or interactive video, synchronous accessing techniques are most efficient. When the traffic tends to be bursty in nature or when real time communication requirements are relaxed, such as in data transmission or file transfers, asynchronous multiplexing schemes are more efficient than synchronous multiplexing.

2.3.3 Classification of OCDMA:

In OCDMA systems, the detection schemes affect the design of transmitters and receivers and play an important role in solving the problem hampers the implementation of the OCDMA system i.e. MAI. In general, there are two basic detection techniques namely coherent and incoherent.

OCDMA communication system can be all-optical or partly optical. In a partly Optical CDMA system at least the communication channel is an optical. The information bits may be originally optical or electrical. The all-optical OCDMA system is usually an incoherent system. In the fiber optic coherent system signature coding is performed electrically and after that the optical carrier of the laser transmitter is modulated coherently.

2.3.3.1 Coherent OCDMA Systems

Coherent OCDMA [54-58] requires the exact knowledge of the carrier's phase. This means, the phase plays an important role in code design for such systems. Since coherent system is phase sensitive, the use of such techniques will of course be more difficult than that of incoherent ones, because of the need to provide adequate optical phase control. On the other hand, if the phase can be controlled adequately, then it should add new dimensions to the design of OCDMA networks with potentially very beneficial results.

The coherent OCDMA system may be partly optical or all-optical. In the partly optical system the chip sequence is generated electronically. The optical receiver gives out the electrical chip sequence which is recognized electronically. Example of coherent OCDMA systems are the delayed line based coherent direct sequence OCDMA. In case of a fiber optic transmission system, tracking the phase of the light wave means an additional effort which is out of all proportion to the expected improvement of performance. For these reasons, coherent CDMA has not been considered in this work.

2.3.3.2 Incoherent OCDMA Systems

While coherent detection refers to the detection signals with knowledge of the phase information of the carriers, incoherent detection [59-63] refers to the case without such knowledge. In other words, a system consisting of unipolar sequences in the signature code is called incoherent system. A system that uses bipolar codeword is called a coherent system. Incoherent detection has attracted the attention of most research groups around the globe because such system does not require phase synchronization. As a result, the hardware complexity of the system is extremely reduced.

In the mid 1980's it was proposed to use this type of optical signal processing to implement multiple access optical networks with asynchronous transmission [12]. The idea was to extend to the optical regime the technique of spread spectrum which is so successful at radio frequency. The major different is that, while the radio frequency is coherent the initial optical work was incoherent. Since then, the incoherent OCDMA is the area of research that has attracted the attention of most research groups up to now due to the practical ease of implementing direct optical detection based systems. In this system, Direct Detection (DD) receiver is used [50].

In DD systems (Figure 2.1), at the transmitter, the information signal intensity is modulated to produce a series of optical pulses. Signal detection in these systems is equivalent to power measurement, i.e. on-off keying ("full" power for transmitting a mark, zero power for space). These systems are modeled as positive systems, i.e. a system that can not manipulate its signals to add to zero, since optical power can not be negative. In positive systems, unipolar codes must be used. Whenever an information "1" bit is to be transmitted, a whole code sequence consisting of "0"s and "1"s is transmitted. Information "0" bit is not encoded.

At the receiver side the received signal is detected by a photodiode, which converts the optical signal into an electric baseband signal.

Furthermore, most of the incoherent DS-OCDMA systems were used to demonstrate the feasibility of the conception of OCDMA. In these systems, broadband optical sources were used. To avoid large optical loss with optical processing, the electronic processing was used only either at encoder or at decoder.

In this thesis we will consider the Incoherent Direct Detection Fiber Optic CDMA, the main advantages and the main problem of this system will be discussed. The implementation of this system will be demonstrated throughout this work.

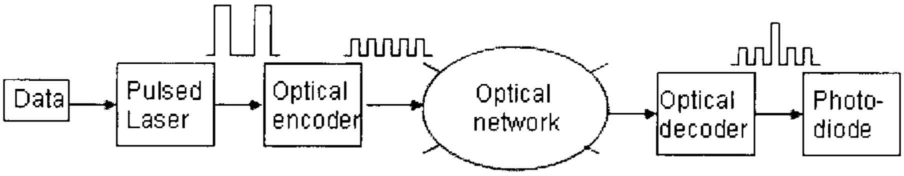


Figure 2.1: Incoherent OCDMA

2.3.4 Optical CDMA Network:

To simplify a concept of the OCDMA system, some assumptions are made in this part: We will consider the non-coherent Direct Sequence Optical CDMA (DS-OCDMA) employing on-off keying (OOK) as a common method of modulation. OOC is adopted as signature sequence with the length L, weight w and the auto-and cross-correlations bounded by 1.

Assume that there are N optical encoder and decoder pairs (users) in the fiber-optic CDMA system under investigation as shown in Figure 2.2. Each user in this system is assigned a unique optical signature code with desired distinguishable correlation properties, so simultaneous users are allowed to send their data asynchronously through this code (Figure 2.3). The signature sequence, $c_k(t)$ of the k^{th} user is given by:

$$c_k(t) = \sum_{j=1}^{L} d_{k,j} P(t - jT_c) \tag{2.1}$$

where $P(t)$ is the unit rectangular pulse with duration T_c and $d_{k,j}$ is the k^{th} periodic sequence of binary optical pulses (0,1).

In the transmitting side, a data bit one is encoded at an optical encoder with intended destination signature code. Data bit zeros are not encoded. Each bit is subdivided into L small units with duration T_c, called chips. The encoded data is then superimposed with the encoded data from other users and coupled into the fiber channel. At the other end of the fiber, the optical data sequences from all simultaneous users are distributed to all optical decoders via an optical star coupler. At the receiver side the desired signal along with the interference from all other $N-1$ users will be received. The receiver has to be able to decide which bit of the desired user has been sent. The received signal $r(t)$ can be expressed by:

$$r(t) = \sum_{k=1}^{N} b_k(t) c_k(t - \tau_k) \tag{2.2}$$

where τ_k, with $0 \leq \tau_k \leq T_c$, is the time-delay associated with k^{th} user and $b_k(t)$ is the bit (0, 1) of the k^{th} user.

Each optical decoder correlates its own signature code with the received optical data sequences to generate correlation functions. Optical data sequences arriving at the decoder with unmatched signature code result in cross-correlation functions which, in turn, are considered as interference. The threshold detector compares the correlation value to a threshold *Th* so as to extract the transmitted data.

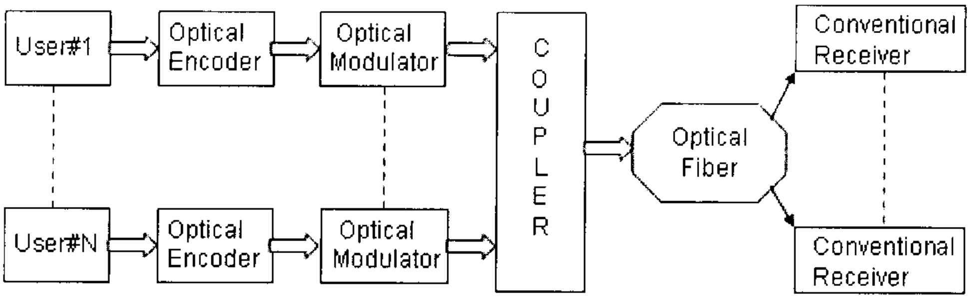


Figure 2.2: Optical CDMA block diagram

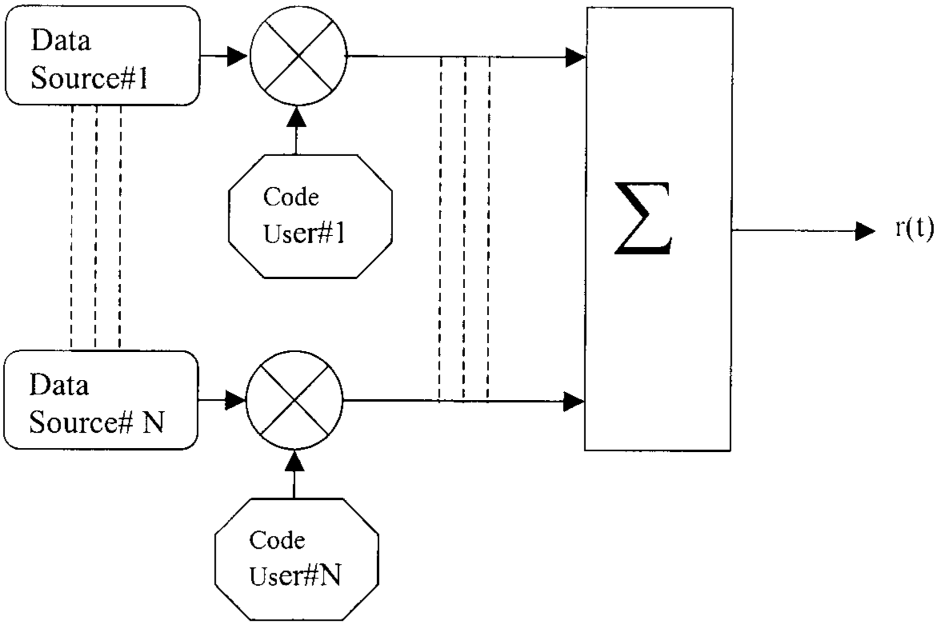


Figure 2.3: transmission part of Optical CDMA

2.3.5 Code of DS-OCDMA System

OCDMA systems like wireless CDMA in which, each user is assigned with unique signature sequence called codeword. The choice of the codewords, the signature sequence, is a key to any successful CDMA scheme either electrical or optical.

In RF CDMA systems, sequences consist of [–1, +1] values and therefore known as bipolar codes. The choice of both positive and negative values is natural since phase of the electromagnetic field can be detected directly. According to the natural different between wireless and optical domain, code used in wireless is not straightforward in optical domain. This is because the optical signal is equivalent to the instant power which is nonnegative. This means, that codes based on [–1, +1] signals, which are used in wireless CDMA system, cannot be applied in optical system. As a result, only unipolar sequences consisting of [0, 1] values can be used for OCDMA systems with the following consideration:

In OCDMA system multiple users are allowed to access the same medium using the same time interval and frequency band. The transmitted concurrent data streams will definitely produce Multiple Access Interference (MAI). In order to reduce the effects of this interference, the code should meet specific conditions for auto- and cross-correlation.

It was shown that, a good OCDMA code has much more 0's than 1's in each codeword, while a well-correlated [-1, +1] sequence typically has about the same number of -1's and +1's. Researches on the OCDMA systems have led to the invention of a few families of code such as Optical Orthogonal Codes (OOC) [30-38] and Prime Sequence Codes [39-42]. This part discusses the main concept of the Optical Orthogonal Code.

2.3.5.1 Optical Orthogonal Code (OOC):

An optical orthogonal code (OOC) [30-38] which is characterized by $(L, w, \lambda_a, \lambda_c)$ is a family of [0, 1] with length L and weight w (number of ones) and good properties of autocorrelation and cross-correlation (high autocorrelation and low cross-correlation). The good auto-correlation facilitates the detection of the desired signal and the low cross-correlation reduces MAI in the network.

One of the primary goals of the OCDMA is to extract data with the desired address code in the presence of all other users' optical pulse sequences. Therefore, the set of code sequence should be designed to satisfy the following conditions:

- Each sequence can easily be distinguished from a shifted version of itself.
- Each sequence can be easily distinguished from (a possibly shifted version of) every other sequence in the set. This means, the cross-correlation between any pair of codewords must be small. This property ensures that, each codeword can easily be distinguished from every other address sequence. In other words, we seek to make the MAI insignificant compared to the energy contained in the received information bit.

The auto-correlation property:

$$\sum_{t=0}^{L-1} x_t x_{t+\tau} = \begin{cases} w & for\ \tau=0 \\ \lambda_a & for\ ,1 \le \tau \le L-1 \end{cases} \tag{2.3}$$

2) The cross-correlation property:

$$\sum_{t=0}^{L-1} x_t y_{t+\tau} \le \lambda_c \qquad for \qquad 0 \le \tau \le L-1 \tag{2.4}$$

In general, for $(L, w, \lambda_a, \lambda_c)$ the upper bound on the cardinality N of a set of OCDMA codes with unity autocorrelation and unity cross-correlation is given by:

$$N = \left[\frac{L-1}{w(w-1)}\right]$$

where the brackets denote the integer portion of the real value.

An upper bound on the Probability of Error (P_e) can be found by assuming a chip synchronous overlap of the codewords (worst case). To derive the (P_e) of OOC, it is necessary first to determine the probability density function (pdf) of one mark in a codeword to overlap with a mark in another codeword.

In OOC, the number of marks is given by w, so there are w possibilities for the marks in the codewords to overlap and the probability of each individual overlap is $1/L$ the probability of an overlap is given by: $\mathrm{P} = \frac{w^2}{L}$

The complement of this event, which corresponds to the probability of no overlap, is $1 - \frac{w^2}{L}$

Therefore, we can define for these events, random variable k with a probability density function P(k) expressed as:

$$\mathrm{P}_k(k) = \left(1 - \frac{w^2}{L}\right)\delta(k) + \frac{w^2}{L}\delta(k-1) \qquad (2.5)$$

where δ denotes Dirac's delta distribution.

Considering the on-off modulation of the bit sequence that has to be encoded, a random variable $u = \frac{1}{2}k$ can be defined, since the bit sequence contains marks and spaces with equal probability. It follows that

$$\mathrm{P}_u(u) = \left(1 - \frac{w^2}{2L}\right)\delta(u) + \frac{w^2}{2L}\delta(u-1) \tag{2.6}$$

In the receiver side the output of the decision device (threshold) is given by

$$\begin{cases} 1, & y_n(t_0) \geq Th \\ 0, & y_n(t_0) < Th \end{cases}$$

where Th the threshold of the decision, its value is depends on the codeword. If the number of the impulses is equal to or higher than threshold Th, the decision device outputs a "1" (Mark), otherwise a "0" (Null). If we assume that no random noise is present in the system, then the false detection of a Mark as a Null is not possible. But if the information bit is a Null, it may be mistaken and detected as a Mark when MAI is present in the system. Due to this, we could validate that, no errors is committed when the desired user sends data "1". However, there is an error with some probability when the desired user sends data "0". Accordingly the P_e of the OOC can be obtained as follows:

$$\frac{1}{2}\sum_{i=Th}^{N-1}\binom{N-1}{i}\left(\frac{w^2}{2L}\right)^i\left(1 - \frac{w^2}{2L}\right)^{N-1-i} \tag{2.7}$$

2.3.5.1.1 Optical Orthogonal Code examples

Table 2.1 and Table 2.2 are representing examples of the code sequence used in OCDMA system. Two families of the OOC are considered for 7 and 5 users respectively.

The code sequence of the OOC consists of more zeros than ones, the chips used here are used to describe the position of the one's and the reset are zeros.

Table 2.1 Optical Orthogonal Code for 7 users [30]:

User No	Chip 1	Chip 2	Chip 3
N 1	0	1	19
N 2	0	2	22
N 3	0	3	15
N 4	0	4	13
N 5	0	5	16
N 6	0	6	14
N 7	0	7	17

Table 2.2 Optical Orthogonal Code for 5 users [30]:

User No	Chip 1	Chip 2	Chip 3	Chip 4
N 1	0	18	31	47
N 2	0	20	30	45
N 3	0	28	37	42
N 4	0	38	40	61
N 5	0	52	53	60

2.3.6 Advantageous of OCDMA:

The asynchronous nature and the capability of ease access in a bursty environment make OCDMA better alternative to the multiple access schemes for LAN. Beside this, OCDMA has attractive advantages and these advantages have motivated the research groups to investigate the potential of OCDMA in LAN. The advantages of OCDMA are summarized as follows:

- Asynchronous and simultaneous access protocol. Neither timing synchronization nor wavelength control is necessary and asynchronous data transmission simplifies network planning, management and control.
- No need for the centralized network control, Simple protocols (e.g. tell-and-go protocol).
- Using optical processing to fulfill certain network applications such as addressing and routing.

- Suitable for the local area networks where the traffic is typically bursty because low delay access, effective allocation of bandwidth responding to requirement.
- High capability of data throughput and accessed users.
- Flexibility of the network architecture and new users can be easily added to the network.
- High speed coding and decoding process.
- High security of data and network.

Summary:

Code Division Multiple Access (CDMA) has been extensively studied in the areas of wireless and satellite communication. In the recent years, the use of CDMA in the optical domain also has been investigated. Like wireless CDMA, in OCDMA systems each user is assigned with a sequence code that serves as its address. An OCDMA user modulates its code (or address) with each data bit and asynchronously initiates transmission. Hence, this modifies its spectrum appearance, in a way recognizable only by the intended receiver. Otherwise, only noise-like bursts are observed.

In the literature, both Synchronous and Asynchronous OCDMA has been investigated. Generally, synchronous accessing schemes follow rigorous transmission schedules, they produce more successful transmissions (higher throughputs) than asynchronous methods where network access is random and collision between users can occur.

OCDMA systems can be divided into two main categories: coherent and incoherent OCDMA. Incoherent OCDMA systems have attracted more attention than their coherent OCDMA counterparts, because the former have a far lower complexity and require simpler devices/components than the latter.

Different families of codes have been developed for the OCDMA system. However, Optical Orthogonal Codes (OOC) has been widely studied for incoherent OCDMA applications. It is known that, OOC have better properties of cross-correlation (low cross-correlation). Due to this, OOC will be used throughout this thesis.

CHAPTER 3

3. OPTICAL PARALLEL INTERFERENCE CANCELLATION (OPIC)

3.1 Introduction:

The performance of OCDMA system described in chapter two depends on the signal processing or detection that is performed at the signal destination. Furthermore, the overall task of the optical receiver is to extract the information that has been placed on the modulated light carrier by the transmitter and restore the information to its original form. Different types of receiver have been used since the invention of OCDMA. The most popular receiver is known as the Conventional Correlation Receiver (CCR) [13].

The correlation detector is simple but has a poor performance for large number of users [64]. It is well known that, the performance of the conventional OCDMA system deteriorates rapidly because of the other user's signals referred as Multiple Access Interference (MAI) [15]. In addition, the need for the dynamic threshold in this receiver to extract the data is critical and is highly demanding especially for high speed networks [43-44].

To overcome these difficulties, there is a strong demand for the design of new detection scheme that will be efficient enough to improve the performance of the OCDMA system while minimizing the effects of the MAI and settle the problem of dynamic threshold. Accordingly, Parallel Interference Cancellation (PIC) has been examined in optical domain through this work to address the stated problems. In fact, PIC has been widely deployed in the areas of wireless to improve the performance of CDMA and mitigate the power of MAI [45]. The successful of PIC in wireless communication systems has motivated the communication community to investigate the potential of PIC in optical domain. Fortunately, PIC exhibits good performance in the OCDMA system because it is able to exclude the contribution of non-desired users.

This chapter discusses the performance of the Optical Parallel Interference Cancellation (OPIC). Furthermore, Optical Hard Limiter (OHL) is used in front of the OPIC to reduce the interference originated from other users and hence reducing the error probability in the system. Moreover, the performance of OPIC is obtained using a fixed threshold "1" and thus we manage to alleviate the problem of the receiver dynamic threshold. In addition, a new technique is proposed in order to reduce the hardware complexity, processing time and eventually the cost on the OPIC referred as One Stage OPIC. The CCR also will be demonstrated.

Nevertheless, this chapter will start by giving some background about the dominant source of the interference in the OCDMA system namely MAI.

3.2 Multiple Access Interference (MAI)

The primary goal of the design of OCDMA systems is to extract data with the desired optical pulse sequence in the presence of all other user's optical pulse sequences (codeword), the presence of Multiple Access Interference (MAI) [15]. In OCDMA systems, MAI originating from other users wishing to access the same medium using the same time and frequencies for transmitting concurrent data streams. MAI severely increases with the number of simultaneous users resulting in deterioration in the performance, increase in the Bit Error Rate (BER) and eventually limits the maximum number of simultaneous users. Therefore, MAI is considered the dominant source of noise in an OCDMA system. Due to the stated problem, a good design of detection scheme is needed to reduce the effect of MAI.

For better understanding to the MAI, let us consider the following example:

$S_1(t), S_2(t), S_3(t), S_4(t)$ are representing the signature sequences of four simultaneous users (Figure 3.1). 1-bit is transmitted to user 1, 2 and 3. 0-bit is transmitted to the user 4. Then user 4 is chosen to be the desired user. The receiver of the user 4 makes a wrong decision when it correlates its own signature sequence $S_4(t)$ with the received signal $S_1(t)+S_2(t)+S_3(t)+S_4(t)$.

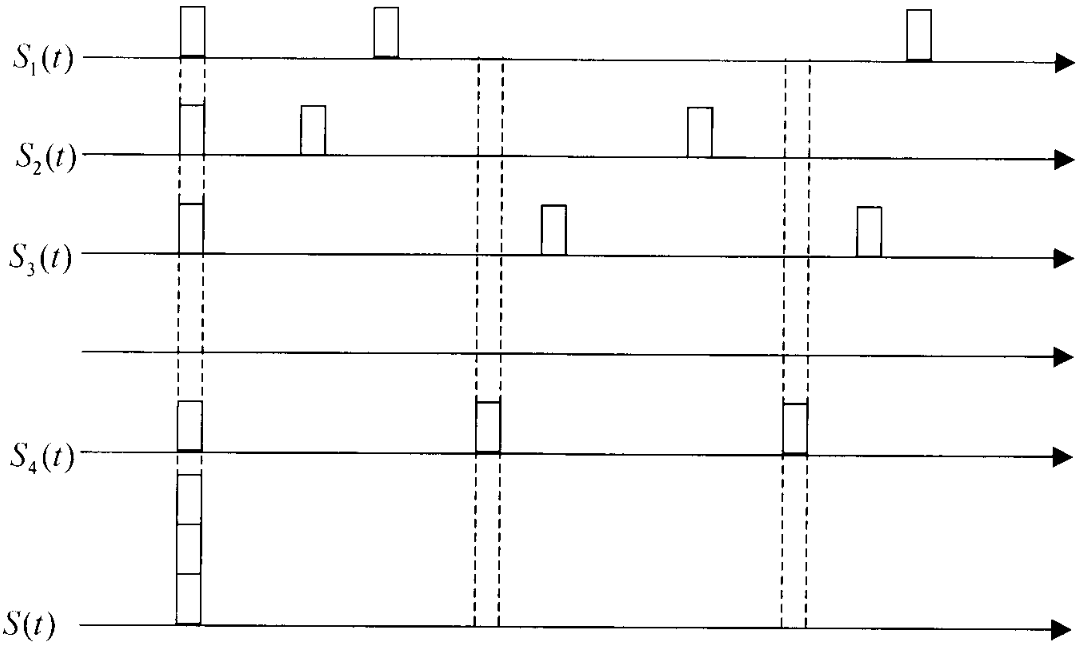


Figure 3.1: Wrong decision caused by overlapping 1's in signature codes

Figure 3.1 shows the effect of the MAI on the final decision. In this figure, the desired user sends data "0" and the interference from other users exceed the threshold level. The threshold in this figure can be set to "1" or "2" or "3" as maximum value. Due to this, if we select any value, the result will be "1", however the desired user sends data "0" which indicate wrong decision.

3.3 Conventional Correlation Receiver (CCR):

Conventional Correlation Receiver (CCR) (Figure 3.2) has been studied in several articles in the literature [13] [15]. It operates by enhancing a desired user while suppressing other users considered as interference. In the CCR, errors occur only if the desired user sends data "0" and the interference from other users exceeds the threshold level [15]. Apparently, MAI threatens the performance of the CCR and limits the maximum number of simultaneous users. The performance of the CCR can be obtained by selecting an optimum threshold level. An Optical Hard Limiter (OHL) [15] [22] has been placed in front of the CCR in order to improve the performance (Figure 3.4). The OHL is able to reduce the MAI if we neglect the effect of other noise in the receiver [15].

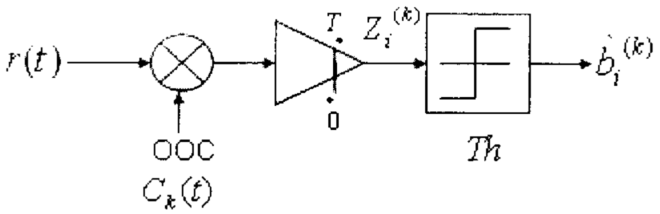


Figure 3.2: Conventional Correlation Receiver

In order to analyze the performance of the CCR, we will consider the following assumptions: the performance degradation is only due to the effects of the presence of other users. This means, the effects of quantum noise and thermal noise are neglected in order to focus on the problem of the MAI. All light sources are incoherent. As a result, the optical light intensity of multiple users occurring at the same time would add in intensity and only the unipolar code is considered. Furthermore, all users have the same effective average power at any receiver so that one user could not overwhelm the others, and all users have identical bit rate and signal format. In this case, at the receiver end, the signal $r(t)$ is the sum of all users' signal and can be written as follows:

$$r(t) = \sum_{k=1}^{N} b_k(t) c_k(t - \tau_k) \tag{3.1}$$

where τ_k, with $0 \le \tau_k \le T_c$, is the time-delay associated with k^{th} user and $b_k(t)$ is the bit (0, 1) of the k^{th} user.

Each optical decoder correlates its own signature code with the received optical data sequences to generate correlation functions. Optical data sequences arriving at the decoder with unmatched signature code result in cross-correlation functions which in turn are considered as interference. The threshold detector compares the correlation value to a Threshold Th in order to extract the transmitted data. As mentioned, an error occurs when the desired user transmits a binary "0" that corresponds to sending no sequence and the interference due to the other $N-1$ user's signals cause a false detection.

3.4 Conventional Correlation Receiver with Optical Hard Limiter (OHL):

Multiple Access Interference (MAI) is the main reason of the performance degradation in the Conventional Correlation Receiver (CCR). Errors occur with some probability if the desired user sends data "0". An Optical Hard Limiter (OHL) is placed at the front end of the CCR before correlation is performed to reduce the effect of MAI (Figure 3.4) [15] [22]. An ideal OHL is defined as follows [15]:

$$g(x) = \begin{cases} 1, x \ge 1 \\ 0, 0 \le x < 1 \end{cases} \tag{3.2}$$

where 1 is the normalized optical light intensity. Therefore, if an optical light intensity is bigger than or equal to one, the OHL would clip the intensity to one, and if the optical light intensity is smaller than one, the output of the OHL would be zero. The OHL clips the incoming light power, resulting in a performance improvement because it is able to exclude some combinations of interference patterns from becoming heavily localized in a smaller part of the non-zero positions of signature codes.

For example, a data bit zero is transmitted at time zero for a user with a signature code:

[0 100 010 000 010 000 000 000 001 101 000]. Without the OHL, the received data sequences of the following form:

[0 300 020 000 010 000 000 000 001 001 000] (Figure. 3.3(a)) would have a maximum value of "8" at the output of its optical decoder, resulting in a decoding error if the threshold is set at 6. With the OHL, the received data sequences would be clipped to the form [0 100 010 000 010 000 000 000 001 001 000] (Figure. 3.3(b)), which would not cause a decoding error at the output the threshold detector.

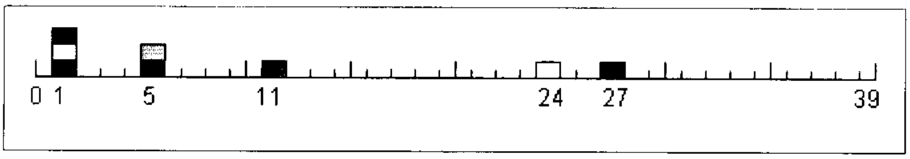


Figure 3.3a: Receiver without OHL

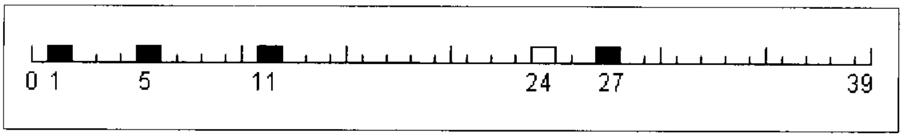


Figure 3.3b: Receiver with OHL

As shown in the Figure 3.3a, a multiplexed OCDMA waveform arriving at a receiver can have strong interference at some pulse positions of the correlation function in which pulses from number of simultaneous users ride a top each other. However, OHL managed to reduce the strength of the interference (Figure 3.3b).

The CCR with OHL (Figure 3.4) has previously shown improved the system performance because OHL can exclude interference from becoming heavily localized in small parts of a correlation function. Furthermore, the interference at all nonempty pulse positions of every cross correlation function equalized. Therefore, an error occurs whenever the transmitted data bit is zero but the total number of nonzero pulse positions contributed by MAI at an intended receiver exceeds the decision threshold Th.

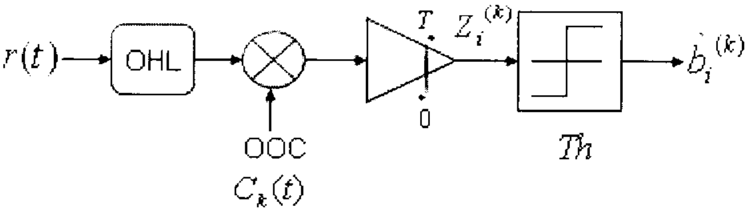


Figure 3.4: Conventional Correlation Receiver with OHL

3.5 Multi-User Interference Cancellation

Studies on interference-cancellation techniques are inspired by Radio Frequency (RF) communications, such as multi-user detection, Parallel Interference Cancellation (PIC) and Serial Interference Cancellation (SIC). These techniques are more complex than the conventional techniques but they are more efficient.

The principle of multi-user interference cancellation is relying on the estimation and reconstruction of the MAI seen by each user, with the objective of canceling it from the received signal.

As illustrated in the previous section, the CCR operates by enhancing a desired user while suppressing other users. The basic idea of the multi-user detection [65] is different from the single user detection. Here, we first enhance the non-desired users, extract their data and remove it from the received signal. The receivers have the knowledge of all the active users' codes patterns and we assume that all the users have the same transmitting energy. So, there are no strongest interfering signals. For the development of theoretical analysis, we consider the chip synchronous case.

In general, when all or a subset of all user codes are known, a multi-user detector can be employed.

Like RF communication, there are two types of interference cancellation receivers that have been studied extensively in OCDMA systems to reduce the MAI, namely, Optical Parallel Interference Cancellation (OPIC) [46] and Optical Serial Interference Cancellation (OSIC) [47].

In this chapter the main concept of OPIC receiver will be discussed and new method will be presented called, One Stage OPIC, based mainly on OPIC and used to reduce the hardware complexity utilized in the OPIC receiver.

3.6 Optical Parallel Interference Cancellation (OPIC)

The method investigated in this section is adopted from wireless Parallel Interference Cancellation (PIC) [45] and it used in the optical domain to reduce the effect of MAI and improve the performance of OCDMA systems (Figure 3.5) [46]. Here, the receiver estimates and subtracts the contribution of each non-desired user in parallel. In particular, the idea of OPIC is to extract the data of all non-desired users using the CCR and sum up the estimated data of all the non-desired users. Then the estimation $\hat{b}_i^{(j)}$ of the non-desired user #j is spread by its code sequence. The estimated interference is then rebuilt and removed from the received signal $r(t)$.

The bit sent by the desired user is then extracted by the CCR. The signal applied to the entry of the receiver is:

$$S(t)=r(t)-\sum_{j=2}^{N}\hat{b}_i^{(j)}c_j(t)=b_i^{(1)}c_1(t)+\sum_{j=2}^{N}(b_i^{(j)}-\hat{b}_i^{(j)})c_j(t) \qquad (3.3)$$

where: $\hat{b}_i^{(j)}$ and $c_j(t)$ are the estimated data and the code sequence of user #j respectively.

The next step is the detection and estimation of the desired user data using CCR. The decision variable for the desired user #1 is:

$$Z_i^{(1)}=w.b_i^{(1)}+\sum_{j=2}^{N}(b_i^{(j)}-\hat{b}_i^{(j)})\int_0^T c_1(t)c_j(t)dt \qquad (3.4)$$

In the above equation, the second term is called the interfering term and we referred as I. Errors in the OPIC are due to this term. However, if the total number of the transmitted signals, i.e., N, is less than or equal to the weight w of their corresponding OOC's, an error free OPIC system can be obtained as it illustrated in chapter 4 using the VPI Transmission Maker.

This method is complicated comparing to the CCR but it is very effective in term of reducing the MAI and thus it can improve the error probability or allow many users to access the medium simultaneously.

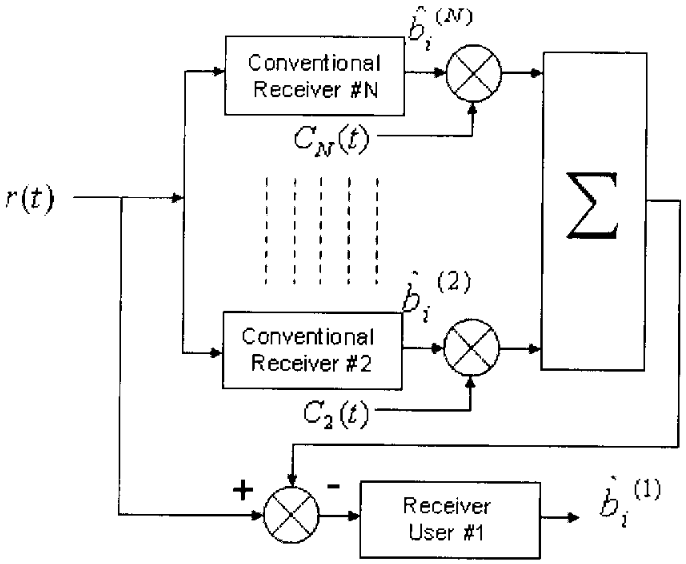


Figure 3.5: Optical Parallel Interference Cancellation

3.7 Optical Parallel Interference Cancellation with OHL (OPIC+OHL)

To improve the OPIC receiver efficiency by the simplest way, an effective design based on interference cancellation schemes for Direct-Sequence DS-OCDMA systems by using an OHL device in front of the OPIC technique (Figure 3.6). The function of the OHL is to lessen the localization of strong interference and equalize the interference strength at all nonempty pulse positions.

The OHL+OPIC receiver is made of an OHL device in front of OPIC receiver. As mentioned above, OHL has the potential of excluding some combinations of interference patterns from becoming heavily localized in a smaller part of the non-zero positions of signature codes and OPIC has the capability to remove the contribution of the non-desired users. Due to this, the resulting system is very effective in the term of interference suppression.

OPIC with OHL is examined using the simulation in chapter four, different number of users and various code families are used. The results are compared to the OPIC and to the CCR.

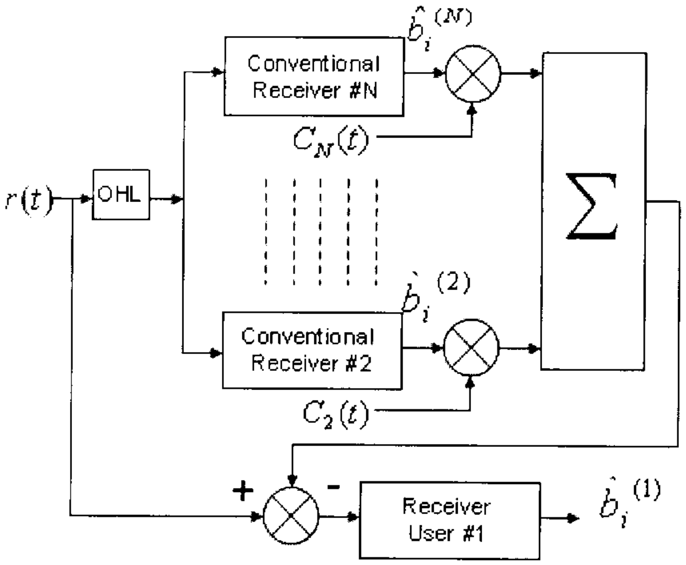


Figure 3.6: Optical Parallel Interference Cancellation with OHL

3.8 OPIC using Optimum Threshold for the Desired User

As mentioned earlier, the main idea behind OPIC is to reproduce the interference term due to all interfering users and then to remove it from the received signal $r(t)$. To achieve this, OPIC detects the $N-1$ non-desired users using the CCR with a threshold level of S_T. Each receiver provides the estimation $\hat{b}_i^{(j)}$ of the non desired user$\#j$. Then, each estimated data is spread by its corresponding code sequence and eventually the estimated interference is built and removed from the received signal $r(t)$.

The bit sent by the desired user ($\#1$) is extracted by the CCR with a threshold level S_F. The signal applied to the entry of the desired receiver is:

$$S(t) = r(t) - \sum_{j=2}^{N} \hat{b}_i^{(j)} c_j(t) = b_i^{(1)} c_1(t) + \sum_{j=2}^{N} (b_i^{(j)} - \hat{b}_i^{(j)}).c_j(t)$$

The methodology used here is the theoretical counting of errors: we define the cases when an error occurs.

In a general way, there is an error for the user #1 in a communication system in 2 cases:

Case (a): $b_i^{(1)}=0$ and $\hat{b}_i^{(1)}=1$

Case (b): $b_i^{(1)}=1$ and $\hat{b}_i^{(1)}=0$

So, the probability of error can be written as follows:

$$P_e=\frac{1}{2}P(\hat{b}_i^{(1)}=1/b_i^{(1)}=0)+\frac{1}{2}P(\hat{b}_i^{(1)}=0/b_i^{(1)}=1) \tag{3.5}$$

The next step is the detection and estimation of the desired user's data, by the CCR. The decision variable related to the desired user #1 is:

$$Z_i^{(1)}=w.b_i^{(1)}+\sum_{j=2}^{N}(b_i^{(j)}-\hat{b}_i^{(j)})\int_0^T c_1(t).c_j(t)dt$$

In the above equation, the second term .i.e.

$$I=\sum_{j=2}^{N}(b_i^{(j)}-\hat{b}_i^{(j)})\int_0^T c_1(t).c_j(t)dt \tag{3.6}$$

is called the interfering term. Errors are due to this term. Thus two cases are appearing for each non-desired user:

[i] If $b_i^{(j)}=1$ then $\hat{b}_i^{(j)}=1$ because with the CCR, an error occurs only when the desired user sends data "0" [13]. On the other hand, no error in the CCR if the desired

user sends data "1". So in this case we obtain: $(b_i^{(j)} - \hat{b}_i^{(j)}) = 0$. The user $\#j$ does not interfere on user$\#1$, $I_i^{(j)} = 0$.

[ii] If $b_i^{(j)} = 0$ then

Either$\hat{b}_i^{(j)} = 0$, so$(b_i^{(j)} - \hat{b}_i^{(j)}) = 0$; .i.e., user #j is not interfering user.

Or$\hat{b}_i^{(j)} = 1$, so$(b_i^{(j)} - \hat{b}_i^{(j)}) = -1$; user $\#j$ interferes with user$\#1$, so we called user $\#j$ interfering user. The interfering users are the ones that sent a "0" detected as a "1", and have a common chip with user #1. Thus I is always negative or null. Note that one interfering user generates an interference of "–1", which implies that k interfering users generate an interference of $I = -k$: thus $|I|$ is an integer and corresponds to the number of interfering users. Because of the negative interference term$I$, the decision variable $Z_i^{(1)}$ is always less than (or equal to) what it should be. Accordingly, if the desired user sends data "0" then: $Z_i^{(1)} = -|I| < S_F$ The comparator takes the decision $\hat{b}_i^{(1)} = 0$: there is no error on user$\#1$. We could then validate that, there is no error at all if the desired user sends data "0" regardless the number of interfering users.

However, if the desired user sends data "1" then: $Z_i^{(1)} = w - |I|$: there can be an error on user #1 if $w - |I| < S_F$.

Generally, we can remark that there can be an error only if the desired user sent a data$b_i^{(1)} = 1$, which is inversely to the CCR. On the other hand, I is always negative (if we have wrong detection for the non-desired user i.e. in the case of sending data equal to 0 [13]) or null (if there are no errors during the extraction of the non-desired user's data). Accordingly, if the number of interfering users is equivalent to$w$, definitely we have wrong decision on the desired user no matter the value of threshold. Hence, to reduce the possibility of the errors on the desired user, one can choose the minimum threshold value. On the contrary, if we set the threshold of the desired user to the maximum, one interfering user can produce error. From now on, we can apparently validate that the optimum performance for the OPIC with and without OHL can be obtained by selecting the smallest threshold value.

The results reveal that, for any number of users and any family of OOC, optimum performance can be obtained by using a fixed threshold "1". Beside this, OPIC with fixed threshold has the advantage of overcome the need for dynamic threshold.

Thus, the new expression of the error probability for the desired user of the OPIC system can be written as follow equation (3.7):

$$P_e = \frac{1}{2} P(\hat{b}_i^{(1)} = 0 / b_i^{(1)} = 1) \tag{3.7}$$

By using OPIC system, we manage to mitigate the effect of MAI or improve the performance of OCDMA system in the present of MAI. In addition, it is clear that the OHL in front of the OPIC improves the system performance because of its ability to exclude some combinations of interference patterns from becoming heavily localized in a smaller part of bit 1's positions of signature codes. Moreover, we can avoid the requirement for the dynamic threshold which hampers the implementation of the CCR by selecting the lowest threshold value for any family of OOC code. Due to this, OPIC is considered attractive alternative receiver for the OCDMA system.

The drawback of OPIC is that it increases the demand for hardware, resulting into more complexity and higher processing time. To overcome these difficulties, an efficient method is presented called One Stage Optical Parallel Interference Cancellation (OS-OPIC) which is based mainly on the OPIC. The proposed method is effective to reduce the hardware complexity, processing time and cost while maintaining the same bit error probability at the cost of increasing threshold value.

3.9 One Stage Optical Parallel Interference Cancellation (OS-OPIC)

In the previous section, the OPIC is demonstrated for N simultaneous users and it is shown that to extract the data of user #1 we must first extract the data of $N-1$ non-desired users. OPIC system is effective to reduce the effect of MAI. However, the need for a receiver with less hardware complexity is one of the main problems that face the implementation of OPIC in local area networks with heavy load. To overcome the stated problem One Stage Optical Parallel Interference Cancellation (OS-OPIC) (Figure 3.7) which is based on the conventional OPIC is demonstrated in this section.

The idea of OS-OPIC is quite simple and very effective in term of cost and complexity. Unlike the OPIC where we have to extract the data of all non-desired user in order to recover the desired user's data, OS-OPIC operates by providing the estimation $\hat{b}_i^{(k)}$ of only one non-desired user referred as user $\#k$. Then the estimated data is spread by corresponding code sequence, i.e., $c_k(t)$ and removed from the received signal $r(t)$. The bit sent by the desired user is then extracted by the Conventional Correlation Receiver (CCR). The resulting system is very simple comparing to the conventional OPIC and then we can manage to reduce the hardware complexity, processing time and eventually the cost while maintaining the same BER as a cost of increasing the threshold level.

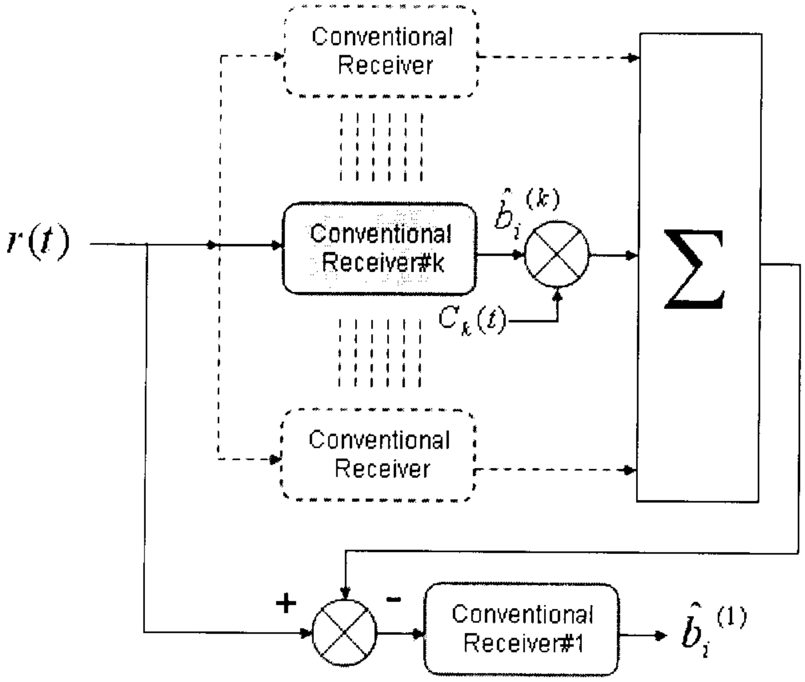


Figure 3.7: One Stage Optical Parallel Interference Cancellation

3.9.1 Theoretical Analysis:

This section discusses: a Non-coherent, Synchronous Direct Sequence OCDMA with On-Off Keying (OOK) as a method of modulation. Optical Orthogonal Code (OOC) is adopted as signature sequence with length L, weight w and the auto-and cross-correlations bounded by 1, so that, for sending "1" bit a user sends its signature code and for "0" bit it sends nothing.

The performance of the proposed system will be analyzed under the following assumption:

- User #1 is chosen to be the desired user with the threshold level given by $S_d(0 < S_d \leq w)$.
- User $\# k$ is the non-desired with the threshold level given by $S_n(0 < S_n \leq w)$.
- All the users have the same transmitting energy so there is no strong interference.
- The case of full synchronization $(\tau_k = 0)$ is considered.

The signal applied to the entry of the receiver can be written as follow:

$$\begin{aligned} s(t) &= r(t) - \hat{b}_i^{(k)} c_k(t) \\ &= \left[b_i^{(1)} c_1(t) + b_i^{(k)} c_k(t) + \sum_{\substack{j=2 \\ j \neq k}}^{N} b_i^{(j)} c_j(t) \right] \\ &\quad - \hat{b}_i^{(k)} c_k(t) \\ &= b_i^{(1)} c_1(t) + \left(b_i^{(k)} - \hat{b}_i^{(k)} \right) c_k(t) \\ &\quad + \sum_{\substack{j=2 \\ j \neq k}}^{N} b_i^{(j)} c_j(t) \end{aligned} \tag{3.8}$$

Before the last detection block, the decision variable for the desired user is:

$$\begin{aligned} Z_i^{(1)} &= w b_i^{(1)} + \left(b_i^{(k)} - \hat{b}_i^{(k)} \right) \int_0^T c_k(t) c_1(t) dt \\ &\quad + \sum_{\substack{j=2 \\ j \neq k}}^{N} b_i^{(j)} \int_0^T c_j(t) c_1(t) dt \\ &= w b_i^{(1)} + H + I \end{aligned} \tag{3.9}$$

The second term appears in the above equation is the non-desired user $\# k$ detected by the OS-OPIC receiver referred as H and the third term is due to the undetected users referred as I. Two cases will be considered:

Case (1): If the desired user, i.e. (user #1) sends data 0

Let P_0 be the error probability on data $b_i^{(1)} = 0$ of the desired user.

We have error if: $H + I \geq S_d$

In this case $H = -1$ (wrong decision) or $H = 0$.

If $H = -1$, then $-1 + I \geq S_d$ accordingly the probability of error if the desired user send data 0 is:

$$P_{0(H=-1)}=\frac{1}{2}\sum_{i=S_d+1}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i} \qquad (3.10)$$

If $H=0$, then we have error on user #1 if $I \geq S_d$. We obtain then:

$$P_{0(H=0)}=\frac{1}{2}\sum_{i=S_d}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i} \qquad (3.11)$$

Then the probability of error when the desired user sends data 0 can be written as follow:

$$P_0=\left\lfloor Q\times P_{0(H=-1)}\right\rfloor+\left\lfloor(1-Q)\times P_{0(H=0)}\right\rfloor$$

$$P_0=\frac{1}{2}\left[Q*\sum_{i=S_d+1}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i}+(1-Q)*\sum_{i=S_d}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i}\right] \qquad (3.12)$$

where Q is the error probability on $b_i(k)=0$ of the non-desired user and can be demonstrated from [1][2] as follow:

$$Q=\frac{1}{2}\sum_{i=S_n}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i} \qquad (3.13)$$

Case 2: If the desired user (user #1) sends data 1:

We have error if: $w+H+I<S_d$

Let us assume that, the following conditions are verified:

- ⇒ The threshold value is equal to the weight w, i.e. $S_d = w$.
- ⇒ User k is interfering user so that $H = -1$.
- ⇒ The value of I is equal to zero.

Then, the probability of error that user $\# k$ is an interfering user can be written as follow:

$$Q^* = \frac{1}{2}\sum_{i=S_n}^{N-1}\binom{N-1}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-1-i} \tag{3.14}$$

Based on the above conditions we obtain here the error probability when the desired user sends 1:

$$P_1 = \frac{1}{2}\left[Q^*\sum_{i=S_d-1}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i}\right] \tag{3.15}$$

In general, the probability of error for OS-OPIC is:

$$P_T = P_0 + P_1$$

$$P_T =$$

$$\frac{1}{2}\left[Q.\sum_{i=S_d+1}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i} + (1-Q).\sum_{i=S_d}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i}\right]+$$

$$\frac{1}{2}\left[Q^*\sum_{i=S_d-1}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i}\right] \tag{3.16}$$

Summary:

It is well known that, Multiple Access Interference (MAI) is the main reason for the performance degradation in the OCDMA. MAI increases with the number of active users resulting into higher Bit Error Rate (BER) and limits the maximum number of active users.

In this chapter, the Optical Parallel Interference Cancellation (OPIC) has been discussed for the use in OCDMA systems to overcome the above problem.

This method is complicated comparing to the Conventional Correlation Receiver (CCR). However it's more efficient in term of MAI mitigation because it has the ability to remove the contribution of the non-desired users. Furthermore, to improve the performance of OPIC, Optical Hard Limiter (OHL) has been used in front of the receiver side because it has the ability to clip the strength of the interference and equalize it among all non-zero positions of the code sequence.

By using the OPIC in the OCDMA systems along with the OHL, we managed to improve the system performance and thus increasing the number of simulations users which is not the case with the CCR.

In addition to MAI, CCR requires dynamic estimation of the threshold which is depends on the number of active users. The performance of the CCR is very sensitive to the threshold. However the dynamic estimation for the threshold is very tedious and complex especially for the high speed LAN. Due to this, some studies also have been done on the threshold values for the desired user in order to overcome the need for the receiver dynamic threshold. We figure out that, OPIC with fixed threshold has the advantage of overcome the dynamic threshold value while outperforming the CCR. The study carried out using the theoretical analysis and the software simulation (see chapter 4).

Apparently, OPIC is an efficient method to reduce the effect of MAI while overcome the need for the dynamic threshold. However, the need for a receiver with less hardware complexity is one of the main problems that hamper the implementation of OPIC in local area networks with heavy load. This problem has been addressed in this chapter as well and new method has been proposed which is depends totally on the OPIC namely, One Stage OPIC (OS-OPIC). Optical Orthogonal Code (OOC) is adopted as a signature sequence for the performance analysis and a new expression for the error probability is derived. The results show that the proposed method is effective to reduce the hardware complexity and processing time while maintaining the same bit error probability at the cost of increasing the threshold value (see Chapter 4).

CHAPTER 4

4. SIMULATION RESULTS AND PERFORMANCE COMPARISON

4.1 Introduction:

While several reports [3][7][18] have shown the general effectiveness of OCDMA, this section takes a closer look at effectiveness of the OCDMA system using Conventional Correlation Receiver (CCR) and Optical Parallel Interference Cancellation (OPIC).

In this work, software simulation is used to obtain and evaluate the performance. The simulation has been carried out using C programming, Matlab and VPI TransmissionMaker. We assume that the noise in the system contribute only by Multiple Access Interference (MAI).

The study on OCDMA [11-28] demonstrates that, the performance of OCDMA is not good enough to be implemented in the real application as expected from the theoretical analysis. MAI is the main reason for performance degradation in OCDMA. Several methods were proposed in the literature aiming at lowering the effect of the MAI such as the use of Optical Hard Limiter (OHL) in front of the CCR [15] [22]. This method effectively enhances the system performance of the CCR. However, the system yields poor performance for network with large number of users.

Multi-user detection [64] has been used in the optical domain to reduce the strength of the interference signal in the system. In particular, Serial Interference Cancellation (SIC) and Parallel Interference Cancellation (PIC) were studied in several articles in the literature [46-47].

In this thesis, we prove that, the OPIC system is outperforming the CCR. By placing an OHL in front of the OPIC we can dramatically mitigate the MAI and thus achieve lower number of errors.

In this chapter, the performance of the following technique will be evaluated and compared: CCR, CCR with OHL, OPIC, OPIC with OHL and One Stage OPIC (OS-OPIC).

The systems considered in this chapter are Non-coherent, Synchronous Direct Sequence OCDMA (DS-OCDMA) employing On-Off keying (OOK) as a method of modulation. Optical Orthogonal Code (OOC) is adopted as signature sequence with the length L, weight w and the auto-and cross-correlations bounded by “1”. Different families of codes are adopted in this analysis for different number of users.

4.2 Performance of the Conventional Correlation Receiver (CCR):

CCR has been studied in several articles in the literature. In this receiver, errors occur only if the desired user sends data “0” and the MAI due to the other users cause wrong decision. In this part, the performance of the CCR is examined for different number of users and different families of OOC.

To improve the system performance of the CCR, Optical Hard Limiter (OHL) has been used in front of the CCR. It has been shown that [15] [22], OHL improves the system performance because of its ability to exclude some combinations of interference patterns from becoming heavily localized in a smaller part of bit 1’s positions of signature codes so that the probability of bit errors is reduced or the number of simultaneous users can be increased.

4.2.1 Conventional Correlation Receiver (CCR) with and without OHL:

Figure 4.1 and Figure 4.2, show the Bit Error Rate (BER) against the threshold values for both CCR with and without OHL using different number of users and different families of codes. The parameters of the codes as follows: L=97,341, w=4, 5 for 8 and 17 users respectively (Appendix A, B and E).

From the result, we can observe that the BER improves by placing the OHL in front of the receiver. Nevertheless, the worst result is for Th = 1, the lowest threshold value. Because, OHL clips and equalizes the strength of the interference among non-zero positions of the code sequence.

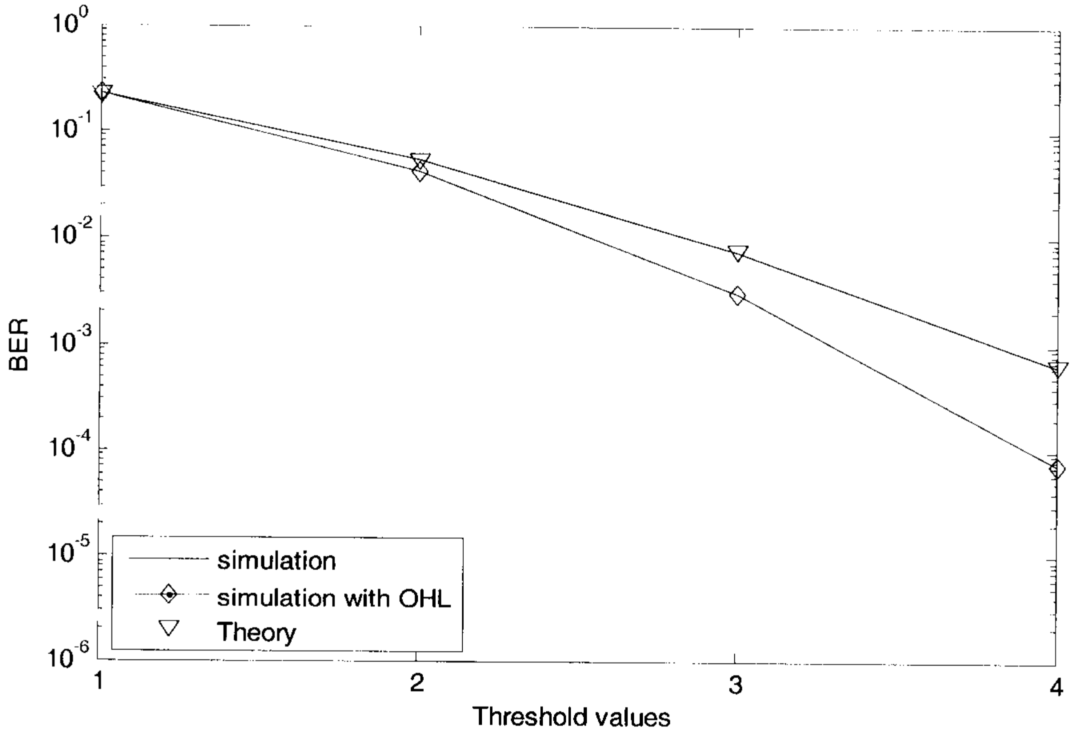


Figure 4.1: CCR with and without OHL for 8 users

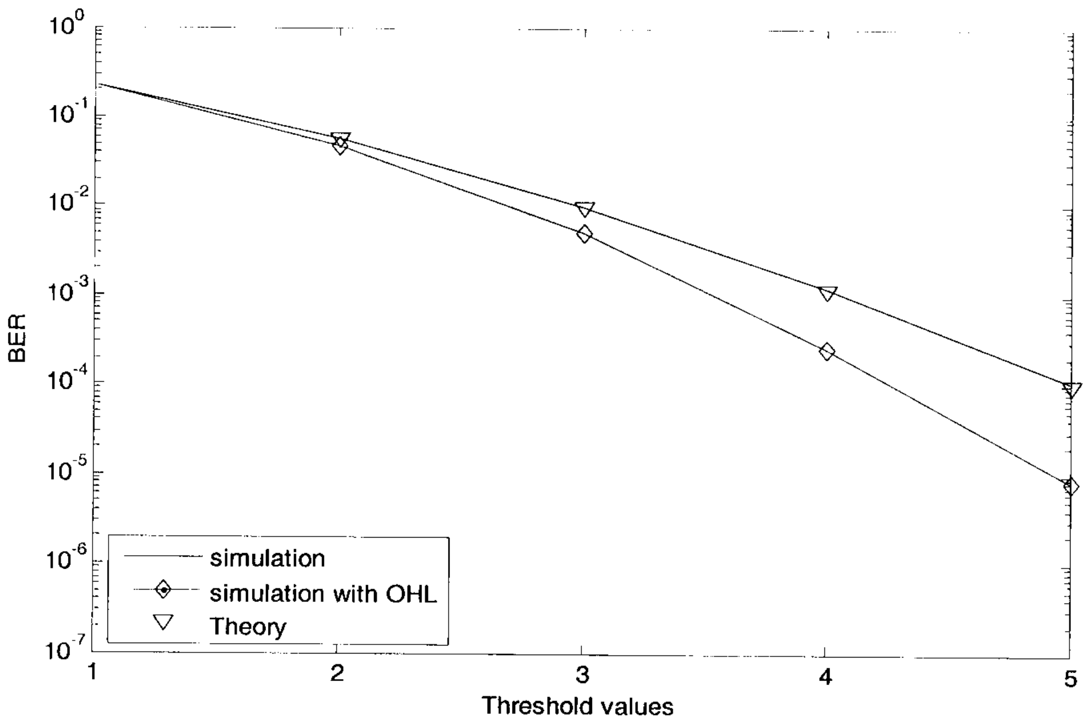


Figure 4.2: CCR with and without OHL for 17 users

4.2.2 CCR Using Different Number of Active Users:

Figure 4.3 shows the BER against the threshold values for the CCR using different number of users and adopting the same code family OOC(341,5,1).

The figure shows that, the performance of the CCR degrades very quickly as the number of active user increases. Due to this, a new detection scheme is needed to replace the existing techniques.

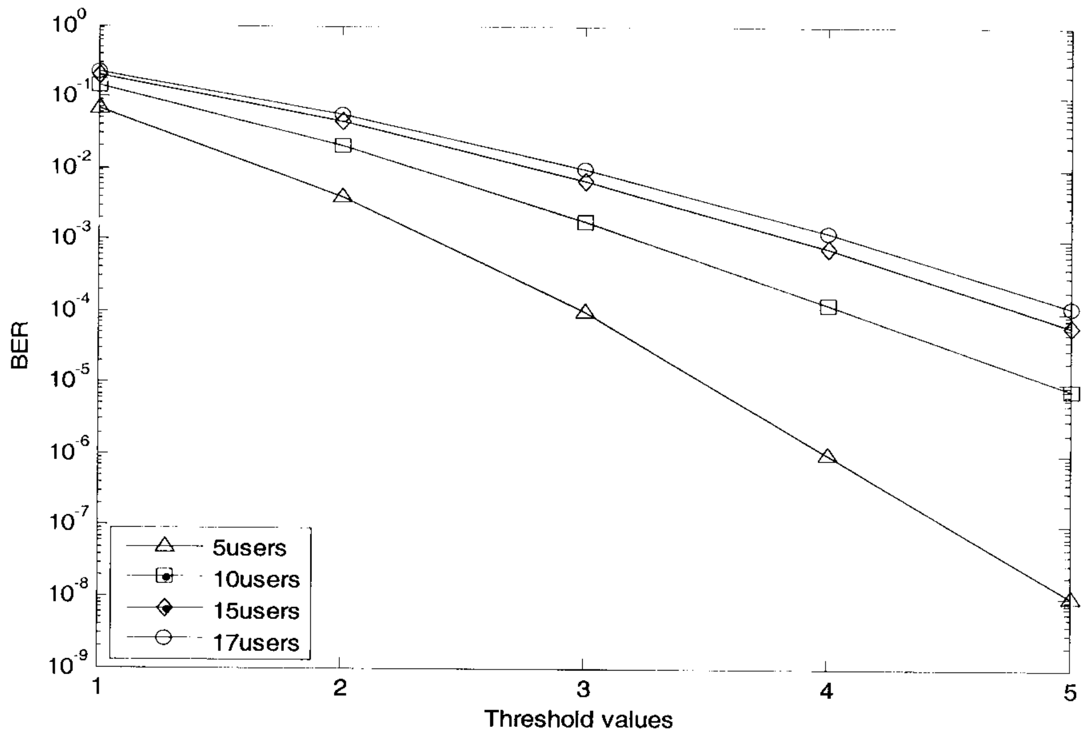


Figure 4.3: CCR using different number of users

4.3 Performance of the OPIC System:

Figures 4.4 shows the performance comparison between OPIC and CCR. In this figure, BER is plotted against the threshold values. OOC is considered in this comparison with the following parameters: L =64 and w =4 for 5 simultaneous users.

From this figure, we can observe that, OPIC outperforms the performance of the CCR using the minimum threshold value. Because OPIC system has the ability to remove the contribution of the non-desired users.

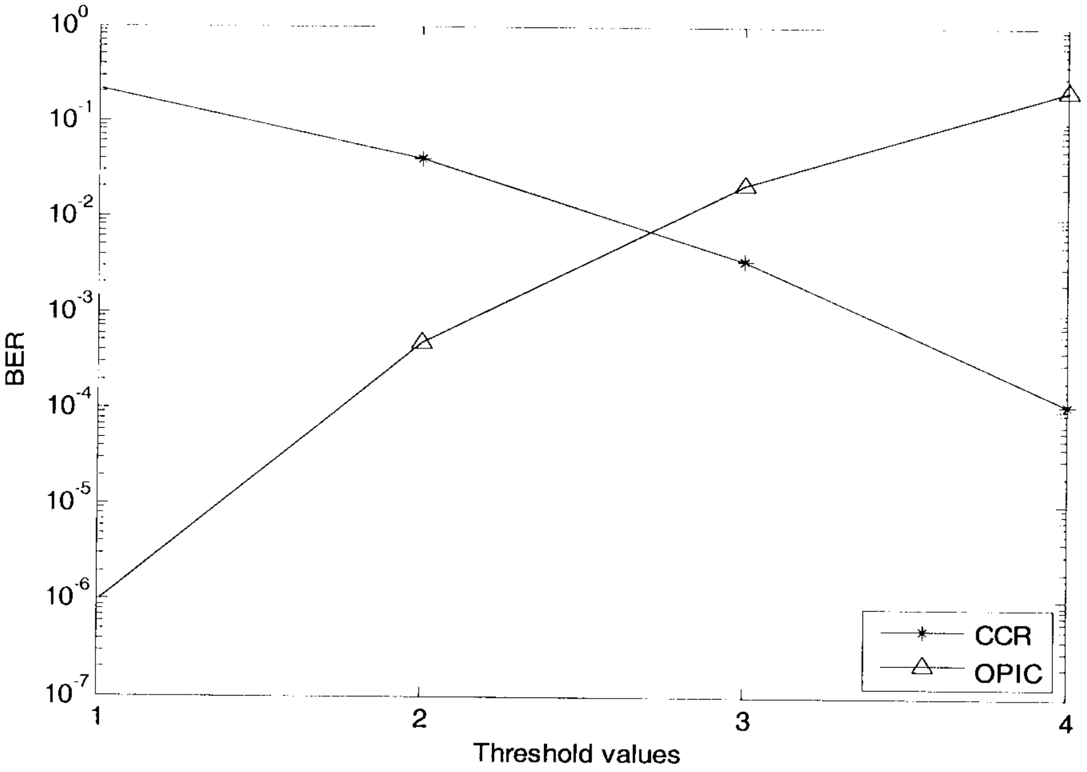


Figure 4.4: OPIC vs. CCR

4.3.1 OPIC System with and without OHL

Figure 4.4 shows that, OPIC is promising technique for the Local Area Network (LAN) because it is able to remove the contribution of the non-desired user and thus reducing the BER.

To improve the performance of the OPIC, OHL is used before the non-desired users and the results are compared to the OPIC without OHL for different number of users.

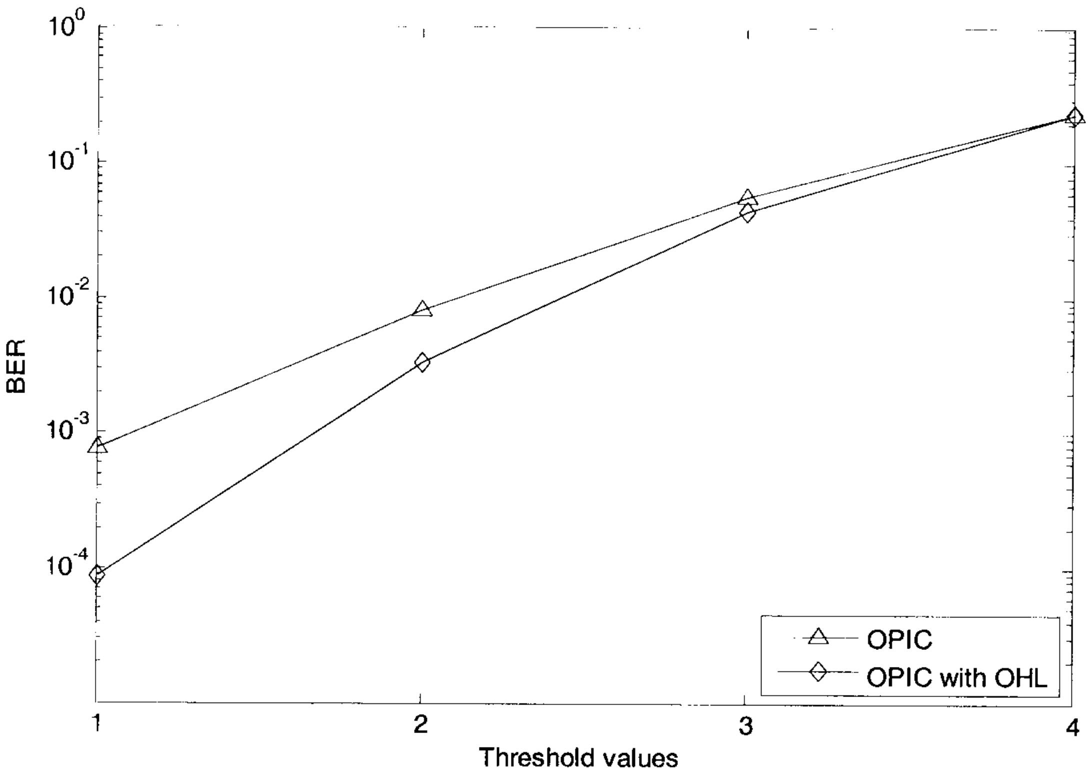


Figure 4.5: OPIC with and without OHL for 15 users

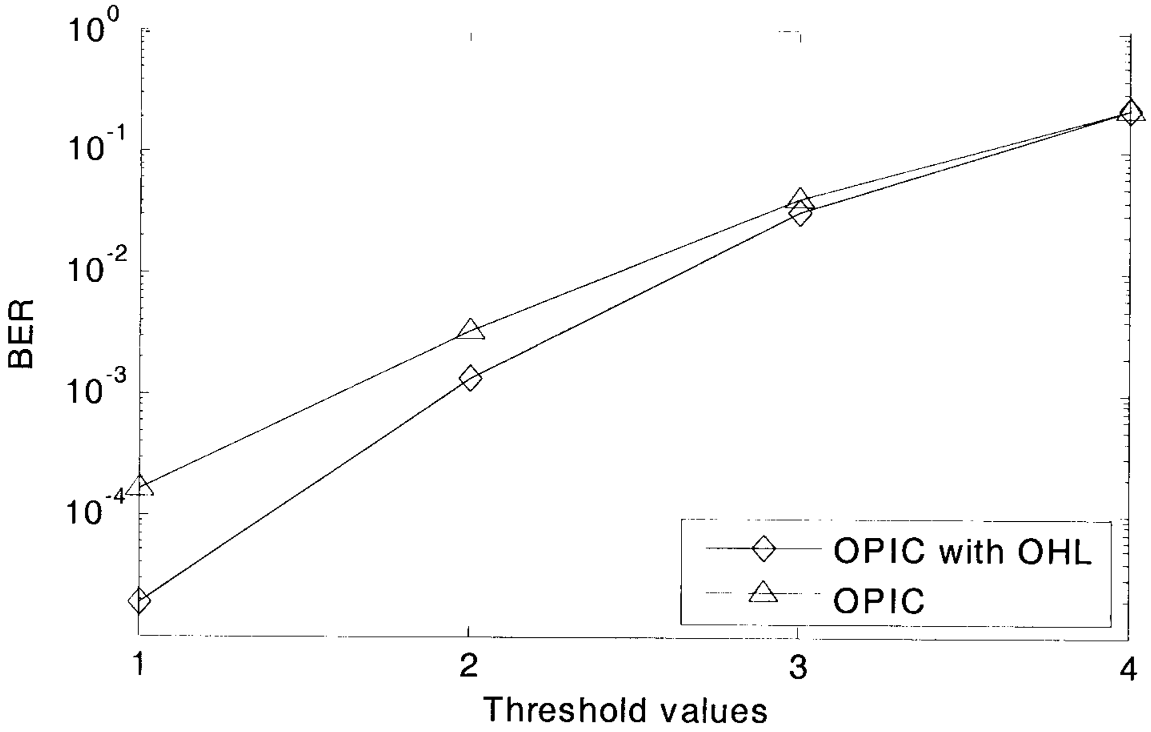


Figure 4.6: OPIC with and without OHL for 8 users

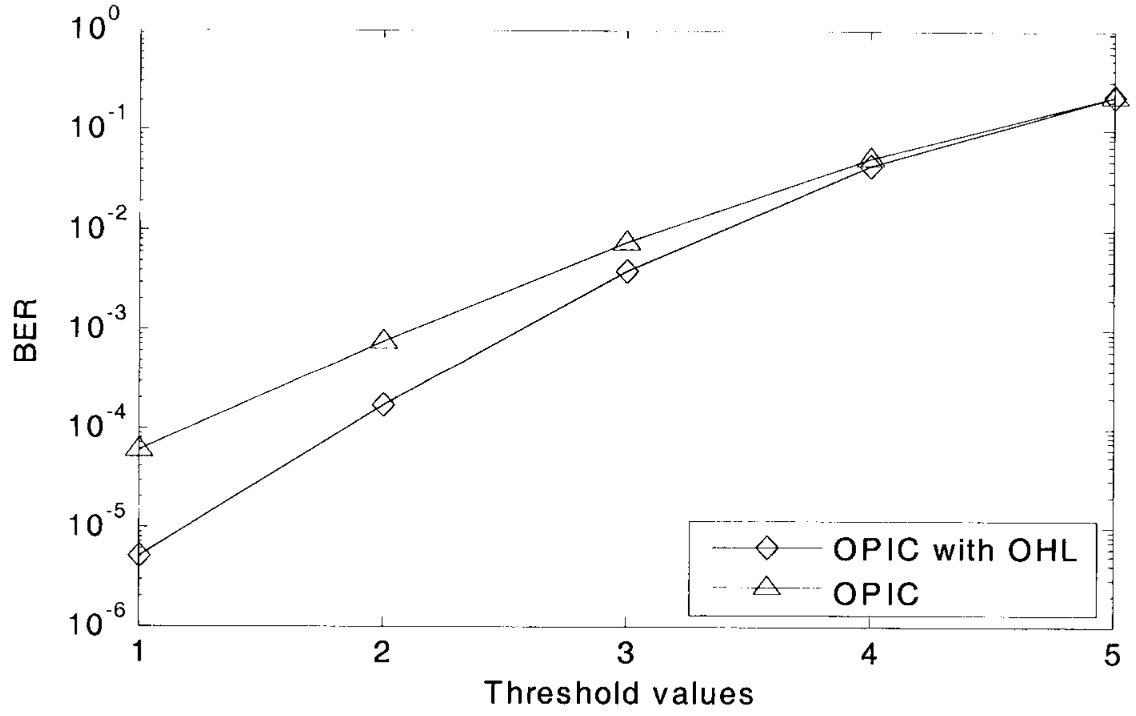


Figure 4.7: OPIC with and without OHL for 17 users

OHL has been used in front of the OPIC receiver to remove some combination of interference and thus reducing the number of errors in the system.

Figure 4.5, Figure 4.6 and Figure 4.7 show the performance of OPIC with OHL for different number of users and different code families. The parameters used for OOC as follows: $L = 181$, 97 and 341 with $w = 4$, 4 and 5 (Appendix C).

From the figures we could observe that by using OHL before the correlation process, a better result is obtained compared to the conventional OPIC receiver. Because, OPIC system removes the non-desired user signal and OHL lessen the strength of the interference among non-empty position of the code sequence.

4.3.2 OPIC System with Various Threshold Values

To optimize the performance of the OPIC, extensive study has been conducted on the threshold values for both the desired and non-desired users. The combination of all possible threshold values is shown in Table 4.1.

Table 4.1: The combination of the threshold for code sequence with 4 marks.

Threshold for the desired user S_d	Threshold for the non-desired user S_n
1	1
	2
	3
	4
2	1
	2
	3
	4
3	1
	2
	3
	4
4	1
	2
	3
	4

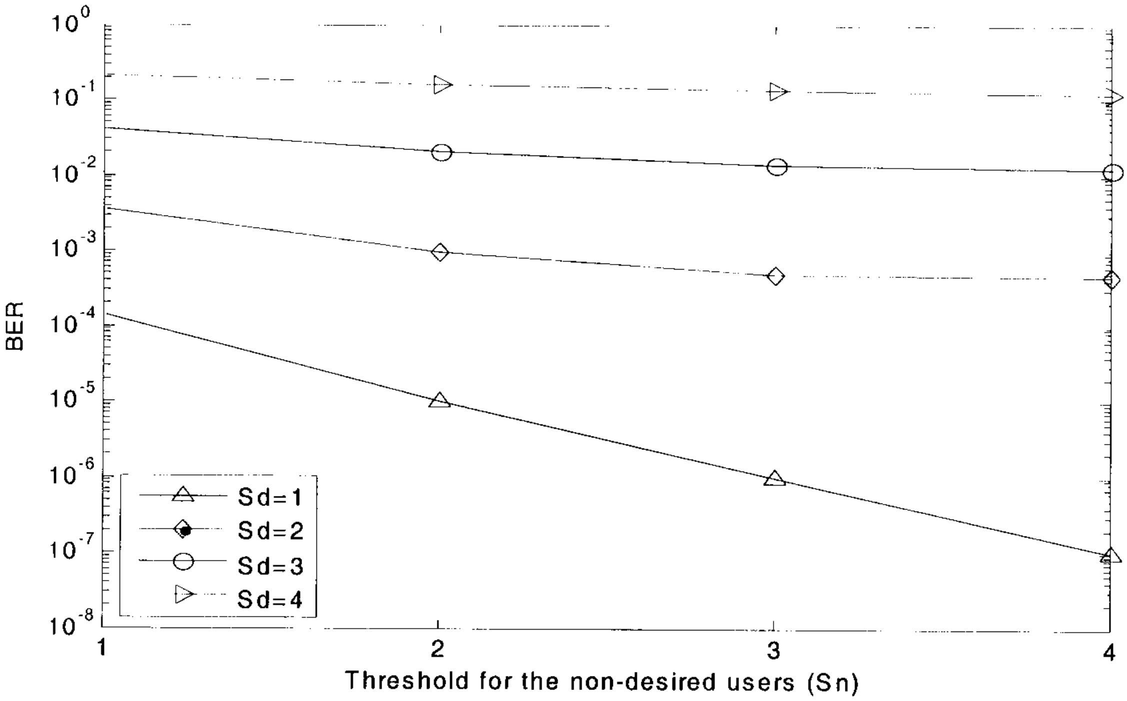


Figure 4.8: BER versus S_n for the OPIC with 5 users

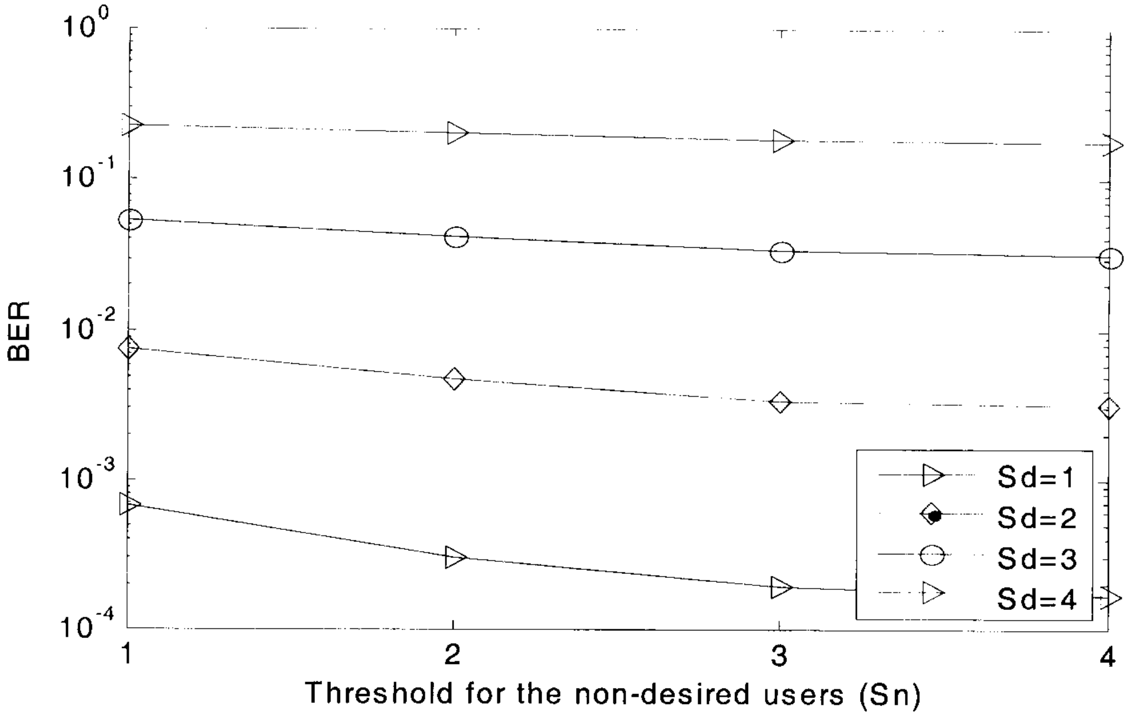


Figure 4.9: BER versus S_n for the OPIC with 8 users

Figure 4.8 and Figure 4.9 show the BER versus the threshold values for the OPIC. Two families of OOC are considered for 5 and 8 simultaneous users respectively.

In this study, all possible combinations for the desired and non-desired user threshold values are examined. We found that, in order to minimize the BER and hence to improve the performance of the OPIC system, it is important to set the threshold value for the desired user, S_d to the minimum value regardless the value of S_n (see section 3.8).

4.3.3 Using the Lowest Threshold Value for the Desired User:

To trace the problem of the dynamic threshold value encountered with the CCR, fixed threshold value is used for the desired user. OPIC has the advantages of fixed threshold value which gives better performance while overcome the stated problem. Nevertheless, CCR has a very poor performance when fixed threshold is used.

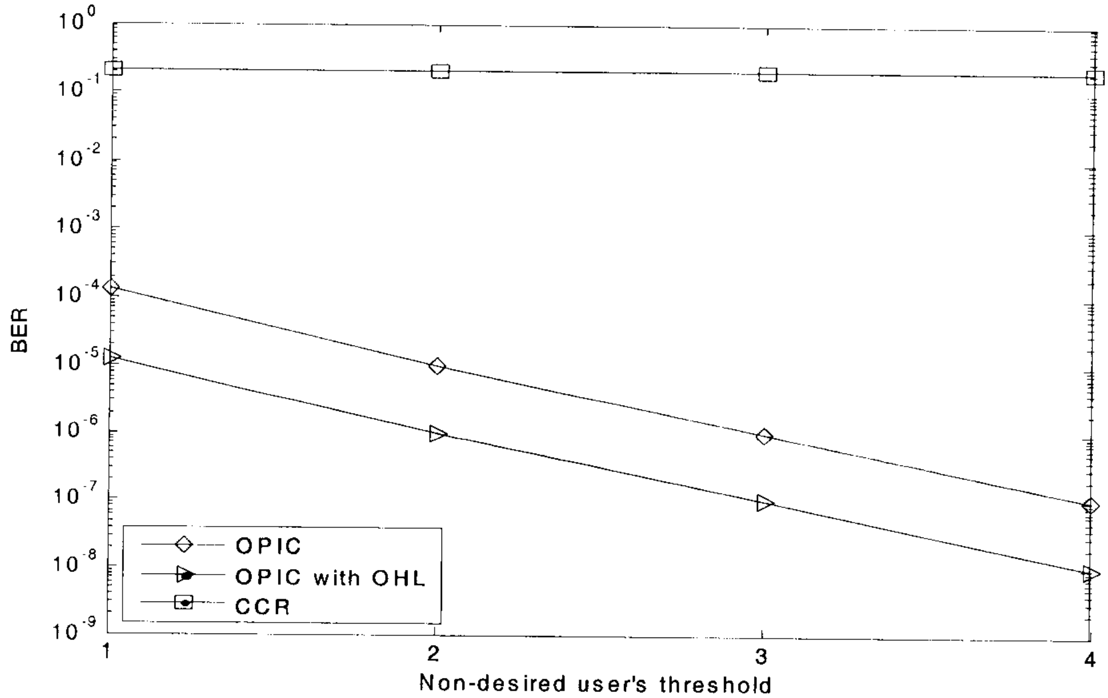


Figure 4.10: performance of the OPIC, OPIC with OHL and CCR using the lowest threshold value for 5users

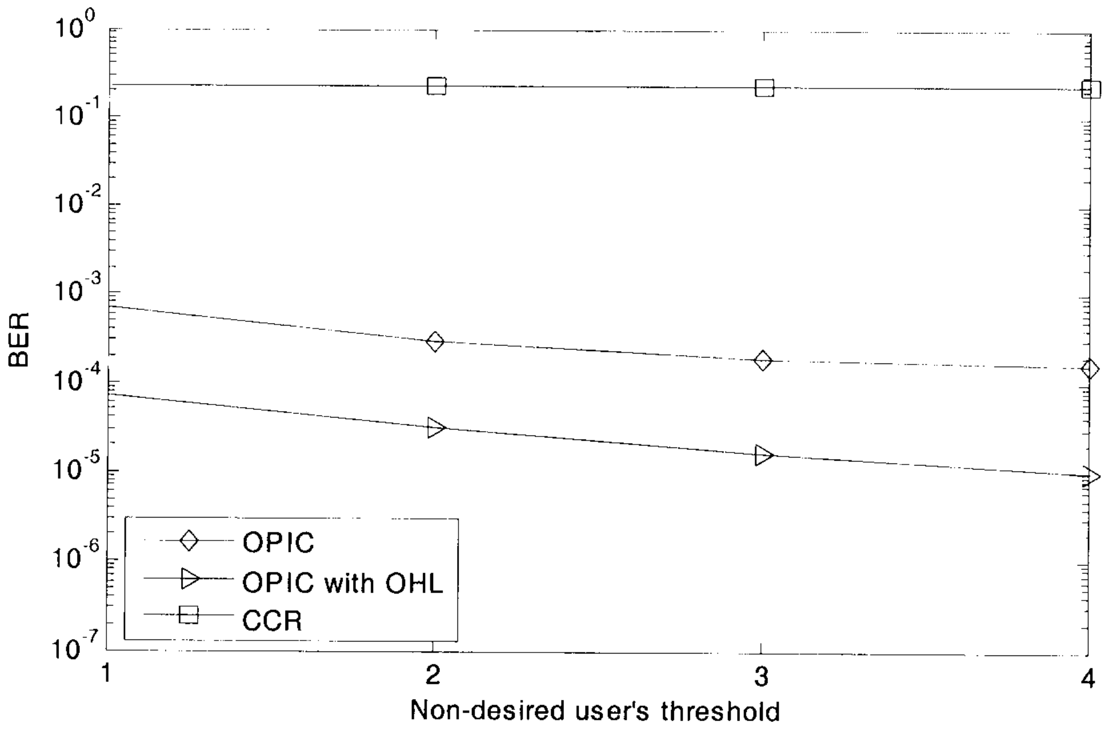


Figure 4.11: performance of the OPIC, OPIC with OHL and CCR using the lowest threshold value for 8 users

Figure 4.10 and Figure 4.11 focus on the lowest threshold value of the desired user i.e., $S_d = 1$. Two families of OOC have been used for 5 and 8 simultaneous users.

From the figures, we could see that to obtain a better performance, the lowest threshold value for the desired user of OPIC with and without OHL should be selected which is not the case with the CCR. Concurrently, the system yields a further improvement if we set the threshold value of the non-desired users, S_n to the maximum (see section 3.8).

Generally, OPIC with OHL is very effective in term of BER improvement. By using the lowest threshold value, we managed to overcome the need for the dynamic threshold which is hampers the implementation of CCR.

4.3.4 Adjusting the Code Length of the OPIC:

It is well known that, code for OCDMA system should have more zeros in the sequence in order to reduce the possibility of overlapping. Due to this, another study has been done on the OOC by selecting very long code and simply this can be achieved by adding more zeros at the end of the sequence. Note that, the weight of the code and the number of simultaneous user are consistent.

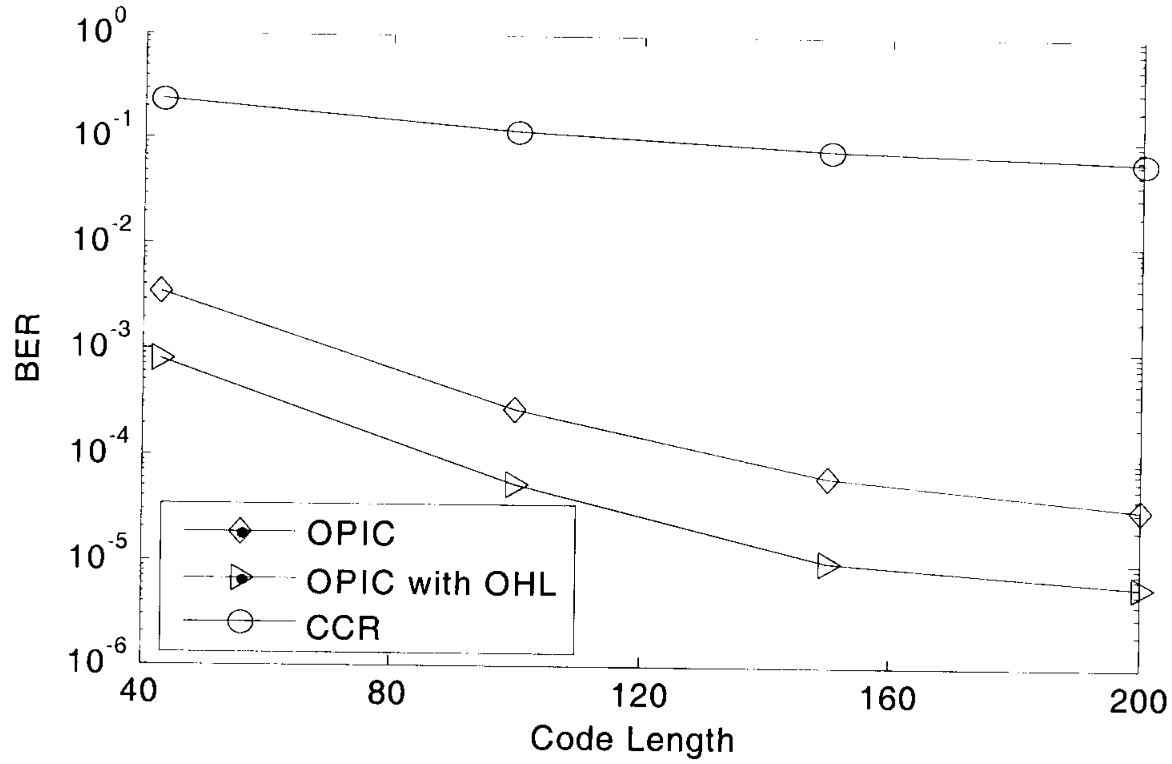


Figure 4.12: BER versus the Code Length for the OPIC, OPIC with OHL and the CCR, using OOC(L,3,1)

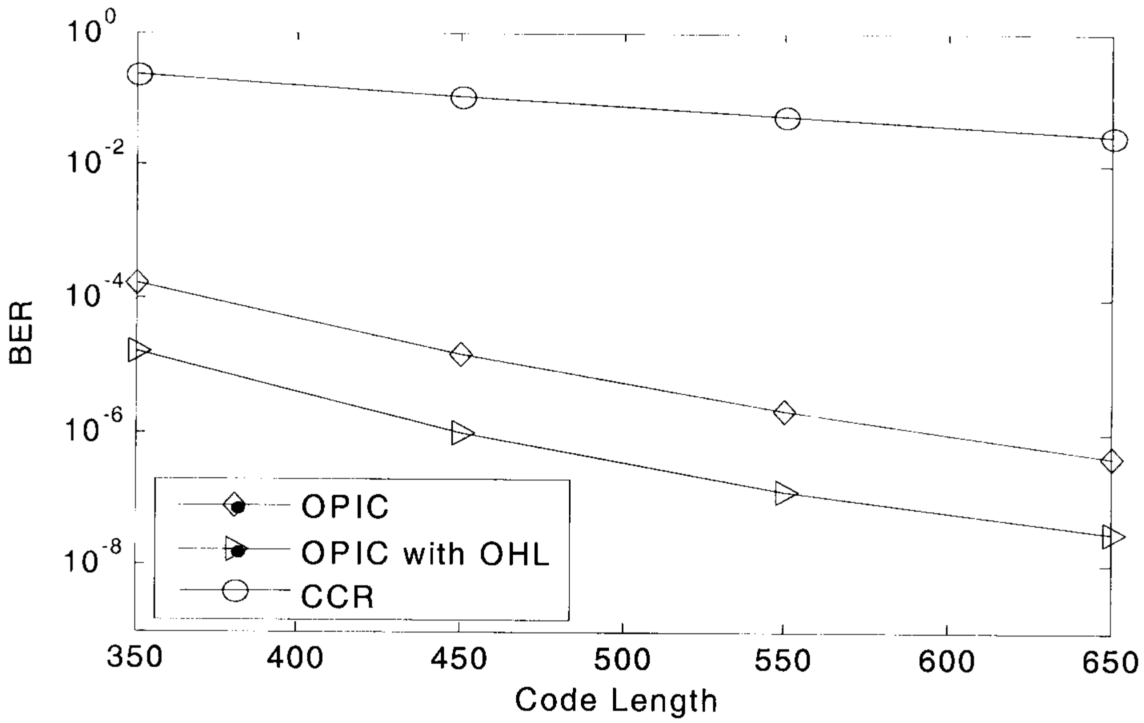


Figure 4.13: BER versus the Code Length for the OPIC, OPIC with OHL and the CCR using OOC(L,5,1)

In Figure 4.12 and Figure 4.13, a different code length has been chosen to observe the above assumption. Three different types of receiver have been examined namely, OPIC, OPIC with OHL and CCR for 7 and 17 simultaneous users respectively.

It can be shown that, the performance of the system improves and the effect of MAI is reduced whenever the code length increases. Further improvement could be achieved by using the OPIC + OHL along with the lowest threshold value. Because, to reduce the effect of MAI, the cross-correlation must be small. For the cross-correlation to be small, we have to minimize the possibility of the overlapping which can be minimizing by increasing the code length.

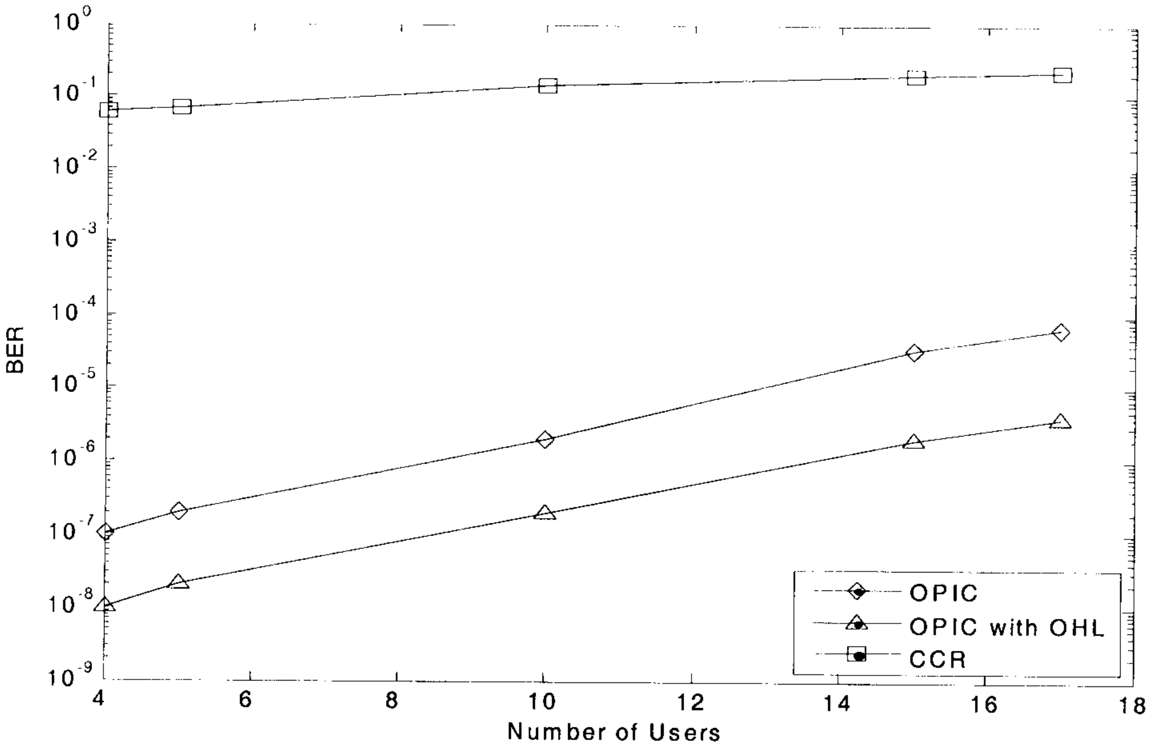


Figure 4.14: OPIC, OPIC with OHL and the CCR for different active users

4.3.5 Different Number of Active Users:

Figure 4.14 shows the effect of active user on the performance. Only the lowest threshold value is considered and OOC is adopted with the following parameters: L=341 and w=4 for different number of active users.

From the figure, OPIC with OHL has the best performance in term of BER, at the meanwhile, CCR shows the worse performance when we use fixed threshold.

4.4 One Stage OPIC

OPIC has been demonstrated in the above work for different number of users and different threshold values. We have seen that OHL plays an important role in the interference suppression. However, the hardware used in each receiver side hampers the implementation of OPIC in LAN at the present time because such hardware would increase the complexity, processing time and eventually the cost. For this reason, a new receiver has been proposed which is based mainly on the OPIC and referred as One Stage OPIC (OS-OPIC) to overcome the stated difficulties.

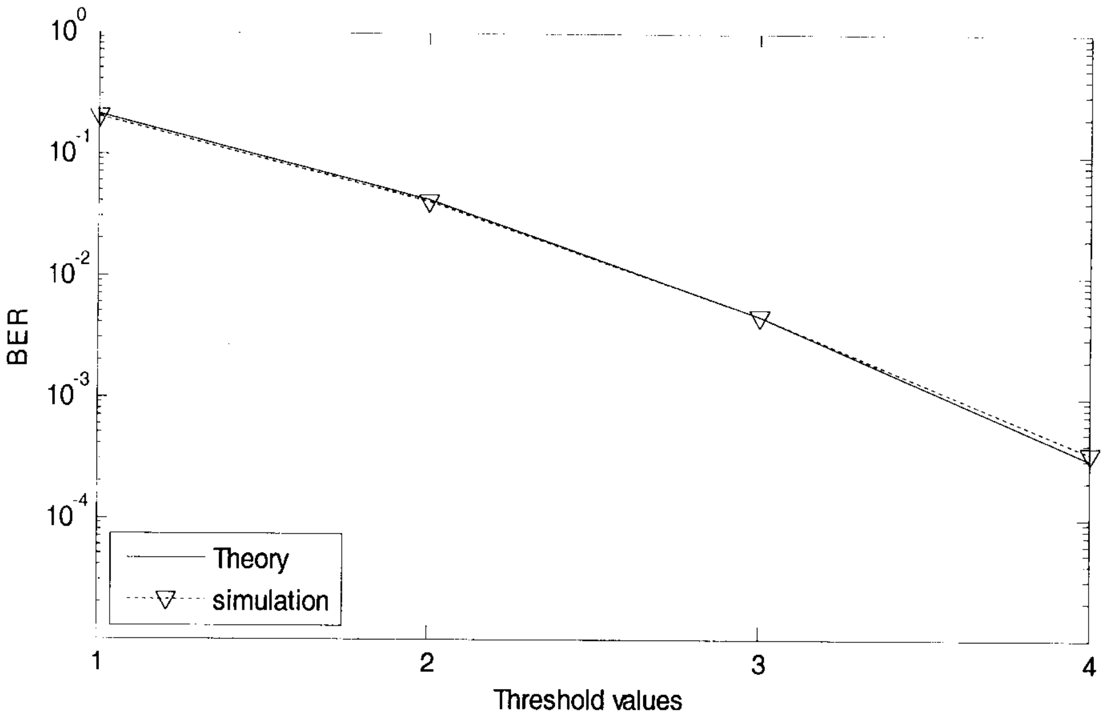


Figure 4.15: Performance of the OS-OPIC for 8 users

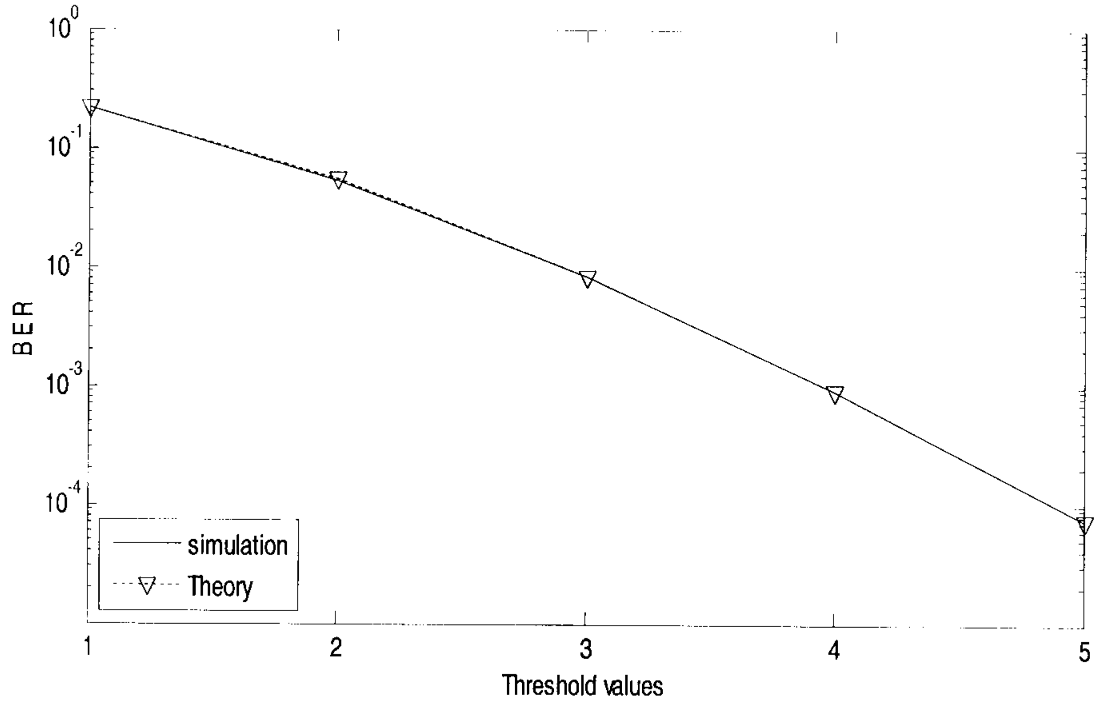


Figure 4.16: Performance of the OS-OPIC for 17 users

Figure 4.15 and Figure 4.16 show the theoretical and simulation results for the proposed system (Appendix D). From the figures, we could observe that the theoretical line of the OS-OPIC correlates with the simulation one. We could then validate the results for further study in this topic. We can see that by using the approach method, a lower BER is obtained when we set the threshold value to a higher value because the errors occur when the desired user sends data "0".

4.5 OPIC System and OS-OPIC

OS-OPIC is quite effective in term of reducing the hardware complexity while maintaining the same BER as a cost of increasing the threshold value.

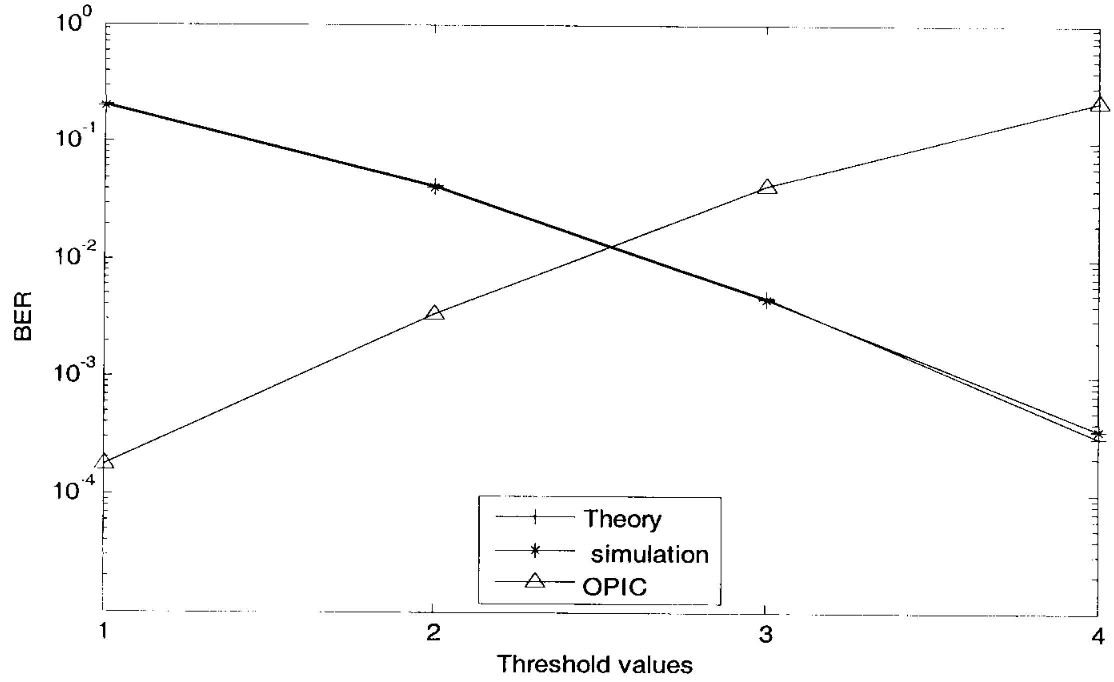


Figure 4.17: BER for the OPIC and OS-OPIC for 8 users

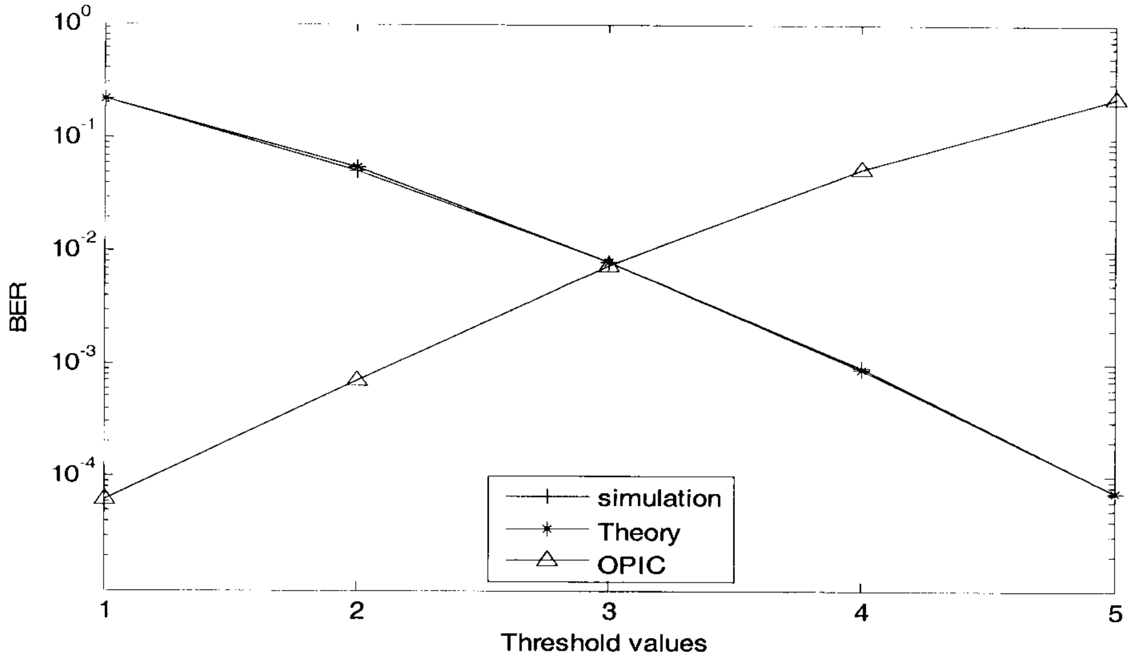


Figure 4.18: BER for the OPIC and OS-OPIC for 17 users

A comparison between the conventional OPIC and OS-OPIC is shown above. Figure 4.17 and Figure 4.18 show the BER versus the threshold value for OPIC and the proposed method OS-OPIC. We can see that by using the proposed method, a lower BER is obtained when we set the threshold value to a higher value. In contrast, we can obtain better performance for the OPIC if we use the minimum threshold value because errors happen in the OPIC system only if the desired user sends data "1". The results also reveal that the OS-OPIC is able to reduce the hardware complexity while maintaining the same performance of the conventional OPIC receiver despite the value of the threshold.

4.6 OS-OPIC and the CCR

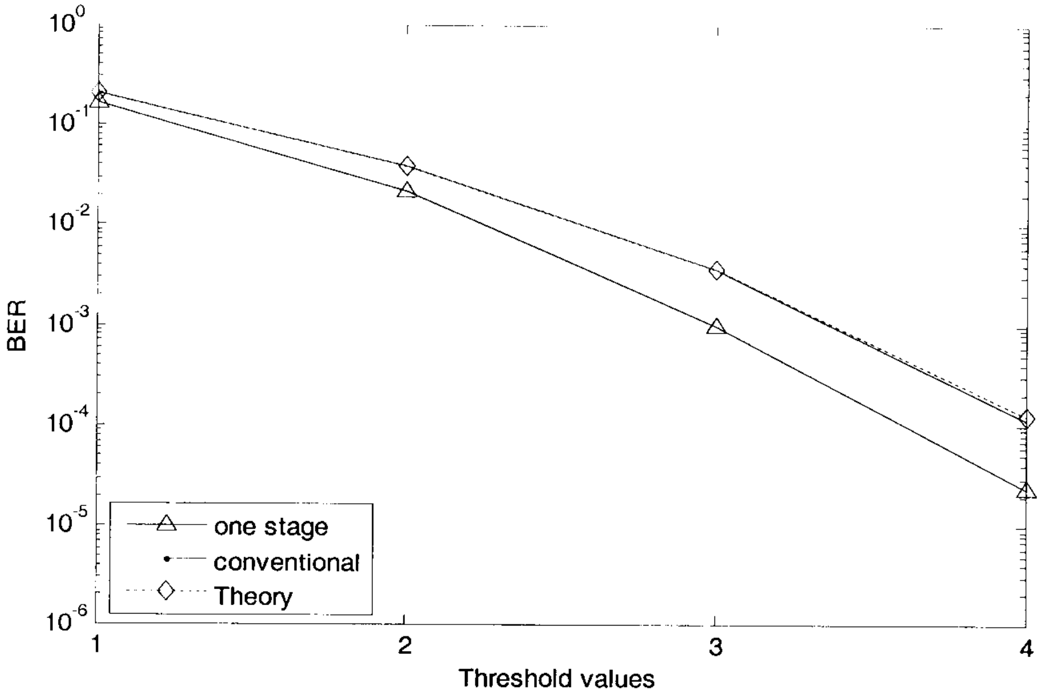


Figure 4.19: BER for the OS-OPIC and CCR

Figure. 4.19 show the comparison between the proposed method and the CCR. In this figure, BER is plotted against the threshold values. From the figure we could observe that, OS-OPIC outperforming the CCR because the strength of the interference is reduced by removing the signal of the non-desired user.

4.7 VPI Transmission Maker Results:

4.7.1 The Transmitter Part:

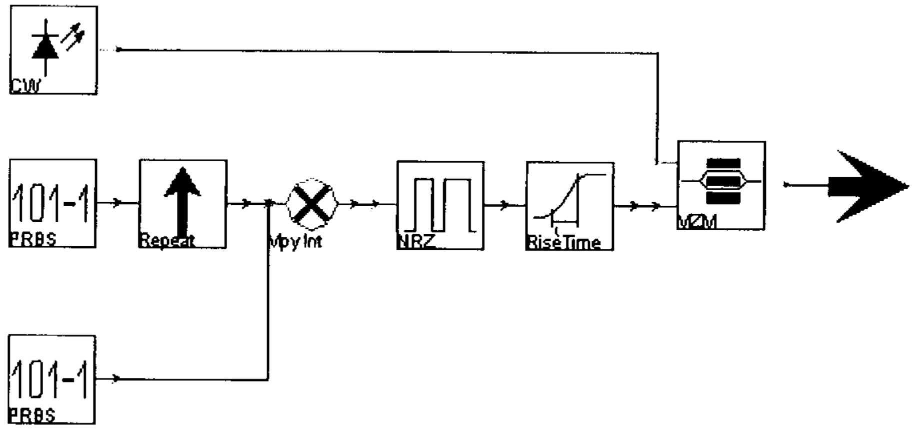


Figure 4.20: transmitter part of the OPIC system

Figure 4.20 represents the transmitter of the OPIC system. In general, each user inserts its code or address in each data bit and asynchronously initiates transmission.

The transmitter described above consists of the following modules:

- Pseudo Random Binary Sequence Generator (PRBS): it used to generate a binary data.
- Repeater: repeats each input particle the specified number of times on the output.
- Multiplier: The MpyInt series of modules outputs the product of the inputs, as an integer value.
- NRZ Coder: The module generates a sampled, NRZ (Non Return to Zero) coded signal defined by a train of bits at its input.
- Rise Time Adjustment: The module is filter that transforms, for example, rectangular electrical input pulses into smoother output pulses.
- Continuous Wave (CW) Laser: producing a continuous wave (CW) optical signal.

- Modulator Mach Zehnder: This module is used for impressing information on a light beam.
- Output: The output module provides output ports to connect a galaxy to external modules.

In the transmitter part of the OCDMA system, each user generate a train of binary data using PRBS module, then the data spreads by the code sequence of the intended receiver. The module NRZ is used to impress the code sequence upon the data. Finally, the laser is used to modulate the coded data using Mach Zehnder modulator in order to send it in fiber optic line.

4.7.2 OCDMA network using OPIC with OHL as a Receiver:

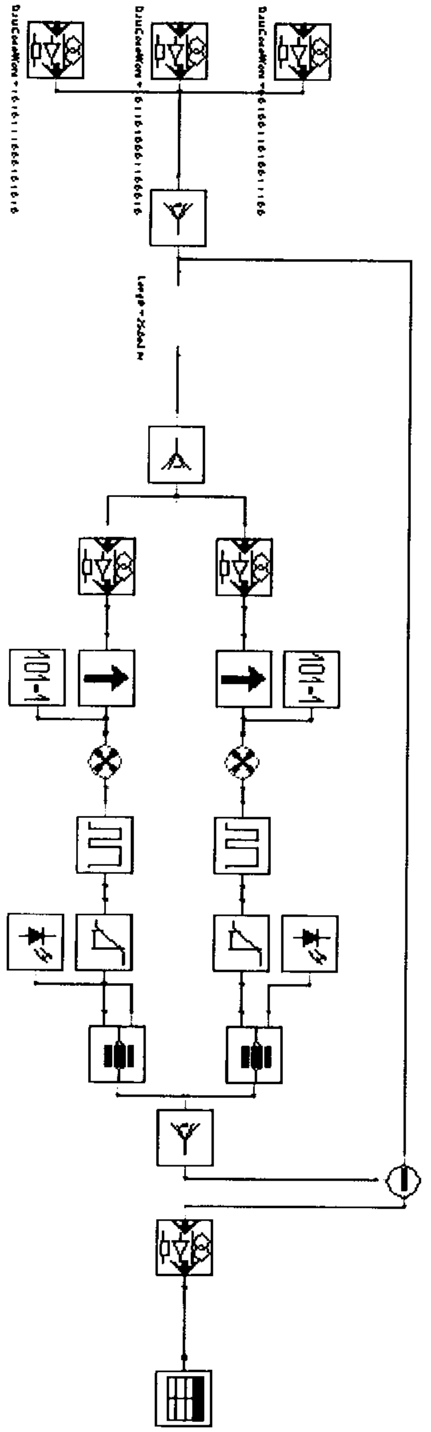


Figure 4.21: OCDMA network with OPIC+OHL at the receiver side using Text Visualizer

Figure 4.21 shows the schematic diagram of OCDMA network employing OPIC with OHL at the receiver side for three simultaneous users. The users are allowed to transmit their data asynchronously through the assignment of different code sequence. OOC is considered as a signature sequence with the following parameter: $L=64$, $w=4$ and auto and cross-correlation bounded by 1 as shown in Table 4.2. In this experiment, VPI Transmission Maker is used with the following parameters:

Fiber optic is used as a physical channel with the length of 2 km and the data rate of each user is 10 GB/s.

User #3 is chosen to be the desired user while user#1 and user#2 are considered as a non-desired user.

The operations of the receiver are described in the following steps:

The splitter splits the signal equally among user #1 and user#2. To extract the non-desired user's data, CCR with OHL is used and the extracted data is spread by its code sequence. Then the signals of the non-desired users are summed up and subtracted from the received signal (the signal of all users including the desired one). Last step is to extract the data of the desired user using the CCR.

The modules that have been used in the above experiment include:

- The first three elements are called galaxies and they represent the transmitters illustrated in Figure 4.20.
- Power Combiner: This module acts as an optical power combiner and it used to combine the signal of all the users in order to send it to the receiver side.
- Fiber Optic: This module transfers a train of pulses from the transmitter part to the receiver.
- Power Splitter: This module acts as an optical power splitter. The incoming signal is equally split on each output port.
- Conventional Correlation Receiver: estimates the transmitted data of the specific user.
- Subtract Optical Signals: The module subtracts two optical signals. It used here to subtract the non-desired user's signal from the received signal.

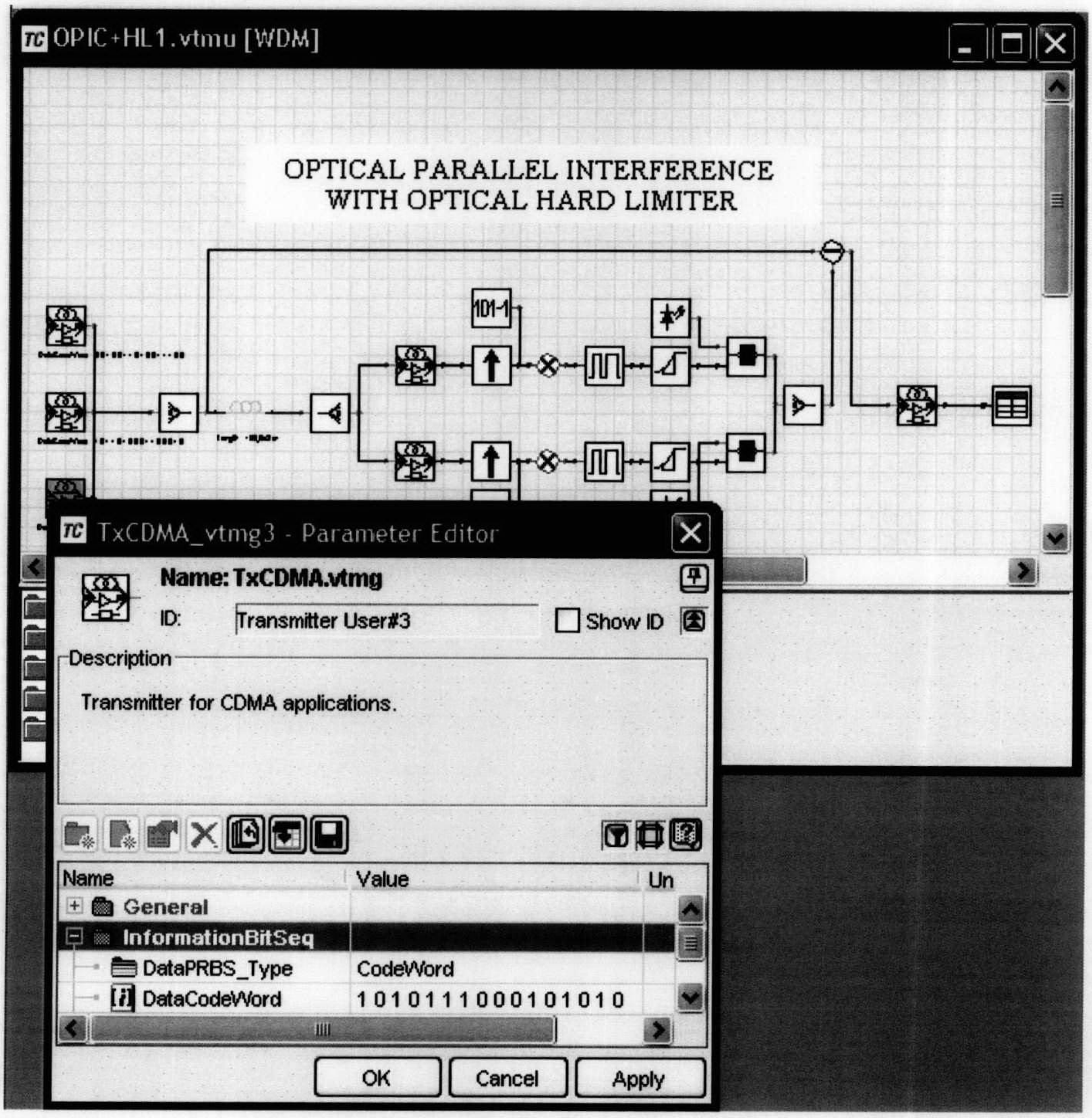
- Text Visualizer: The ViText module can be used to output data to be displayed textually in a table format. It used to display the data of the desired user.

Table 4.2: OOC (64,4,1)

	Chip #1	Chip #2	Chip #3	Chip #4
User #1	0	18	31	47
User #2	0	20	30	45
User #3	0	28	37	42

Two experiments have been conducted on the OPIC with OHL:

1. In the first experiment: the desired user wishes to transmit some bits as it shown in Figure 4.22. OPIC with OHL is used to extract the desired user's data. The module "Text Visualizer" is used to display the data in table format. Figure 4 .23 shows the output of this experiment



Name: TxCDMA.vtmg

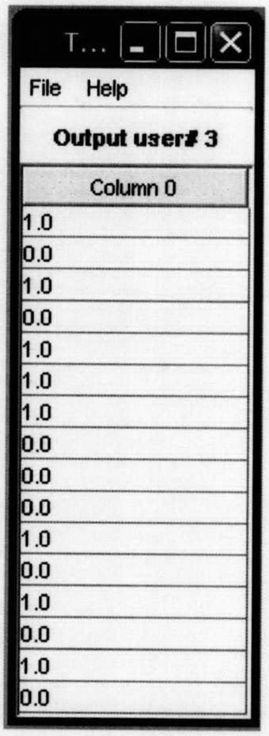
ID: Transmitter User#3

Description

Transmitter for CDMA applications.

Name	Value	Un
⊞ General		
⊟ InformationBitSeq		
DataPRBS_Type	CodeWord	
DataCodeWord	1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 0	

Figure 4.22: Transmission of data sequence



Output user# 3

Column 0
1.0
0.0
1.0
0.0
1.0
1.0
1.0
0.0
0.0
0.0
1.0
0.0
1.0
0.0
1.0
0.0

Figure 4.23: The extracted data of user #3.

2. The second experiment is denoted to observe the signal of the desired user in the transmitter and the output. Beside this, the signal of non-desired users also is considered. To display the optical waveform, the Scope is used instead of the Text Visualizer as it shown in Figure 4.24.

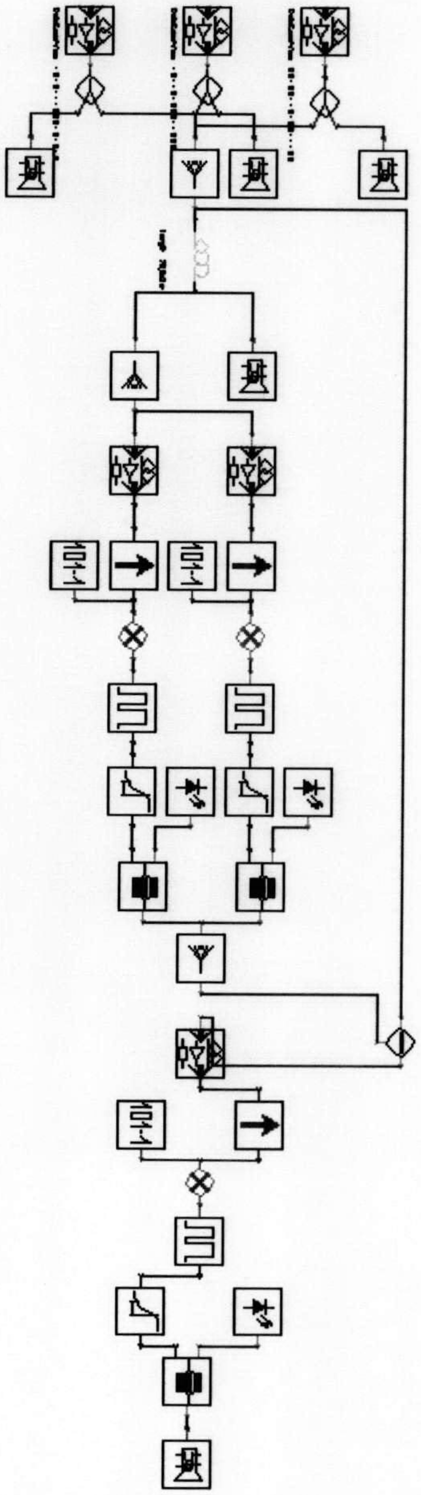


Figure 4.24: OCDMA network with OPIC+OHL at the receiver side using Scope

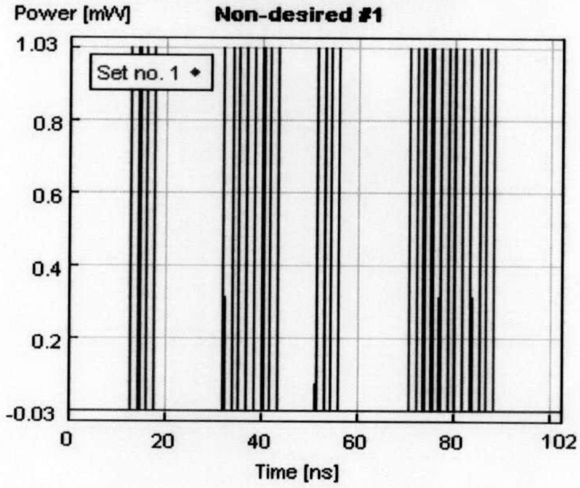


Figure 4.25(a): the input signal of the non-desired user #1

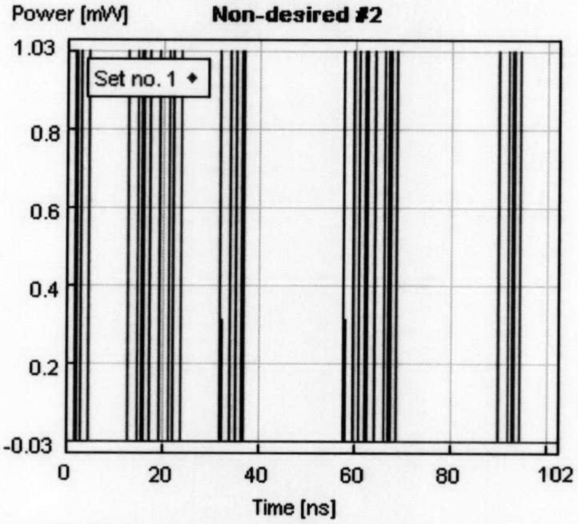


Figure 4.25(b): the input signal of the non-desired user #2

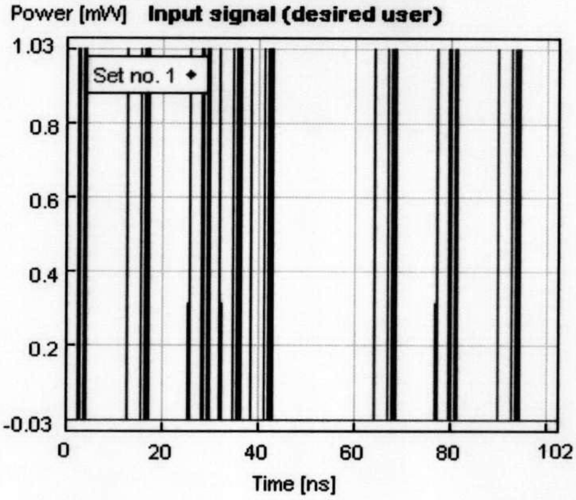


Figure 4.25(c): the input signal of the user #3

Figures 4.25(a)-(c) show the optical waveforms of the non-desired users beside the desired user at the transmitter part.

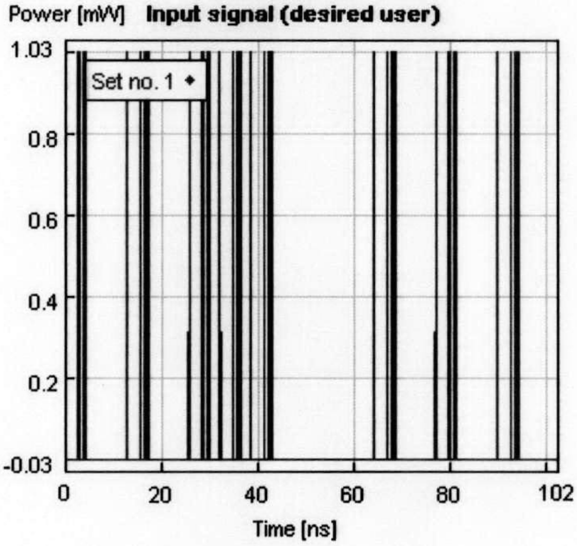


Figure 4.26(a): the input signal of the desired user

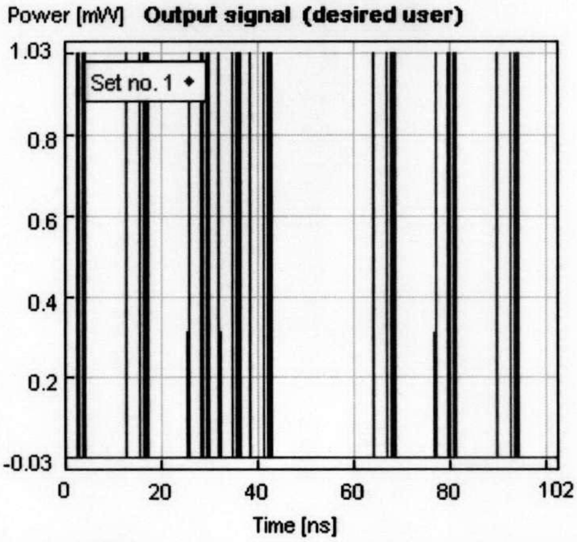


Figure 4.26(b): the output signal of the desired user

Figures 4.26(a-b) consider the desired user's signal in the transmitter and in the output. From the figure we could observe that, a typical signal is extracted because the total number of signals, i.e., N is less than the weight w. In particular, N is equal to 3 and w is 4 so that an error free OPIC system can be obtained as it illustrated in chapter 3.

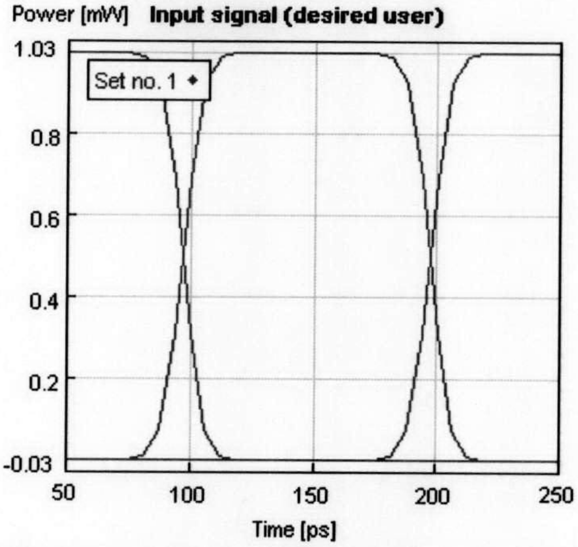


Figure 4.27(a): eye diagram of the input signal of the desired user

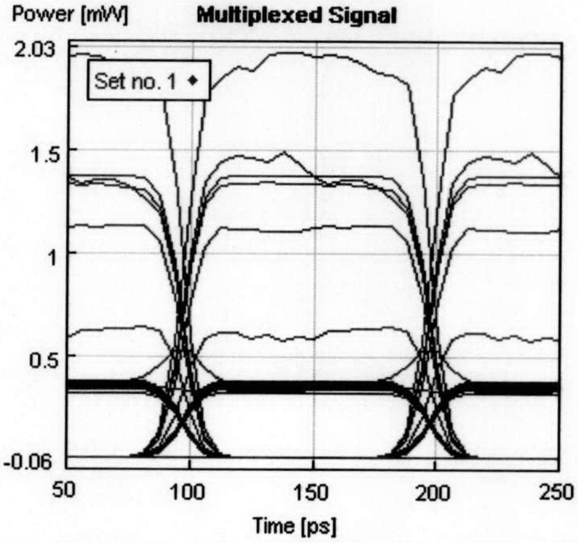


Figure 4.27(b): eye diagram of the multiplexed signal

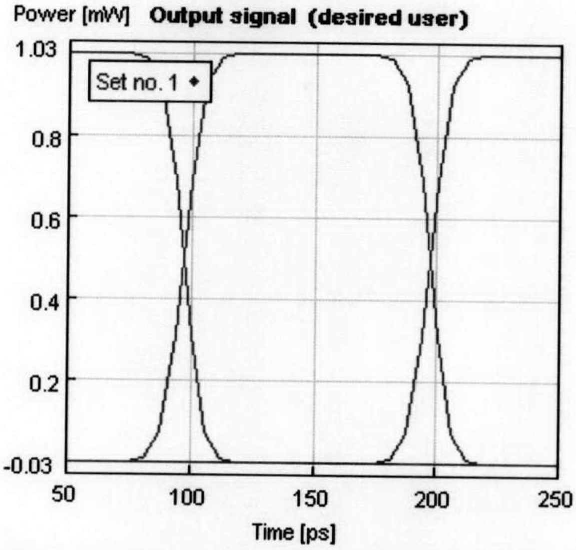


Figure 4.27(c): eye diagram of the output signal of the desired user

In Figure 4.27(a-c), the Scope is used to obtain the Eye diagram for the desired user's signal in the transmitter, fiber optic and the output. Since the signals of the desired user are identical, this indicates that their Eye diagrams also should be identical. From the figure we could validate that, the transmitted signal and the extracted signal are typically in the Eye diagram which affirms our assumption.

As it shown in figure 4.27(b), the signal in the fiber optic looks like noise and it is very difficult to be traced or jammed by unauthorized user. This means, a very high level of security can be achieved in the physical layer. On the other words, by spreading the data and send it through fiber optic, a very high level of security can be achieved.

Summary:

In this chapter, the performance of different types of OCDMA receiver is analyzed. The Multiple Access Interference (MAI) is known to hamper the implementation of the Conventional Correlation Receiver (CCR) [15]. In addition, the need for dynamic threshold to recover the data is very complex and tedious especially in the high speed LANs.

The Optical Parallel Interference Cancellation (OPIC) receiver is demonstrated in this work. Different techniques have been used throughout this chapter aiming at lowering the effect of MAI while overcome the problem of the receiver with dynamic threshold. In particular, Optical Hard Limiter (OHL) has been placed in front of the non-desired user to remove the interference signal. The results are compared to the CCR and to the OPIC without OHL. The results reveal that, OPIC with OHL has the potential to improve the performance of the OCDMA system.

In addition, some study has been conducted on the threshold value to obtain better performance and settle the dynamic threshold value. So far, the simulation results show that, the performance of OPIC with OHL can be obtained by selecting the lowest threshold value which gives the worse performance for the CCR with and without OHL. In other words, this study shows that, the OPIC with OHL is able to improve the performance of OCDMA system for the smallest threshold value which could not be done before. In contrast to the CCR, OPIC with OHL can achieve a better performance when the threshold value for the desired one i.e. $S_d=1$ is minimum. Concurrently, the system yielded a further improvement when we set the threshold value of the non-desired users, S_n to the maximum.

Moreover, another study has been done on the Optical Orthogonal Code (OOC), we have seen that, to improve the performance of the OPIC, long code sequence is needed in order to reduce the possibility of the overlapping. The simulation showed that, the performance improves dramatically whenever we increase the code length. The code length can be improved simply be adding more zeros at the end of the code sequence.

Beside this, the performance of new method namely, One Stage OPIC (OS-OPIC) has been also examined using the simulation. The results are compared to the OPIC and to the CCR. We figure out that, same Bit Error Rate could be obtained as the cost of the threshold. In addition, the proposed system managed to outperform the CCR.

Eventually, free error OPIC with OHL can be achieved if the number of the simultaneous users is equal to or less that their corresponding weight. The VPI Transmission Maker has been used to evaluate the performance. The results validate that, a typical data or signal can be extracted if the above condition is true.

CHAPTER 5

5. CONCLUSION AND FUTURE WORKS

5.1 Conclusion

The technology of CDMA has been successfully used in wireless data transmission but OCDMA remains outside the mainstream of the research in optical communications. However, with the progress in the optical network technology and the increasing demand for simple access protocol, OCDMA has become a potential technology for future optical networks especially for Local Area Networks (LANs). This technique is necessary at present due to the explosive growth of the Internet. For the LANs in order to be able to support many users at high bit rates a new technology had to be implemented. OCDMA is the key to fulfill the requirement of the future because optical fiber provides enormous bandwidth and CDMA offers the flexibility needed in the bursty LAN environment.

In this work, we reviewed the previous study on fiber optic CDMA systems. We found that, the abundance of bandwidth available in fiber optic would never be fully utilized by applying the conventional multiple access schemes and electronic devices. Therefore it will be beneficial that, if part of the processing or all processing can be done in the optical domain by taking the advantage of the available bandwidth in optical fibers. Thus, one could improve the throughput of the network. Based on this assumption, Prucnal [12] and Salehi [13] have proposed the use of optical processing along with the spread spectrum in the LAN. Salehi showed that, in the absence of quantum and thermal noise, the performance degrades only due to the Multiple Access Interference (MAI) which is caused by other users trying to use the medium simultaneously. MAI increases with the number of simultaneous users leading to higher error probability and eventually decrease the capacity of the entire system.

In addition, another studies [43-44] showed that, the Conventional Correlation Receiver (CCR) seriously in need for dynamic threshold in order to recover the data of the desired user. However, this requirement is very difficult especially for the high speed LAN.

To overcome the problem of MAI, one of the important considerations in designing OCDMA systems is the coding. Direct detection of the optical signal intensity has been classified as the most practical in optical communications due to its ease implementation of such type of detection. Since intensity is a positive signal, it is difficult to maintain orthogonally in those systems. It turns out that, the penalty due to non-orthogonally is very large. Even though tremendous efforts have been made in designing new codes families, the BER is still very poor. Then OCDMA system cannot be designed by considering the coding technique only, the detection technique also plays an important role and should be considered as well. Due to this, there is a strong demand for the design of new detection scheme that will be efficient enough to mitigate the effect of MAI while overcome the problem encountered with the CCR. Several techniques appeared in the literature aiming at finding a permanent solution for the stated problems.

In particular, Optical Parallel Interference Cancellation (OPIC) has been used through this thesis. OPIC is more complex compared to the CCR but it is more efficient in term of interference suppression because of its ability to remove the contribution of the non-desired users.

In order to reduce the effect of MAI, Optical Hard Limiter (OHL) has been placed at the front of the OPIC decoder. The use of the OHL resulting in a performance improvement because it is able to exclude some combinations of interference patterns from becoming heavily localized in non-zero positions of signature codes. The software simulation is then used to evaluate the performance. The results reveal that, OPIC with OHL outperformed the conventional OPIC and the CCR.

To overcome the need for receiver with dynamic threshold, theoretical study has been done on the OPIC threshold value. In this study, better performance can be obtained by selecting the minimum threshold for the desired user. Concurrently, the system will yield a further improvement if we set the threshold value of the non-desired users, S_n to the maximum. The theoretical analysis has been validated using the software simulation for different number of users and different code families. So far, the simulation results show that the performance of OPIC with OHL can be obtained by selecting the lowest threshold value which gives the worse performance for the CCR with and without OHL. In other words, this study shows that the OPIC with OHL is able to improve the performance of the OCDMA system for the smallest threshold value which could not be done before.

To avoid overlapping of the signature sequence of the simultaneous users, the code length should be long enough. Based on this assumption we have carried out another study on the code length we applied the resulting code for the OPIC with and without OHL. Different code length has been selected randomly and the unity threshold was selected for the OPIC, OPIC with OHL and the CCR. Simulation showed that OPIC upgraded the performance of the CCR whenever the code length is increased. Further improvement has been achieved when OHL was used in front of the receiver side.

The main problem encountered with the using of OPIC in LAN is that more hardware is needed when the number of transmitters (users) increases which results into more complexity. To overcome such limitation, a new method has been proposed based on the OPIC referred as One Stage OPIC (OS-OPIC) and the new expression of error probability is developed. Software is used to assure the results. We figure out that, by using the proposed method we managed to reduce the hardware complexity and maintain the same error probability as the cost of threshold value.

5.2 Future Works:

There is a need for future research works on OCDMA systems particularly in the area of development and implementation of new detection schemes that will be able to improve the performance of OCDMA systems and to minimize the effect of MAI. Besides, some possible research opportunities are summarized as follows:

In the current work, One Stage OPIC (OS-OPIC) is proposed to reduce the hardware complexity. With this technique, we can anticipate further progress by performing different number of stages which will provide substantial advantages in reducing the hardware complexity and reduce the BER. Moreover, a general equation is needed in order to obtain the optimum number of stages that could yield a better performance.

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APPENDIX A

Theory of the Conventional Correlation Receiver (CCR)

```
#include<stdio.h>
#include<conio.h>
#include<math.h>
double fact(int N){
int j;
double pro;
pro=1.00;
for(j=N;j>1;j--)
pro=pro*j;
return pro;}

double combine (int A,int P)
{
  double q;
  q = (fact(P)/(fact(P-A)*fact(A)));
  return q;
}
main()
{
int k,N,Th,i,F;
double Result,h,BER,sum;

printf("\nEnter the number of users N:");
scanf("%d",&N);
printf("\nEnter the length of the code F:");
```

```
scanf("%d",&F);
printf("\nEnter the wight of the code K:");
scanf("%d",&k);


h=(pow(k,2))/(2*F);
sum=0;
for(i=N-1;i>0;i--)
{
  sum=sum+(0.5*combine(i,N-1)*pow(h,i)*pow(1-h,N-1-i));
  if(i<k+1)printf("\nProb Err for th = %d : %lf", i,sum);
}
getch();
return 0;
}
```

APPENDIX B

Simulation of the CCR with and without OHL

B.1 Eight simultaneous users

```
#include<stdio.h>
#include<conio.h>
#include<stdlib.h>
main()
{
    srand(time(0));
    int i,j,k,r, wg=4, users=8, leng=97;
    int data, data1;
    int h,Th=1,ERROR=0, sumint, sumintohl;
    int error;
    int cd, cd32[32];
    float N,BER,ber, err[4], errohl[4];
    int u[8][4],ushift[8][4];
    int total[97];

    cd32[0]=0;cd32[1]=1;cd32[2]=35;cd32[3]=61;
    cd32[4]=0;cd32[5]=2;cd32[6]=25;cd32[7]=70;
    cd32[8]=0;cd32[9]=4;cd32[10]=43;cd32[11]=50;
    cd32[12]=0;cd32[13]=3;cd32[14]=8;cd32[15]=86;
    cd32[16]=0;cd32[17]=6;cd32[18]=16;cd32[19]=75;
    cd32[20]=0;cd32[21]=12;cd32[22]=32;cd32[23]=53;
    cd32[24]=0;cd32[25]=9;cd32[26]=24;cd32[27]=64;
    cd32[28]=0;cd32[29]=18;cd32[30]=31;cd32[31]=48;
```

```
for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    u[i][j]=cd32[(i*wg)+j];
                      }
}

/***** code non shifted *****/
for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    printf("%d   ",u[i][j]);
                      }
  printf("\n");
}
/*****input number of bits******/
for(i=0;i<wg;i++)
{
    err[i]=0;
  errohl[i]=0;
              }

printf("\nEnter the number of bits:");
scanf("%f",&N);

for(h=0;h<N;h++){
int error=0;

/********** shifted code **********/
```

```
for(i=0;i<users;i++)
{
    r=rand()%97;
    for(j=0;j<wg;j++)
  {
    cd=u[i][j];
    cd=(cd+r)%leng;
    ushift[i][j]=cd;
                }
}
/*****total*****/

for(i=0;i<leng;i++)total[i]=0;

     for(j=0;j<users;j++)
  {
    data=rand()%2;
    if(j==0)
    {
            data1=data;
    //  printf("\nData :%d", data);
    }

    if(data!=0)
    {
                                    for(k=0;k<wg;k++)
                      {
                      cd=ushift[j][k];
            total[cd]++;
                                    }
    }
```

```
                        }


  /************ user no 1 ********/
  i=0;
  sumint=0;
  sumintohl=0;
      for(j=0;j<wg;j++)


    {
      cd=ushift[i][j];
      sumint=sumint + total[cd];
      if(total[cd]>0)sumintohl++;
    }

  /******* inialize to 0 the error table ******/


  for(Th=1;Th<5;Th++)
  {
      if(sumint>=Th && data1==0)err[Th-1]++;
    if(sumintohl>=Th && data1==0)errohl[Th-1]++;
  }
  //ber=error/N;}
                  }
  for(Th=1;Th<5;Th++) {
  printf("\n\nError Conventional Th =%d",Th);
  printf(" is:%d",int(err[Th-1]));
  printf(" \nBER:%f",err[Th-1]/N);
  printf("\nError OHL Th =%d",Th);
  printf(" is:%d",int(errohl[Th-1]));
  printf(" \nBER:%f",errohl[Th-1]/N);
  printf("\n");}
```

```
    getch();
    return 0;
  }
```

B.2 Seventeen simultaneous users:

```
#include<stdio.h>
#include<conio.h>
#include<stdlib.h>
main()
{
    srand(time(0));
    int i,j,k,r, wg=5, users=17, leng=341;
    int data, data1;
    int h,Th=1,ERROR=0, sumint, sumintohl;
    int error;
    int cd, cd85[85];
    float N,BER,ber, err[5], errohl[5];

    int u[17][5],ushift[17][5];
    int total[341];

    cd85[0]=0;  cd85[1]=1;  cd85[2]=85;  cd85[3]=21;  cd85[4]=5;
    cd85[5]=0;  cd85[6]=2;  cd85[7]=170;  cd85[8]=10;  cd85[9]=42;
    cd85[10]=0;  cd85[11]=3;  cd85[12]=111; cd85[13]=104; cd85[14]=53;
    cd85[15]=0;  cd85[16]=6;  cd85[17]=222; cd85[18]=106; cd85[19]=208;
    cd85[20]=0;  cd85[21]=9;  cd85[22]=268; cd85[23]=151; cd85[24]=105;
    cd85[25]=0;  cd85[26]=11; cd85[27]=45;  cd85[28]=76;  cd85[29]=198;
    cd85[30]=0;  cd85[31]=12; cd85[32]=103; cd85[33]=75;  cd85[34]=212;
```

```
cd85[35]=0;  cd85[36]=13; cd85[37]=305; cd85[38]=277; cd85[39]=43;
cd85[40]=0;  cd85[41]=15; cd85[42]=107; cd85[43]=146; cd85[44]=164;
cd85[45]=0;  cd85[46]=17; cd85[47]=264; cd85[48]=203; cd85[49]=165;
cd85[50]=0;  cd85[51]=19; cd85[52]=88;  cd85[53]=267; cd85[54]=220;
cd85[55]=0;  cd85[56]=22; cd85[57]=90;  cd85[58]=55;  cd85[59]=152;
cd85[60]=0;  cd85[61]=23; cd85[62]=293; cd85[63]=252; cd85[64]=118;
cd85[65]=0;  cd85[66]=24; cd85[67]=206; cd85[68]=83;  cd85[69]=150;
cd85[70]=0;  cd85[71]=25; cd85[72]=54;  cd85[73]=169; cd85[74]=221;
cd85[75]=0;  cd85[76]=26; cd85[77]=269; cd85[78]=86;  cd85[79]=113;
cd85[80]=0;  cd85[81]=37; cd85[82]=147; cd85[83]=217; cd85[84]=81;

for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    u[i][j]=cd85[(i*wg)+j];
                    }
}

/***** code non shifted *****/
for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    printf("%d   ",u[i][j]);
                    }
  printf("\n");
}

/*****input number of bits******/
for(i=0;i<wg;i++)
```

```
{
    err[i]=0;
  errohl[i]=0;
            }

printf("\nEnter the number of bits:");
scanf("%f",&N);

for(h=0;h<N;h++){
int error=0;

/********** shifted code **********/
for(i=0;i<users;i++)
{
    r=rand()%341;
    for(j=0;j<wg;j++)
  {
    cd=u[i][j];
    cd=(cd+r)%leng;
    ushift[i][j]=cd;
                    }
}

/*****total*****/

for(i=0;i<leng;i++)total[i]=0;

    for(j=0;j<users;j++)
  {
    data=rand()%2;
    if(j==0)
```

```
    {
            data1=data;
    //  printf("\nData :%d", data);
    }

    if(data!=0)
    {
                                        for(k=0;k<wg;k++)
                    {
                    cd=ushift[j][k];
            total[cd]++;
                                        }
    }
                    }

/************ user no 1 ********/
i=0;
sumint=0;
sumintohl=0;
    for(j=0;j<wg;j++)
  {
    cd=ushift[i][j];
    sumint=sumint + total[cd];
    if(total[cd]>0)sumintohl++;
  }

/******* inialize to 0 the error table ******/

for(Th=1;Th<6;Th++)
{
    if(sumint>=Th && data1==0)err[Th-1]++;
```

```
  if(sumintohl>=Th && data1==0)errohl[Th-1]++;
 }
 //ber=error/N;}
            }


 for(Th=1;Th<6;Th++) {
 printf("\n\nError Conventional Th =%d",Th);
 printf(" is:%d",int(err[Th-1]));
 printf(" \nBER:%f",err[Th-1]/N);
 printf("\nError OHL Th =%d",Th);
 printf(" is:%d",int(errohl[Th-1]));
 printf(" \nBER:%f",errohl[Th-1]/N);
 printf("\n");}
 getch();
 return 0;
}
```

APPENDIX C

Simulation of the OPIC with and without OHL

C.1 Fifteen Simultaneous users:

```
#include<stdio.h>
#include<conio.h>
#include<stdlib.h>
main()
{
    srand(time(0));
    int i,j,k,r, wg=4, users=15, leng=181;
    int data, data1;
    int h,Th,ERROR=0, sumint, sumintohl;
    int error;
    int cd, cd60[60];
    float N,BER,ber, err[4], errohl[4];
    int u[15][4],ushift[15][4];
    int total[181], totalth[4][181];

    cd60[0]=0;cd60[1]=1;cd60[2]=48;cd60[3]=132;
    cd60[4]=0;cd60[5]=4;cd60[6]=11;cd60[7]=166;
    cd60[8]=0;cd60[9]=16;cd60[10]=44;cd60[11]=121;
    cd60[12]=0;cd60[13]=64;cd60[14]=122;cd60[15]=176;
    cd60[16]=0;cd60[17]=75;cd60[18]=126;cd60[19]=161;
    cd60[20]=0;cd60[21]=101;cd60[22]=119;cd60[23]=142;
    cd60[24]=0;cd60[25]=25;cd60[26]=42;cd60[27]=114;
    cd60[28]=0;cd60[29]=94;cd60[30]=100;cd60[31]=168;
    cd60[32]=0;cd60[33]=14;cd60[34]=38;cd60[35]=129;
```

```
cd60[36]=0;cd60[37]=56;cd60[38]=152;cd60[39]=154;
cd60[40]=0;cd60[41]=43;cd60[42]=73;cd60[43]=65;
cd60[44]=0;cd60[45]=79;cd60[46]=111;cd60[47]=172;
cd60[48]=0;cd60[49]=82;cd60[50]=135;cd60[51]=145;
cd60[52]=0;cd60[53]=37;cd60[54]=147;cd60[55]=178;
cd60[56]=0;cd60[57]=45;cd60[58]=148;cd60[59]=169;

for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    u[i][j]=cd60[(i*wg)+j];
                    }
}

/***** code non shifted *****/
for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    printf("%d  ",u[i][j]);
                    }
  printf("\n");
}

/*****input number of bits******/
for(i=0;i<wg;i++)
{
    err[i]=0;
  errohl[i]=0;
            }
```

```
printf("\nEnter the number of bits:");
scanf("%f",&N);


for(h=0;h<N;h++){
int error=0;
/********** shifted code **********/
for(i=0;i<users;i++)
{
    r=rand()%181;
    for(j=0;j<wg;j++)
  {
    cd=u[i][j];
    cd=(cd+r)%leng;
    ushift[i][j]=cd;
                    }
}
/*****total*****/


for(i=0;i<leng;i++)total[i]=0;
for(i=0;i<leng;i++)totalth[0][i]=0;
for(i=0;i<leng;i++)totalth[1][i]=0;
for(i=0;i<leng;i++)totalth[2][i]=0;
for(i=0;i<leng;i++)totalth[3][i]=0;
    for(j=0;j<users;j++)
  {
    data=rand()%2;
    if(j==0)
    {
            data1=data;
      //printf("\nData :%d", data);
    }
```

```
      if(data!=0)
      {
                                        for(k=0;k<wg;k++)
                        {
                        cd=ushift[j][k];
              total[cd]++;
                                        }
      }
                        }


    /****** parallel cancellation***********/
   sumint=0;


   for(i=1;i<users;i++)
   {
    for(j=0;j<wg;j++)
    {
              cd=ushift[i][j];
      sumint=sumint + total[cd];
    }
    for(Th=1;Th<5;Th++)
      {
              if(sumint>=Th)
      {
              for(j=0;j<wg;j++)
                        {
                        cd=ushift[i][j];
              totalth[Th-1][cd]++;
                                        }
      }
      }
```

```
}


 /************ user no 1 ********/
i=0;
sumint=0;
sumintohl=0;

for(i=0;i<181;i++)
{
    total[i]=total[i]-totalth[3][i];
}

i=0;
sumint=0;
sumintohl=0;
    for(j=0;j<wg;j++)

  {
    cd=ushift[i][j];
    sumint=sumint + total[cd];
    if(total[cd]>0)sumintohl++;
  }

/******* inialize to 0 the error table ******/

for(Th=1;Th<5;Th++)
{
  if(sumint>=Th && data1==0)err[Th-1]++;
  if(sumint<Th && data1==1)err[Th-1]++;
  if(sumintohl>=Th && data1==0)errohl[Th-1]++;
  if(sumintohl<Th && data1==1)errohl[Th-1]++;
```

```
    }
              }

    for(Th=1;Th<5;Th++) {
    printf("\n\nError Conventional Th =%d",Th);
    printf(" is:%d",int(err[Th-1]));
    printf(" \nBER:%f",err[Th-1]/N);
    printf("\nError OHL Th =%d",Th);
    printf(" is:%d",int(errohl[Th-1]));
    printf(" \nBER:%f",errohl[Th-1]/N);
    printf("\n");}

    getch();
    return 0;
  }
```

C.2 Eight simultaneous users:

```
#include<stdio.h>
#include<conio.h>
#include<stdlib.h>
main()
{
    srand(time(0));
    int i,j,k,r, wg=4, users=8, leng=97;
    int data, data1;
    int h,Th,ERROR=0, sumint, sumintohl;
    int error;
    int cd, cd32[32];
```

```
float N,BER,ber, err[4], errohl[4];
int u[8][4],ushift[8][4];
int total[97], totalth[4][97];

cd32[0]=0;cd32[1]=1;cd32[2]=35;cd32[3]=61;
cd32[4]=0;cd32[5]=2;cd32[6]=25;cd32[7]=70;
cd32[8]=0;cd32[9]=4;cd32[10]=43;cd32[11]=50;
cd32[12]=0;cd32[13]=3;cd32[14]=8;cd32[15]=86;
cd32[16]=0;cd32[17]=6;cd32[18]=16;cd32[19]=75;
cd32[20]=0;cd32[21]=12;cd32[22]=32;cd32[23]=53;
cd32[24]=0;cd32[25]=9;cd32[26]=24;cd32[27]=64;
 cd32[28]=0;cd32[29]=18;cd32[30]=31;cd32[31]=48;

for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    u[i][j]=cd32[(i*wg)+j];
                    }
}

/***** code non shifted *****/
for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    printf("%d   ",u[i][j]);
                    }
  printf("\n");
}
```

```
/*****input number of bits******/
for(i=0;i<wg;i++)
{
    err[i]=0;
  errohl[i]=0;
            }

printf("\nEnter the number of bits:");
scanf("%f",&N);

for(h=0;h<N;h++){
int error=0;

/********** shifted code **********/
for(i=0;i<users;i++)
{
    r=rand()%97;
    for(j=0;j<wg;j++)
  {
    cd=u[i][j];
    cd=(cd+r)%leng;
    ushift[i][j]=cd;
                    }
}

/*****total*****/
for(i=0;i<leng;i++)total[i]=0;
for(i=0;i<leng;i++)totalth[0][i]=0;
for(i=0;i<leng;i++)totalth[1][i]=0;
for(i=0;i<leng;i++)totalth[2][i]=0;
for(i=0;i<leng;i++)totalth[3][i]=0;
```

```
     for(j=0;j<users;j++)
  {
    data=rand()%2;
    if(j==0)
     {
             data1=data;
      //printf("\nData :%d", data);
     }

    if(data!=0)
     {
                                      for(k=0;k<wg;k++)
                      {
                     cd=ushift[j][k];
             total[cd]++;
                                       }
     }
                      }

  /****** parallel cancellation***********/
sumint=0;

for(i=1;i<users;i++)
{
  for(j=0;j<wg;j++)
   {
             cd=ushift[i][j];
    sumint=sumint + total[cd];
   }
  for(Th=1;Th<5;Th++)
     {
```

```
            if(sumint>=Th)
    {
            for(j=0;j<wg;j++)
                    {
                    cd=ushift[i][j];
            totalth[Th-1][cd]++;
                                    }
    }
    }
}

/************ user no 1 ********/
i=0;
sumint=0;
sumintohl=0;

for(i=0;i<97;i++)
{
    total[i]=total[i]-totalth[3][i];
}

i=0;
sumint=0;
sumintohl=0;
    for(j=0;j<wg;j++)
  {
    cd=ushift[i][j];
    sumint=sumint + total[cd];
    if(total[cd]>0)sumintohl++;
  }
```

```
/******* inialize to 0 the error table ******/


for(Th=1;Th<5;Th++)
{
    if(sumint>=Th && data1==0)err[Th-1]++;
  if(sumint<Th && data1==1)err[Th-1]++;
  if(sumintohl>=Th && data1==0)errohl[Th-1]++;
  if(sumintohl<Th && data1==1)errohl[Th-1]++;


}


              }
for(Th=1;Th<5;Th++) {
printf("\n\nError Conventional Th =%d",Th);
printf(" is:%d",int(err[Th-1]));
printf(" \nBER:%f",err[Th-1]/N);
printf("\nError OHL Th =%d",Th);
printf(" is:%d",int(errohl[Th-1]));
printf(" \nBER:%f",errohl[Th-1]/N);
printf("\n");}
getch();
return 0;
}
```

APPENDIX D

One Stage OPIC for 17 simultaneous users

```
#include<stdio.h>
#include<conio.h>
#include<stdlib.h>
main()
{
    srand(time(0));
    int i,j,k,r, wg=5, users=17, leng=341;
    int data, data1;
    int h,Th=1,ERROR=0, sumint, sumintohl;
    int error;
    int cd, cd85[85];
    float N,BER,ber, err[5], errohl[5];
    int u[17][5],ushift[17][5];
    int total[341], totalth[5][341];
    short ir;

    cd85[0]=0;  cd85[1]=1;  cd85[2]=85;  cd85[3]=21;  cd85[4]=5;
    cd85[5]=0;  cd85[6]=2;  cd85[7]=170; cd85[8]=10;  cd85[9]=42;
    cd85[10]=0; cd85[11]=3; cd85[12]=111; cd85[13]=104; cd85[14]=53;
    cd85[15]=0; cd85[16]=6; cd85[17]=222; cd85[18]=106; cd85[19]=208;
    cd85[20]=0; cd85[21]=9; cd85[22]=268; cd85[23]=151; cd85[24]=105;
    cd85[25]=0; cd85[26]=11; cd85[27]=45;  cd85[28]=76;  cd85[29]=198;
    cd85[30]=0; cd85[31]=12; cd85[32]=103; cd85[33]=75;  cd85[34]=212;
    cd85[35]=0; cd85[36]=13; cd85[37]=305; cd85[38]=277; cd85[39]=43;
    cd85[40]=0; cd85[41]=15; cd85[42]=107; cd85[43]=146; cd85[44]=164;
```

```
cd85[45]=0;  cd85[46]=17; cd85[47]=264; cd85[48]=203; cd85[49]=165;
cd85[50]=0;  cd85[51]=19; cd85[52]=88;  cd85[53]=267; cd85[54]=220;
cd85[55]=0;  cd85[56]=22; cd85[57]=90;  cd85[58]=55;  cd85[59]=152;
cd85[60]=0;  cd85[61]=23; cd85[62]=293; cd85[63]=252; cd85[64]=118;
cd85[65]=0;  cd85[66]=24; cd85[67]=206; cd85[68]=83;  cd85[69]=150;
cd85[70]=0;  cd85[71]=25; cd85[72]=54;  cd85[73]=169; cd85[74]=221;
cd85[75]=0;  cd85[76]=26; cd85[77]=269; cd85[78]=86;  cd85[79]=113;
cd85[80]=0;  cd85[81]=37; cd85[82]=147; cd85[83]=217; cd85[84]=81;

for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    u[i][j]=cd85[(i*wg)+j];
                    }
}

 /***** code non shifted *****/
for(i=0;i<users;i++)
{
    for(j=0;j<wg;j++)
  {
    //printf("%d   ",u[i][j]);
                    }
  //printf("\n");
}

/*****input number of bits******/
for(i=0;i<wg;i++)
{
    err[i]=0;
```

```
  errohl[i]=0;
              }

 printf("\nEnter the number of bits:");
 scanf("%f",&N);

  randomize();
 ir = (rand()% 16)+1 ;
// for(i=1;i<users-15
// ;i++)
// {
 //ir =5;

 printf(" rand = %d \n", ir);

 for(h=0;h<N;h++){
 int error=0;

 /********** shifted code **********/
 for(i=0;i<users;i++)
 {
     r=rand()%341;
     for(j=0;j<wg;j++)
   {
     cd=u[i][j];
     cd=(cd+r)%leng;
     ushift[i][j]=cd;
                        }
 }
```

```
/*****total*****/
   for(i=0;i<leng;i++)total[i]=0;
   for(i=0;i<leng;i++)totalth[0][i]=0;
   for(i=0;i<leng;i++)totalth[1][i]=0;
   for(i=0;i<leng;i++)totalth[2][i]=0;
   for(i=0;i<leng;i++)totalth[3][i]=0;
   for(i=0;i<leng;i++)totalth[4][i]=0;

       for(j=0;j<users;j++)
     {
      data=rand()%2;
      if(j==0)
      {
              data1=data;
        //printf("\nData :%d", data);
      }

      if(data!=0)
      {
                                  for(k=0;k<wg;k++)
                       {
                       cd=ushift[j][k];
              total[cd]++;
                                  }
      }
                       }

  sumint=0;

    for(j=0;j<wg;j++)
    {
```

```
            cd=ushift[ir][j];
        sumint=sumint + total[cd];
      }
      for(Th=1;Th<6;Th++)
        {
            if(sumint>=Th)
        {
            for(j=0;j<wg;j++)
                {
                cd=ushift[ir][j];
            totalth[Th-1][cd]++;
                          }
        }
        }
    //}

    /************ user no 1 ********/
    i=0;
    sumint=0;
    sumintohl=0;

    for(i=0;i<341;i++)
    {
        total[i]=total[i]-totalth[4][i];
      //printf("\ntotal %d : %d",i,total[i]);
    }

    i=0;
    sumint=0;
    sumintohl=0;
        for(j=0;j<wg;j++)
```

```
  {
    cd=ushift[i][j];
    //printf("\n %d",cd);
    sumint=sumint + total[cd];
    if(total[cd]>0)sumintohl++;
  }

  //printf("\nsumint : %d",sumint);
  //printf("\nsumintohl : %d",sumintohl);

//printf("\n\nsum integration is :%d", sumint);

/******* inialize to 0 the error table ******/

for(Th=1;Th<6;Th++)
{
    if(sumint>=Th && data1==0)err[Th-1]++;
  if(sumint<Th && data1==1)err[Th-1]++;
  //printf("\nError :%d", err[Th-1]);
  if(sumintohl>=Th && data1==0)errohl[Th-1]++;
  if(sumintohl<Th && data1==1)errohl[Th-1]++;
  //printf("\nError :%d", errohl[Th-1]);
}
            }

  for(Th=1;Th<6;Th++) {
  printf("\n\nError Conventional Th =%d",Th);
  printf(" is:%d",int(err[Th-1]));
  printf(" \nBER:%f",err[Th-1]/N);
  printf("\nError OHL Th =%d",Th);
  printf(" is:%d",int(errohl[Th-1]));
```

```
    printf(" \nBER:%f",errohl[Th-1]/N);
    printf("\n");}


    getch();
    return 0;
}
```

APPENDIX E

Optical Orthogonal Code Families

D.1 Optical Orthogonal Code family for 5 users, OOC (64, 4, 1)

	Chip 1	Chip 2	Chip 3	Chip 4
U 1	0	18	31	47
U 2	0	20	30	45
U 3	0	28	37	42
U 4	0	38	40	61
U 5	0	52	53	60

D.2 Optical Orthogonal Code family for 8 users, OOC (97, 4, 1)

	Chip 1	Chip 2	Chip 3	Chip 4
U 1	0	1	35	61
U 2	0	2	24	70
U 3	0	4	43	50
U 4	0	3	8	86
U 5	0	6	16	75
U 6	0	12	32	53
U 7	0	9	24	64
U 8	0	18	31	48

D.3 Optical Orthogonal Code family for 15 users, OOC (181, 4, 1)

	Chip 1	Chip 2	Chip 3	Chip 4
U 1	0	1	48	132
U 2	0	4	11	166
U 3	0	16	44	121
U 4	0	64	122	176
U 5	0	75	126	161
U 6	0	101	119	142
U 7	0	25	42	114
U 8	0	94	100	168
U 9	0	14	38	129
U 10	0	56	152	154
U 11	0	43	73	65
U 12	0	79	111	172
U 13	0	82	135	145
U 14	0	37	147	178
U15	0	45	148	169

D.4 Optical Orthogonal Code family for 17 users, OOC (341, 5, 1)

	Chip 1	Chip 2	Chip 3	Chip 4	Chip 5
U 1	0	1	85	21	5
U 2	0	2	170	10	42
U 3	0	3	111	104	53
U 4	0	6	222	106	208
U 5	0	9	268	151	105
U 6	0	11	45	76	198
U 7	0	12	103	75	212
U 8	0	13	305	227	43
U 9	0	15	107	146	164
U 10	0	17	264	203	165
U 11	0	19	88	267	220
U 12	0	22	90	55	152
U 13	0	23	293	252	118
U 14	0	24	206	83	150
U15	0	25	54	169	221
U16	0	26	269	86	113
U17	0	37	147	217	81