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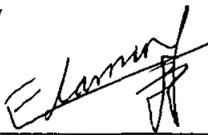
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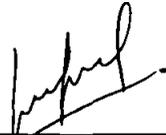
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submitted by

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Date

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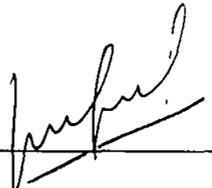
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Development of Zero Cross Correlation-Double Weight Code for Optical CDMA

By

Elamin Idriss Babekir Idriss

A THESIS

SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME

AS A REQUIREMENT FOR THE

DEGREE OF MASTERS OF SCIENCE IN ELECTRICAL AND ELECTRONIC

ENGINEERING

Electrical and Electronic Engineering

BANDAR SERI ISKANDAR,

PERAK

November, 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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ACKNOWLEDGEMENT

ABSTRACT

Optical fibers are very attractive communication media if compared to the conventional guided media like twisted wire pairs and coaxial cables since they offer large bandwidth and low attenuation. Hence, by utilizing optical fibers as the media of communication links, more advantages can be obtained if compared to traditional media.

The three major multiple access for optical networks are Time Division Multiple Accees (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). OCDMA has advantages over TDMA and FDMA because first of all it makes efficient use of communication media by allowing asynchronous access to each user. Second no scheduling is required in CDMA and new users can easily be added to the networks.

The Optical Code Division Multiple Access (OCDMA) suffers from various types of noise but the dominant source of noise is Multiple Access Interference (MAI). Therefore, the cancellation or suppression of MAI is a big problem in OCDMA. Much OCDMA codes have been designed to reduce the MAI and to enhance the performance of the system. This thesis concentrates on how to reduce the MAI in OCDMA.

In this thesis Zero Cross Correlation-Double Weight Code (ZCC-DW) is proposed based on Modified Double Weight Code (MDW) for OCDMA system to decrease the cross correlation value from one to zero hence the Multiple Access Interference (MAI) should be decrease and this will improve the system performance.

After completion the code construction techniques a simulation is used to study the performance of ZCC-DW code. The performance is carried out to various data rate and various optical fiber lengths to calculate the Bit Error Rate (BER) which it used to evaluate the code performance. Lastly Comparisons are then made between Direct Detection (ZCC-DW code Detection) and Hybrid Detection (MDW code Detection). Direct Detection Technique offers better result than Hybrid Detection Technique.

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ABBREVIATIONS

CDMA	Code Division Multiple Access
VPI	Virtual Photonics Incorporated
MA I	Multiple Access Interference
OTDMA	Optical Time Division Multiple Access
OFDMA	Optical Frequency Division Multiple Access
MFH	Modified Frequency Hopping code
OOC	Optical Orthogonal Code
ZCC-DW	Zero Cross correlation Code Double Weight Code
DW	Double Weight Code
MDW	Modified Double Weight Code
OSCDMA	Optical Spectral Code Division Multiple Access
OOK	Off Keyed modulation
PLC	A Programmable Liquid Crystal
LED	Light E mission Diode
PIIN	Phase Induced Intensity Noise
BER	Bit Error Rate

NOMENCULATURE

d_k	The data bit of the Kth user that is "1" or "0",
$P(t)$	The unit rectangular.
T_c	Pulse duration.
$r(t)$	The sum of signals transmitted by all active users.
$b_k(t)$	The bit (0, 1) of the kth user.
N	The total number of users.
$s_1(t)$	Refers to output signal of the first stage cancellation
N_B	The basic code length of Modified Double Weight Code
K_B	The basic number of users of Modified Double Weight Code
W	The weight of Modified Double Weight Code
N_{B1}	The basic code length of Zero Cross Correlation Code.
K_{B1}	The basic number of users of zero crosses correlation code
W_1	The weight of Zero Cross Correlation Code

CHAPTER 1

INTRODUCTION

1.1 Background

The expectation of future telecommunication network is to provide a diversity of integrated narrowband and broadband services to customers. In order to satisfy the future needs, this integrated network is expected to show a substantial increase in the throughput as well as the range of bandwidth supported.

The transmission line such as twisted wire pairs and coaxial cables use bandwidth limited media. Hence, they will not be able to integrate these broadband services sufficiently. To solve this issue, the advanced development in fiber optic for the last few years has made usage of optical fiber as a transmission media possible in modern communication system [1-3].

Optical fibers offer an array of advantages such as they are able to support a large transmission bandwidth and have lower signal attenuation factor if compared to traditional media.

Meanwhile, Code Division Multiple Access (CDMA) was invented and first used for wireless communication. This technique gives a better performance when compared to other multiple access techniques [4-5].

In the Code Division Multiple Access (CDMA), all users are transmitting at the same time on the same carrier frequency. To distinguish the data belonging to the different users, a user is identified by a unique signature code, which is known by both the transmitter and the receiver. The receiver uses cross correlation property to detect the signal [6].

Code Division Multiple Access (CDMA) has advantages over the other multiple access techniques. It is a random and simultaneous protocol. In addition, it does not need centralized network and it also has a self-routing by code sequence.

CDMA has become very popular in cellular radio network and also in optical fiber communication system because it can be utilized in high speed LAN, MAN, and FTTH. Thus, this has motivated researchers to study the possibility of optical fiber role in optical communication system.

The studies of Optical Code Division Multiple Access (OCDMA) began recently because the number of optical communication system has rapidly increased. However, the OCDMA suffers from various types of noise like Multiple Access Interference (MAI), photo detector, shot noise, dark current and thermal noise. The dominant source of noise is MAI and thus the cancellation or suppression of MAI is the major issue in OCDMA [7] [8].

Many OCDMA codes have been designed to reduce the MAI and to enhance the performance of the system such as the Prime Code [1] [10], Optical Orthogonal Code [11-27] which had been introduced by Salehi [28] and the Modified Frequency Hopping (MFH) [29].

1.2   Optical Multiple Access Schemes

Optical fiber provides huge bandwidth for multiple access techniques, allowing many users to simultaneously communicate over the same medium by dividing and allocating time, bandwidth or some other features of transmitted signal.

Generally there are three types of optical multiple access techniques [1], which are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Optical Code Division Multiple Access (OCDMA).

1.2.1   Frequency Division Multiple Access (FDMA)

Frequency Division Multiple Access assigns individual channels to individual users.
In other words In FDMA system, each channel occupies a narrow optical bandwidth around a center wavelength or frequency [68-69]. The modulation format and speed at each frequency can be independent of those of other channels. Because each channel is transmitted at a different frequency, they can be selected using an optical filter [70].
FDMA suffers from Channel crosstalk; Channel idle most of the time and Low bandwidth efficiency
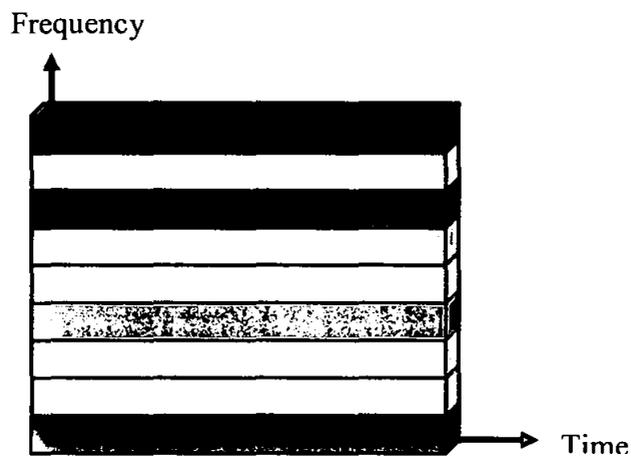
Figure 1.1: Frequency Division Multiple Access FDMA

1.2.2   Time Division Multiple Access (TDMA)

TDMA system divides the fiber optic spectrum in to time slots and in any slot only one user is allowed to transmit or receive. Each user is assigned a fixed time slot in every transmission frame during which that user can receive a bit of information. The length of transmission frame is determined by the data-bit-period and is subdivided in to a number of time slots, according to the width of optical clock pulses.

TDMA systems offer a large number of node addresses; however, the performance of TDMA systems is ultimately limited by the time-serial nature of the technology. TDMA systems also require strong centralized control to allocate time slots and to maintain synchronous operation.

Frequency
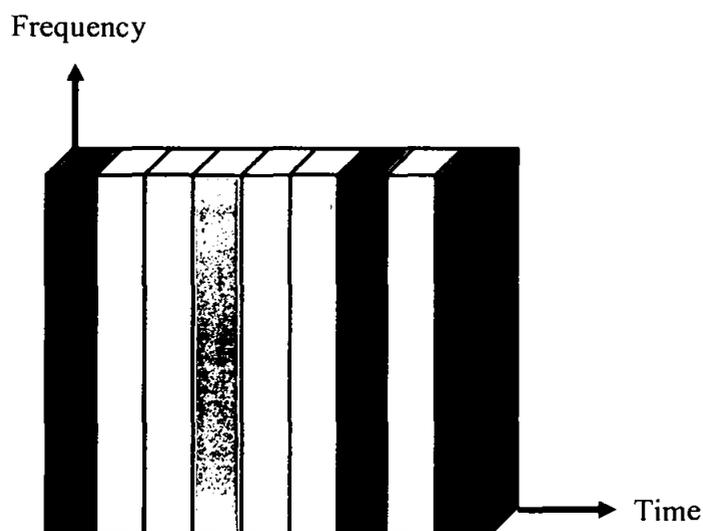
Time

Figure 1.2: Time Division Multiple Access (TDMA)

1.2.3 Optical Code Division Multiple Access

OCDMA combine the large bandwidth of fiber optic medium with the flexibility of CDMA to perform high-speed connectivity. In OCDMA each user is assigned a fixed, unique code sequence. The code of each user contains a binary number zero or one according to the code types. The length of each code sequence is determined by the data bit period and is subdivided in to a number of small units called chips according to the width of the optical pulse.

OCDMA offers an interesting alternative for LANs because neither time management nor frequency management of all nodes is necessary. OCDMA can operate asynchronously, without centralized control, and does not suffer from packet collisions (in case of well designed codes with reduced multi-user interference). Dedicated time or frequency slots do not have to be allocated, so statistical multiplexing gains can be high.
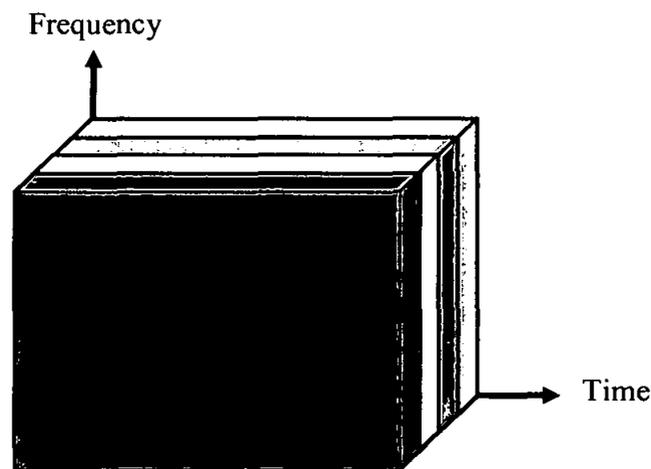
Figure 1.3: Optical Code Division Multiple Access (OCDMA)

1.3 Advantages and Disadvantages of Optical Multiple Access Schemes

All advantage and disadvantage of these techniques are illustrated in Table 1.1.

TDMA system, users are allocated time slots during which they can transmit their data. . Because of its rigorous transmission schedule, TDMA yield high throughput and it is suitable for real time service with high traffic densities and signaling rates. Since only one user can transmit at time, the total system throughput is limited by the product of the number of users and their respective transmission rate. TDMA systems also introduce significant latency penalties because of the coordination required to coordinate and grant requests for time slots from users by the central node.

Besides utilizing time, the vast optical spectrum of the low attenuation region optical fibers can be partitioned and allocated in frequency which it called FDMA. In FDMA each user is provided a transparent communication channel in term of frequency without using complex high-speed electronics. This kind of technique tends to occupy a large region of optical spectrum for transmission in order to trade for simple hardware and network design. But it is difficult to construct a FDMA system for a dynamic set of

multiple users because of the significant amount of coordination among the nodes required for successful operation. To build a FDMA network with a dynamic user base, control channels and collision detection schemes would need to be implemented that would waste significant bandwidth [1].

In OCDMA because all of the code sequences are orthogonal or pseudo orthogonal, two or more users can access the transmission medium simultaneously and asynchronously as long as their intended receiving users are not the same. Because of randomness in network access due to non-scheduled transmission, however, OCDMA usually supports a limited number of simultaneous users before a rapid deterioration of system performance occurs.

Table 1.1: Comparison of Common Optical Multiple Access Schemes

Multiple Access Schemes	Advantages	Disadvantages
1. TDMA	a. Dedicated channels provided b. High throughput c. Deterministic access	a. Accurate synchronization needed b. Not efficient in bursty traffic c. Bandwidth wasted d. Channel not efficiently used e. 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 with the number of simultaneous users
3. FDMA	a. Dedicated channels provided	a. Channel crosstalk b. Channel idle most of the time c. Low bandwidth efficiency d. Non-linear effects

1.4   Problem Statement

The success of CDMA in wireless communication led the researcher to study the possibility of exploiting CDMA advantages in optical communication system. Optical fibers offer a large transmission bandwidth and in CDMA every user is distinguished by a unique code. Therefore, the user can use the entire bandwidth of fiber optic media.

OCDMA is an attractive communication technique that can be divided into two main parts, which time and frequency domains. In the frequency domain all the detections systems are used to detect the signal but MAI decreases significantly the system performance. MAI reduces the system performance as the number of users increase.

To solve the problem of MAI, a lot of researchers concentrate on the code design and there are several codes have been invented like prime code [1] [10], optical orthogonal code[11-27] which was first introduced by Salehi [28] and modified frequency hopping code MFH[29]. Some of those codes are too long in length (e.g. optical orthogonal code and prime code) and some of them are too complicated in design (e.g. optical orthogonal code).

Double Weight (DW) code families are proposed in [30-32] and they offer some good features if compared to the previous codes. However, they have unity cross correlation, which will result in MAI.

Based on such problems, ZCC-DW Optical CDMA code is obtained from MDW code to solve the problem of MAI. Instead of construct ZCC-DW code using the traditional method, general new equations construction techniques are derived. Also, a simulation and analysis of Direct Detection of ZCC-DW code are carried out and compared with the Hybrid Detection Technique [66-67].

1.5 Objectives

The primary objective of this research is to establish a new construction technique of ZCC-DW code and to develop new a detection technique for this code.

The following approaches will be covered:

a- Eliminate the intersection columns of MDW code to obtain ZCC-DW code; hence the detection complexity, time process and the cost should be reduced.

b- Establish new construction techniques for ZCC-DW code instead of the traditional one.

c- Simulate a new set of equations using Java software and compare the result with traditional techniques.

d- Analyze the result of ZCC-DW code detection technique using VPI version7.1 software and compared it with Hybrid Detection technique.

1.6 Scope of Work

In OCDMA, new code construction techniques for ZCC-DW code are developed to overcome the drawback in the traditional code construction technique. The number of users in the conventional construction technique depends on the basic matrix and the number of mapping. While the new construction techniques are used offered the required number. By using these new techniques, the calculation of code length is much easier.

In this research a literature review about the DW code, MDW code is studied. All the mathematical relations between the code length and weight are studied and discussed. Also, the existing construction techniques of these codes are studied.

For code development ZCC-DW code is obtained by eliminating the intersection columns of MDW code and this technique is called traditional method. However new construction techniques are proposed to generate ZCC-DW code instead of the traditional method.

Besides theoretical model development, extensive studies are also performed through software simulation using VPI software version 7.1 which is stand for Virtual Photonics Incorporated.

Also in this stage comparison between ZCC-DW code Detection Technique (Direct Detection) and DW code Detection Technique (Hybrid Detection) is carried out.

1.7   Methodology

This section contains the methodology of this research. The new construction techniques of ZCC-DW code are obtained to overcome the disadvantages of the traditional method. Besides, a detection technique (Direct Detection) of ZCC-DW code is simulated. Generally, this research can be divided in to three stages:

In the first stage the theoretical analysis is done for DW code and MDW, Optical Orthogonal Code (OCC) code, Hadamard Code and Prime Code. In this stage the mathematical relations are discussed.

In the second stage, new construction techniques for basic matrix and mapping technique of ZCC-DW code are obtained instead of the traditional construction and they are simulated using Java.

In the final stage, after the completion of all the mathematical models, a simulator is used to study the performance of the code in CDMA systems. VPI (Virtual Photonics Incorporated) versions 7.1 are used to accomplish this work. Optimization is needed at this stage to get the best combination of codes that are suitable for the applications in MAN. A software simulation is important since it normally considers all practical factors (although numerically) which may be too extensive to be considered in the theoretical development

1.8 Thesis Overview

The thesis contains 5 chapters. In this chapter, the introduction, a general view of the fiber optic communication and optical multiple access technique are highlighted. Problem statements, objectives and scope of study are also outlined.

From the general introductory background in Chapter 1, Chapter 2 continues with the details OCDMA system and various Optical CDMA codes properties and strengths and weaknesses.

Chapter 3 contains the derivation of ZCC-DW code based on MDW code and the development of this code in details including the new equations construction techniques, which are used to get ZCC-DW code instead of using the traditional method. In this chapter the simulation is conducted using JAVA software to get any user of ZCC-DW code.

Chapter 4 discusses the results of the simulation of direct detection ZCC-DW code conducted using VPI software version 7.1 and also the comparison between Direct Detection and Hybrid Detection Technique is carried out.

Finally, chapter 5 discusses the entire study and summarizes the important findings, contributions and suggestions for the future works.

CHAPTER 2

OPTICAL CODE DIVISION MULTIPLE ACCESS SYSTEM

This chapter presents the advantages of OCDMA, Optical Code Division Multiple Access equipment, two major types of OCDMA, various Optical CDMA codes and their properties and the application of OCDMA.

2.1   Introduction

The Optical Code Division Multiple Access (OCDMA) communication system can be all optical or partly optical. Also, it may be an optical fiber or wireless channel. Fiber Optic Code Division Multiple Access (FO-CDMA) is a technique which allows all users to transmit simultaneously over the same optical fiber.

OCDMA consists of transmitter and receiver equipments as illustrated in figure2.1
Transmitter equipment:-
It contains a light source, a splitter, an encoder, an external modulator, and a multiplexer.
Receiver equipment:-
This part consists of a splitter, a decoder and a receiver.
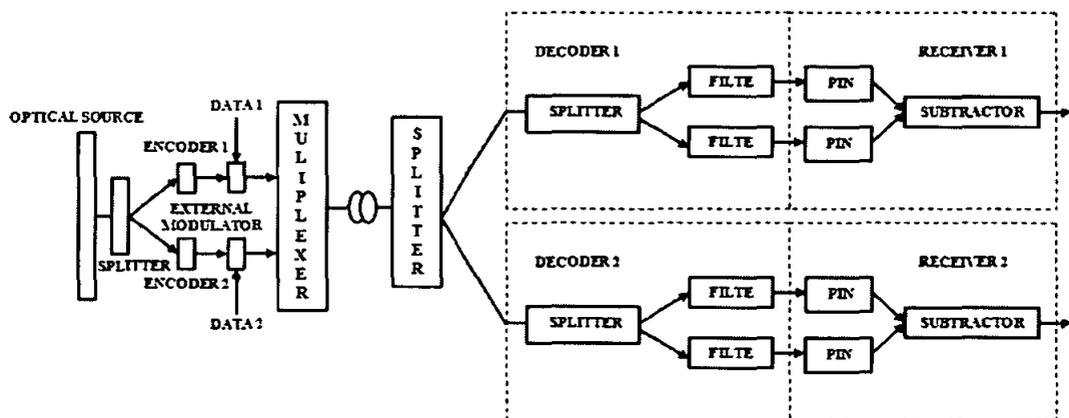
Figure 2.1: Optical CDMA equipments [75]

Generally, OCDMA can be classified as incoherent and coherent [1], depending on whether the intensities or field of optical pulses are processed.

2.2   Fiber Optical Code Division Multiple Access

A Fiber Optic Code Division Multiple Access system for each user can be described as a process of encoding of data followed by a conversion of the signal from electrical to light to enable the signal to propagate through the fiber optic medium. At the receiver, the correlation property will be carried out in order to extract the encoded data signal. Figure2.2 shows the Fiber Optic Code Division Multiple Access (FO-CDMA) system block diagram.

In Fiber Optic Code Division Multiple Access (FO-CDMA) 1989 each user has a unique signature sequence. The encoder of each user transmits 1 bit by sending the signature sequence. However, a binary 0 bit is not encoded and represented as zero sequences. The encoded signal is sent to the (N×N) star coupler and broadcast to all nodes [7].

The signature sequence, $C_k(t)$, of the kth user is given by

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

Where P (t) is the unit rectangular pulse with duration T_c. And $d_{k,j}$ is the kth periodic sequence of binary optical Pulses (0, 1). The N output signals are combined at the coupler and are transmitted or broadcast to all receivers. The received signal $r(t)$ is the sum of signals transmitted by all active users and can be expressed by:

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

τ_k, with $0 \leq \tau_k \leq Tc$, is the time-delay associated with k^{th} user and $b_k(t)$ is the bit (0,1) of the kth user. To distinguish a desired user at the receiver, the equation (2.1) should be timed by the signature code sequence of the desired user. These multiplications derive the desired signal plus Multiple Access Interference (MAI), which is a dominant source of noise. This type of noise has a negative side effect on the desired signal, thus a lot of studies have been concentrated on this to cancel or mitigate this Multiple Access Interference (MAI).
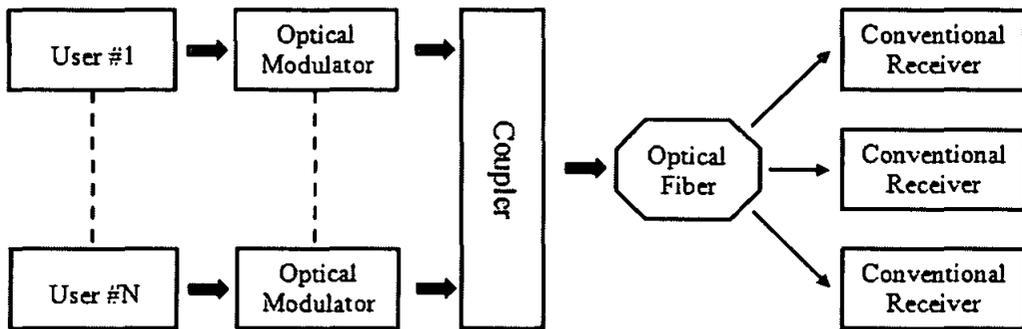
Figure 2.2: Fiber Optic Code Division Multiple Access (FO-CDMA) system block diagram [33, 42]

2.3   The Coherent OCDMA Systems

This is a complex form of the optical field, which is exploits in the encoding process. In coherent optical signal processing, the optical pulses in every code sequence generated at an optical encoder are phase coherent and the optical fields of all these coherent pulses are superimposed in an optical decoder [71-72]. Because of using phase information, coherent optical processing allows the use of bipolar (+1,-1) code sequence.

An example of coherent OCDMA system is the delay line based coherent direct sequence OCDMA and time spread OCDMA.

2.3.1 Delay Line Based Coherent Direct Sequence OCDMA

In this type the modulation technique, each pulse is on off keyed data and then it is divided into sub-pulses during the optical paths [34].

Figure 2.3 shows the optical delay line based coherent direct sequence. After that the combiner or passive coupler gathers all the pulses into the same fiber. When this data arrives at the receiver, it will be decoded to distinguish the desired signal from others. Then the decoded signal should be compared to the threshold value. The main disadvantages of this system it needs synchronization and is costly because of the usage of laser source.
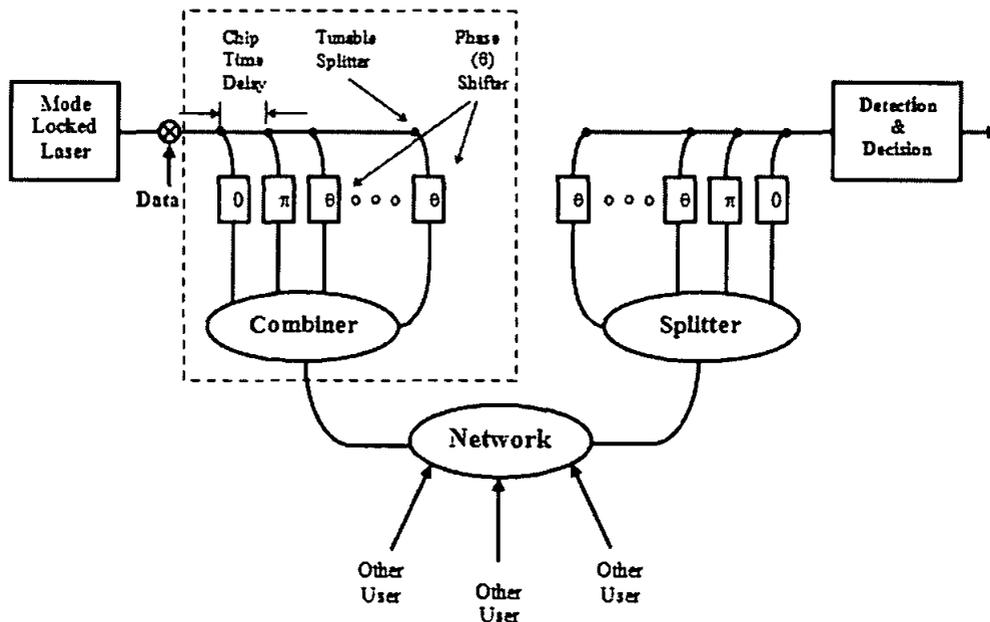
Figure 2.3: Delayed Lines Based Coherent Direct Sequence Optical CDMA [34]

2.3.2 Time Spread Optical CDMA

Time spread-CDMA, developed by Weiner [35-41] in the early 90s is considered among the most attractive alternative. This system requires a Mode locked Loop Laser with a broad coherent bandwidth. The output of the laser is modulated with On Off Keyed modulation (OOK) modulation by the binary data. Laser light is focused

on a Brag grating that separates the frequency or wavelength components of the light. A Programmable Liquid Crystal (PLC) phase mask then shifts the phase of each of the spectral components according to the assigned bipolar code. Finally, the other Brag grating recombines the separated spectral components and gathered light is rejected into the fiber. Unfortunately the use of lenses suffers from high splitting or insertion losses. The time spread optical CDMA is shown in Figure 2.4
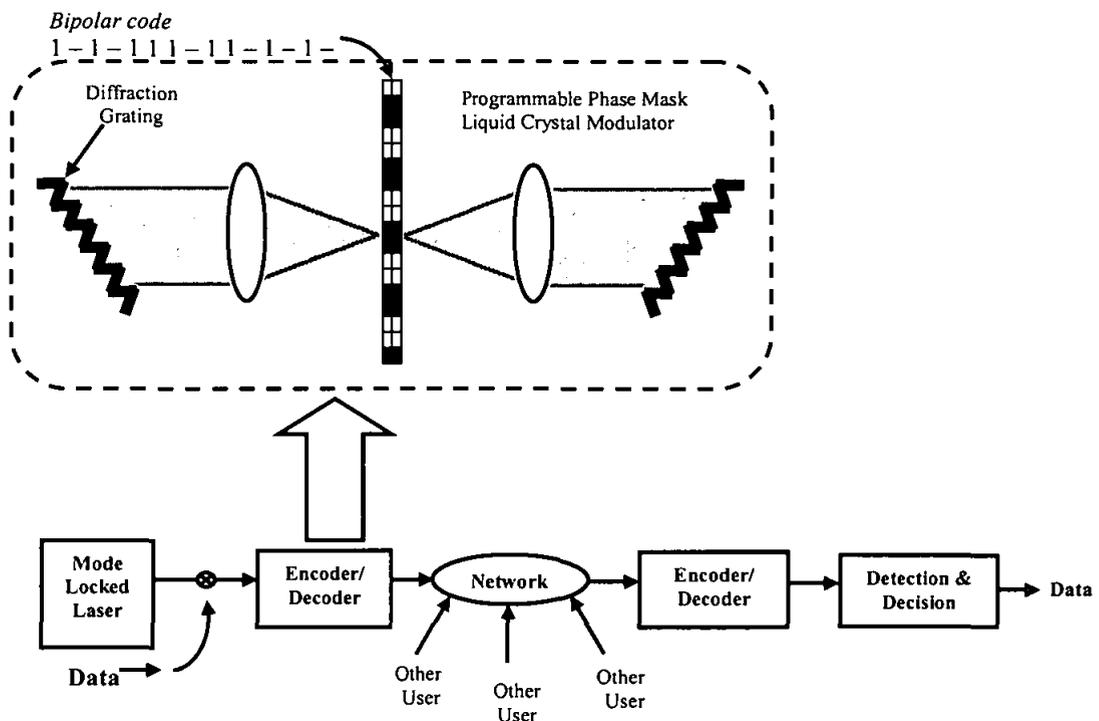
Figure 2.4: Time Spread Optical CDMA [35]

2.4   Incoherent OCDMA system

This area has attracted the attention of most researchers because the implementation of optical detection is easier than that with coherent OCDMA. A lot of effort has been put into the design of novel codes and encoders/decoders for such systems. In this area, the signature sequence is orthogonal to avoid interference from other users. Non

coherent OCDMA uses the direct detection receiver and this receiver depends on the received optical power level and the chip of logical 1 has a real positive power. The chip values are never negative according to the orthogonality which can be performed when the chip has the value 1 at some chip positions. The chip value of other signature sequences at the same chip position must be 0.When the receiver receives bit 1, the interference from other users does not disturb the level detection but when the received bit is 0, the interference may cause a wrong decision.

To reduce the interference power, an optical hard limiter which is a nonlinear device is discovered to clip the power to the normal chip power level during every chip interval. Figure 2.5 shows the optical hard limiter.

P_{in} P_{out}

Optical hard limiter
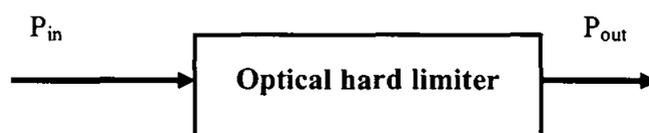
Figure 2.5: An optical hard limiter

Examples of the OCDMA incoherent system are the Incoherent spectral intensity optical CDMA system and the Optical spectral CDMA system

2.4.1 Incoherent Spectral Intensity Optical CDMA System:-

In this type [42-48], each code channel uses a spectral amplitude encoder either to selectively block or transmit certain frequency components as in Figure 2.6. Also, there is a balance receiver, which contains two photo detectors. This balance receiver is used as a part of the receiver which filters the incoming signal with the same spectral amplitude filter, also called the direct filter. This filter is used at the transmitter as well as its complementary filter [49-50]. Then, the two photo detectors detect the output from the complementary filter. These two photo detectors are connected in a balanced fashion. For unmatched transmitters, half of transmitter spectral components will match the direct filter and the other half will match the complementary filter. The output of the balance receiver represents the difference between the two photo detectors, with unmatched channels being cancelled, while the

matched channel is demodulated. It is possible to design codes with the full orthogonality in the incoherent spectral intensity OCDMA system since there is a subtraction between two photo detectors.
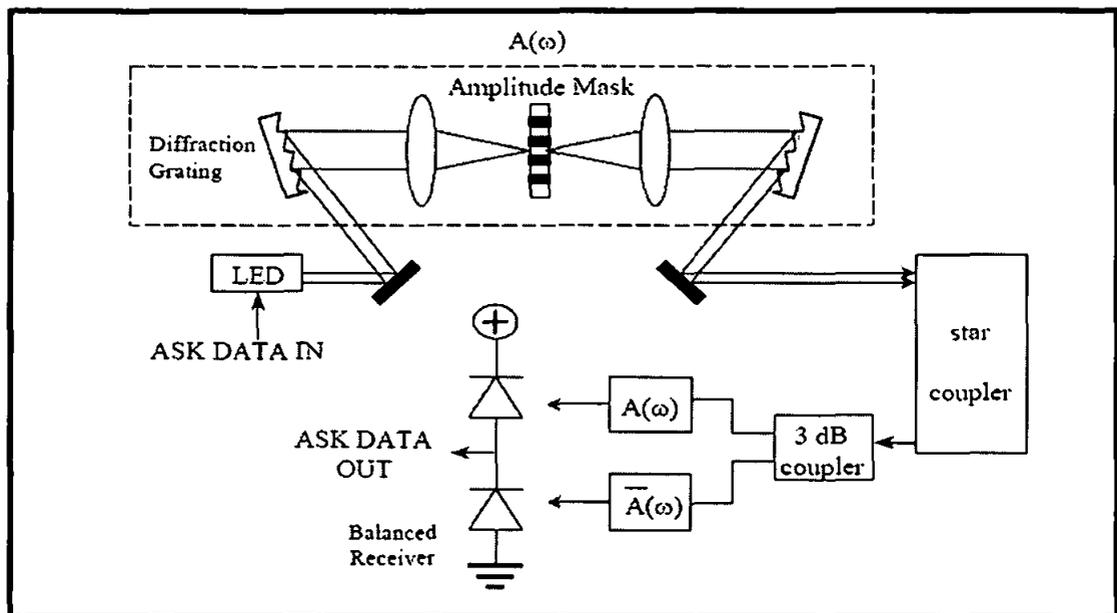
Figure 2.6: Incoherent Spectral Intensity Encoded Optical CDMA System [42]

The advantages of the Incoherent Spectral Intensity Encoded Optical CDMA System are as follows:

- It does not require a system clock.
- It uses LED and with no tapped delay line.

The disadvantage of the Incoherent Spectral Intensity Encoded Optical CDMA System is as follows:

- Loss of perfect orthogonolity between users due to the Gaussian shape of the LED spectrum and it needs tunable filters to reshape the spectrum.

2.4.2 Optical Spectral CDMA

In OSCDMA, there are N users with optical transmitters and receivers [30-31, 51]. The system uses incoherent broadband light source to derive its channel by selectively

blocking out part of the light, giving it the appearance of a bar code as shown in Figure 2.7. The architecture of the OSCDMA can be seen in Figure 2.8. The encoder and the decoder of OSCDMA are implemented using any type of optical filtering technology including thin-film filters, fiber Bragg gratings, or free space diffraction gratings.
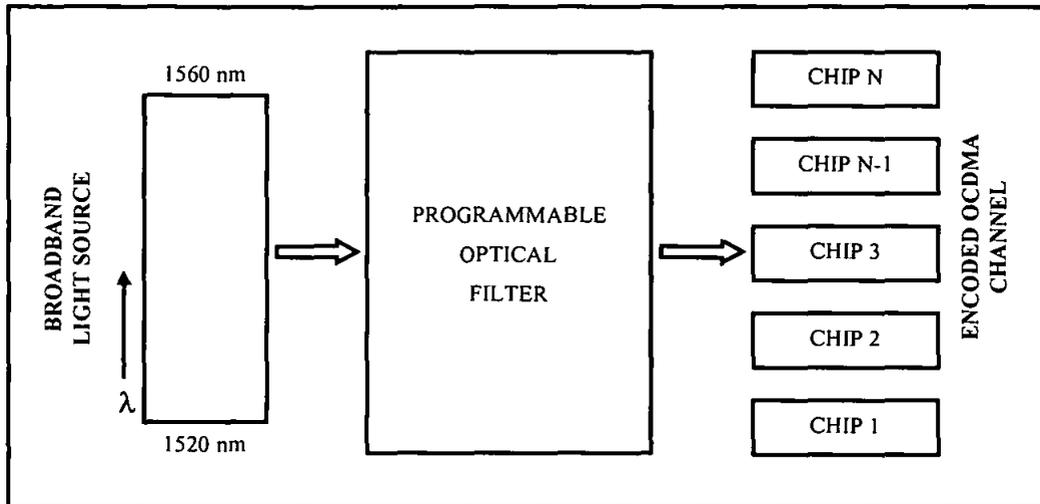
Figure 2.7: Bock diagram of the OSCMA system [30-31]

The advantages of the Optical Spectral (OSCDMA) system are:

- It does not require synchronization.
- It uses LED (cheaper) and with no tapped delay lines
- The encoder and decoder are much simpler in design.
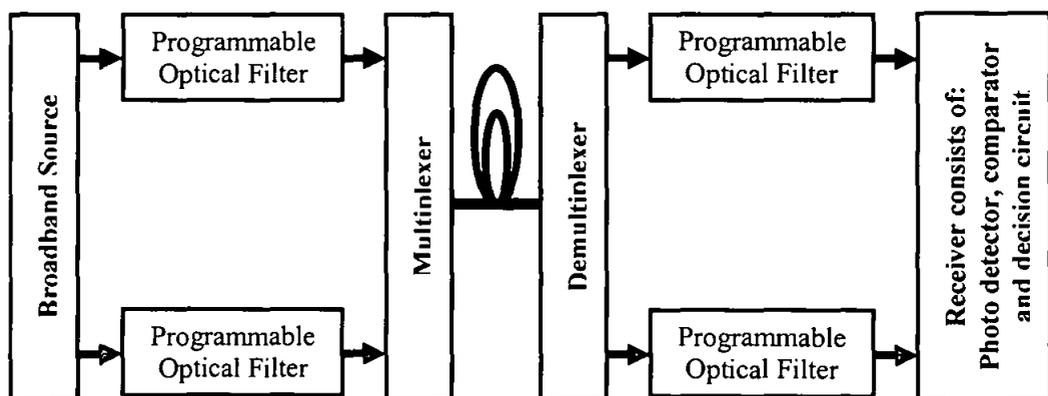
Figure 2.8: The Architecture of the OSCDMA system [31]

2.5   Optical CDMA Codes

Any network architecture like star, bus, or mesh requires a data signal to be encoded at the transmitter. After the distribution through the network, a decoder has to be capable of extracting the correct channel identified by a unique code in the presence of other codes in order for the user to recover the data.

There are many generic coding strategies that can be adopted to create an OCDMA network

- Incoherent encoding.
- Coherent encoding
- Spectral encoding.
- Hybrid techniques using a combination of time, frequency and spectral encoding

OCDMA code is represented in three main elements which are the code length of the code sequence (N), the weight of each code sequence (W) (the number of ones inside the code sequence) and a maximum cross correlation value between any two-code sequences.

There are two types of correlation techniques; auto-correlation and cross-correlation. When the correlation is calculated between a sequences and a logged version of itself, it is called auto correlation. The cross correlation is a standard method of estimating the degree to which two sequences are correlated. In other words it is the mutual interference between any two sequences.

In general, any code should be designed to satisfy two conditions:

I- The value of auto correlation λ_a is equal to the weight of the code sequence and this will happen in non-shifted auto correlation. The general equation of none shifted auto correlation is shown in equation (2.3).

For code sequence $X = (x_1, x_2, \dots x_N)$ the non-shifted auto correlation is given by

$$\lambda_a = \sum_{i=1}^{N} x_i x_i \qquad (2.3)$$

II- The value of cross correlation λ_c between any two-code sequences should be as small as possible. The target to make this value of cross correlation λ_c small is to distinguish each code sequence from other address sequences. The general equation of non-shifted cross correlation is shown in equation (2.4).

For code sequence $X = (x_1, x_2, ... x_N)$ and $Y = (y_1, y_2, ...y_N)$ the non-shifted cross correlation is given by

$$\lambda_c = \sum_{i=1}^{N} x_i y_i \qquad (2.4)$$

In order to decrease the multiple access interference caused by multiple users sending at the same time, the value of cross correlation should be very small. All codes with optimum in-phase cross correlation ($\lambda_c \leq 1$) are required in the OCDMA system to mitigate the multiple access interference and also the effect of phase induced intensity noise (PIIN). There are a lot of types of noise in the OCDMA system but the dominant one is multiple access interference (MAI).

There are two main types of OCDMA code invented which are Optical Orthogonal Code (OOC) and Prime Codes used in optical delay line networks. Those codes have a very long code length and a small codeword to reduce crosstalk. Until now, the codes, which have been proposed, are based on a modification of the prime code. Some types of Optical CDMA codes such as (OOC), prime code, modified frequency hopping, Hadamard code Double Weight code (DW) and Modified Double Weight Code (MDW) will be discussed in detail in this section.

2.5.1 Optical Orthogonal Code (OOC)

This code was introduced by Salehi [28]. Optical orthogonal codes CDMA are a set of (0,1) sequences without negative components. In this section, we give the definition and some of the properties of OOC's.

An $(n, w, \lambda_a, \lambda_c)$ optical orthogonal code of length n and weight w which satisfies the following two properties [11-17].

i.   The autocorrelation property.

$$\sum_{t=0}^{n-1} x_t x_{t+r} \leq \lambda_a \qquad (2.5a)$$

For any $x \in C$ and any integer t, $0 < t < n$

ii.   The cross correlation property

$$\sum_{t=0}^{n-1} x_t y_{t+r} \leq \lambda_c \qquad (2.5b)$$

For any $x \neq y \in C$ and any integer t.

λ_a, λ_c are called the auto and cross correlation constraints. The (0,1) sequences of an optical orthogonal code are called the code words. The size of an optical orthogonal code C is the total number of code word. The sequences of OOC are designed to satisfy two conditions;

- Each sequence can easily be distinguished from a shifted version of itself.
- Each sequence can be easily distinguished from every other sequence in the set.

The relationship between the number of users C, code length n and code weight w is given by

$$C \leq \frac{n-1}{w(w-1)} \qquad (2.6)$$

In Table 2.1 some optimal constructions are presented, showing what code word length is required to construct a code with given size C and weight w.

Table 2.1: An example of OOC code [76]

C	W	N
12	5	241
14	5	281
6	6	181
21	6	631
11	7	463
21	7	883
18	8	1009
66	8	3697

The autocorrelation and cross correlation of OOC are the best but the computation of such codes is too complicated. In fact, the only way to implement the code would be to use an extra system memory to store the constructed code before. All OOC families are designed following the requirement for $\lambda_a = \lambda_c \leq 1$.

2.5.2 Prime Code

The prime codes [1, 10] were the first optical codes proposed for an optical code division multiple access communication system.

For any prime number p, there exists a finite field of p elements, which is denoted by Galois field GF (p) where p is a prime number. The length of this code is $N = P^2$, the code size and weight are equal to p and this number of users and weight of code can be any prime number.

The code generating using the following steps: -

    a- The construction of the original prime code starts with the Galois field GF (P) of a prime number p.

$$GF (P) = \{0, 1 \ldots P\text{-}1\}.$$

A prime sequence $S_1 = \{s_{i,0}, s_{i,1}, \ldots, s_{i,j}, \ldots s_{i,p-1}\}$ is constructed by element

$$X_{ij} = i.j(\text{mod } p) \text{ For i,j=(0,1,2,...,p-1)} \tag{2.7}$$

    b- To construct the original prime code, each one of the prime codes is mapped into a binary (0, 1) code sequence C.

$C_i = (c_{i,0}, c_{i,1}, ..., c_{i,k}, ...c_{i,p^2-1})$ of length p^2 according to

$$c_{i,k} = \begin{cases} 1 \text{ if } k = s_{i,j} + jp \text{ for } j = \{0,1,2,...,p-1\} \\ 0 \text{ otherwise} \end{cases} \tag{2.8}$$

As mentioned, a prime code is generated using a prime number and the number of 1's in that code is that of the prime number p, and the code length is p^2. The auto correlation peak of prime codes is p while the cross correlation is always less than 2. That means the performance of these codes depends upon the correlation properties. The main issue in the prime code is that the weight w is always fixed to the number of code words and must be a prime number p. To increase the number of users, a big p should be required, as is the case with the code weight W. The decoder and encoder for the prime code use is a parallel configuration and the resulting optical power cross and complexity of an encoder or decoder would be high if W becomes large.

2.5.3 Modified Frequency Hopping Code (MFH)

MFH is a family of frequency hopping (FH) [29] is constructed based on prime power and it has ideal cross-correlation. The code length of this code is $N = q^2 + q$ code weight w=q+1 and cross correlation $\lambda_c = 1$. The construction of this code can be done in two steps:-

Step1:-

Let GF (q) be a finite field of element and β a primitive element of GF(q).

We can construct a number sequence $Y_{a,b}(k)$ with the elements of GF (q) using the following formula:-

$$y_{a,b}(K) = \begin{cases} \beta^{(a+K)} + b, & K = 0,1,2,......,q-2 \\ b, & K = q-1 \\ \alpha, & K = q \end{cases} \tag{2.9}$$

Where α and **b** are elements of GF(**q**) expressed by $\alpha \in \{0,1,2,....,q-2\}$ and $b \in \{0,1,2,....,q-1\}$. The parameters α and b are fixed for each specified number sequence.

Because the values of β^{K} are not equal to zero regardless the value of K, the first elements of each sequence are all different and they can exactly constitute a whole set of GF(q) . Another sequence in the new code can be added without affecting the ideal in-phase cross correlation of the final binary code. These number sequences are constructed using the formula below:-

$$y^{'}(K) = \begin{cases} b, & K = 0,1,2,......,q-1 \\ q-1, & K = q. \end{cases} \qquad (2.10)$$

Hence, a full set of q^2 number sequences are obtained which is denoted by $y(k)$ in the rest of this part.

Step 2:-

Depending on each generated number sequence $y(k)$, we construct a sequence of binary number S (i) by using the mapping method.

$$s(i) = \begin{cases} 1, & \text{if } i = Kp + y(K) \\ 0, & \text{else} \end{cases} \qquad (2.11)$$

The properties of modified frequency Hopping:-

a.   Each code sequence $q^2 + q$ has elements that can be divided into $(q+1)$ groups, and each group contains one "1" and $(q-1)$ "0"s.

b.   The in-phase cross correlation between any two sequences is always equal to 1

The table below explains the examples for different values of parameters α and b when q is equal to 2^2 (i.e. =4). Here, the selected primitive irreducible polynomial is written as $x^2 + x + 1$ and the primitive element β is (10) in binary form, which can be represented as '2' in the decimal system. Table 2.2 shows an example of Modified Double Weight Code.

Table 2.2: Example of MFH [29]

	y(k)	s(i)
a=0, b=1	(03210)	1000 0001 0010 0100 1000
a=1, b=0	(23101)	0010 0001 0100 1000 0100
a=2, b=3	(02132)	1000 0010 0100 0001 0010
a=0, b=3	(21030)	0010 0100 1000 0001 1000
a=2, b=2	(13022)	0100 0001 1000 0010 0010
b=2 for y'(k)	(22223)	0010 0010 0010 0010 0001

This code has an ideal cross correlation and a shorter code length but the code construction is complicated.

2.5.4 Hadamard Code:-

These codes [52-55] have been widely used in digital signal processing and code division multiple access (CDMA) communication systems. A hadamard matrix is an orthogonal $n \times n$ matrix of the entries +1 and -1 with the property that any row differs from any other row in exactly n/2 position. One row of the matrix contains all +1s.while the other rows contain evenly the +1s and -1s of n/2 each. Furthermore, all the entries in the first row and the first column of H_n have all +1s. The $n \times n$ Hadmard matrixes can exist only if n is a power of 2 meaning that $n = 2^m$.

The $n \times n$ is Hadmard matrix H_n where $n = 2^m$ is generated by the cone matrix.

$$H_{M=1} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

For M=2 the Hadmard matrix will be

$$
H_2 = \begin{bmatrix} H_1 & H_1 \\ H_1 & \overline{H_1} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}
$$

The Unipolar Hadamard matrix H_M has the following properties;

a. *M* should be greater than 2.

b. Code length $N = 2^M$.

c. Code Weight $W = 2^{M-1}$

d. User $K = 2^M - 1$ (The case $K = 1$ has been excluded since the row of the unipolar Hadamard matrix is all ones.

e. The ratio of $\frac{W}{\lambda} = 2$ (i.e λ is cross-correlation properties).

It is well known that an ($n \times n$) Hadmard matrix of 1's and -1's has the property that any row differs from any other row in exactly the n/2 position. In the wavelength domain, the -1 replace with 0. The sequence (1,0) is a unipolar Hadmard code, for example, for n=4

$$
H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix}
$$

The Hadmard code supports ($2^M - 1$) number of users. For example, if only 20 users are required that means M should be equivalent to 5, which support 31 users, however, there are 11 codes unused. Hadmard codes increase the value of cross correlation as the number of user increases. Also it requires more filters for each code as the number of user increases. Table 2.3 is an example of Hadmard code.

Table 2.3 Example of Hadmard code sequence for 6 users [52-53]

Kth	C_8	C_7	C_6	C_5	C_4	C_3	C_2	C_1
1	1	0	1	0	1	0	1	0
2	1	1	0	0	1	1	0	0
3	1	0	0	1	1	0	0	1
4	1	1	1	1	0	0	0	0
5	1	0	1	0	0	1	0	1
6	1	1	0	0	0	0	1	1

2.5.5 Double Weight (DW) Code Construction

DW code family was proposed in [8, 30-31] by S.A.Aljunid and it offered good result compared with others OCDMA codes.

DW code [30-31] is new code with weight equal 2

To construct the double weight code there are two steps

- Step one

This type of code is represented by using the dimension **K x N** when K is the rows and N is the columns which represent the number of users and the minimum code length respectively. In order to start the construction of this code a basic DW code is given by 2X3 matrix as shown below in equation (2.12)

$$
H_{M=1} = \begin{bmatrix} \overset{1}{\downarrow} & \overset{2}{\downarrow} & \overset{1}{\downarrow} \\ 0 & 1 & 1 \\ 1 & 1 & 0 \end{bmatrix} \tag{2.12}
$$

The chip combination sequence of $H_{M=1}$ is 1,2,1 for three columns

- Step two

To increase the number of users K the mapping technique is carried out as shown below;

$$
H_{M=2} = \begin{vmatrix} 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ \hline 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & H_1 \\ H_1 & 0 \end{vmatrix} \tag{2.13}
$$

In (2.13), notice that the number of rows and columns should be doubled. The relation between mapping process (M) and K and N is given by

$$
K = 2^M \tag{2.14}
$$

$$
N = 2^M + 2^{M-1} \tag{2.15}
$$

From equations (2.14) and (2.15) the length of the code can be derived as equation (2.16) below

$$
N = \begin{cases} \frac{3}{2}K, & \text{when } K \text{ is even} \\ \frac{3K}{2} + \frac{1}{2}, & \text{when } K \text{ is odd} \end{cases} \tag{2.16}
$$

For both even and odd, equation (2.16) above can be written as

$$
N = \frac{3K}{2} + \frac{1}{2}\left[\sin(\frac{K\pi}{2})\right]^2 \tag{2.17}
$$

Table 2.4: Example of the DW Code Sequences [30-31]

Kth \ C	6	5	4	3	2	1
1	0	0	0	0	1	1
2	0	0	0	1	1	0
3	0	1	1	0	0	0
4	1	1	0	0	0	0

In Table 2.4 above, C is the column number of the code which also represents the spectral position of the chip where C is 1, 2, 3....N. In this type of code (DW), the spectral positions of two weights $C_{1,K}$ for the first weight and $C_{2,K}$ for the second weight for Kth users are given by:

$$C_{2,K} = C_N \qquad (2.18)$$

and

$$C_{1,K} = C_{N-1} \qquad (2.19)$$

In equation (2.17), bbserve that the spectral position of the second weight $C_{2,K}$ is usually the same as the minimum code length , N (also illustrated in Table 2.4) while the first weight $C_{1,K}$ is always one position before.

The DW code properties can be summarized as follows

    a. Each code sequence has a fixed weight of 2.

    b. Cross correlation λ_c is always equal to 1.

    c. The weighted chips are always in pairs.

d. The chips combination is maintained 1, 2, 1 for every three columns for

consecutive pairs of codes.

e. The relation between the number of users (*K*) and code length (*N*) is

given by:

$$N = \frac{3K}{2} + \frac{1}{2}\left[\sin(\frac{K\pi}{2})\right]^2$$ (2.20)

2.5.6 Modified Double Weight Code (MDW)

The MDW is a type of DW family [30-31]. The properties of DW and MDW are the same except that the MDW has a weight more than two (multiple of two) to increase the signal to noise ratio (SNR).Because the increasing of the code weight increases the signal power of the user, hence, it also increases signal to noise ratio. The MDW code can also be represented by using the **K x N** matrix. The Figure 2.9 shows the basic matrix construction of MDW. This basic matrix consists of a minimum number of K and N for a specific number of code weight. The construction of all matrixes A, B, C and D depends on the weight W.

$$\begin{bmatrix} [A] & \vdots & [B] \\ \cdots & \cdots & \cdots \\ [C] & \vdots & [D] \end{bmatrix}$$

Figure 2.9: General form for MDW basic matrix construction

Since A, B, C and D are obtained as :

[A] Consists of a $1 \times 3 \sum_{j=1}^{\frac{W}{2}-1} j$ matrix of zeros.

[B] Consists of a 1 x $3n$ matrix of $[X_2]$ for every 3 columns. (i.e. a 1 x $3n$ matrix with n times repetition of $[X_2]$), where $n = \frac{w}{2}$.

[C] Is the basic code matrix for the next smaller weight, $W = 2(n-1)$.

[D] Is an n x n matrix of $[X_3]$ as shown in equation (2.21)

$$[D] = [X_3] = \begin{bmatrix} 000 & 000 & [X_3] \\ 000 & [X_3] & 000 \\ [X_3] & 000 & 000 \end{bmatrix} \tag{2.21}$$

Where:

$$X_1 = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix} \tag{2.22}$$

$$X_2 = \begin{bmatrix} 0 & 1 & 1 \end{bmatrix} \tag{2.23}$$

$$X_3 = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix} \tag{2.24}$$

The two basic components in the basic matrix of MDW code are:-

Basic Code Length:

$$N_B = 3 \sum_{m=1}^{\frac{w}{2}} m \tag{2.25}$$

Basic number of users:

$$K_B = \frac{w}{2} + 1 \tag{2.26}$$

Where the basic code length N_B represents the basic code's column size and the basic number of user K_B is the basic code's row size.

After studying the matrix construction of the MDW code, we found the cross correlation is one. To obtain the specific code for a unique user you must construct the entire matrix to get different users by the form matrix construction above. It is easy to represent the MDW code basic matrix as $K_B \times N_B$. For example, to get the MDW code with a weight equal to four (W=4) from equation 2.25 the basic number of users and the column size is

$$N_B = 3\sum_{j=1}^{\frac{W}{2}} j = 3(1+2) = 6$$

And from Equation (2.26), the basic row size is:

$$K_B = \frac{W}{2}+1 = (4/3)+1 = 3$$

This basic matrix of the MDW code with W=4 consists of 4X18 matrix. The elements in each section depend on the value of n, for W= 4, n=W/2=2. The elements in the basic matrix for the MDW code at W=6 are thus:-

a. [A] consists of a $1 \times 3\sum_{j=1}^{\frac{W}{2}-1} j$ matrix of zeros, where [A] = [X_1] = [0 0 0]

b. [B] consists of a 1 x 3n matrix which is n repetition of [X_2] or in other words, [B] = [[X_2],[X_2]] = [0 1 1 0 1 1]

c. [C] Consists of basic matrix of the MDW for the next smaller value of W (i.e. $W = 2(n-1) =2$). The basic matrix for W=2 is $[H_2] = \begin{bmatrix} 011 \\ 110 \end{bmatrix} =$ [H] (refer Equation (2.12)).

d. [D] is a matrix of n x n consisting of matrices of [X_3],

$$[D] = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

So that the basic matrix of the MDW code at W=4 is shown in Table 2.5. Table 2.5 shows the basic MDW code denoted by (9, 4, 1), which can be explained as 9 is the length of the code sequence, 4 is the weight of the code (the number of ones in each code sequence) and 1 is the cross correlation between any two code sequences.

Table 2.5: The basic matrix of MDW of W=4

$$[H_4] = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

In this basic matrix, the cross correlation value between any two sequences maintains one ($\lambda_c=1$) as the DW code. To increase the number of users, the mapping technique should be applied. The example in Table 2.6 illustrates the mapping technique which is used here to increase the number of users from 3 to 6 while the weight is still fixed at 4.

Table 2.6: Example of MDW Mapping ($W = 4$) Code Sequences

$K\downarrow h$	C_{18}	C_{17}	C_{16}	C_{15}	C_{14}	C_{13}	C_{12}	C_{11}	C_{10}	C_9	C_8	C_7	C_6	C_5	C_4	C_3	C_2	C_1
1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1
2	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0
3	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0
4	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0
5	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
6	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

The properties of MDW codes are as follows:

a. Maximum cross-correlation is equal to 1. Note that certain combinations of the simultaneous transmission of codes may result in zero cross correlation. One example is when codes 1 and 4 of Table 2.6 are transmitting together.

b. MDW code weight can be any even number that is greater than 2 (multiple of 2).

c. The weight-pair structure is maintained.

d. The chips combination is maintained 1,2,1 for every three columns for every consecutive pairs of codes.

e. The relation between the Number of users (K) and code length (N) at weight of 4 is given by equation (2.17)

$$N = 3K + \frac{8}{3}\left[\sin(\frac{K\pi}{3})\right]^2 \qquad (2.27)$$

The number of users, K, supported by the MDW code is equivalent to n. For MDW codes, W can be fixed at any even number regardless of the number of users. By fixing W, encoder/decoder design and the signal SNR will be maintained and will **not** be affected by the number of users. Thus, the same quality of service can be provided for all users. These are the two features that cannot be achieved by other existing codes.

2.6   OCDMA Applications

OCDMA was investigated over the past few years for applications in optical fiber networks.

The main reasons, which have motivated the communications community to examine the potential of CDMA in optical networks are the asynchronous access capability and the inherent security in transmission offered by OCDMA. These characteristics distinguish OCDMA from other optical multiple access techniques such as TDMA or FDMA, which are based on time or frequency allocation as discussed. An example of the OCDMA system application is in Metropolitan Area Network (MAN).

The metropolitan area networks (MAN) cover an area between 10 and 100 km on diameter. MAN may be as small as a group of buildings or as large as a group of cities. The MAN can function as an intermediate bridge between LANs and WANs.

OCDMA (OCDMA) used for MAN in order to meet the demand for high capacity. Another reason is to easily provide various new information services such as high-resolution image, video-on-demand, and multimedia communications.

2.7   Summary

Optical Code Division Multiple Access (OCDMA) is a multiplexing technique adapted from the successful implementation in wireless networks. In this system all the users are transmitting simultaneously on the same carrier frequency.   To distinguish the signal of the different users each information bit is coded by a signature sequence, which has a pseudo noise character and the same temporal length as the information bit. Each user has a different 0, 1 code pair which is known by a transmitter and receiver. The receiver identifies the information bits of the user by correlating the received signal with the user's 0-and-1 sequences. The signature sequence consists of a chip having the value 0-1. OCDMA is a communication system which deserves our attention for present and future research, but it suffers from (MAIs) which affect the Bit Error Rate (BER). The main goal of all researchers is how to reduce the (MAIs) in achieving an OCDMA system with a good performance.

CHAPTER 3

THE CONSTRUCTION TECHNIQUES OF ZCC-DW CODE

This chapter contains the ZCC-DW code and the development of this code in detail. Besides, new construction techniques for ZCC-DW are obtained.

3.1 Zero Cross Correlation Double Weight Code (ZCC-DW)

The cross correlation of MDW code is equal to one and this will increase the MAI in order to obtain zero cross correlation and cancel the MAI. The ZCC-DW code is proposed based on MDW code. There are two methods to find the basic matrix of the Zero Cross Correlation Code.

3.1.1 Method one

The DW family, which is used as a proposed code in the OSCDMA is studied using the MDW, which has a cross correlation value, equals to one. By eliminating the intersection columns of this code, the cross correlation value is reduced from one to zero. This code, after eliminating the intersection columns, is named as the (ZCC-DW) code. Therefore, the Multiple Access Interference (MAI) can be reduced. It is important to reduce the cross correlation from one to zero because this will reduce the multiple access interference. Hence the system performance is enhanced.

For example the basic matrix of the MDW code with W equals to six (W=6) is given in Table 3.1. To get the cross correlation equal to zero, the intersection columns should be eliminated which have the cross correlation value equal to one. After removing the intersection columns, the zero cross correlation value can be obtained as shown in Table 3.2.

The basic component construction of Table 3.2, which has a cross correlation value equal to zero can be written as:-

Basic code length:

$$N_{B1} = 2\sum_{m=1}^{W_1} m \qquad (3.1)$$

Basic number of users:

$$K_{B1} = W_1 + 1 \tag{3.2}$$

W_1 is the weight of the ZCC –DW code which has a zero cross correlation value.

Table 3.1: Basic Matrix MDW code of Weight Six (W=6) and one cross correlation with rectangles showing the different groups

k	C18	C17	C16	C15	C14	C13	C12	C11	C10	C9	C8	C7	C6	C5	C4	C3	C2	C1
1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	1	1
2	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	1	1	0
3	0	1	1	0	0	0	0	1	1	0	0	0	1	1	0	0	0	0
4	1	1	0	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0

Table 3.2: Basic Matrix ZCC-DW code of Weight three ($W_1 = 3$) and zero cross correlation with rectangles showing the different groups

k	C12	C11	C10	C9	C8	C7	C6	C5	C4	C3	C2	C1
1	0	0	0	0	0	0	0	1	0	1	0	1
2	0	0	0	1	0	1	0	0	0	0	1	0
3	0	1	0	0	1	0	0	0	1	0	0	0
4	1	0	1	0	0	0	1	0	0	0	0	0

3.1.2 Method two

The new proposed ZCC-DW code is presented in a matrix **KXC** where **K** rows will represent the number of users and C column represents the minimum code length. These matrices have binary coefficients and a basic ZCC-DW code (for weight = 1) is defined recursively.

For $W_1 = 1$

$$Z_1 =$$

	C1	C2
K1	0	1
K2	1	0

Notice that Z1 has no overlapping of '1' for either user. In order to increase the number of users and codes, a mapping technique is used as shown below in the equation 3.3 .

$$Z_2 = \begin{bmatrix} 0 & Z_1 \\ Z_1 & 0 \end{bmatrix} \tag{3.3}$$

Table 3.3: Example of ZCC-DW code mapping technique

	C1	C2	C3	C4
K1	0	0	0	1
K2	0	0	1	0
K3	0	1	0	0
K4	1	0	0	

From the mapping, it is noted that when the number of users K increases, the code length C increases as well. The pattern of the mapped code is mirror diagonally expanded and K is equally increased with C. The relation between the number of mapping processes M, number of users K, and code length C is given by:

$$K = 2^M \tag{3.4}$$

And

$$C = 2^M \tag{3.5}$$

Thus $$K = C \tag{3.6}$$

The ZCC-DW code has flexibility in the number of weight consideration. To increase the number of weight, it needs to be formulated using a few steps of so-called 'code transformation' [65]. In the ZCC-DW code, the basic code represents weight = 1. To transform the code from $W_1 = 1$ to $W_1 = 2$, the general form of the transformation is given by equation 3.7

$$Z_I = \begin{bmatrix} A & B \\ D & D \end{bmatrix} \tag{3.7}$$

Where

[A] – Consists of $[1, W_1 \ (W_1 - 1)]$ matrix of zero.

[B] – Consists of W_1 replication of matrix $[0 \ 1]$.

[C] – Consists of duplication of matrix from $W_1 - 1$.

[D] – Consists of diagonal pattern with alternate column Zeros matrix.

For example, the transformation code from $W_1 = 1$ to $W_1 = 2$ is shown in Table 3.5

W1=1

Table 3.4: The basic matrix of ZCC-DW code when $W_1 = 1$

	C1	C2
K1	0	1
K2	1	0

When $W_1 = 2$

Table 3.5: using transformation to obtain ZCC-DW with W_1 equal 2

	C1 A	C2	C3	C4 B	C5	C6
K1	0	0	0	1	0	1
K2	0	C 1	0	0 D	1	0
K3	1	0	1	0	0	0

The relationship between parameters K, W1 and C is given by

$$K = W_1 + 1 \tag{3.8}$$

$$C = W_1 (W_1 + 1) \tag{3.9}$$

Where

K - Number of users.

C – Code length.

W_1 - Code weight.

Notice that the code words corresponding to parallel lines are orthogonal to each other.

To increase the number of simultaneous users with the increasing code weight, the mapping technique can be easily implemented as discussed previously.

3.2 The Equation Based Code Construction of the Basic Matrix for ZCC code:

Table 3.6 shows an example of the basic matrix of weight 2 after the intersection columns removed in order to get zero cross correlation.

Table 3.6: The basic matrix of ZCC-DW code of weight two (W1=2) and zero cross correlation with rectangular showing the different groups

k_m	C6	C5	C4	C3	C2	C1
1	0	0	0	1	0	1
2	0	1	0	0	1	0
3	1	0	1	0	0	0

Table 3.7 shows an example of the basic matrix of weight 3 after the intersection columns removed in order to get zero cross correlation.

Table 3.7: The basic matrix of ZCC-DW code of weight three (W$_1$=3) and zero cross correlation with rectangular showing the different groups

k	C12	C11	C10	C9	C8	C7	C6	C5	C4	C3	C2	C1
1	0	0	0	0	0	0	0	1	0	1	0	1
2	0	0	0	1	0	1	0	0	0	0	1	0
3	0	1	0	0	1	0	0	0	1	0	0	0
4	1	0	1	0	0	0	1	0	0	0	0	0

Table 3.8 shows an example of the basic matrix of weight 4 after the intersection columns removed in order to get zero cross correlation.

Table 3.8: The basic matrix of ZCC-DW code of weight four (W_1=4) and zero cross correlation with rectangular showing the different groups

K_{B1}	C20	C19	C18	C17	C16	C15	C14	C13	C12	C11	C10	C9	C8	C7	C6	C5	C4	C3	C2	C1
1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1
2	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	1	0
3	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0
4	0	1	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
5	1	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0

Tables 3.6, 3.7 and 3.8 is an example of ZCC-DW code basic matrix for different weight

In those Tables there are two groups which are:

(a) The first group (black rectangular) consists of a number of 1's which are situated in odd squares. It has a maximum W_1 in the first row and decreases when we go down towards the bottom. It reduces to zero for the last user (user number K_{B1}).

(b) The second group (grey rectangular) comprises a number of 1's which are situated in even squares starting from user number two with (W_1=1) and increases when we move down towards the bottom. For the last user (user number K_{B1}), it takes a maximum value of W_1. The first right column is column number one and the first row as row number one. The general equation of Tables 3.6, 3.7, 3.8 can be generated as equation (3.11a) and equation (3.11b).

In this new construction, there are two partial equations. Equation (3.11a) is for the odd group and equation (3.11b) is for the even group.

The symbol lower bounded $\lfloor x \rfloor$ denotes the integer portion of the real value of X. n_1 and n_2 which represent the number of ones in each group.

$$n_1 + n_2 = W_1 \tag{3.10}$$

In equation (3.11a), the first part is used for plotting the odd one while the second part is used to shift the starting point of the odd group.

$$ZCC_{i,j} = 1 \text{ if } j = (n_1 - 1) + \left\lfloor \frac{(2n_1 + 1)}{2} \right\rfloor + \sum_{m=0}^{i \bmod k_{B1} - 2} (2W_1 - 2m) \tag{3.11a}$$

for $n_1 = \{1, 2, .., W_1 - (i - 1)\}$

$n_1 = \{1, 2, .., W_1 - (i - 1)\}$, this formula is chosen because it takes W_1 in the first row and decrease when we go down towards until the last row it becomes zero.

Equation (3.11b) is used to plot the even square group (grey rectangular) which is controlled by the number of rows (i). The first part is used to put the odd ones in their squares and the second is used to shift the one to the next square in the same row (i).

$$ZCC_{i,j} = 1 \text{ if } j = 2(i - 1) + \sum_{m=1}^{\lfloor n_2 - 1 \rfloor} (2W_1 - 2m) \qquad \text{for } n_2 = \{1, 2, ..., (i - 1)\} \tag{3.11b}$$

$n_2 = \{1, 2, ..., (i - 1)\}$, this formula is chosen because it takes W_1 in the last row and decrease when we go up until the first row it becomes zero.

In the above equations (3.11a, 3.11b) ZCC equal to 1 otherwise the result equal to zero.

For the user number i

$$1 \leq i \leq K_{B1} \tag{3.12}$$

And column j for the position of each chip

$$1 \le j \le L \hspace{4cm} (3.13)$$

When L is the maximum length and is given by the formula as shown in equation number (3.14)

$$L = \{ \sum_{m=1}^{i \bmod K_{B1}} 2(W_1 - (m-1)) - (\frac{1}{i \bmod K_{B1}}) \} + \left\lfloor \frac{i}{K_{B1}} \right\rfloor N_{B1} \hspace{1.5cm} (3.14)$$

For example, to fabricate a user code number 3 (i=3) in Table 3.7 for a weight equal to 3

$$N_{B1} = 2 \sum_{m=1}^{W_1} m \hspace{0.5cm} = 2(1+2+3) = 12$$

$$K_{B1} = W_1 + 1 \hspace{0.5cm} = 3+1 = 4$$

To drive the maximum length for Table 3.7 row number 3, equation number (3.14) is used

$$L = \sum_{m=1}^{3_{B1}} 2(3 - (m-1)) - (\frac{1}{3}) = 11$$

Hence

$$n_1 = W1-(i-1), \text{ hence } \quad n_1 = 3-(3-1) = 1$$

$$n_2 = (i-1), \text{ hence } \quad\quad n_2 = (3-1) = 2$$

it means that $n_1 = \{1\}$ is for one value and $n_2 = \{1 \ 2\}$ is for two values. By putting n_1, n_2 in the general equations (3.11a, 3.11b), the value of j is obtained as follows

Table 3.9: The fabricated code word number 3 using equations (3.11a, 3.11b)

K	12	11	10	9	8	7	6	5	4	3	2	1
ZCC	0	1	0	0	1	0	0	0	1	0	0	0

The entire codes derived by equations (3.11a, 3.11b) are the same as the code word in Table 3.7. Using equations (3.11a, 3.11b) the same code has been obtained without constructing the basic matrix in the traditional way.

To get user number three (i =3) for the basic matrix, which is shown in Table 3.9 with weight equal 3 (W_1=3) using equations (3.11a) and equation (3.11b), the simulation result is shown in Figure 3.1. (See appendix A)
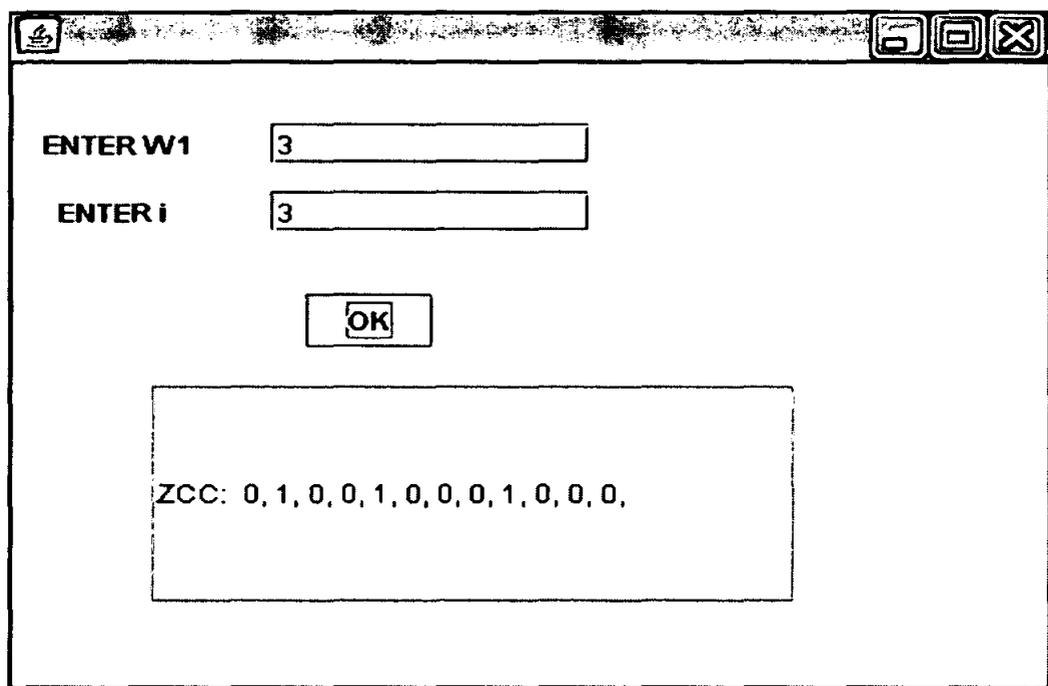

Figure 3.1 the simulation result of user number 3 in Table 3.7

3.3   The Equation Based Code Construction of Mapping Technique for ZCC-DW code

In Table 3.11, there is an example of the basic matrix after intersection columns removed in order to obtain zero cross correlation, hence the weight is changed from 4 in Table 3.10 to 2 in Table 3.11.

In Table 3.11 there are two groups where the first group (black rectangular) consists of the number of ones, which are situated in odd squares. It has a maximum W_1 in the

first row and decreases when we go down towards the bottom. It reduces to zero for the last user (user number K_{B1}).

The second group (grey rectangular) involves the number of the ones which are situated in even squares starting from user number two with $(W_1=1)$ and increases when we go down towards the bottom. For the last user (user number K_{B1}), it takes a maximum value of W_1. In Table 3.9 the first right column is being column number one and the first row as row number one.

Mapping technique is used for Table 3.11 to get Table 3.12.

To get any user from Table 3.12, which explained the mapping technique, equations (3.15a) and (3.15b) are derived.

Table 3.10: The basic matrix MDW code of weight four (W=4) and one cross correlation

k_j	C9	C8	C7	C6	C5	C4	C3	C2	C1
1	0	0	0	0	1	1	0	1	1
2	0	1	1	0	0	0	1	1	0
3	1	1	0	1	1	0	0	0	0

Table 3.11: The basic matrix of ZCC-DW code of weight two $(W_1=2)$ and zero cross correlation with rectangular showing the different groups.

k_B	C6	C5	C4	C3	C2	C1
1	0	0	0	1	0	1
2	0	1	0	0	1	0
3	1	0	1	0	0	0

Table 3.12: The ZCC-DW code mapping technique of basic matrix in Table 3.11

k	C12	C11	C10	C9	C8	C7	C6	C5	C4	C3	C2	C1
1	0	0	0	0	0	0	0	0	0	1	0	1
2	0	0	0	0	0	0	0	1	0	0	1	0
3	0	0	0	0	0	0	1	0	1	0	0	0
4	0	0	0	1	0	1	0	0	0	0	0	0
5	0	1	0	0	1	0	0	0	0	0	0	0
6	1	0	1	0	0	0	0	0	0	0	0	0

In this equation, there are two partial equations; the first equation is for the odd group and the second one for the even group. The symbol lower bounded $\lfloor x \rfloor$ denotes the integer portion of the real value of X, n_1 and n_2 which represents the number of ones in each group and are illustrated in equation 4.11

In equation (3.15a), the first part is used for plotting the odd one, while the second two parts are used to shift the starting point of the odd group.

$$ZCC_{i,j} = 1 \text{ if } \quad j = (n_1 - 1) + \left\lfloor \frac{(2n_1 + 1)}{2} \right\rfloor + \sum_{m=0}^{i \bmod K_{B1} - 2} (2W_1 - 2m) + \left\lfloor \frac{(i-1)}{K_{B1}} \right\rfloor N_{B1} \quad (3.15a)$$

for $\quad n_1 = \{1, 2, .., W_1 - ((i-1) \bmod K_{B1})\}$

Equation (3.15b) is used to plot the even square group (grey rectangular), which is controlled by the number of rows (i). The first part and the third are used to put the even ones in their squares and the second is used to shift the one to the next square in the same row (i).

$$ZCC_{i,j} = 1 \text{ if } \quad j = 2\{(i-1) \bmod K_{B1}\} + \sum_{m=1}^{\lfloor n_2 - 1 \rfloor} (2W_1 - 2m) + \left\lfloor \frac{(i-1)}{K_{B1}} \right\rfloor N_{B1} \quad (3.15b)$$

for $\quad n_2 = \{1, 2, ..., (i-1) \bmod K_{B1}\}$

In the above equations (3.11a, 3.11b) ZCC equal to 1 otherwise the result equal to zero.

Equation (3.14) is also used to derive the maximum length of the mapping technique. To fabricate user number 5 (code word number 5) for weight equals two ($W_1 = 2$) in table 3.10, the calculation is done and the maximum length of user number 5 is obtained.

$$N_{B1} = 2\sum_{m=1}^{2} m = 6$$

$$K_{B1} = 2 + 1 = 3$$

To calculate the maximum length equation (4.14) is used

$$L = \{\sum_{m=1}^{5\bmod 3} 2(2-(m-1))\_(\frac{1}{5\bmod 3})\} + \left\lfloor \frac{5}{3} \right\rfloor 6 = 11$$

From the general equation number (4.15)

$n_1 = 1$

and

$n_2 = 1$.

For n_1 and n_2 , j= {11}, j= {8} respectively.

By inserting the values of j the code word of user 5 obtained as illustrated in Table 3.13 below

Table 3.13: The fabricated code word number 5 from table 3.12 using equation (3.15a) and equation (3.15 b)

k	12	11	10	9	8	7	6	5	4	3	2	1
ZCC-DW	0	1	0	0	1	0	0	0	0	0	0	0

Finally, the code obtained by equation (3.15) is the same as code word number 5 in Table 3.12.

To find user number five (i=5) for the mapping technique which is shown in Table 3.12 with weight equal 2 (W_1=2) using equation (3.15a) and (3.15b) above, the simulation result is shown in Figure 3.2. (See appendix B).

To calculate the maximum length of user number 5 in Table 3.12 with weight equal 2 (W_1=2), using equation (3.14), the simulation result is shown in Figure 3.3. (See appendix C)
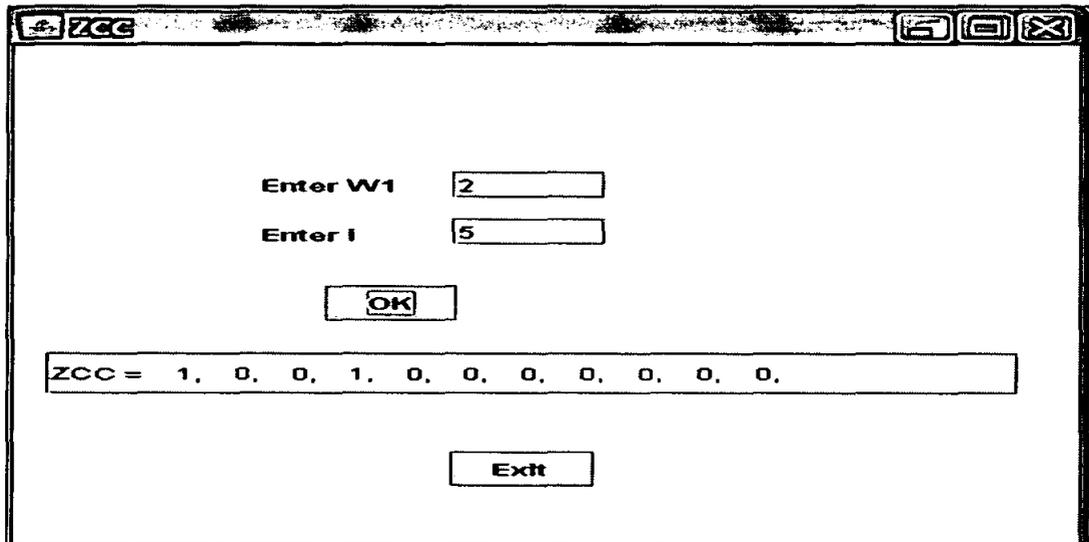
Figure 3.2: The simulation result of user number 5 in Table 3.12
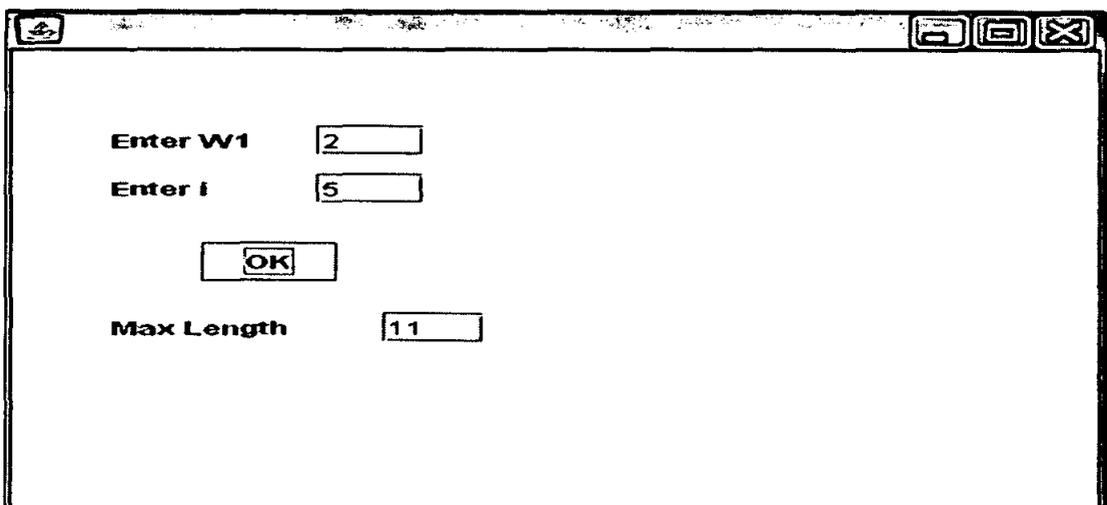
Figure 3.3: The simulation result of the maximum length of user number 5 in Table 3.12

3.4   Summary

The general equation for the ZCC code is constructed for the basic matrix instead of using the traditional way. Also, a general equation for this code is obtained for the mapping. Apart from that, the exact length of the specific code for any weight has been derived.

In the previous construction technique, the number of user depends on the basic matrix and the mapping technique, which has complicated construction while the new construction techniques are used to offer the required number of user. Also using these new techniques the calculation of exact code length for each user can be easily performed than the traditional method.

CHAPTER 4

THE SIMULATION ANALYSIS

This chapter contains the simulation analysis of ZCC-DW code using different data rate and different length of optical fiber. Also it is involves the simulation comparison between the detection technique of ZCC-DW code (Direct Detection) and the latest Detection of DW code (Hybrid Detection).

4.1 Direct Detection Simulation Technique

A simple schematic block diagram consisting of 4 users with the weight of each user being equal to two (w1=2) is illustrated in Figure 4.1 .The tests were carried out using VPI version 7.1 at the rate of 2.5 Gbps and 10 Gbps for 10 km, 50 km to 70 km distance with Nonlinear Dispersive Fiber (NLDS) . All the attenuation (0.2dB/Km), dispersion ($16e-6$ s/m^2) and non-linear effects were activated.
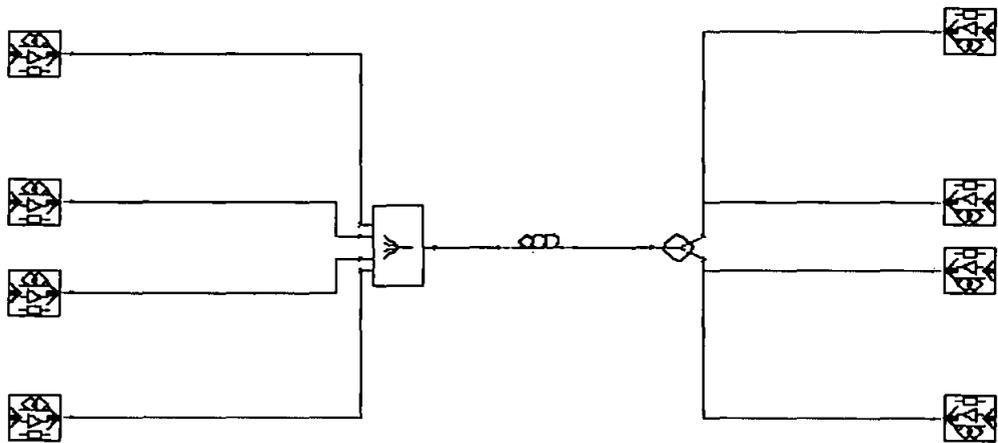

Figure 4.1: Simulation set up for the OCDMA System with the Direct Detection Technique.

The simulation set up consists of the Transmitter, the fiber optic used as medium and the Receiver.

4.1.1   The Transmitter

Each Transmitter contains the components as illustrated in Figure 4.2 which are;

1-PRBS Generator, a pseudo random bit sequence generator as the input data of each user.

2- NRZ Coder produces an electrical NRZ coded signal.

3- Rise Time Adjustment, adjusts the rise time of the pulse.

4- Laser CW, generates a continuous wave (cw) optical signal of a DFB laser.

5- WDM MUX N-1 Ideal, an ideal optical multiplexer.

6- Modulator Mach-Zehnder.

7- Combiner_4_1, this module combines four optical input channels and transmits it through fiber optic to desire receiver.

The number of the laser CW depends on the weight of the code. In general, if the weight of the code is N, the number of laser CW must be N.

The encoded data of all transmitters is summed up by the combiner and is sent through the fiber optic channel.
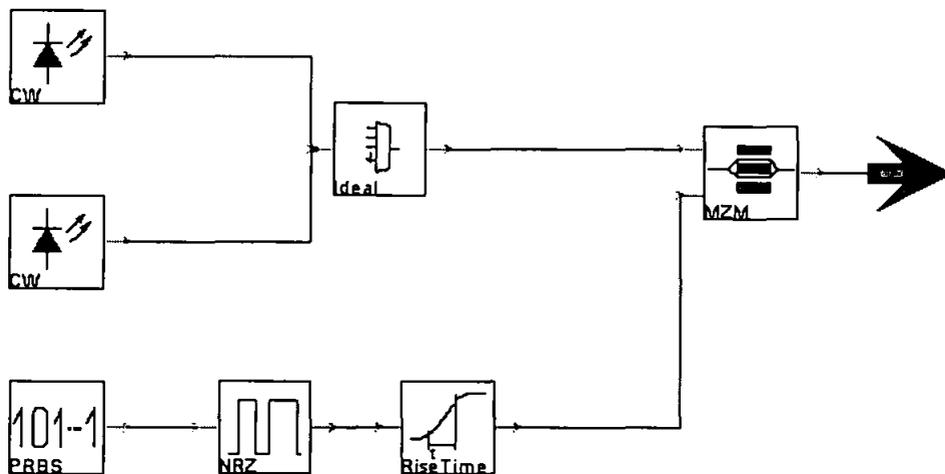
Figure 4.2: Transmitter part of the OCDMA System using Direct Detection Technique

4.1.2   The Receiver

This Receiver part contains the components as illustrated in Figure 4.3 which are;

1- Fork to divide data into two identical paths.

2- The universal optical filter model for simulations of band pass which is determined by the number of laser CW in the encoder part.

3- Power Combiner N-1, ideal optical power combiner.

4- A model of photodiodes to convert the data from the optical domain to the electrical domain

5- Filter LP Bessel (Electrical), low pass filter.

6- Clock Recovery Ideal, performs ideal clock recovery using specified logical channel.
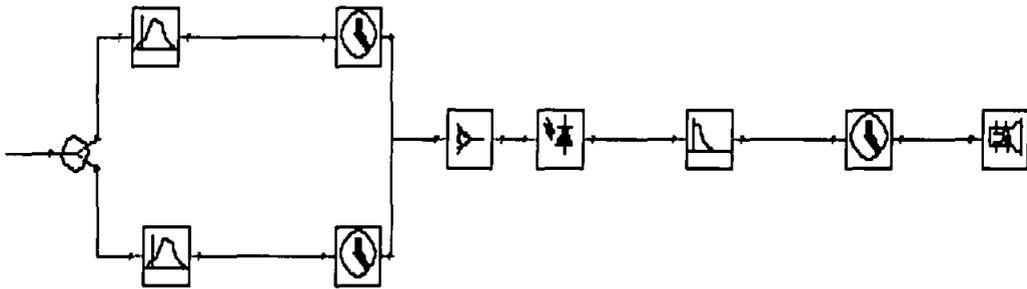
Figure 4.3: Receiver part of the OCDMA System using Direct Detection Technique.

The Direct Detection technique is used instead of the complementary [73] and AND [74] subtraction techniques because it is used for codes which have cross correlation equal to zero. This means there are no two chips in the same position and the MAI tends towards zero. Complementary and AND techniques are used for DW and MDW to cancel the MAI because the cross correlation value of these codes is equal to one.

The main difference between the detections techniques is in the receiver part. The Direct Detection technique has a fewer components in the receiver part compared with AND and complementary subtraction. To be more precise, in terms of architecture, the Direct Detection technique needs fewer filters and just one photo

diode in the decoder of the desire user. The filter is only needed at the position of the chip of code sequences and any chip has a unique position for the ZCC code. Fewer filters in the decoder will improve the performance of the OCDMA system. Also, the overall system cost and complexity can be reduced by using fewer filters in direct detection technique

The results (eye pattern) taken after the detection technique are conducted for the ZCC-DW code for the data rate equal to 2.5 Gbps and 10 Gbps with a variety of fiber optic cable lengths. The lengths taken in this simulation are 10 km, 50 km and 70 km. For a data rate equal to 2.5 Gbps and 10 Gbps when the length is shorter the eye diagram of the system gives good performance. For example, when the length is 10 km the performance is much better than 50 km and 70 km. when we compare 2.5 Gbps with 10 Gbps with the same length, 2.5 Gbps gives good results as illustrated in the simulation result.

The distance was expected to influence the performance in two ways: loss and dispersion.

At low transmission rates, when the dispersion was not significant, the loss would be dominant. As is known, the longer fiber optic will provide a huge dispersion and attenuation, hence increasing the bit error rate.

Simulations were conducted for different data rates and different fiber optic lengths. The simulation result is done for the ZCC code with weight equal to 2 and this leads to implement two laser diodes to generate a continuous wave (CW) optical signal. The two laser diodes are represented by the weight of the code by choosing different emission frequency for every chip.

In this simulation, the emission frequency of laser number one represents the first chip of the code, while the second laser with a different emission frequency represents the second chip. Also, any one of the other undesired users has two laser diodes, any one of them with different emission frequency.

The nonlinear dispersive fiber (NLDS) of different lengths is used as medium to send the data of all users with attenuation equal to 0.2dB/Km and dispersion $16e-6s/m^2$.

4.2 Effect of Distance on System Performance at data rate equal 2.5Gbps

Firstly the simulation is carried out for same data rate equal to 2.5Gbp with different optical fiber length which are 10Km, 50Km and 70Km.

I- data rate equal to 2.5Gbps and the length 10 km

Figure 4.4 shows the simulation result for 2.5Gbps and 10km which provides a good BER compared with other distances (50 km and 70 km). Besides, the data rate 2.5 Gbps offers good BER compared to the data rate 10 Gbps for the same length.
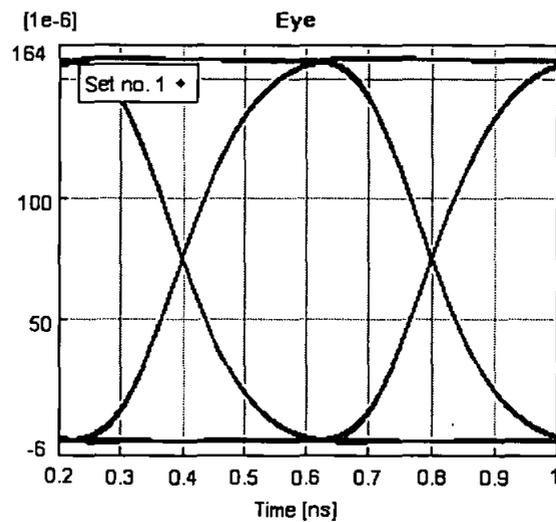

Figure 4.4: Eye Diagram of the ZCC-DW code Channels at 2.5 Gbps and 10km.

II- data rate equal to 2.5Gbps and the length 50 km

Figure 4.5 shows the simulation result for 2.5Gbps and 50km which gives a good BER compared with 70 km but not better than 10km. The data rate 2.5Gbps with length 50 offers good BER compared to the data rate 10Gbps for the same length.
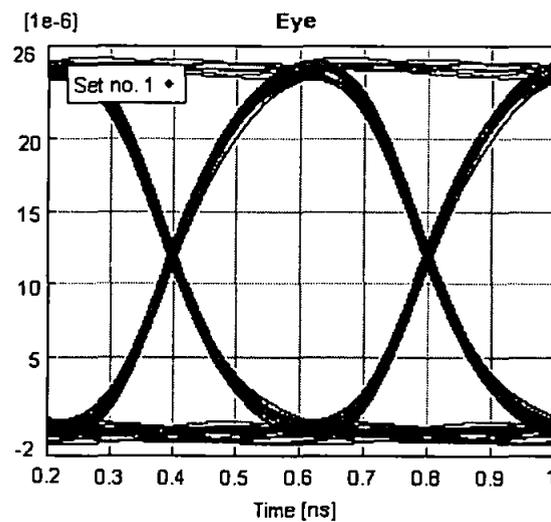

Figure 4.5: Eye Diagram of the ZCC-DW code Channels at 2.5Gbps and 50km.

III- data rate equal to 2.5Gbps and the length 70 km

Figure 4.6 shows the simulation results for 2.5Gbps and 70km which provides the worst BER compared with 10 km and 50 km. The data rate 2.5Gbps with length 70 offers good BER compared to the data rate 10Gbps with the same length.
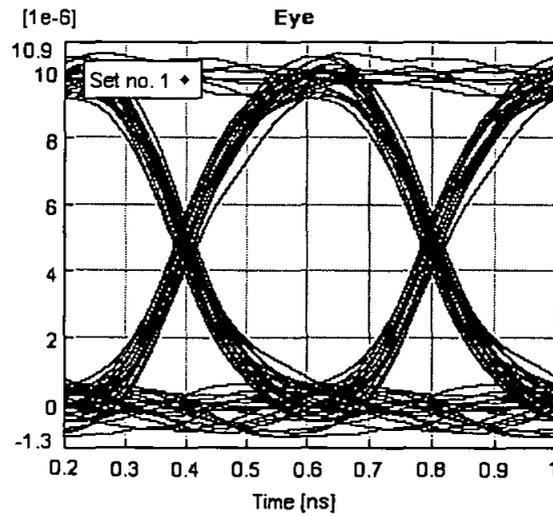

Figure 4.6: Eye Diagram of the ZCC-DW code Channels at 2.5 Gbps and 70km.

4.3   Effect of Distance on System Performance at data rate equal 10Gbps

Secondly the simulation carried out for same data rate equal 10Gbps but for different optical length which are 10Km, 50Km and 70Km.

I- data rate equal to 10Gbps and the length 10 km

Figure 4.7 shows the simulation results for 10Gbps and 10 km which provides a good BER compared with 50 km and 70 km. The data rate 10Gbps with a length of 10 offers the worst BER compared to the data rate 2.5Gbps with the same length.
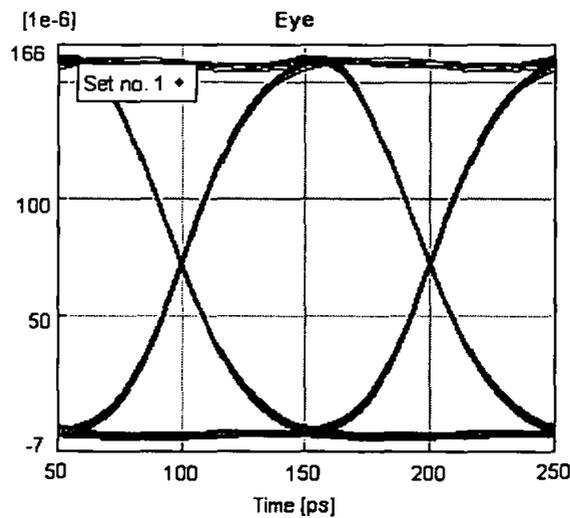

Figure 4.7: Eye Diagram of the ZCC-DW code Channels at 10 Gbps and 10km.

II- data rate equal to 10Gbps and the length 50 km

Figure 4.8 shows the simulation results for 10Gbps and 50km which result in a good BER compared with 70 km but not better than 10 km. the data rate of 10Gbps with length 50 offers worst BER compared to data rate 10Gbps with the same length.
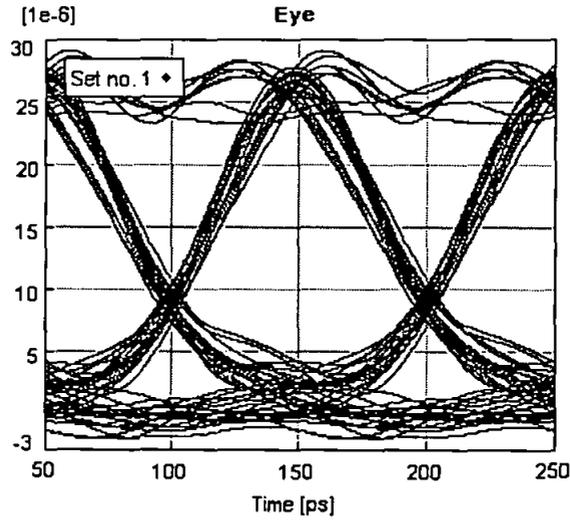

Figure 4.8: Eye Diagram of the ZCC-DW code Channels at 10Gbps and 50 km.

III- data rate equal to 10Gbps and the length 70 km

Figure 4.9 shows the simulation results for 10Gbps and 70km which result in the worst BER compared with 10 km and 50 km. The data rate of 10Gbps with length of 70 Km offers the worst BER compared to data rate 2.5Gbps with the same length.
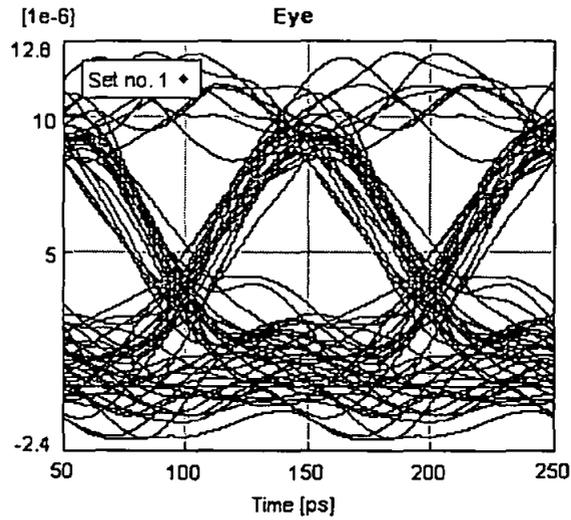

Figure 4.9: Eye Diagram of the ZCC-DW code Channels at 10Gbps and 100km.

4.4 Effect of Distance on System Performance at different Bit Rate

Figure 4.10 shows the relation of the BER rate versus the length with different data rate. When the length of the fiber optic increases, the loss and the dispersion will increase and this effected on the BER. Also the performance of the system is hampered with increasing the data rate.
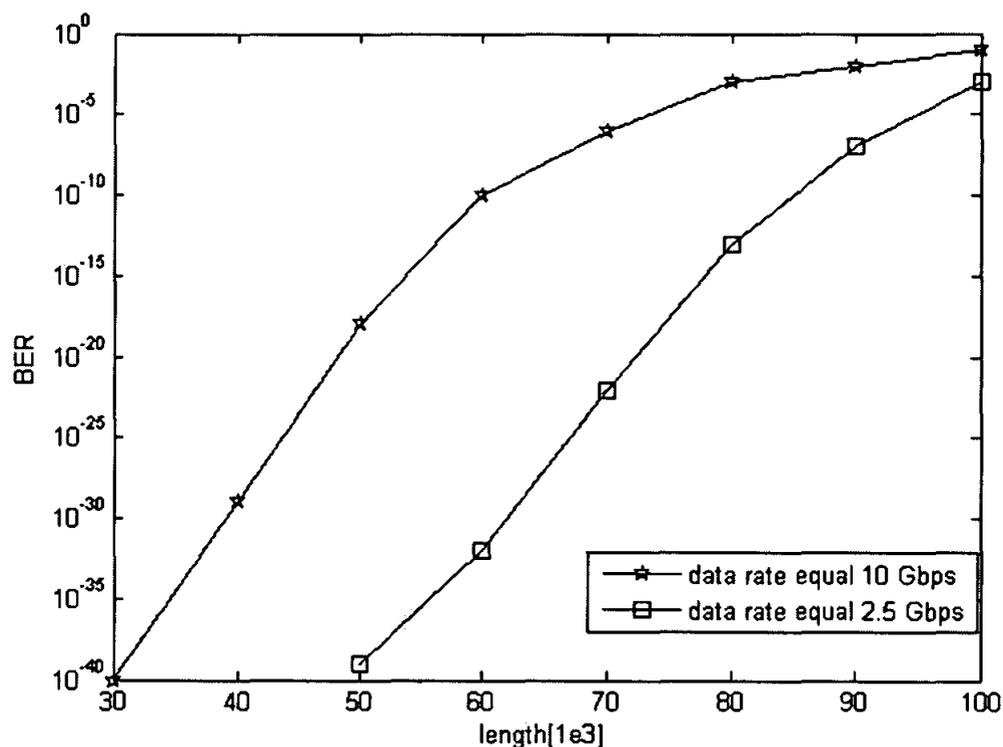

Figure 4.10 BER versus Distance at Different Transmission Rates

The purpose of this study is to analyze the behavior of the OCDMA systems using different data rate with different fiber optic length. The tests were carried out for both the systems at data rate of 2.5 Gbps and 10 Gbps for 30 km to 100 km distance of fiber. The performance of the system was characterized by referring to the bit error rate (BER).

The graph shown in Figures 4.10 above clearly showed that the ZCC-DW code system gave a significantly good performance as expected when the data rate equal to 2.5 Gbps. The graph of data rate 10 Gbps shows very bad BER rate compared to data rate 2.5 as the result of increasing loss and dispersion .

4.5   Effect of Input Power on System Performance

Figure 4.11 shows the relation between the input power and the BER. And as shown in the Figure when the input power increases the BER is getting better and vice versa because with increasing the power the signal become strong.
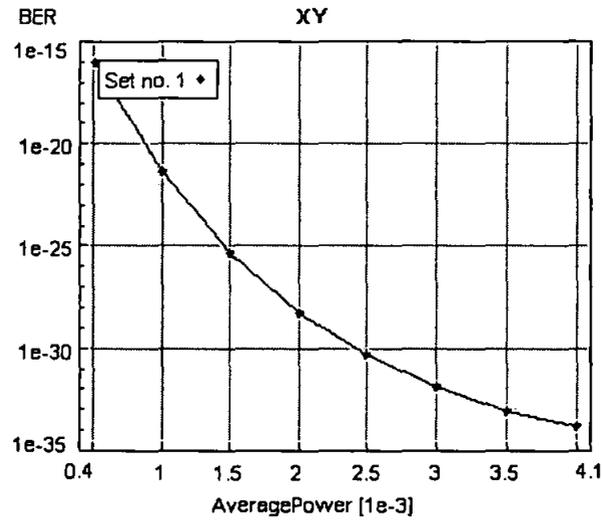

Figure 4.11 BER versus Input Power

4.6 Performance comparison between Hybrid Detection and Direct detection Techniques

This comparison shows the BER of The detection used for DW code which is hybrid Detection Technique [66] [67] and the detection of ZCC-DW code which is Direct Detection Technique.

The encoder part of both detections is same, the different between them in the decoder part as the result of the cross correlation.

Figure 4.12 shows the decoder part of Hybrid Detection while Figure 4.13 shows the decoder technique of Direct Detection.
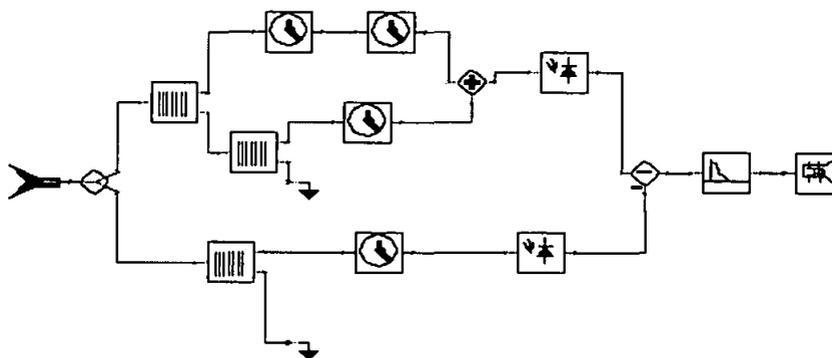
Figure 4.12 : The Receiver part of Hybrid Detection Technique
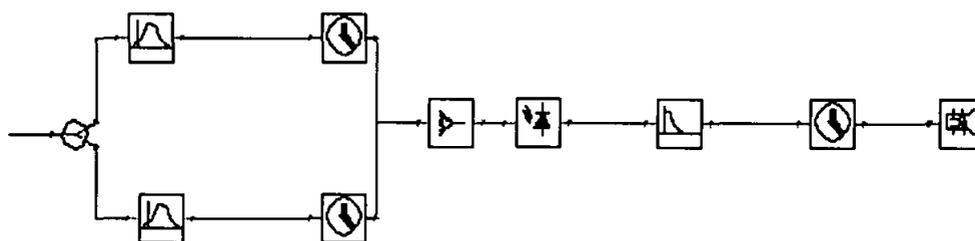
Figure 4.13 : The Receiver part of Direct Detection Technique

The comparison is done for data rate equal 2.5Gbps and 10Gbps. The eye Diagrams shows the enchantments of the signal when for Direct Detection Technique compared with the Hybrid Detection with same data rate
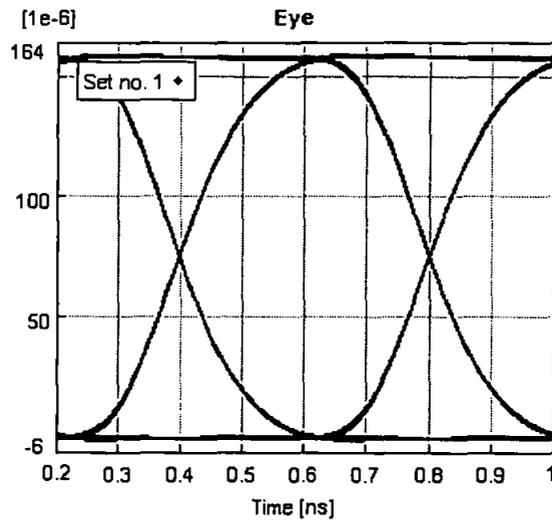
Figure 4.14: Eye Diagram of the Direct Detection Technique at 2.5Gbps and 10km.
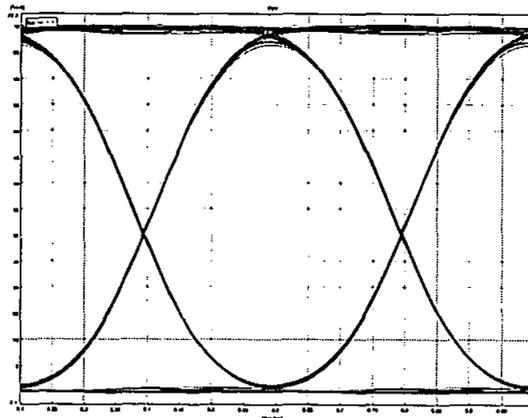
Figure 4.15: Eye Diagram of the Hybrid Detection Technique at 2.5Gbps and 10km.
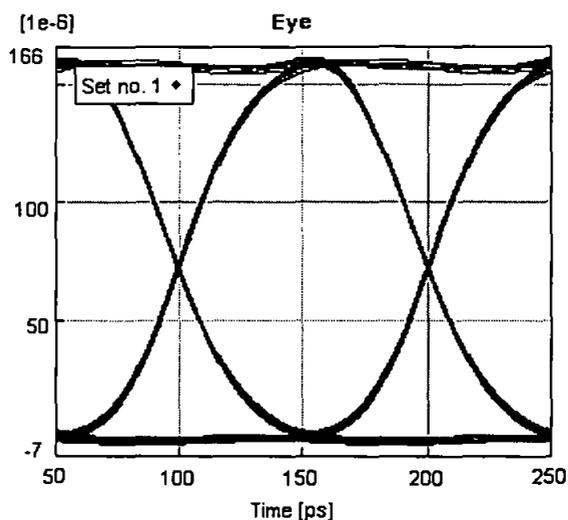
Figure 4.16: Eye Diagram of the Direct Detection Technique at 10Gbps and 10km.
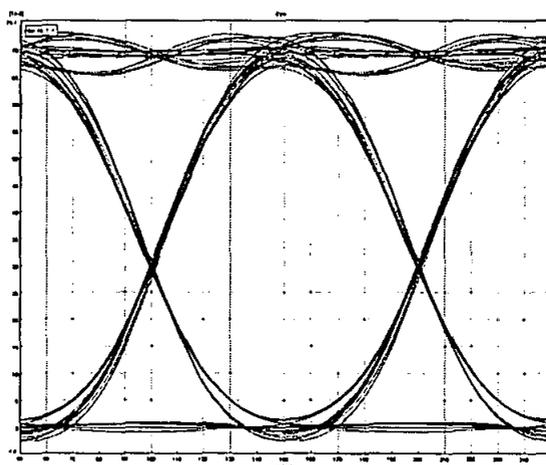
Figure 4.17: Eye Diagram of the Hybrid Detection Technique at 10Gbps and 10km.

Figure 4.18 shows the relation of the BER rate versus the length with same data rate equal to 10Gbps For the Direct Detection and Hybrid Detection Techniques

When the length of the fiber optic increases, the loss and the dispersion will increase and this effected on the BER. From the graph and eye diagrams the performance of Direction detection technique is better than the Hybrid Detection Technique because

the Direct Detection Technique offers very good BER compared with Hybrid Detection with the same data rate and same optical fiber length.
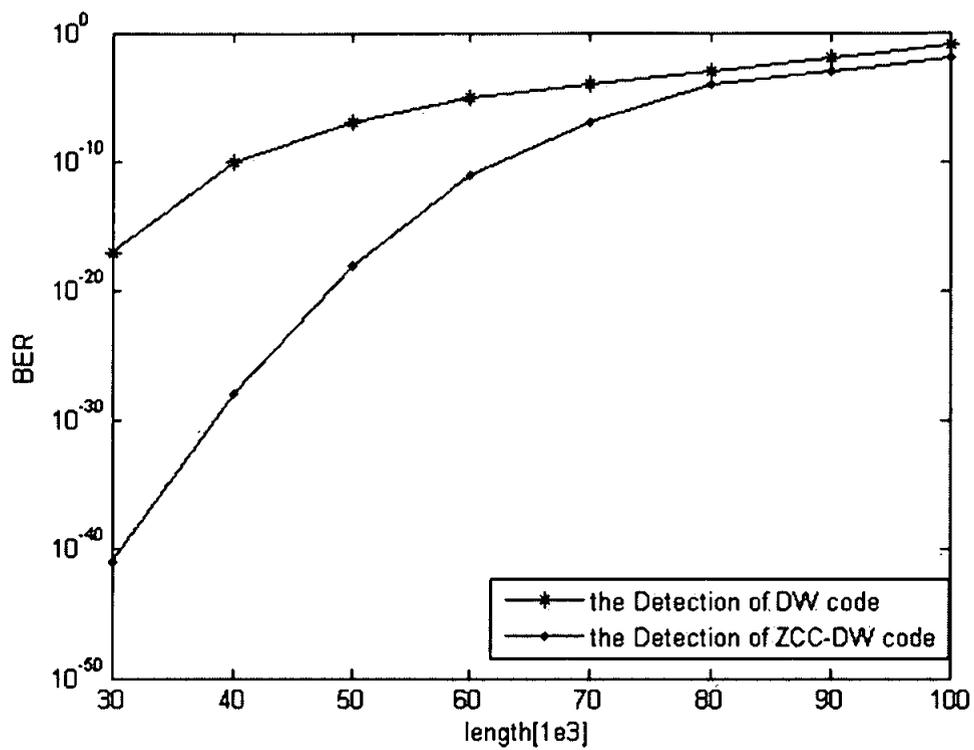
Figure 4.18: Comparison between Direct Detection and Hybrid Detection

4.7 Summary

In this chapter, the results presented are based on simulation work. The result discussed in details the effect of various lengths and various data rate of OCDMA system using ZCC-DW code.

Using ZCC-DW code as shown from eye diagrams and the graphs the system performance is good when the data rate and the length are decrease and vice versa.

The ZCC-DW code has good code properties that can eliminate the MAI and this enhances performance of the system.

The performance of the ZCC-DW code based on various input power and various fiber optical length is also shown in this chapter.

Besides, the simulation comparison between the Hybrid Detection, which it used for DW code family, and the Direct Detection, which is used as the proposed Detection for ZCC-DW code is done. The result shown that, the performance of Direct Detection is better than Hybrid Detection.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.3 Conclusion

This chapter describes the thesis contribution and future works. In this thesis ZCC-DW code is obtained by eliminating the intersection columns of MDW code, also equations construction Technique for this code are developed to generate the basic matrix, mapping technique and the maximum length for any user. The new construction improves the traditional one.

ZCC-DW code is derived by eliminating the intersection columns of Modified Double Weight (MDW) code which has the same properties like DW code. Also there is another method to find ZCC-DW code which is transformation technique as mentiond previously in chapter of ZCC-DW code constructions. This new proposed code possesses numerous advantages including the easy code construction, simple encoder/decoder design, existence for every natural number n, and the cross correlation value is zero ($\lambda_c = 0$).

The study includes the calculations of the new code and software simulation of direct detection technique which is proposed in this research as anew detection for ZCC-DW code. In the simulation the fiber parameters such as the nonlinear effect, noise profile, insertion loss and the photodetector parameters were included.

The study was carried out using various design parameters namely; distance, and data rate. The effect of these parameters on the system was elaborated through the eye diagram of the system when we change the parameters. The simulation was carried out for data rate equal 2.5 Gbps and 10 Gbps with fiber optic length equal to 10, 50, 70. From the simulation, ZCC-DW codes show better performance when we use data rate equals to 2.5 Gbps with length equal 10 Km compared with the simulation of high bit rate and long distance.

Also relation between different lengths with different data rate versus BER is shown. Besides, the relation between the BER and the input power is presented.

A new detection technique proposed to improve the OCDMA system performances and to reduce receiver complexity. The newly proposed technique, namely direct detection technique, shows a better performance in comparison to the last technique of MDW code which is Hybrid detection technique

The complementary subtraction, AND subtraction and Hybrid Detection techniques were used in MDW and DW codes to cancel the MAI which is caused by cross correlation value. Therefore the cross correlation value of ZCC-DW code is zero hence Direct Detection technique is proposed instead of those techniques.

The main advantage of Direct Detection technique is that it reduces the complexity of the receiver, time processing and cost.

5.3 Contributions from this thesis

The main contributions of this thesis are:

- Construct new OCMDA code named ZCC-DW code based on MDW code.
- Develop a new construction technique of this code instead of using the traditional code construction.
- Develop a new detection technique to solve the drawbacks of the existent detection techniques.

5.3 Future Work

- To increase the signal to noise ratio (SNR), hence decrease the Bit Error Rate (BER) of ZCC-DW code the number of weight must be greater than existent weight and this will be obtained by substituting one intersection 1's of Modified Double Weight code to 0 instead of eliminating the intersection column.

- In the transmitter part the Light Emission Diode (LED) can be used instead of Laser Diode (LD) because the LED is cheaper than LD.

In conclusion, this thesis has demonstrated that ZCC-DW code gives better result compared to MDW code.

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Appendix A

```
/*
 *  BasicMatrixZCC-DW.java
 *
 *
 */

import javax.swing.JOptionPane;

/**
 *
 * @author  abou idriss
 */
public class BasicMatrixZCC-DW extends javax.swing.JFrame {

    /** Creates new form NewJFrame */
    public BasicMatrixZCC-DW () {
        initComponents();
    }
        private void initComponents() {
        jLabel1 = new javax.swing.JLabel();
        W = new javax.swing.JTextField();
        jLabel2 = new javax.swing.JLabel();
        I = new javax.swing.JTextField();
        jButton1 = new javax.swing.JButton();
        result = new javax.swing.JTextField();

        setDefaultCloseOperation(javax.swing.WindowConstants.EXIT_ON_CLOSE);
        jLabel1.setText("ENTER W ");

        jLabel2.setText("ENTER I");

        jButton1.setText("OK");
        jButton1.addActionListener(new java.awt.event.ActionListener() {
            public void actionPerformed(java.awt.event.ActionEvent evt) {
                jButton1ActionPerformed(evt);
            }
        });

        result.setEditable(false);
        result.setText("jTextField3");
```

```
        javax.swing.GroupLayout layout = new
javax.swing.GroupLayout(getContentPane());
    getContentPane().setLayout(layout);
    layout.setHorizontalGroup(
        layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)
        .addGroup(layout.createSequentialGroup()
        .addGap(18, 18, 18)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.TRAILING)
            .addComponent(jLabel2, javax.swing.GroupLayout.Alignment.LEADING,
javax.swing.GroupLayout.DEFAULT_SIZE, 58, Short.MAX_VALUE)
            .addComponent(jLabel1, javax.swing.GroupLayout.Alignment.LEADING,
javax.swing.GroupLayout.PREFERRED_SIZE, 58,
javax.swing.GroupLayout.PREFERRED_SIZE))
            .addGap(16, 16, 16)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING,
false)
            .addComponent(I)
            .addComponent(W, javax.swing.GroupLayout.DEFAULT_SIZE, 128,
Short.MAX_VALUE))
        .addContainerGap(180, Short.MAX_VALUE))
        .addGroup(layout.createSequentialGroup()
        .addGap(116, 116, 116)
        .addComponent(jButton1)
        .addContainerGap(237, Short.MAX_VALUE))
        .addGroup(layout.createSequentialGroup()
        .addGap(55, 55, 55)
        .addComponent(result, javax.swing.GroupLayout.PREFERRED_SIZE, 255,
javax.swing.GroupLayout.PREFERRED_SIZE)
        .addContainerGap(90, Short.MAX_VALUE))
    );
    layout.setVerticalGroup(
        layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)
        .addGroup(layout.createSequentialGroup()
        .addGap(26, 26, 26)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.BASELINE
)
            .addComponent(jLabel1, javax.swing.GroupLayout.PREFERRED_SIZE, 27,
javax.swing.GroupLayout.PREFERRED_SIZE)
            .addComponent(W, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE))
        .addPreferredGap(javax.swing.LayoutStyle.ComponentPlacement.RELATED)
```

```
.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.BASELINE
)
            .addComponent(jLabel2, javax.swing.GroupLayout.PREFERRED_SIZE, 26,
javax.swing.GroupLayout.PREFERRED_SIZE)
            .addComponent(I, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE))
          .addGap(27, 27, 27)
          .addComponent(jButton1)
          .addGap(19, 19, 19)
          .addComponent(result, javax.swing.GroupLayout.PREFERRED_SIZE, 105,
javax.swing.GroupLayout.PREFERRED_SIZE)
          .addContainerGap(41, Short.MAX_VALUE))
      );
      pack();
  }// </editor-fold>

private int getJ1(int n,int w1,int kb1, int i)
{
   int j,cal,up,sum;
   up = i%kb1-2;
   sum = 0;
   if (up>=0)
     for(int m=0; m<=up; m++ )
        sum += 2*w1-2*m;
   cal = (2*n+1)/2;
   j=(n-1)+cal+sum;
   // JOptionPane.showMessageDialog(null," "+j);
   return j;
}
private int getJ2(int n,int w1, int i)
{
    int j,cal,up,sum;
   up = n-1;
   sum = 0;
   if (up>0)
     for(int m=1; m<=up; m++ )
        sum += 2*w1-2*m;
   cal = 2*(i-1);
   j=cal+sum;
     // JOptionPane.showMessageDialog(null," "+j);
   return j;
}

    private void jButton1ActionPerformed(java.awt.event.ActionEvent evt) {
```

```java
// TODO add your handling code here:

    int w1 = Integer.parseInt(W.getText());
    int ival = Integer.parseInt(I.getText());
    int last =w1-(ival-1);
    int nlast = ival-1 ;
    String res="";
    n1 = new int[last];
    j = new int[last];
    n2 = new int[nlast];
    j2 = new int[nlast];
    for(int i=0; i<last; i++)
       n1[i]=i+1;
    for(int i=0; i<nlast; i++)
       n2[i]=i+1;
    NB1 = 0;
    for(int i=1; i<=w1; i++)
       NB1+=i;
    NB1*=2;
    KB1 = w1+1;
    for(int i=0; i<nlast; i++)
       j2[i]=getJ2(n2[i],w1,ival);
    for(int i=0; i<last; i++)
       j[i]=getJ1(n1[i],w1,KB1,ival);
    int mat[] = new int[NB1];
    int index =0;
    for(int i=0; i<NB1&&index<last; i++)
       if(i == j[index]-1)
       {
          mat[i]=1;
          index++;
       }
       else
          mat[i]=0;
    index =0;
    for(int i=0; i<NB1&&index<nlast; i++)
       if(i == j2[index]-1)
       {
          mat[i]=1;
          index++;
       }
    res="ZCC: ";
    for(int i=NB1-1; i>=0; i--)
       res+= " "+mat[i]+",";
    result.setText(res);
```

```
    }

    /**
     * @param args the command line arguments
     */
    public static void main(String args[]) {
        java.awt.EventQueue.invokeLater(new Runnable() {
            public void run() {
                new NewJFrame().setVisible(true);
            }
        });
    }

    // Variables declaration - do not modify
    private javax.swing.JTextField I;
    private javax.swing.JTextField W;
    private javax.swing.JButton jButton1;
    private javax.swing.JLabel jLabel1;
    private javax.swing.JLabel jLabel2;
    private javax.swing.JTextField result;
    // End of variables declaration
    private int NB1;
    private int KB1;
    private int n1[];
    private int j[];
    private int n2[];
    private int j2[];
}
```

Appendix B

```
/*
 * Zcc2.java
 *
 * Created on April 19, 2007, 9:33 PM
 */

package examples;
import javax.swing.JOptionPane;
/**
 *
 * @author  abou idriss
 */
public class Zcc2 extends javax.swing.JFrame {

    /** Creates new form Zcc2 */
    public Zcc2() {
        super("ZCC");
        initComponents();
    }

    /** This method is called from within the constructor to
     * initialize the form.
     * WARNING: Do NOT modify this code. The content of this method is
     * always regenerated by the Form Editor.
     */
    // <editor-fold defaultstate="collapsed" desc=" Generated Code ">
    private void initComponents() {
        jLabel1 = new javax.swing.JLabel();
        jLabel2 = new javax.swing.JLabel();
        W = new javax.swing.JTextField();
        I = new javax.swing.JTextField();
        jButton1 = new javax.swing.JButton();
        result = new javax.swing.JTextField();
        jButton2 = new javax.swing.JButton();

        setDefaultCloseOperation(javax.swing.WindowConstants.EXIT_ON_CLOSE);
        addMouseListener(new java.awt.event.MouseAdapter() {
            public void mouseClicked(java.awt.event.MouseEvent evt) {
                formMouseClicked(evt);
            }
        });
```

```
jLabel1.setText("Enter W1");

jLabel2.setText("Enter i");

jButton1.setText("OK");
jButton1.addActionListener(new java.awt.event.ActionListener() {
    public void actionPerformed(java.awt.event.ActionEvent evt) {
        jButton1ActionPerformed(evt);
    }
});

jButton2.setText("Exit");
jButton2.addActionListener(new java.awt.event.ActionListener() {
    public void actionPerformed(java.awt.event.ActionEvent evt) {
        jButton2ActionPerformed(evt);
    }
});

javax.swing.GroupLayout layout = new
javax.swing.GroupLayout(getContentPane());
    getContentPane().setLayout(layout);
    layout.setHorizontalGroup(
        layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)
        .addGroup(layout.createSequentialGroup()
        .addGap(118, 118, 118)
        .addComponent(jButton1)
        .addContainerGap(235, Short.MAX_VALUE))
        .addGroup(layout.createSequentialGroup()
        .addGap(94, 94, 94)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.TRAILING)
        .addComponent(jLabel2, javax.swing.GroupLayout.Alignment.LEADING,
javax.swing.GroupLayout.DEFAULT_SIZE, 57, Short.MAX_VALUE)
        .addComponent(jLabel1, javax.swing.GroupLayout.Alignment.LEADING,
javax.swing.GroupLayout.DEFAULT_SIZE, 57, Short.MAX_VALUE))
        .addGap(14, 14, 14)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.TRAILING)
        .addComponent(W, javax.swing.GroupLayout.DEFAULT_SIZE, 57,
Short.MAX_VALUE)
        .addComponent(I, javax.swing.GroupLayout.DEFAULT_SIZE, 57,
Short.MAX_VALUE))
        .addGap(178, 178, 178))
        .addGroup(layout.createSequentialGroup()
        .addContainerGap()
```

```
                    .addComponent(result, javax.swing.GroupLayout.PREFERRED_SIZE, 370,
javax.swing.GroupLayout.PREFERRED_SIZE)
                .addContainerGap(20, Short.MAX_VALUE))
            .addGroup(layout.createSequentialGroup()
                .addGap(166, 166, 166)
                .addComponent(jButton2)
                .addContainerGap(183, Short.MAX_VALUE))
        );
        layout.setVerticalGroup(
            layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)
            .addGroup(layout.createSequentialGroup()
                .addGap(94, 94, 94)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.BASELINE
)
                    .addComponent(jLabel1)
                    .addComponent(W, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE))
                .addGap(15, 15, 15)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.TRAILING)
                    .addComponent(jLabel2)
                    .addComponent(I, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE))
                .addGap(30, 30, 30)
                .addComponent(jButton1)
                .addGap(24, 24, 24)
                .addComponent(result, javax.swing.GroupLayout.PREFERRED_SIZE, 31,
javax.swing.GroupLayout.PREFERRED_SIZE)
                .addGap(42, 42, 42)
                .addComponent(jButton2)
                .addContainerGap(43, Short.MAX_VALUE))
        );
        pack();
    }// </editor-fold>

    private void jButton2ActionPerformed(java.awt.event.ActionEvent evt) {
// TODO add your handling code here:
        System.exit(0);
    }

    private void jButton1ActionPerformed(java.awt.event.ActionEvent evt) {
// TODO add your handling code here:
        int w1 = Integer.parseInt(W.getText());
```

```
int ival = Integer.parseInt(I.getText());
 NB1 = 0;
 int len=0;
for(int i=1; i<=w1; i++)
   NB1+=i;
NB1*=2;

KB1 = w1+1;
int last =w1-(ival-1)%KB1;
int nlast = (ival-1)%KB1 ;
String res="";
n1 = new int[last];
j = new int[last];
n2 = new int[nlast];
j2 = new int[nlast];
 for(int i=0; i<last; i++)
    n1[i]=i+1;
 for(int i=0; i<nlast; i++)
    n2[i]=i+1;
int len2=0;
 for(int i=0; i<nlast; i++)
 {
    j2[i]=getJ2(n2[i],w1,ival);
    len2 = j2[i];
 }
 for(int i=0; i<last; i++)
 {
    j[i]=getJ1(n1[i],w1,KB1,ival);
    len = j[i];
 }
if (len2>len)
   len = len2;


int mat[] = new int[len];
int index =0;
for(int i=0; i<len&&index<last; i++)
   if(i == j[index]-1)
   {
      mat[i]=1;
      index++;
   }
   else
      mat[i]=0;
index =0;
for(int i=0; i<len&&index<nlast; i++)
```

```java
        if(i == j2[index]-1)
        {
            mat[i]=1;
            index++;
        }
    res="   K:   |";
    for(int i=len-1; i>=0; i--)
        res+= "C"+(i+1)+" |";


    res="ZCC = ";
    for(int i=len-1; i>=0; i--)
        res+= "   "+mat[i]+", ";



    result.setText(res);


}


    private void formMouseClicked(java.awt.event.MouseEvent evt) {
// TODO add your handling code here:


    }
    private int getJ1(int n,int w1,int kb1, int i)
{
    int j,cal,up,sum;
    up = i%kb1-2;
    sum = 0;
    if (up>=0)
        for(int m=0; m<=up; m++ )
            sum += 2*w1-2*m;
    cal = (2*n+1)/2;
    j=(n-1)+cal+sum+((i-1)/kb1)*NB1;

    return j;
}
private int getJ2(int n,int w1, int i)
{
    int j,cal,up,sum;
    up = n-1;
    sum = 0;
    if (up>0)
        for(int m=1; m<=up; m++ )
            sum += 2*w1-2*m;
    cal = 2*((i-1)%KB1);
    j=cal+sum+((i-1)/KB1)*NB1;
```

```java
    return j;
}

/**
 * @param args the command line arguments
 */
public static void main(String args[]) {
    java.awt.EventQueue.invokeLater(new Runnable() {
        public void run() {
            new Zcc2().setVisible(true);
        }
    });
}

// Variables declaration - do not modify
private javax.swing.JTextField I;
private javax.swing.JTextField W;
private javax.swing.JButton jButton1;
private javax.swing.JButton jButton2;
private javax.swing.JLabel jLabel1;
private javax.swing.JLabel jLabel2;
private javax.swing.JTextField result;
// End of variables declaration
private int NB1;
private int KB1;
private int n1[];
private int j[];
private int n2[];
private int j2[];
}
```

Appendix C

```java
/*
 * MaxLength.java
 *
 * Created on May 2, 2007, 10:05 PM
 */

package examples;

/**
 *
 * @author  abou idriss
 */
public class MaxLength extends javax.swing.JFrame {

    /** Creates new form MaxLength */
    public MaxLength() {
        initComponents();
    }

    /** This method is called from within the constructor to
     * initialize the form.
     * WARNING: Do NOT modify this code. The content of this method is
     * always regenerated by the Form Editor.
     */
    // <editor-fold defaultstate="collapsed" desc=" Generated Code ">
    private void initComponents() {
        jLabel1 = new javax.swing.JLabel();
        jLabel2 = new javax.swing.JLabel();
        W = new javax.swing.JTextField();
        I = new javax.swing.JTextField();
        jButton1 = new javax.swing.JButton();
        result = new javax.swing.JTextField();
        jLabel3 = new javax.swing.JLabel();

        setDefaultCloseOperation(javax.swing.WindowConstants.EXIT_ON_CLOSE);
        jLabel1.setText("Enter W1");

        jLabel2.setText("Enter i");
        jButton1.setText("OK");
        jButton1.addActionListener(new java.awt.event.ActionListener() {
            public void actionPerformed(java.awt.event.ActionEvent evt) {
                jButton1ActionPerformed(evt);
```

```
        }
    });

    jLabel3.setText("Max Length");

    javax.swing.GroupLayout layout = new
javax.swing.GroupLayout(getContentPane());
    getContentPane().setLayout(layout);
    layout.setHorizontalGroup(
        layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)
        .addGroup(layout.createSequentialGroup()
            .addGap(37, 37, 37)


.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)
                .addGroup(layout.createSequentialGroup()
                    .addGap(33, 33, 33)
                    .addComponent(jButton1)
                    .addContainerGap(283, Short.MAX_VALUE))
                .addGroup(layout.createSequentialGroup()


.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)
                    .addGroup(layout.createSequentialGroup()


.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.TRAILING)
                        .addComponent(jLabel2,
javax.swing.GroupLayout.Alignment.LEADING,
javax.swing.GroupLayout.DEFAULT_SIZE, 55, Short.MAX_VALUE)
                        .addComponent(jLabel1,
javax.swing.GroupLayout.Alignment.LEADING))
                        .addGap(18, 18, 18))
                    .addGroup(layout.createSequentialGroup()
                        .addComponent(jLabel3,
javax.swing.GroupLayout.PREFERRED_SIZE, 69,
javax.swing.GroupLayout.PREFERRED_SIZE)


.addPreferredGap(javax.swing.LayoutStyle.ComponentPlacement.RELATED)))


.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)


.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING,
false)
                        .addComponent(I)
                        .addComponent(W, javax.swing.GroupLayout.DEFAULT_SIZE, 41,
Short.MAX_VALUE))
                    .addGroup(layout.createSequentialGroup()
                        .addGap(25, 25, 25)
```

```
                    .addComponent(result,
javax.swing.GroupLayout.PREFERRED_SIZE, 39,
javax.swing.GroupLayout.PREFERRED_SIZE)))
                    .addContainerGap(226, Short.MAX_VALUE))))
        );
        layout.setVerticalGroup(
            layout.createParallelGroup(javax.swing.GroupLayout.Alignment.LEADING)
            .addGroup(layout.createSequentialGroup()
                .addGap(48, 48, 48)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.BASELINE
)
                    .addComponent(jLabel1, javax.swing.GroupLayout.PREFERRED_SIZE, 22,
javax.swing.GroupLayout.PREFERRED_SIZE)
                    .addComponent(W, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE))
                .addPreferredGap(javax.swing.LayoutStyle.ComponentPlacement.RELATED)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.BASELINE
)
                    .addComponent(jLabel2, javax.swing.GroupLayout.PREFERRED_SIZE, 30,
javax.swing.GroupLayout.PREFERRED_SIZE)
                    .addComponent(I, javax.swing.GroupLayout.PREFERRED_SIZE,
javax.swing.GroupLayout.DEFAULT_SIZE,
javax.swing.GroupLayout.PREFERRED_SIZE))
                .addGap(21, 21, 21)
                .addComponent(jButton1)
                .addGap(21, 21, 21)

.addGroup(layout.createParallelGroup(javax.swing.GroupLayout.Alignment.BASELINE
)
                    .addComponent(result)
                    .addComponent(jLabel3))
                .addContainerGap(109, Short.MAX_VALUE))
        );
        pack();
    }// </editor-fold>
    private void jButton1ActionPerformed(java.awt.event.ActionEvent evt) {
// TODO add your handling code here:
        int w1 = Integer.parseInt(W.getText());
        int ival = Integer.parseInt(I.getText());
        NB1 = 0;
        int len=0;
        for(int i=1; i<=w1; i++)
            NB1+=i;
```

```
    NB1*=2;

    KB1 = w1+1;

  float sum=0,max;
    for (int m=1; m<=ival%KB1; m++)
    {
       sum+=2*(w1-(m-1))-((float)1/(ival%KB1));
    }
    max = sum+(ival/KB1)*NB1;
    int m = (int)max;
    String res="";
   res+=m;
  result.setText(res);
}


/**
 * @param args the command line arguments
 */
public static void main(String args[]) {
   java.awt.EventQueue.invokeLater(new Runnable() {
      public void run() {
         new MaxLength().setVisible(true);
      }
   });
}


// Variables declaration - do not modify
private javax.swing.JTextField I;
private javax.swing.JTextField W;
private javax.swing.JButton jButton1;
private javax.swing.JLabel jLabel1;
private javax.swing.JLabel jLabel2;
private javax.swing.JLabel jLabel3;
private javax.swing.JTextField result;
// End of variables declaration
private int NB1;
private int KB1;
}
```

Appendix D

Clock recovery

Fiber Bragg Grating Filter

Low pass filter
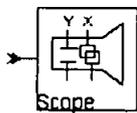
Scope, Oscilloscope
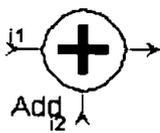
Add Optical Signals
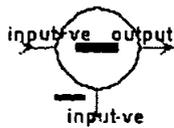
Subtract electrical signals
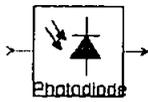
Photodiode

Ground

A pseudo random bit sequence generator
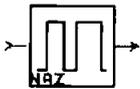
Produces an electrical NRZ coded signal

Rise Time Adjustment
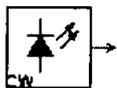


Laser CW
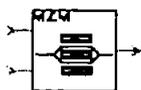
Modulator Mach-Zehnder
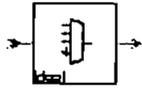
an ideal optical multiplexer

Output
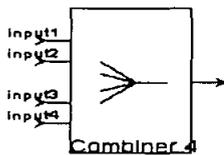
The module combines four optical input channels

Fork

Power Combiner