PERFORMANCE ANALYSIS OF ONE-DIMENSIONAL AND TWO-DIMENSIONAL CODES IN OPTICAL CODE DIVISION MULTIPLE ACCESS SYSTEM

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Submitted by

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DECLARATION

I, Vishav Jyoti hereby declare that this report entitled **"Performance analysis of one-dimensional and two-dimensional codes in optical code division multiple access system"** is an authentic record of my own work carried out towards the partial fulfillment for the award of degree of M.E. (Master of Engineering) in Electronics and Communication Engineering Department, Thapar University, Patiala, under the guidance of Dr. R.S. Kaler, Professor, ECED, during January to June 2009.

The matter presented in this report has not been submitted in any other University or Institute for the award of any degree.

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Signature of student

Dated: 1st July, 2009

This is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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ABSTRACT

Code Division Multiple Access (CDMA) is a "spread spectrum" technology, allowing many users to occupy the same frequency band at the same time. As its name implies, CDMA assigns unique codes to each user to differentiate it from others in the same spectrum. In a world of finite spectrum resources, CDMA enables many more people to share the airwaves at the same time. The optical fiber communications have the high bandwidth, large capacity and high reliability by the use of the broadband of the optical fiber. To take the full advantage of both of the technologies, CDMA and optical fiber communication, one of the basic concepts is the idea of allowing several users to transmit data simultaneously over the optical fiber communication channel by simultaneously allocating the available bandwidth to each user, which is called multiple access. There are several techniques to provide multiple access and one of them is optical code division multiple access (OCDMA). In OCDMA, the type of codes used is a major factor influencing its performance. The objective of the thesis is to analyze the performance of one and two dimensional codes for an OCDMA system.

Firstly, the design, implementation and performance analysis of various one dimensional codes in an OCDMA system for different data formats is presented. A number of different codes are used with Optical CDMA to improve its error performance. Here, three such codes, Optical orthogonal codes (OOC), Walsh Hadamard codes and Zero cross correlation (ZCC) codes have been compared using different data formats, NRZ raised cosine, NRZ rectangular, RZ raised cosine and RZ rectangular. It is found that NRZ raised cosine has the best system performance for all the codes used. After that, these three codes have been compared in terms of the BER, eye diagrams and received optical power using NRZ raised cosine modulation format. It is analyzed that ZCC codes have zero cross correlation property. The simulation results revealed that ZCC codes can provide a better BER compared to the OOC and Walsh Hadamard codes and it is most suitable to be employed in the OCDMA systems.

Secondly, the design, implementation and performance analysis of two dimensional wavelength/time codes in OCDMA system are also presented. The 2-D codes are constructed by a technique based on folding of Golomb rulers. The performance evaluation of OCDMA

system based on wavelength/time code has been analyzed by measuring the values of bit error rates and eye diagrams for different number of active users. It is shown that eye opening decreases and BER increases with increase in number of active users. It is also shown that BER further increases with increase in number of active users when number of decoders increases on receiver side. Hence, it is concluded that MAI is the dominant source of BER and there is graceful degradation in system performance when number of simultaneously active users increases. The received optical power is also measured at different transmission distances. It has been observed that received optical power decreases with increase in length of fiber due to attenuation.

Lastly, the security enhanced OCDMA system based on spectral encoding using code switching scheme is analyzed. The security issues are investigated by measuring eye diagrams and received signals for various cases. It has been observed; an eavesdropper based on a simple energy detector can easily read the information being transmitted by a single user using On-Off keying. In order to increase the security a code switching scheme is implemented on OCDMA. It is shown that the eye diagram at the eavesdropper becomes true noise waveform due to code switching scheme and at the receiver end a clear eye diagram is observed. The code switching scheme shows an immunity of the OCDMA system against eavesdropping and like conventional OCDMA schemes an authorized user clearly decodes an original data when a single user is active in the network.

Thus, the thesis presents the performance analysis of one and two dimensional codes for an OCDMA system.

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ABBREVIATIONS

1-D	One Dimensional
2-D	Two Dimensional
BER	Bit Error Rate
CD	Code Dimension
CDMA	Code Division Multiple Access
FDMA	Frequency Division Multiple Access
FOCDMA	Fiber Optic Code Division Multiple Access
LAN	Local Area Network
MAI	Multiple Access Interference
NRZ	Non Return to Zero
OCDMA	Optical Code Division Multiple Access
OOC	Optical Orthogonal Codes
OOK	On-Off Keying
PRBS	Pseudo Random Bit Sequence
PSO	Pseudo Orthogonal
RZ	Return to Zero
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
WDM	Wavelength Division Multiplexing
WHTS	Wavelength Hopping Time Spreading
ZCC	Zero Cross Correlation

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION TO OPTICAL COMMUNICATION

Twenty first century is an era of 'Information technology'. There is no doubt that information technology has had an exponential growth through the modern telecommunication systems. Particularly, optical fiber communication plays a vital role in the development of high quality and high-speed telecommunication systems. Fiber-optic communication is a method of transmitting information from one place to another by sending light through an optical fiber. Fiber-optic communication systems have revolutionized the telecommunications industry and played a major role in the advent of the information age. Often the optical fiber offers much higher speed than the speed of electronic signal processing at both ends of the fiber. Because of its advantages over electrical transmission, the use of optical fiber has largely replaced copper wire in the communications world. The main benefits of fiber are its exceptionally low loss, allowing long distances between amplifiers or repeaters and its inherently high data-carrying capacity, such that thousands of electrical links would be required to replace a single high bandwidth fiber. Another benefit of fiber is that even when run alongside each other for long distances, fiber cables experience effectively no crosstalk, in contrast to some types of electrical transmission lines. The main advantages of the optical fiber communications are the high speed, large capacity and high reliability by the use of the broadband of the optical fiber. The huge bandwidth of optical fiber communication system can be utilized to its maximum by using multiple access techniques.

So to be able to take the full advantage of the speed in optical fibers one of the basics concepts in fiber optic communication is the idea of allowing several users to transmit data simultaneously over the communication channel by simultaneously allocating the available bandwidth to each user. This is called multiple access. There are two types of multiple access techniques: Asynchronous and Synchronous. Asynchronous multiple access methods, where network access is random and collisions occur are well suited to LAN's with low traffic demand [1]. However, these asynchronous access methods suffer from cumulative delay as the traffic intensity increases. On the other hand, synchronous accessing methods, where transmissions are perfectly scheduled provide more successful transmissions than asynchronous methods [2].

There are several techniques to provide multiple access and one of them is optical code division multiple access (OCDMA). In OCDMA each user is assigned one or more binary signature sequence, so called codewords. The data to be sent is mapped onto the codewords and the different user’s codewords are “mixed” together and sent over the channel. At the receiver end a decoder, which is individual for each user, compares the incoming sequence with stored copies of the codewords to be able to extract the information bits.

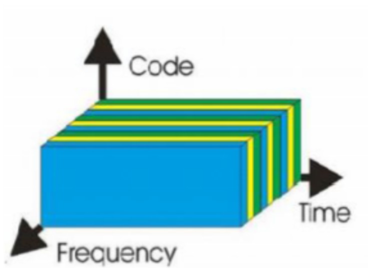
1.2 MULTIPLE ACCESS TECHNIQUES

The major multiple access protocols are:

- Wavelength Division Multiple Access (WDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)

1.2.1 Wavelength Division Multiple Access

WDMA is one of the earliest multiple-access techniques for cellular systems when continuous transmission is required for analog services. In WDMA system, bandwidth is divided into number of channels and each channel occupies a narrow optical bandwidth around a center wavelength or frequency [3]. WDMA technique is shown in figure 1.1 a). The channels are assigned only when demanded by the users. Therefore when a channel is not in use it becomes a wasted resource. Because each channel is transmitted at a different wavelength, they can be selected using an optical filter. In this, each user is assigned a fixed slot of wavelength all the time which makes it simple to implement, control and use [4]. Since the user has his portion of the bandwidth all the time, WDMA does not require synchronization or timing control, which makes it algorithmically simple. Even though no two users use the same frequency band at the same time, guard bands are introduced between frequency bands to minimize adjacent channel interference. Guard bands are unused frequency slots that separate neighboring channels. This leads to a waste of bandwidth [5]. When continuous transmission is not required, bandwidth goes wasted since it is not being utilized for a portion of the time. To increase the capacity of the fiber link using WDMA we need to use more carriers or wavelengths. Due to greater number of channels and larger optical power the increased nonlinear effects in fibers cause optical crosstalk such as four wave mixing over wide spectral ranges.



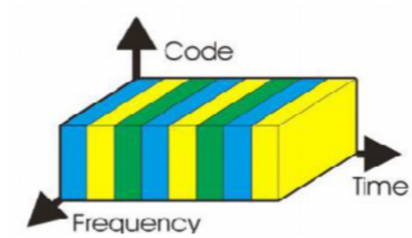


Figure 1.1: a) Channel usages by WDMA or FDMA b) Channel usages by TDMA [6]

1.2.2 Time Division Multiple Access

In TDMA, the entire bandwidth is available to the user but only for a finite period of time. In most cases, the available bandwidth is divided into fewer channels compared to FDMA and the users are allotted time slots during which they have the entire channel bandwidth at their disposal. In a TDMA system, each channel occupies a pre-assigned time slot, which interleaves with the time slots of other channels [4]. Global Systems for Mobile communications (GSM) uses the TDMA technique. TDMA technique is illustrated in Figure 1.1 b). TDMA requires careful time synchronization since users share the bandwidth in the frequency domain [5]. Since the number of channels are less, inter channel interference is almost negligible, hence the guard time between the channels is considerably smaller. Guard time is spacing in time between the TDMA bursts. TDMA uses different time slots for transmission and reception. In cellular communications, when a user moves from one cell to another there is a chance that user could experience a call loss if there are no free time slots available.

1.2.3 Code Division Multiple Access

Code division multiple access (CDMA) is a form of multiplexing and a method of multiple access to a physical medium such as a radio channel, where different users use the medium at the same time using different code sequences. In CDMA, every user will be allocated the entire spectrum all of the time. CDMA uses unique spreading codes to spread the baseband data before transmission [5]. The signal is transmitted in a channel, which is below noise level. The receiver then uses a correlator to despread the wanted signal, which is passed through a narrow bandpass filter. Unwanted signals will not be despread and will not pass through the filter. Codes take the form of a carefully designed one/zero sequence produced at a much higher rate than that of the baseband data [6]. The rate of a spreading code is referred to as chip rate rather than bit rate.

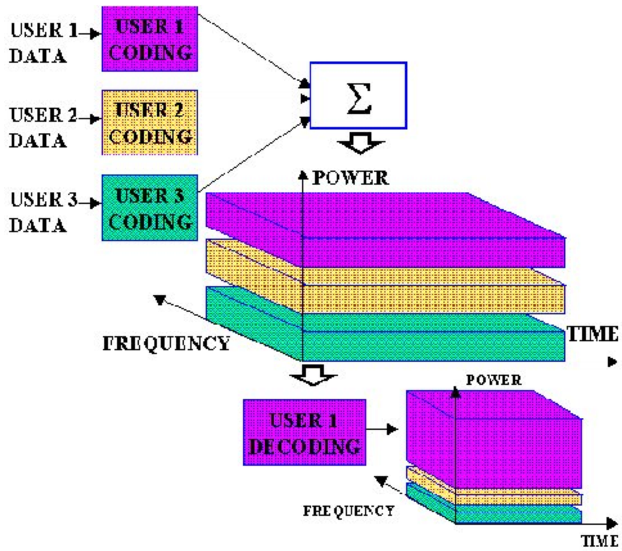


Figure 1.2: CDMA Spreading [6]

Spread spectrum code division multiple access (CDMA) allows asynchronous multiple access to a local area network (LAN) with no waiting. The additional bandwidth required by spread spectrum can be accommodated by using a fiber-optic channel and incoherent optical signal processing [7]. Optical CDMA is a scheme which is used for multiplexing optical communication channels that is based on the method of direct-sequence spread spectrum.

1.3 ADVANTAGES OF OCDMA

Some of the advantages [1] of optical code division multiple access are listed here.

- *Fully Asynchronous Access*: OCDMA uses random and simultaneous access protocol. So, there is no need for the strict timing synchronization.
- *Dynamic allocation of bandwidth and soft capacity on demand*: There is no need for the strict wavelength control. This makes adding new subscribers or removing unsubscribed subscribed users from the network much easy.
- *Decentralized architecture*: Simple protocols (e.g. tell-and-go protocol) are used in OCDMA. So, there is no need for the centralized network control.

- *Self-routing*: There is self routing by code sequence in OCDMA, as different codes are assigned to each user. There is an effective utilization of bandwidth in OCDMA.
- *Robust information security*: Optical CDMA systems offer an inherent security to each user's information at the physical transmitting medium level as well as the coding level used for transmission. OCDMA has high tolerance to noises.

1.4 INTRODUCTION TO OCDMA

CDMA was originally investigated in the context of radio frequency communications systems, and was first applied to the optical domain in the mid-1980s [7]. OCDMA allows multiple users to access the network asynchronously and simultaneously. OCDMA techniques have received a growing interest because neither time management nor frequency management at the transmitting nodes is necessary. The roots of OCDMA are found in Spread Spectrum communication techniques. 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); therefore, very low latencies can be achieved. Dedicated time or wavelength slots do not have to be allocated, so statistical multiplexing gains can be high. OCDMA allows flexible network design because the BER depends on the number of active users (i.e., soft-limited) [8]. In OCDMA the maximum number of users is not fixed but allowing more users to access the channel means lower rates for active users. In OCDMA system you can control the potential number of active users versus the rate and this makes the system flexible. Optical CDMA is most suitable to be applied to high speed LAN to achieve contention-free, zero delay access, where traffic tends to be busty rather than continuous. In OCDMA systems, the BER performance is degraded by the multiple access interference (MAI), which comes from all the other active users. This in turn ultimately limits the number of active users in a given OCDMA network.

1.5 OCDMA SYSTEM: A REVIEW

An OCDMA system share a common strategy of distinguishing data channels not by the wavelength or the time slot, but by distinctive spectral or temporal code (or signature) impressed onto the bits of each channel. Suitably designed receivers isolate channels by code-specific detection. The figure 1.3 shows an OCDMA network with N pairs of transmitters and receivers. Fiber optic code division multiple access is one technique to allow several users to transmit simultaneously over the same optical fiber. An OCDMA can, for each user, be described by a data source, containing the data that will be sent, followed by an encoder and then a laser that maps the signal from electrical form to an optical pulse sequence by using a modulator. At the receiver end an optical correlator is used to extract the encoded data.

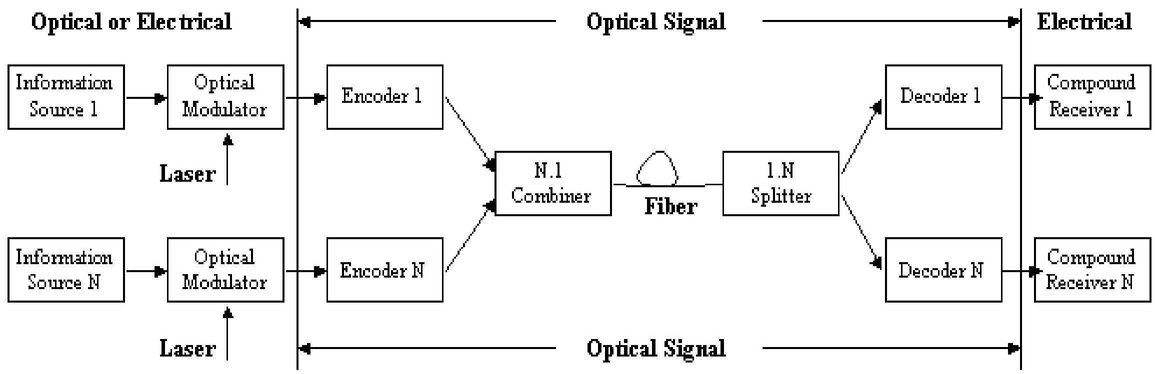


Figure 1.3: Block diagram of Optical CDMA network

1.5.1 Classification of OCDMA systems

Optical CDMA systems can be divided into two broad categories based on the way in which a particular user's code is applied to the optical signal. These classifications include:

1) *coherent optical CDMA*
2) *incoherent optical CDMA*

In a coherent OCDMA system, a given user's code is generally applied via phase coding of the optical signal field, which is often derived from a highly coherent wideband source, such as a mode-locked laser. The receiver for a coherent OCDMA system relies on a coherent reconstruction of the signal field to recover the decoded user's data. In this the signals are bipolar in nature. Coherent systems achieve higher performance than the incoherent ones but require high-precision control of the optical path within the encoder and decoder [9]. In contrast, an incoherent OCDMA system typically relies on amplitude-modulated codes rather than directly manipulating the optical phase. Also, the receiver is based upon an incoherent decoding and recovery process. A number of incoherent OCDMA system architectures utilize wideband incoherent sources, such as a broadband amplified spontaneous emission source, while other incoherent architectures utilize coherent laser sources as part of their implementation. In most incoherent OCDMA systems, each user is assigned a specific code sequence: a coded transmission is sent to represent a data bit “1,” and a null is used to represent a bit “0.” Due to the incoherent nature of the system, there are no negative signal components and the signals are unipolar. To avoid loss of code confidentiality using simple energy level detectors, these schemes can be modified to assign two codes per user; a 1 being represented by a code and a 0 being represented by another [10]. Incoherent systems are regarded as more practical because the light sources and encoding and decoding techniques have low complexity and are cost effective [9].

1.5.2 Types of Codes

As a core of an OCDMA system, various different types of optical codes have been proposed and studied for various OCDMA technologies:

i) One-dimensional (1-D) codes

ii) Two-dimensional (2-D) codes

1.5.2.1 One dimensional (1-D) codes:

The One-dimensional codes spread either in time [9] or in frequency [11]. According to the way the optical signal is encoded 1-D codes can be classified as:

- Temporal OCDMA
- Spectral OCDMA

Temporal OCDMA

The temporal OCDMA performs the coding in time domain, by using very short optical pulses, using optical delay lines to compose the coded optical signal [7]. Time encoded optical CDMA system as shown in figure 1.4 is based on discrimination in the time domain to reduce the effects of pulse overlaps. This time encoding process is most commonly implemented by encoding each data bit with high-rate sequence, that is, a pulse laser source is intensity-modulated by electrical (0, 1) data bit and the narrow pulse is emitted in the first chip in a slot. Here, data are usually modulated in On-Off keying (OOK) or pulse position modulation formats [1], and a slot is divided into chips where the number of chips in a slot equals to the length of the spreading code consisting of 1 and 0 allocated for users.

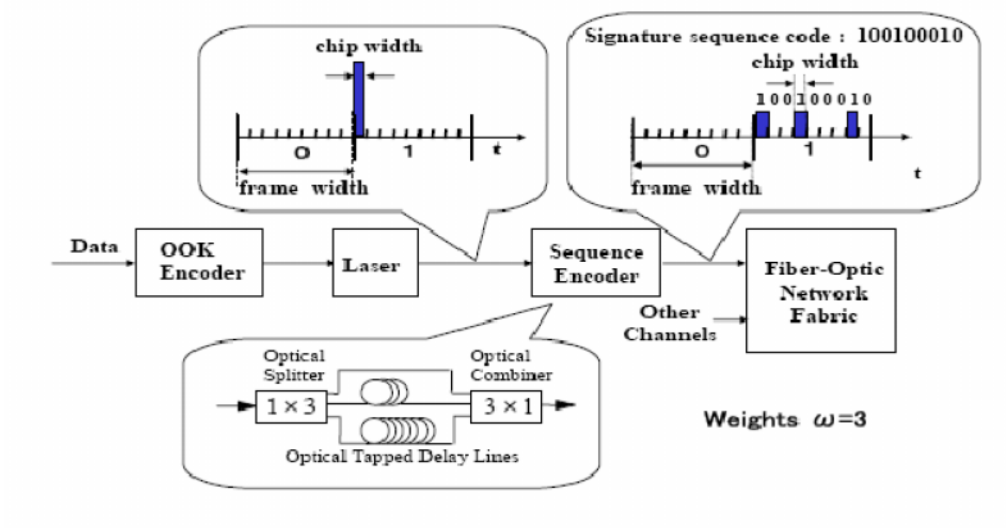


Figure 1.4 Time encoded optical CDMA [1]

Then, in the time-encoder, narrow pulse is time-spread into several chips within the slot according to each user's unipolar signature code. Thus, the time-encoding process relies on a simple, intensity based, pulse time addressing process.

Spectral OCDMA

Spectral OCDMA codes the phase or intensity of the spectral content of a broadband optical signal by using phase or amplitude masks. The phase encoding scheme of phase-encoded OCDMA is presented in Figure 1.5. The phase code employed in the spectral phase-encoded OCDMA system is a pseudo-random code. The SPC-OCDMA system requires a broadband multi-wavelength source. The stream of mode-locked laser pulses is then modulated with the user’s data which is equivalent to spectral broadening of the discrete spectral components generated by the mode-locked laser. After data modulation, the signal is sent into a spectral phase encoder, which applies a particular OCDMA phase code to the spectrum. Each user is assigned one of a set of *N*-element spectral phase codes [10]. Once the signal has been encoded, it can be passively combined with other OCDMA signals, each of which have their own unique spectral phase codes but overlap completely in the frequency domain. In order to recover a particular OCDMA user’s signal at the receiver end of the system, a spectral phase decoder is first employed. Physically it is nearly identical to the spectral phase encoder located at the transmitter, but it has a conjugate spectral phase mask.

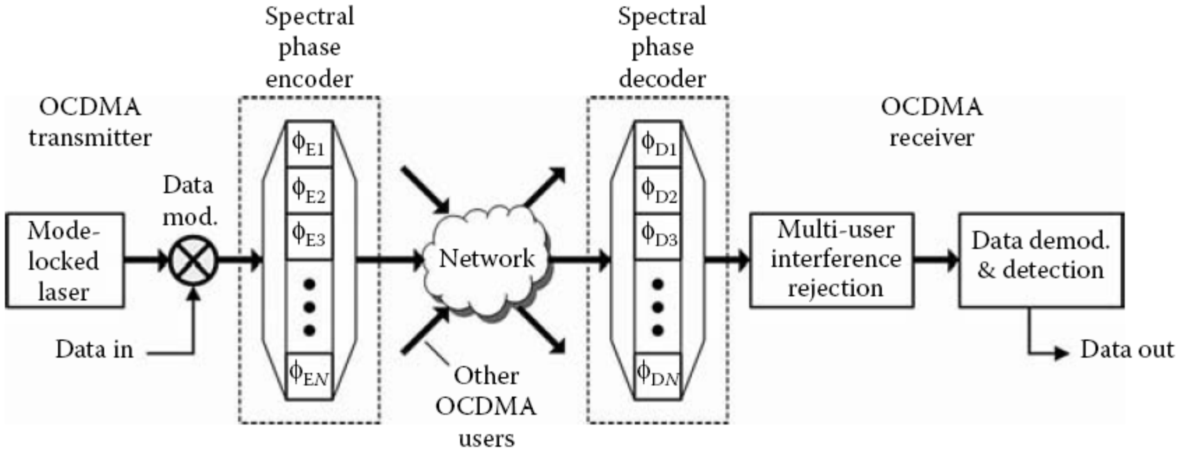


Figure 1.5: Block diagram of the spectral phase coded OCDMA system [10].

After spectral phase decoding, it is necessary to remove the multiuser interference (MUI) noise resulting from undesired OCDMA users. The desired user's data signal can be recovered through data demodulation and detection.

1.5.2.2 Two-Dimensional (2-D) codes

The two-dimensional codes spread in both time and wavelength simultaneously [12]. Wavelength hopping time spreading is a 2-D coding approach in which pulses are placed in different chips across the bit period and each chip is of different wavelength, thus following a wavelength-hopping and time spreading pattern. The 2-D codes can provide more flexibility and greater capacity than 1-D codes [9]. The wavelength-time schemes provide lower probability of interception and offers scalability and flexibility. The probability of interception is enhanced because the pulses of each code sequence are transmitted in different wavelengths, making eavesdropping more difficult. In addition, with 2-D codes, the requirement of ultra short pulses is lessened [10]. In this all active users share the same wavelength and time domain space, providing a fair division of the bandwidth. It provides truly asynchronous access, which in turn greatly simplifies network control and management.

1.6 MULTIPLE ACCESS INTERFERENCE

The co-channel interference from other users, who are using the same frequency allocation at the same time, is known as Multiple Access Interference (MAI) as shown in figure 1.6. Generally, optical CDMA systems suffer from MAI originating from other active users. As the number of active users increases, the bit error rate (BER) performance degrades due to the increase in MAI. A critical limitation of OCDMA networks is the reduction of throughput when many users are simultaneously trying to transmit over a common medium, thus producing extreme congestion at high network loads [13]. In fact, networks can suffer from “congestion collapse” in which the network’s throughput is degraded when traffic exceeds a threshold and it eventually approaches to zero under extremely high loads, i.e., when several users transmit simultaneously, their packets and hence their code-words overlap [14]. When the optical pulses in the codeword overlap, their power will be added, thus optical pulses from one codeword may be detected by other receivers tuned to other code-words. As a result, a receiver may incorrectly detect other user’s code-words, resulting in packet transmission errors [15].

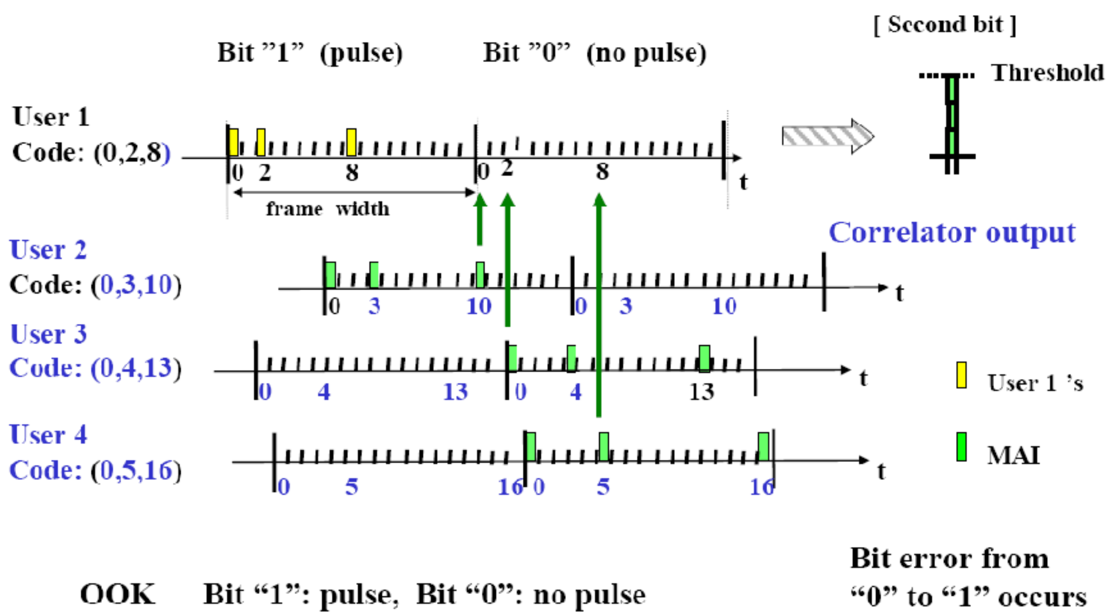


Figure 1.6: Multiple access interference [1]

Several interference cancellation techniques have been proposed aiming at lowering these asymptotic error floors. MAI can be minimized by either increasing the code length or choosing codes whose cross-correlations are low. Optical power selector based on optical hard limiter can also mitigate the effect of MAI [16].

CHAPTER 2
LITERATURE REVIEW

2.1 LITERATURE SURVEY

The history of Optical Code Division Multiple Access dates back to the 1970s.

Antonio J. Mendez et al. [2] presented a technique for generating PSO matrices from sets of optimum Golomb rulers. It is shown that 2-D codes have higher cardinality and good spectral efficiency, especially when compared to linear or direct sequence code. This paper describes the design and construction of the matrices; analyzes their performance from a communications viewpoint; describes their use as codes for the asynchronous, concurrent communication of multiple users; and analyzes the bit error rate performance based on capturing and modeling a typical network topology and performing a numerical modeling of the system.

A. Stok et al. [8] proposed the optical code-division multiple-access as a natural solution to achieving asynchronous, high-speed connectivity in a local area network environment. Optical CDMA is shown to be competitive with other networking technologies such as WDMA and TDMA, but has the benefit of more flexibility, simpler protocols, and no need for centralized network control. The limitations of one-dimensional optical orthogonal codes for CDMA have motivated the idea of spectral spreading in both the temporal and wavelength domains. It is found that if the constraints on constant weight in these two-dimensional codes are relaxed, differentiated levels of service at the physical layer become possible.

Bin Ni et al. [9] studied the effect of the coherence time of light sources on the performance of an incoherent temporal-spreading optical-code-division multiple-access (OCDMA) system. Broadband noise-like light sources, such as amplified spontaneous emission sources, are used by the transmitters. Three different kinds of receiver structures are examined and compared. Results show the impact of the non ideal light sources on the system performances relative to the ideal case. Analysis shows that to achieve the best performance when the available optical bandwidth and data rate are fixed, there is an optimal range for the spreading code length.

K. Yu et al. [12] proposed a two-dimensional (2-D) code family and transmitter/receiver structures for incoherent multi-wavelength- time spread optical CDMA networks. The combination of metal-coated reflection delay lines and arrayed waveguide gratings gives the proposed optical coder/decoder much enhanced flexibility in accommodating different code sets. Successful encoding/decoding has been demonstrated on signals up to 3-GHz time-chip rate with 4 * 15 code words.

Anuar et al. [17] proposed a new code structure for Spectral-Amplitude Coding Optical Code Division Multiple Access (OCDMA) system with zero cross-correlation. In contrary to the existing code, Zero Cross-correlation (ZCC) code provides much better performance of Bit Error Rate (BER) due to non-existence of Phase Induced Intensity (PIIN) noise. The newly proposed code can adapt to any variable number of weight and user without any constraint by using transformation and mapping technique respectively. It is theoretically demonstrated to compare the performance of ZCC code with the existing codes such as Hadamard, Modified Frequency Hopping and Modified Double-Weight (MDW) codes. For typical error rate of optical communication system, 10^{-9}, it can accommodate 84 users simultaneously.

S.A. Aljunid et al. [18] proposed a new code structure for spectral-amplitude-coding optical code-division multiple-access system based on double weight code families. The DW code has a fixed weight of two. It is shown that by using a mapping technique, codes that have a larger number of weights can be developed. Modified double-weight code is a double weight code family variation that has variable weights of greater than two. The newly proposed code possesses ideal cross-correlation properties and exists for every natural number. Based on theoretical analysis and simulation, MDW code is shown here to provide a much better performance compared to Hadamard and modified frequency-hopping codes.

Chung et al. [21] introduced the notion of optical orthogonal codes and addressed their applications to a variety of areas in communications. Methodologies in the design and analysis of optical orthogonal codes with tools from projective geometry, the greedy algorithm, iterative constructions, algebraic coding theory, block designs and various other combinatorial disciplines are discussed.

Jawad A. Salehi [22] examined fiber-optic code division multiple access (FO-CDMA) communications techniques. A new class of codes (signature sequences), namely, optical orthogonal codes (OOCs), that are suitable for (FO-CDMA) are introduced. An experiment that shows the desired auto- and cross-correlation properties of these codes and their use in FO-CDMA is reported. Furthermore, the concept of optical disk patterns, an equivalent way of representing OOC's is introduced. The optical disk patterns are used to derive the probability density functions associated with any two interfering OOC's. Also presented is a detailed study of different interference patterns from which the strongest and the weakest interference patterns are introduced.

M.S. Anuar et al. [25] proposed a new code structure for spectral amplitude coding Optical code division multiple access systems with zero cross-correlation and theoretically demonstrated the performance of this code by using direct decoding technique. The proposed code be adapted to any weight and user by using transformation and mapping techniques, respectively. The direct decoding technique is exploited since there is no overlapping in the code construction. The code performance shows that it outperforms the existing SAC OCDMA codes such as Hadamard, Modified Frequency Hopping (MFH), Modified Double Weight (MDW).

I.B. Djardjevic et al. [26] proposed three novel classes of optical orthogonal codes (OOCs) based on combinatorial designs. It is shown that hey are applicable to both synchronous and asynchronous incoherent optical code-division multiple access and compatible with spectral-amplitude-coding (SAC), fast frequency hopping, and time-spreading schemes. Simplicity of construction, larger codeword families, and larger flexibility in cross-correlation control make the proposed OOC families interesting candidates for future OCDMA applications. A novel balanced SAC receiver for multiuser interference cancellation that can handle unequal in-phase cross correlation of OOC is also proposed. The upper bound on the bit-error rate as a function of the number of users in SAC schemes is given for all proposed OOC classes.

S. Yegnanarayanan et al. [27] demonstrated a new technique for implementation of fast wavelength-hopping incoherent OCDMA. The output pulse from a mode locked laser is spectrally broadened through super-continuum generation. This pulse is then encoded into fast wavelength-hopped time-spread waveforms through a wavelength-selective time-delay device. A 1-Gb/s digital transmission experiment through a 15-km dispersion-shifted single-mode fiber link is presented. This technique avoids the need for a fast wavelength tunable optical source.

L. Tanceski et al. [28] introduced an incoherent optical code division multiple access (CDMA) concept using a combination of wavelength hopping and time spreading employing prime-hop sequences, which feature an autocorrelation function with zero sidelobes and crosscorrelation function of at most 1. Consequently, the number of stations in the network and the number of simultaneous users that can he supported is greatly increased. The system is suitable for truly asynchronous highly secure LAN applications.

A. J. Mendez et al. [32] demonstrated that code division multiple access permits concurrent communication over all virtual channels (in principle), independent of the data rate and the network size. In reality, most CDMA approaches have a bandwidth penalty due to the code length and a loss penalty due to the broadcasting required by CDMA. Both of these penalties can be reduced or ameliorated by means of multi-attribute coding. Matrices constructed from relatively inefficient (0, 1) pulse sequences are suitable multi-attribute non-coherent CDMA codes which are both bandwidth and broadcast efficient. A novel approach to synthesize matrix CDMA codes is exhibited; a 4 x 4 physical model is developed, and concurrent communication at concurrent data rates of 100, 150 and 250 Mbps per port is demonstrated experimentally.

Mendez et al. [33] demonstrated that 2-D wavelength/time codes have better SE than one-dimensional (1-D) CDMA/WDM combinations (of the same cardinality). Then, the paper described a specific set of wavelength/time codes and their implementation. The 2-D codes have high performance because they simultaneously have high cardinality >>10), per-user high bandwidth (>1 Gb/s), and high SE (>0.10 b/s/Hz). The physical implementation of these W/T codes is described and their performance evaluated by system simulations and measurements on an OCDMA technology demonstrator. This research shows that OCDMA implementation complexity (e.g., incorporating double hard-limiting and interference estimation) can be avoided by using a guard time in the codes and an optical hard limiter in the receiver.

Vincent J. Hernandez et al. [34] described a technology demonstrator for an incoherent optical code-division multiple-access scheme based on wavelength/time codes. The system supports 16 users operating at 1.25 Gsymbols/s/user while maintaining bit-error rate (BER) 10^11 for the correctly decoded signal. Experiments support previous simulations which show that coherent beat noise, occurring between the signal and multiple access interference, ultimately limits system performance.

Thomas H. Shake [35] examined the degree and types of security that may be provided by OCDMA encoding. A quantitative analysis of data confidentiality is presented for OCDMA encoding techniques. It is shown that increasing code complexity can increase the signal-to-noise ratio (SNR) required for an eavesdropper to “break” the encoding by only a few dB. Rapid reconfiguration of codes can also increase the difficulty of interception. The overall degree of confidentiality obtainable through OCDMA encoding is also compared with that obtainable through standard cryptography.

D.E. Leaird et al. [36] experimentally investigated spectrally phase coded OCDMA with a modulation format based on switching between two codes. The code switching data modulation format enhances security compared to On-Off keying by eliminating a vulnerability to eavesdropping based on a simple energy detector.

Hwan S Chung et al. [40] experimentally demonstrated a security improved optical code division multiplexed access scheme based on spectrally encoded incoherent broadband light source with bipolar coding. The details of coding scheme are shown and security issues have been investigated by measuring eye diagrams and bit error rates for various cases. The analytical and numerical simulation results are presented for secure transmission of spectrally encoded incoherent optical CDMA signal.

2.2 MOTIVATION

According to the literature survey it has been observed that the type of codes used is a major factor influencing the performance of any OCDMA system. Up till now, various 1-D codes for the OCDMA systems are proposed and compared theoretically but comparison of codes on the basis of data modulation format has been rarely done. The existing 1-D codes are having restrictions on code lengths and weights. Two dimensional codes operate in both time and wavelength domain can be a good solution to the limitations offered by one dimensional codes. Various approaches have been suggested for design of 2-D codes. The performance analysis of OCDMA system using 2-D codes is done for the increase in number of users on the transmitter side only. As the number of users increases bit error probability degrades. The performance analysis for the increase in number of users at both transmitter and receiver side is not done yet. Most arguments advocating OCDMA for secure communication against eavesdropping in the research literature are qualitative and vague. Various approaches have been suggested for enhancing the network security mechanisms in order to protect the network from attack by unauthorized users.

2.3 OBJECTIVE OF THESIS

The objectives of the thesis are:

- To analyze the design and performance of various one dimensional codes using different data formats for OCDMA system.
- To design and implement the two dimensional wavelength/time codes for OCDMA system.
- To investigate security enhancement of OCDMA system against eavesdropping using code switching scheme.

2.4 ORGANIZATION OF THESIS

This thesis is divided into six chapters.

The first chapter presents a brief introduction of an OCDMA system which includes classification of OCDMA systems and types of codes used.

The second chapter includes the literature survey of various one dimensional and two dimensional codes for OCDMA system. The literature survey for security against eavesdropping is also done.

In the third chapter, various one dimensional codes i.e. Walsh Hadamard codes, OOC and ZCC are designed for an OCDMA system. Then, the performance analysis of these codes in an OCDMA system for different data formats (i.e. NRZ raised cosine, NRZ rectangular, RZ raised cosine and RZ rectangular) is presented. After that, the three codes have been compared in terms of the BER, eye diagrams and received optical power using NRZ raised cosine modulation format.

In the fourth chapter, two dimensional wavelength/time codes are designed using a technique based on folding of Golomb rulers. The performance evaluation of OCDMA system based on wavelength/time code has been analyzed by measuring the values of bit error rates and eye diagrams for different number of active users.

The fifth chapter analyzes the security enhanced OCDMA system based on spectral encoding using code switching scheme. The security issues are investigated by measuring eye diagrams and received signals for various cases. It is shown that an eavesdropper based on a simple energy detector can easily read the information being transmitted by a single user using On-Off keying. In order to increase the security a code switching scheme is implemented on OCDMA system.

Finally, the sixth chapter includes conclusion and future scope of the work done.

CHAPTER 3

DESIGN AND PERFORMANCE ANALYSIS OF VARIOUS ONE DIMENSIONAL CODES USING DIFFERENT DATA FORMATS FOR OCDMA SYSTEM

In this chapter, the design, implementation and performance analysis of various one dimensional codes in an OCDMA system for different data formats is presented. A number of different codes are used with Optical CDMA to improve its error performance. Here, three such codes, Optical orthogonal codes (OOC), Walsh Hadamard codes and Zero cross correlation (ZCC) codes have been compared using different data formats, NRZ raised cosine, NRZ rectangular, RZ raised cosine and RZ rectangular. It is found that NRZ raised cosine has the best system performance for all the codes used. After that, the three codes have been compared in terms of the BER, eye diagrams and received optical power using NRZ raised cosine modulation format. It is analyzed that ZCC codes have zero cross correlation property. The simulation results revealed that ZCC codes can provide a better BER compared to the OOC and Walsh Hadamard codes and it is most suitable to be employed in the OCDMA systems.

3.1 INTRODUCTION

An OCDMA system shares a common strategy of distinguishing data channels not by the wavelength or the time slot, but by distinctive spectral or temporal code impressed onto the data bits of each channel. Each user is assigned one signature sequence called codeword. Each bit of information data is encoded by the codeword consisting of a number of shorter bits called chips. When this code is sent, it represents that a user with that unique code has sent the information bit ’1’. If the information bit is ’0’, it simply means that the corresponding length of zeros is sent i.e. no light pulses during that interval. The One-dimensional (1-D) codes spread either in time [9] or in frequency [11] domain. Several types of such codes are available i.e. Walsh Hadamard codes, Optical Orthogonal codes (OOC), Zero cross correlation codes (ZCC) etc for the coding process. However, these codes suffer from various limitations in one way or another. The cross-correlation is not ideal for Walsh Hadamard codes so it suffers from multiple access interference. [17]. The code construction is complicated for OOC. In spite of the use of orthogonal codes, the main effect limiting the effective signal-to-noise ratio of the overall system is the interference resulting from the other users transmitting at the same time, which is called Multiple Access Interference (MAI). MAI is the major source of noise in OCDMA systems [18]. The key to an effective OCDMA system is the choice of efficient address codes with good or almost zero correlation properties for encoding the source [8]. The ZCC codes have zero cross correlation. The long code length is a disadvantage of ZCC code since either very wide band sources or very narrow filter bandwidths are required [17].

The nature of codes is another important factor in OCDMA system which means that whether the codes used are unipolar or bipolar. In bipolar (-1, +1) codes, both the positive and negative logic levels are used to encode the data bits, but in unipolar (0, 1) codes, positive level is used to encode the data bit “1” and zero logic level is used to encodes the data bit “0”. In OCDMA systems, the unipolar codes are used because optical power is used to transmit the information and optical power cannot be negative.

Moreover, there are two possible modulation formats, non return-to-zero (NRZ), in which a constant power is transmitted during the entire bit period, and return-to-zero (RZ), in which power is transmitted only for a fraction of the bit period [19], in intensity-modulated direct-detection (IM/DD) optical communication systems. The NRZ pulses have a narrow optical spectrum. The reduced spectrum width improves the dispersion tolerance but it has the effect of intersymbol interference between the pulses. The narrow spectrum of NRZ pulses yields a better realization of dense channel spacing in DWDM systems. The RZ pulse shape enables an increased robustness to fiber nonlinear effects and to the effects of polarization mode dispersion (PMD) [20].

Anuar et al. [17] proposed a new code structure for Spectral-Amplitude Coding Optical Code Division Multiple Access (OCDMA) system with zero cross-correlation. In contrary to the existing code, Zero Cross-correlation (ZCC) code provides much better performance of Bit Error Rate (BER) due to non-existence of Phase Induced Intensity (PIIN) noise. The newly proposed code can adapt to any variable number of weight and user without any constraint by using transformation and mapping technique respectively. It is theoretically demonstrated to compare the performance of ZCC code with the existing codes such as Hadamard, Modified Frequency Hopping and Modified Double-Weight (MDW) codes. For typical error rate of optical communication system, 10^{-9}, it can accommodate 84 users simultaneously.

Chung et al. [21] introduced the notion of optical orthogonal codes and addressed their applications to a variety of areas in communications. Methodologies in the design and analysis of optical orthogonal codes with tools from projective geometry, the greedy algorithm, iterative constructions, algebraic coding theory, block designs and various other combinatorial disciplines are discussed.

Up till now, various 1-D codes for the OCDMA systems are proposed and theoretically compared but, the comparison on the basis of data modulation format has been rarely done. In this chapter, comparison of Walsh Hadamard, OOC and ZCC codes is done for various modulation formats i.e. NRZ raised cosine, NRZ rectangular, RZ raised cosine and RZ rectangular .

This chapter is divided into different sections. In the first section, the brief introduction about various one dimensional codes is presented. In second section, an analytical model is proposed. In the third section, construction of Walsh Hadamard, OOC and ZCC codes is presented. The fourth section describes the simulation setup for OCDMA system implementing these 1-D codes. In fifth section the performance analysis of OCDMA system using 1-D codes for different modulation format is done. The sixth section gives the conclusion of this chapter.

3.2 ANALYTICAL MODEL

An (n, w, λ_a, λ_c) optical orthogonal code C is a set of (0, 1) sequences of length n and weight w (the number of ones in every codeword). The size of the code is the number of codewords in C and is called its cardinality. The set is constructed so that it has the following two properties [21].

The Auto-Correlation Property

$$\sum_{t=0}^{n-1} x_t \, x_{t+\tau} \leq \lambda_a$$

for any $x \in C$ and any integer τ, 0 < t < n.

λ_a is the auto correlation constraint.

The Cross-Correlation Property

$$\sum_{t=0}^{n-1} x_t \, y_{t+\tau} \leq \lambda_c$$

for any $x \neq y \in C$ and any integer τ.

λ_c is the cross correlation constraint.

Here, a sequence is defined to be orthogonal with respect to its shifted version if λ_a, takes on its minimal value and two sequences are considered to be orthogonal if λ_c, takes on its minimal value [22]. The autocorrelation of each sequence in the optical orthogonal code exhibits the thumbtack shape and the cross correlation between any two sequences remain low throughout [21]. Since each sequence x has the weight w, the autocorrelation equals w when $\tau = 0$. Thumbtack-shaped auto-correlation enables the effective detection of the desired signal and low-profiled cross-correlation makes it easy to reduce interference due to other users and channel noise. The strict orthogonality would require that $\lambda_a = \lambda_c = 0$ [22].

3.2 CONSTRUCTION OF 1-D CODES

The construction of Walsh Hadamard codes, Optical orthogonal codes and zero cross correlation codes is presented below.

3.2.1 Construction of Walsh Hadamard Codes

A Z-element Hadamard code is a row from Z × Z orthogonal Hadamard matrix, which has (1,-1) valued binary entries. The Z × Z Hadamard matrix H_M where $Z = 2^M$ [23] is generated by the code matrix:

$$H_M = \begin{vmatrix} 1 & 1 \\ 1 & -1 \end{vmatrix}$$

For M = 2, the Hadamard matrix is generated as below [23]:

$$H_2 = \begin{bmatrix} H_1 & H_1 \\ H_1 & \overline{H}_1 \end{bmatrix} = \begin{vmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{vmatrix}$$

Unipolar Hadamard matrix H_M having the following properties:

1. *M* should be greater than or equal to 2.
2. Code length $N = 2^M$
3. Code Weight $W = 2^{M-1}$
4. User $K = 2^M - 1$ (The case Z = 1 has been excluded since the row of the unipolar Hadamard matrix is all ones).
5. The ratio of $\frac{W}{\lambda} = 2$ (i.e λ is cross-correlation properties).

A (Z × Z) Hadamard matrix of 1's and –1's has the property that any row differs from any other row in exactly $\frac{Z}{2}$ positions. All rows except one contains $\frac{Z}{2}$ (-1)'s and $\frac{Z}{2}$ (1)'s, usually in wavelength domain we replace the –1 with 0. The sequence (1, 0) is a unipolar Hadamard code for example, for Z = 4

$$H_2 = \begin{vmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{vmatrix}$$

This code can support $2^M - 1$ number of users.

For example, if only 20 users are required, *M* will have to be at least equivalent to 5 which supports up to 31 users, thus rendering 11 codes as unused. It is clear that Walsh Hadamard code is not efficient code because the sequence cannot be constructed exactly according to the number of users. It has increasing value of cross-correlation as the number of user increases. And it also requires more number of filters for each code as the number of user increases.

3.2.2 Construction of Optical Orthogonal Codes (OOC)

The following procedure yields a class of optimizing orthogonal codes for $\lambda_a = \lambda_c = 1$ and variable n and w. This class is denoted by the notation {n, w, s}, where s represents the number of sources that may be simultaneously active.

Before presentation of the procedure, certain additional notation is now defined [24]. Given a pulse pattern of K chips, $c_1, c_2 \ldots c_k$, then the delay between chips c_i and c_j is defined as $|(i - j)|$. The vector representation of a code of K chips in which M are marked to indicate pulses is as follows: the vector has form < e_1, e_2, e_3… e_M >, where e_i, for $1 \le i \le M - 1$, equals the delay between the i^{th} and $(i + 1)^{st}$ marked chip and e_M equals $K - \sum_{i=1}^{M-1} e_i$.

The procedure for generating the {n, w, s} class is as follows [24]:

1) Construct a design matrix P_1 of w × (w - 1) rows and w columns whose elements form the following design:

$$P_1 = \left[\begin{array}{l}
\left.\begin{array}{l} 1\;0\;0\;0\dots0\;0\\ 0\;1\;0\;0\dots0\;0\\ 0\;0\;1\;0\dots0\;0\\ \qquad\vdots\\ 0\;0\;0\;0\dots0\;1\end{array}\right\}\text{One “1” per row}\\
\left.\begin{array}{l} 1\;1\;0\;0\dots0\;0\\ 0\;1\;1\;0\dots0\;0\\ 0\;0\;1\;1\dots0\;0\\ \qquad\vdots\\ 0\;0\;0\;0\dots1\;1\\ 1\;0\;0\;0\dots0\;1\end{array}\right\}\text{Two “11” per row with wrap around effect}\\
\left.\begin{array}{l} 1\;1\;1\;0\dots0\;0\\ 0\;1\;1\;1\dots0\;0\\ \qquad\vdots\\ 0\;0\;0\;0\dots1\;1\\ 1\;1\;0\;0\dots0\;1\end{array}\right\}\text{Three “1” per row with wrap around effect}\\
\left.\begin{array}{l} 1\;1\;1\;1\dots1\;0\\ 0\;1\;1\;1\dots1\;1\\ \qquad\vdots\\ 1\;1\;1\;1\dots0\;1\end{array}\right\}\text{(w-1) “1”s per row with wrap around effect}
\end{array}\right]$$

2) Create a vector E = < e_1, e_2… e_w > by: first randomly selecting w-1 integers, without replacement, from [1, n-1] whose sum is less than n; then setting the first w-1 entries of E to these integers, and setting entry

$$e_w = n - \sum_{i=1}^{w-1} e_i$$

3) Perform the matrix multiplication

$$P_1 \times E^T, \text{ where } E^T \text{ is the transpose of E.}$$

The entries in the resulting vector, when transposed, are referred to as the set of delays associated with E.

4) If a vector obtained from $P_1 \times E^T$ yields distinct elements, accept E as a code.

Repeat the process of creating E for r -1 more times. After each creation, determine the vector resulting from $P_1 \times E^T$. If the entries in this vector are distinct not only from each other, but from the set of delays associated with the codes previously accepted, then accept the resulting E as a code.

Once the s vectors are chosen, to obtain the pulse pattern corresponding to each accepted vector E,

i) Mark the first chip to signify a pulse

ii) Continue to mark the frame so that the delay between the j^{th} and $(j-1)^{st}$ marked chips is e_j, $1 < j \le w$.

3.2.3 Construction of Zero Cross-Correlation Code (ZCC)

The ZCC code is represented in a matrix of K × C where K (row) represents the number of users and C (column) represents the minimum code length [25]. The matrix contains the binary coefficients. A basic ZCC code (for weight = 1) is shown below

$$Z_1 = \begin{vmatrix} 0 & 1 \\ 1 & 0 \end{vmatrix}$$

Z_1 has no overlap of 1 for both users. In order to increase the number of users and codes, a mapping technique is used as below;

$$Z_2 = \begin{bmatrix} 0 & Z_1 \\ Z_1 & 0 \end{bmatrix} = \begin{vmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{vmatrix}$$

$$Z_3 = \begin{bmatrix} 0 & Z_2 \\ Z_2 & 0 \end{bmatrix} = \begin{array}{cccc|cccc} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}$$

It can be seen from the mapping that the code length C also increases as the value of K is increased. The basic matrix is mirrored diagonally to increase K. Here 1s represents the position of spectral component or chip position in the code length. The relationships between the mapping process M, K and C is given by:

$$K = 2^M \quad \text{and} \quad C = 2^M$$

thus

$$C = K$$

The ZCC shown above has the fixed code weight that is 1. In order to make flexible code weight means to increase w, some code transformation steps need to be followed [26]. The transformation steps are:

$$Z_w = \begin{array}{c|c} A & B \\ \hline C & D \end{array}$$

where A consists of [1, w (w - 1)] matrix of zero.

B consist of w times replication of the matrix $\sum_{j=1}^{w} j[0\ 1]$.

C consists of duplication matrix from w-1.

D consists of diagonal pattern of [m × n] with alternate column of zeros matrix [m × n]

By following these steps, transformation from w = 1 → w = 2 → w = 3 is given below:

$$Z_{w=1} = \begin{array}{cc} 0 & 1 \\ 1 & 0 \end{array}$$

$Z_{w=1}$ consists of two codes with code weight 1 and code length 4.

A (↓) B (↓)

$$Z_{w=2} = \begin{array}{cc|cccc} 0 & 0 & 0 & 1 & 0 & 1 \\ \hline 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 \end{array}$$

C (↑) D (↑)

$Z_{w=2}$ consists of three codes with weight 2 and code length 6.

$$
Z_{w=3} = \begin{array}{cccccc|cccccc}
 & & \overset{A}{\downarrow} & & & & & & \overset{B}{\downarrow} & & & \\
\underline{0} & \underline{0} & \underline{0} & \underline{0} & \underline{0} & \underline{0} & \underline{0} & \underline{1} & \underline{0} & \underline{1} & \underline{0} & \underline{1} \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
 & & \underset{C}{\uparrow} & & & & & & \underset{D}{\uparrow} & & &
\end{array}
$$

$Z_{w=3}$ cosists of four codes with code weight 3 and code length 12.

From above, the relationship between K_B, C_B and w are found

$K_B = w + 1$ and $C_B = w\,(w + 1)$

where, w is the weight of code

K_B is the number of users with variable weight

C_B is the basic code length with variable weight.

Notice that the codeword corresponding to parallel lines are orthogonal to each other. To increase the number of user in simultaneously with the increasing of code weight, we can easily implement the mapping technique as described previously.

Basic code length $C_B = 2\sum_{m=1}^{w} m$

Basic number of user $K_B = w + 1$

3.4 SIMULATION SETUP

The simulation setups for OCDMA system implementing Walsh Hadamard codes, OOC and ZCC codes consisting of three users are shown in figure 3.1, 3.2 and 3.3 respectively. The continuous wave lasers are used to create the carrier signal using the combiner. For Walsh Hadamard codes four lasers are used with a wavelength range 1549.7 nm to 1550.0 nm, for OOC codes 7 lasers are used with a wavelength range 1549.7 nm to 1550.3 nm, and for ZCC codes 6 wavelengths are used with a wavelength range 1549.7 nm to 1550.2 nm. Each chip has spectral width of 0.1 nm. The carrier signal is then spectrally encoded using the various codes. The spectral encoding is done by using the optical filters. The pnseq is used to generate the random input data bit sequence at the rate of 10 Gbps. After that the coded light signal modulates the input data. The modulator is driven by the modulator driver which decides the input data format. The input data formats used here are NRZ raised cosine, NRZ rectangular, RZ raised cosine and RZ rectangular. The modulated data from all the users is combined and then sent to optical fiber of length 25 Km which is suitable for local area network. All the attenuation (i.e. 0.25 dB/Km), dispersion (i.e. 18 ps/nm-km) and non-linear effects are activated and specified according to the typical industry values to simulate the real environment as close as possible. The receiver consists of a decoder and a photo-detector. At the receiver side of the system implementing Walsh Hadamard codes, the incoming signal splits into two parts, one to decoder that has an identical filter structure with the encoder and the other that has the complementary filter structure. A photodiode is used for optical to electrical conversion which is placed after the filter. A subtractor is then used to subtract the overlapping data from the intended code. For OOC and ZCC codes, direct decoding technique is implemented which require a single input only to receiver as compared to the technique used for Walsh codes. It will reduce the number of filters required at the receiver side. The decoded signal finally arrives at optical receiver, the BER tester and an eye diagram analyzer. The Scope2 has been used to take the plot of Eye pattern at the receiver end. Bit error rate values have been taken from BER Estimator. The received power is measured using Electrical power meter. The system has been redesigned for different modulation formats.

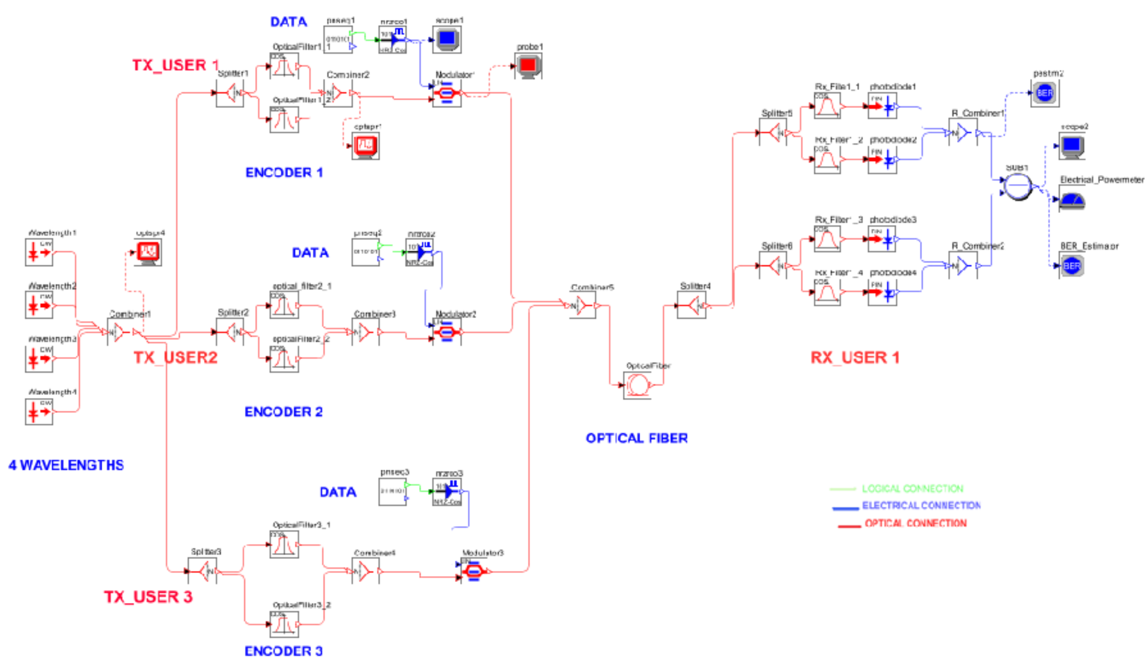


Figure 3.1: An OCDMA system implementing Walsh Hadamard codes

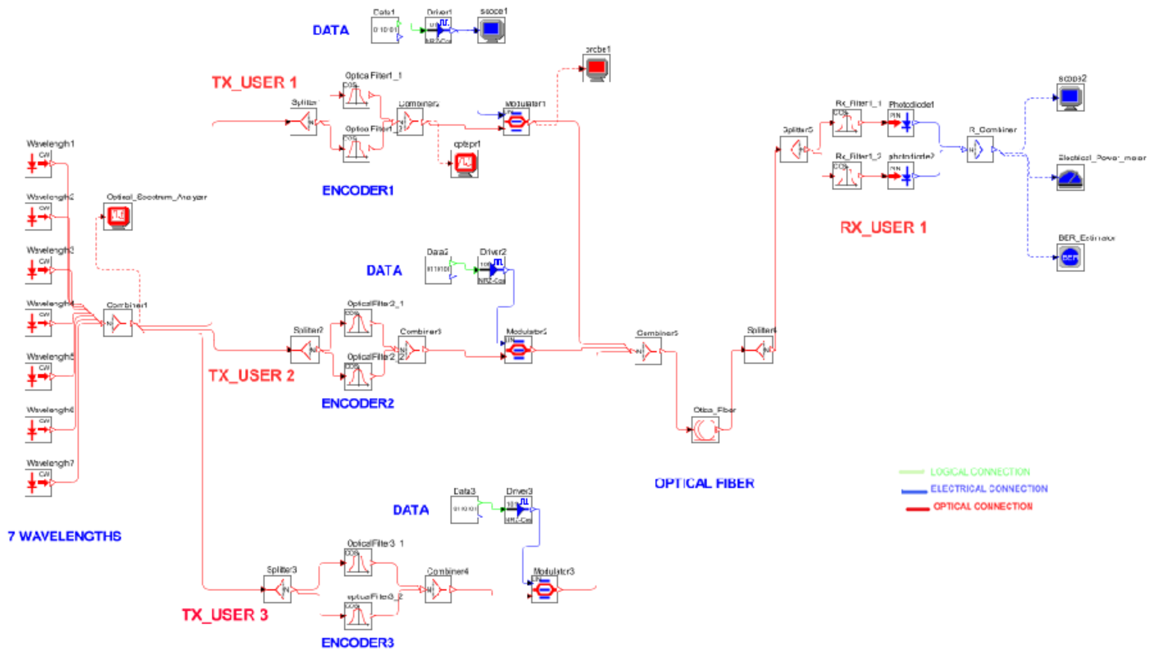


Figure 3.2: An OCDMA system implementing OOC codes

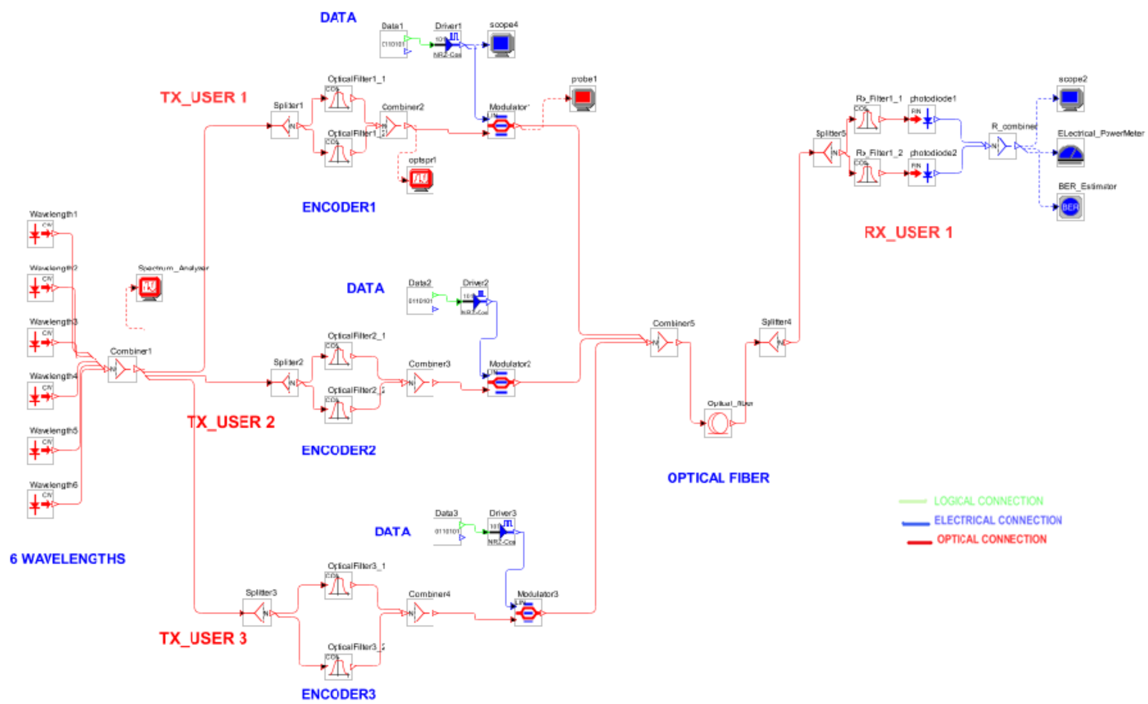


Figure 3.3: An OCDMA system implementing ZCC codes

3.5 RESULTS AND DISCUSSION

Using simulation setup the value of bit error rate (BER), wavelength spectrum, eye diagrams, optical power are measured. Optical spectrum analyzer measures the input wavelength spectrum. Eye diagrams are measured at receiver end by using scope2. BER is measured at the receiver end by using the BER estimator. With the help of electrical power meter, received power is measured at receiver side.

Figure 3.4 shows optical spectrum for Walsh Hadamard codes. The four frequency peaks shown are used to modulate the data bits using spectral encoding for three simultaneously active users.

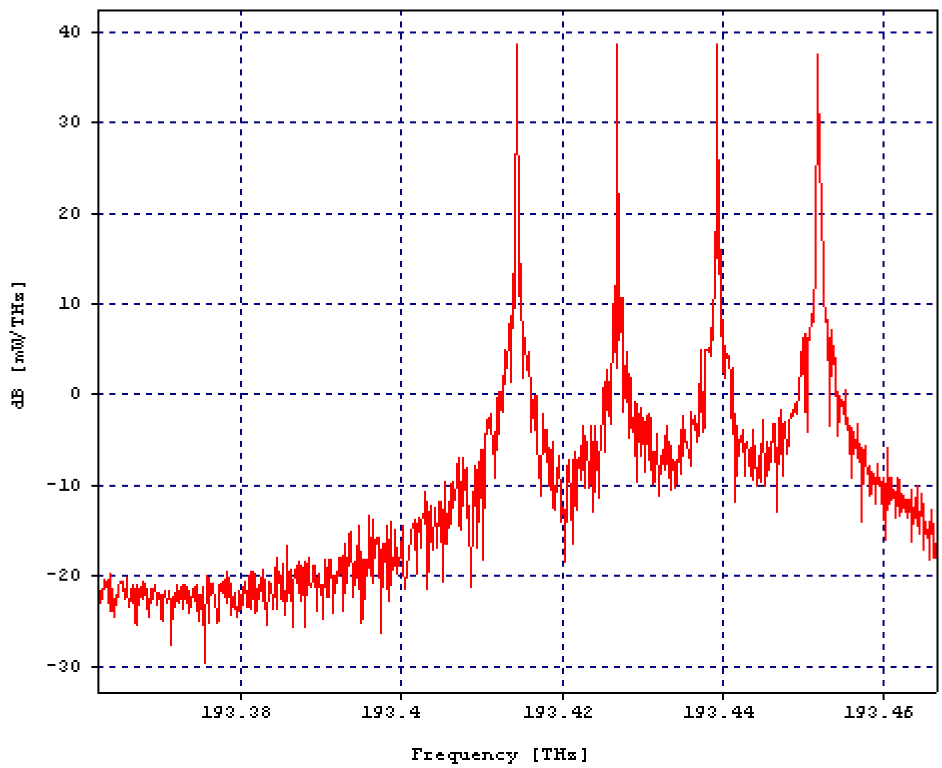


Figure 3.4: Optical spectrum used for Walsh Hadamard codes

Figure 3.5 shows the variation of BER with respect to bit-rate for NRZ raised cosine, NRZ rectangular, RZ raised cosine and RZ rectangular data modulation formats using Walsh Hadamard codes. It can be seen that out of the four modulation formats used, NRZ raised cosine has somewhat better BER. The overall BER for the Walsh Hadamard codes is very high.

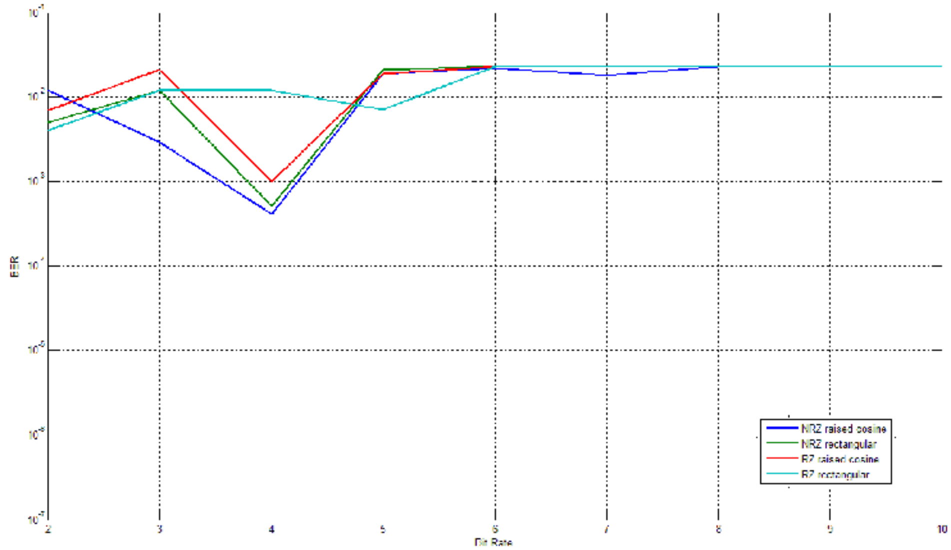


Figure 3.5: BER versus Bit-rate for various modulation formats using Walsh Hadamard codes

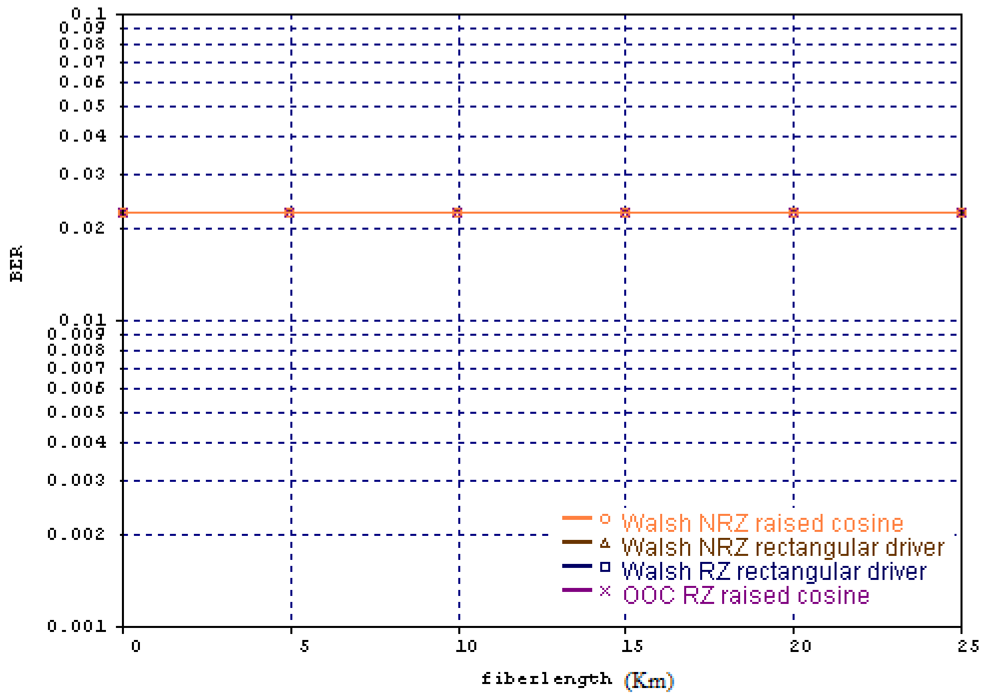


Figure 3.6: BER versus Fiber length for various modulation formats Walsh Hadamard codes

Figure 3.6 shows the graph between BER and fiber length using Walsh Hadamard codes for various modulation formats. It can be seen that all lines are constant over the fiber length and overlap each other. The constant line means that BER is very high and truncated to the value .02275 for all the data formats.

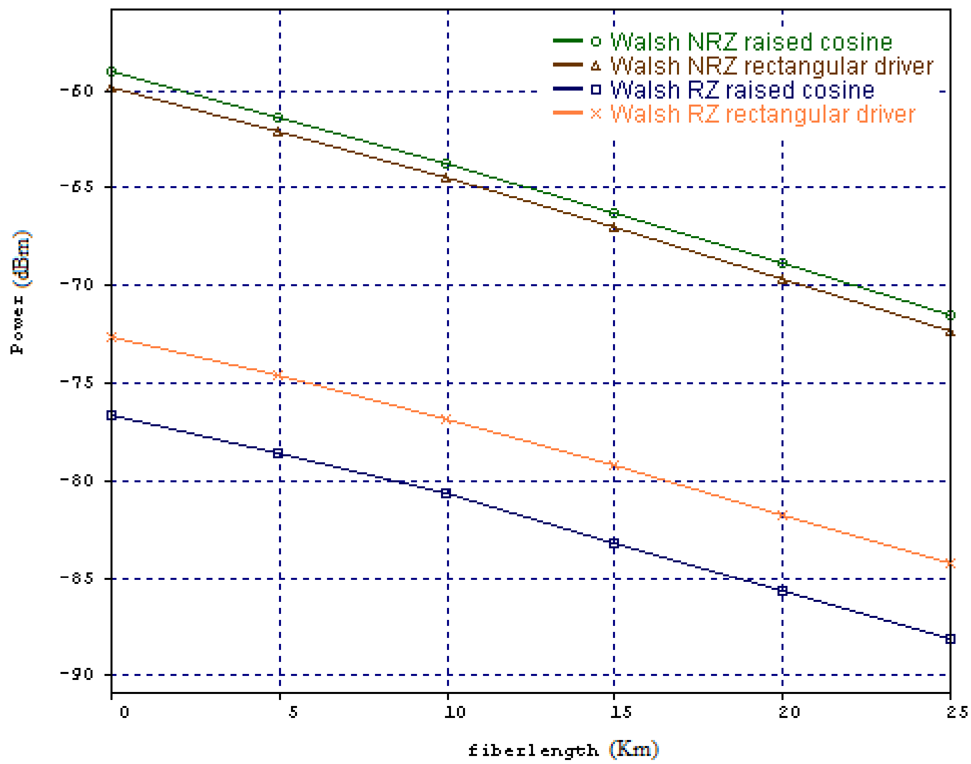


Figure 3.7: Received power versus Fiber length for various modulation formats using Walsh Hadamard codes

Figure 3.7 shows variation of received power over fiber length for various data formats when Walsh Hadamard codes are used. It can be seen that for all the modulation formats, power is uniformly decreasing with the increase in fiber length but NRZ raised cosine has the maximum power.

Figure 3.8 shows optical spectrum for Optical Orthogonal codes. The seven frequency peaks shown are used to modulate the data bits using spectral encoding for three simultaneously active users.

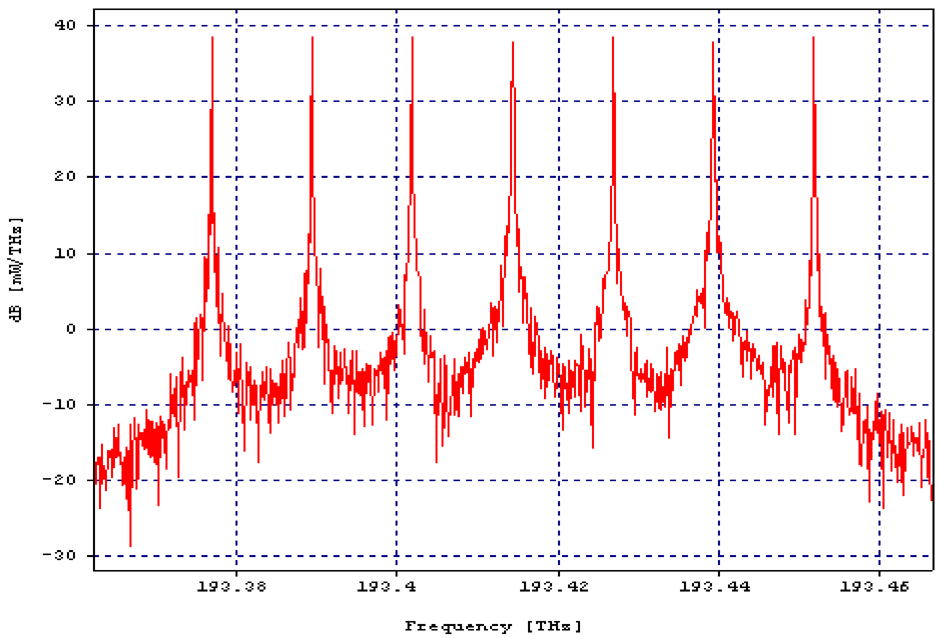


Figure 3.8: Optical spectrum used for Optical Orthogonal codes.

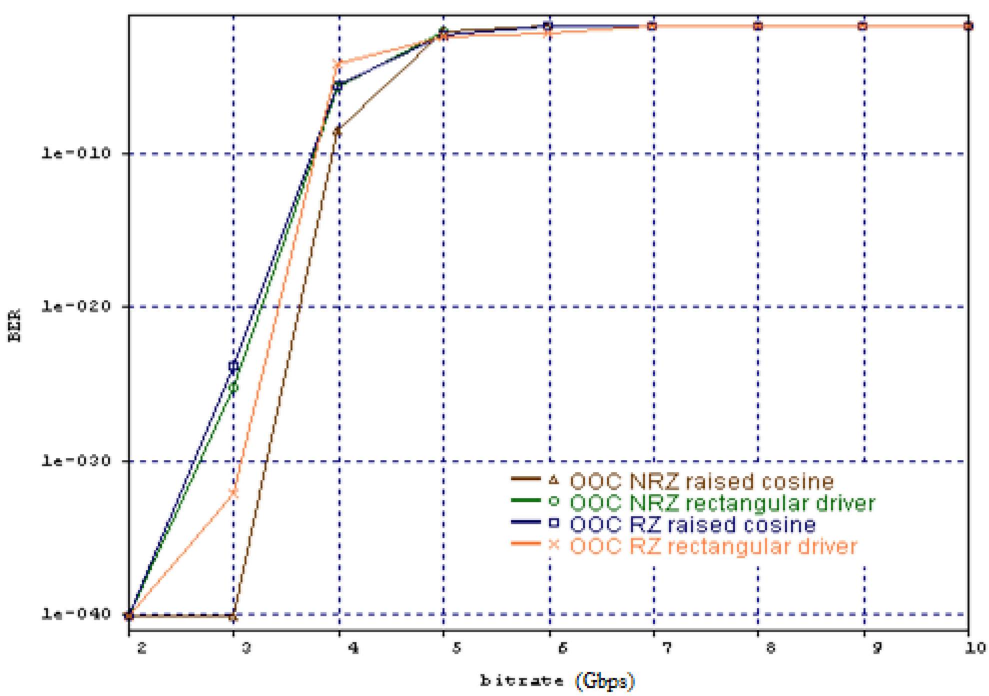


Figure 3.9: BER versus Bit-rate for various modulation formats using Optical Orthogonal codes

Figure 3.9 shows the variation of BER with respect to bit-rate for NRZ raised cosine, NRZ rectangular, RZ raised cosine and RZ rectangular data modulation formats using OOC codes. The BER is increasing from 2 Gbps to 6Gbps bit-rate and after that a constant line is observed. It can be seen that out of the four data formats, NRZ raised cosine has the lowest BER.

Figure 3.10 shows the variation of the BER over the fiber length using OOC codes for different modulation formats. It can be seen that BER is first increasing and then becomes constant for NRZ data formats but for RZ data formats a constant line is observed throughout the fiber length. The constant line means that BER is very high and truncated to the value .02275. So, the NRZ raised cosine has the lowest BER.

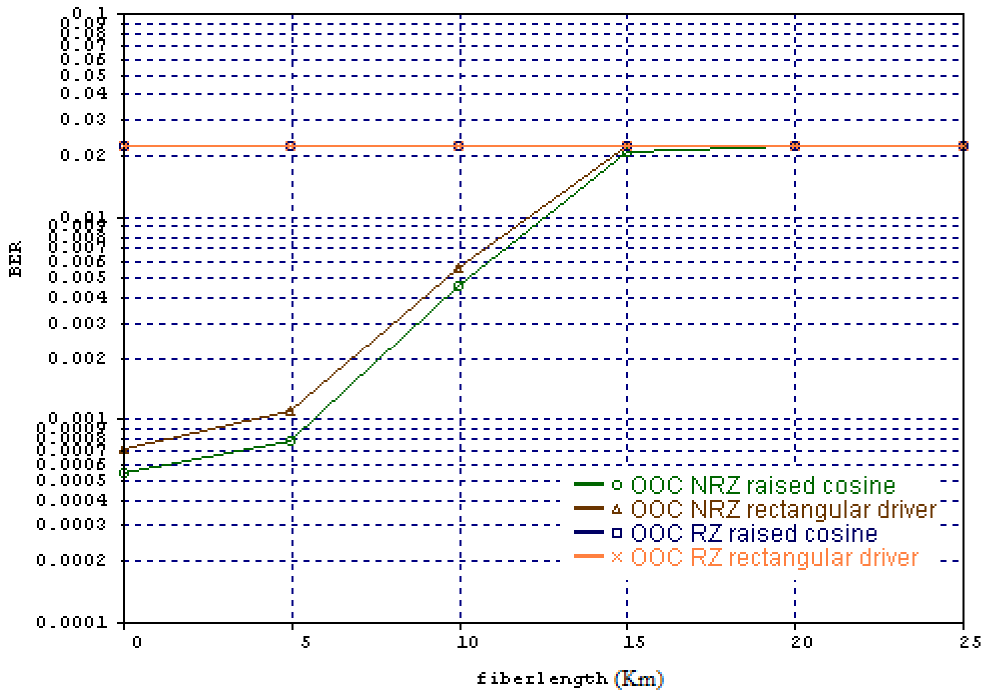


Figure 3.10: BER versus Fiber length for various modulation formats using Optical Orthogonal codes

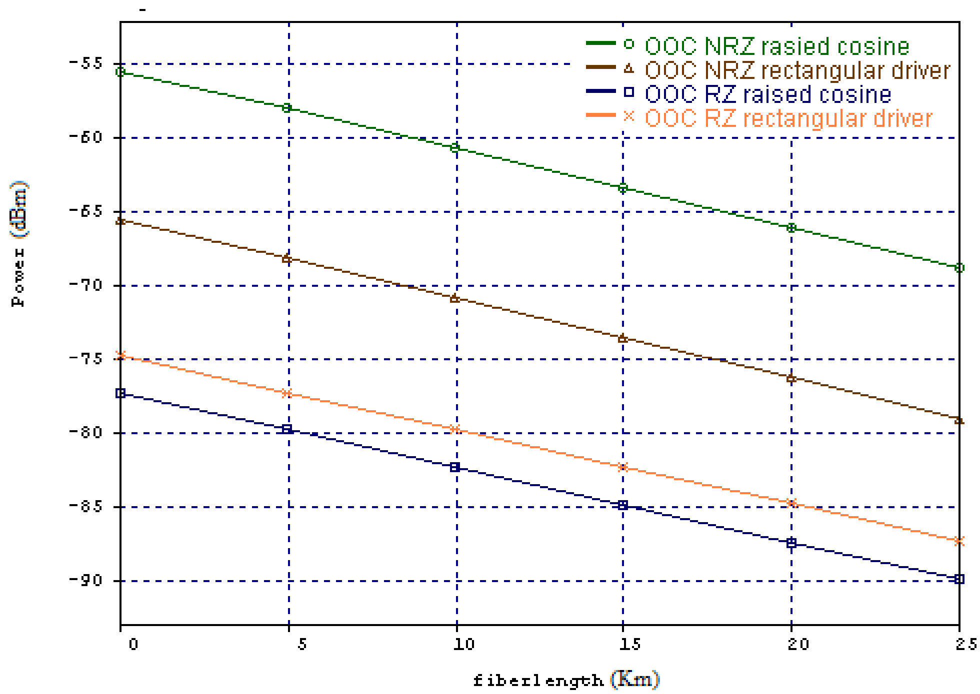


Figure 3.11: Received power versus Fiber length for various modulation formats using Optical Orthogonal codes

The variation of received power over fiber length for various data formats, when OOC codes are used is shown in figure 3.11. It can be seen that for all the modulation formats, power is constantly decreasing with the increase in fiber length but NRZ raised cosine has the maximum power.

Figure 3.12 shows optical spectrum for Zero Cross Correlation codes. The seven frequency peaks shown are used to modulate the data bits based on spectral encoding for three simultaneously active users.

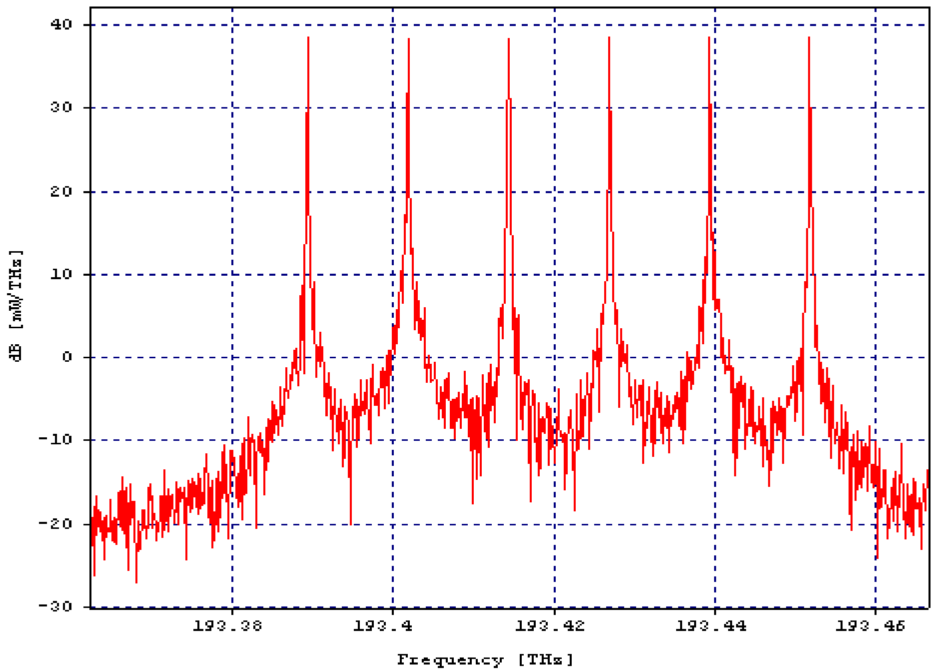


Figure 3.12: Optical spectrum used for Zero cross correlation codes

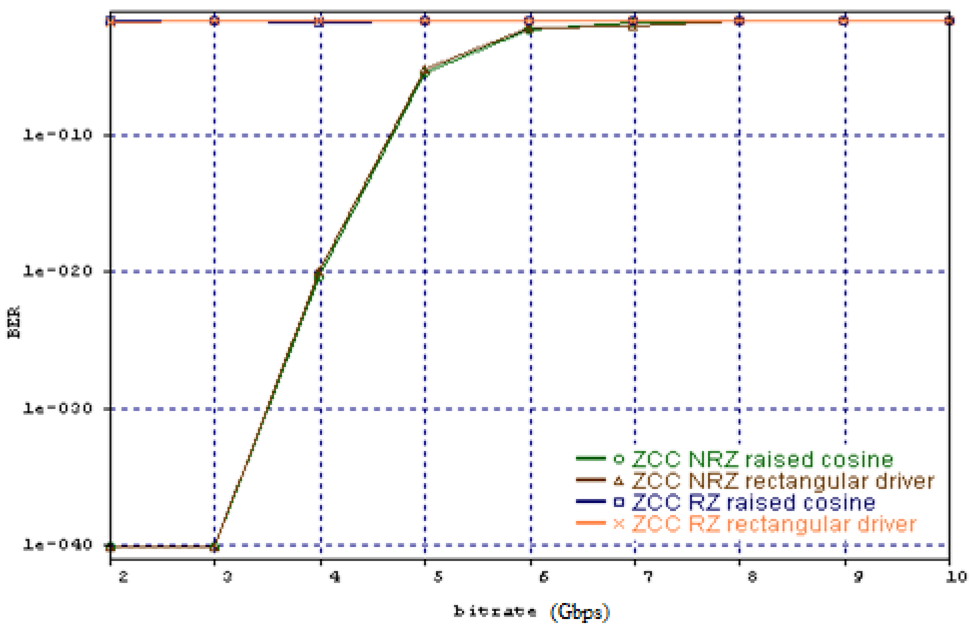


Figure 3.13: BER versus Bit-rate for various modulation formats using Zero cross correlation codes.

The variation of BER with respect to bit-rate for various data modulation formats is shown in the figure 3.13 using ZCC codes. For NRZ raised cosine, the BER is increasing from 2 Gbps to 7Gbps bit-rate and after that a constant line is observed and it is constant for both of the RZ formats. It can be seen that out of the four data formats, NRZ raised cosine has the lowest BER. The constant line means that BER is very high and truncated to the value .02275.

Figure 3.14 shows the variation of the BER over the fiber length using ZCC codes for different modulation formats. It can be seen that NRZ raised cosine has the lowest BER out of the four data formats.

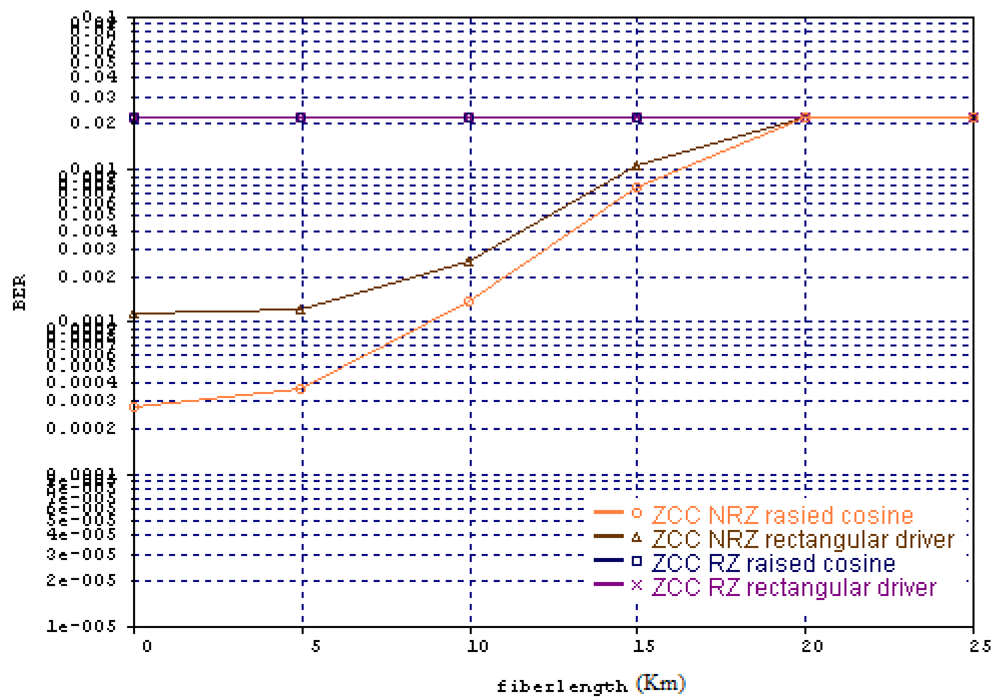


Figure 3.14: BER versus Fiber length for various modulation formats using Zero cross correlation codes

Figure 3.15 shows the plot between the received power and fiber length for various data formats using ZCC codes. It can be seen that power is decreasing constantly with the increase in fiber length for all the data modulation formats. Out of all the formats, NRZ raised cosine has the maximum power.

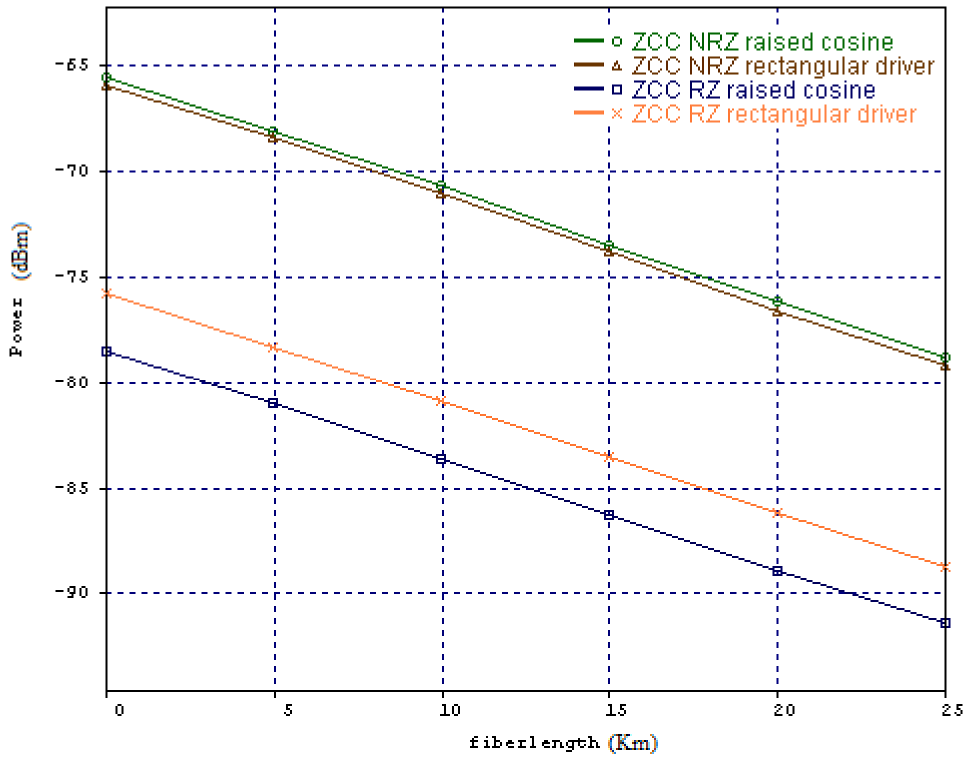


Figure 3.15: Received power versus Fiber length for various modulation formats using Zero cross correlation codes

From all of the above comparisons, it is observed that NRZ modulation format has better performance than RZ for all of the codes used. Out of both NRZ formats, NRZ raised cosine has the lowest BER. Hence, NRZ raised cosine can be recommended for the distances suitable for local area networks using OCDMA system at very high bit rates.

Now, the comparison of different 1-D codes which are Walsh Hadamard codes, OOC and ZCC codes is done using the NRZ raised cosine data format. Figure 3.16, 3.17 and 3.18 shows the eye diagrams for Walsh Hadamard codes, OOC codes and ZCC codes respectively. There is very small eye opening for Walsh Hadamard codes and it has very high BER which is truncated to the value .02275. Using the OOC codes, the eye opening increases and the BER is of the order 10^{-2}. The eye opening further increases using the ZCC codes. The BER for the ZCC codes is of the order 10^{-6}.

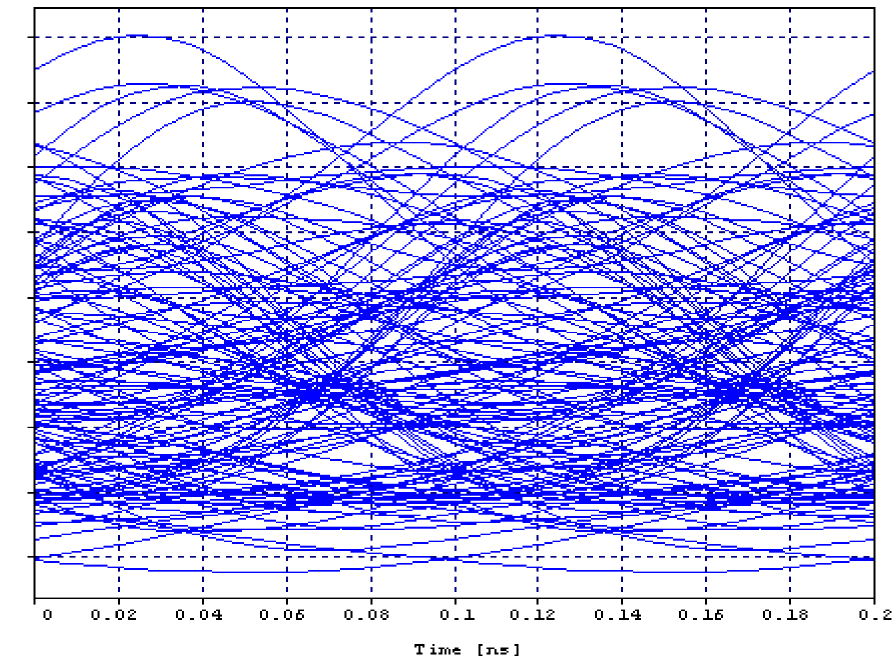


Figure 3.16: Eye diagram using Walsh codes.

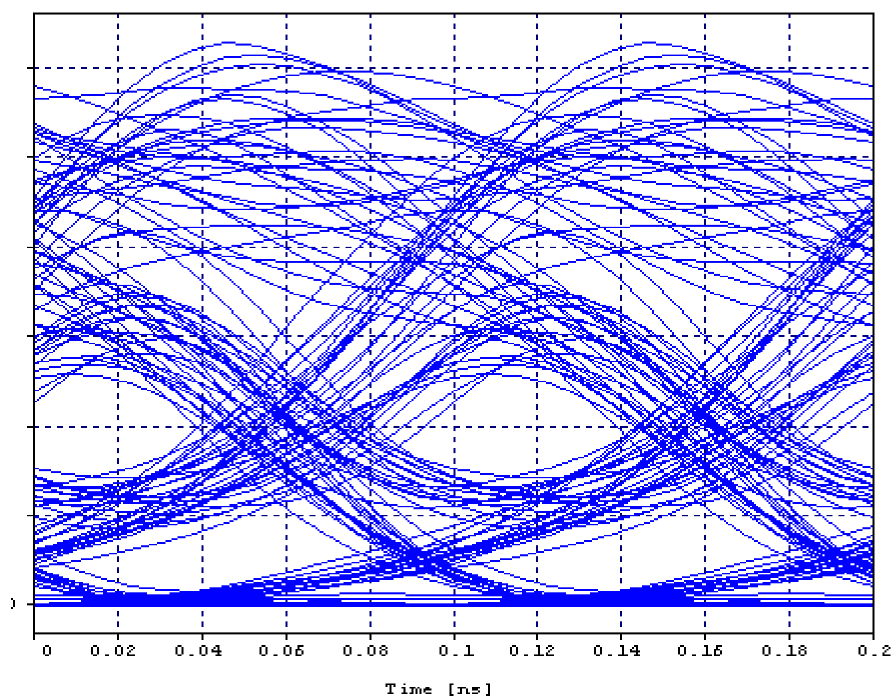


Figure 3.17: Eye diagram using OOC codes

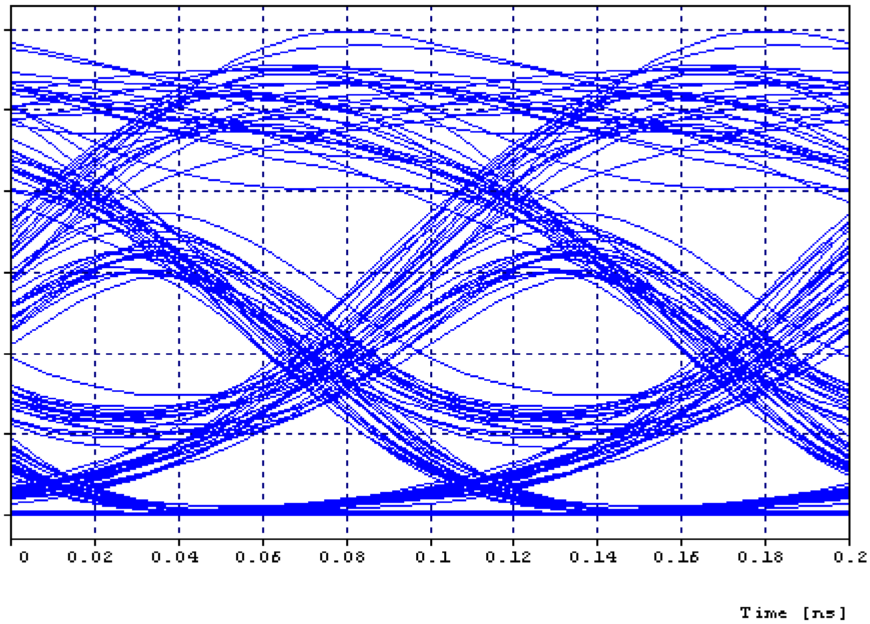


Figure 3.18: Eye diagram using ZCC codes

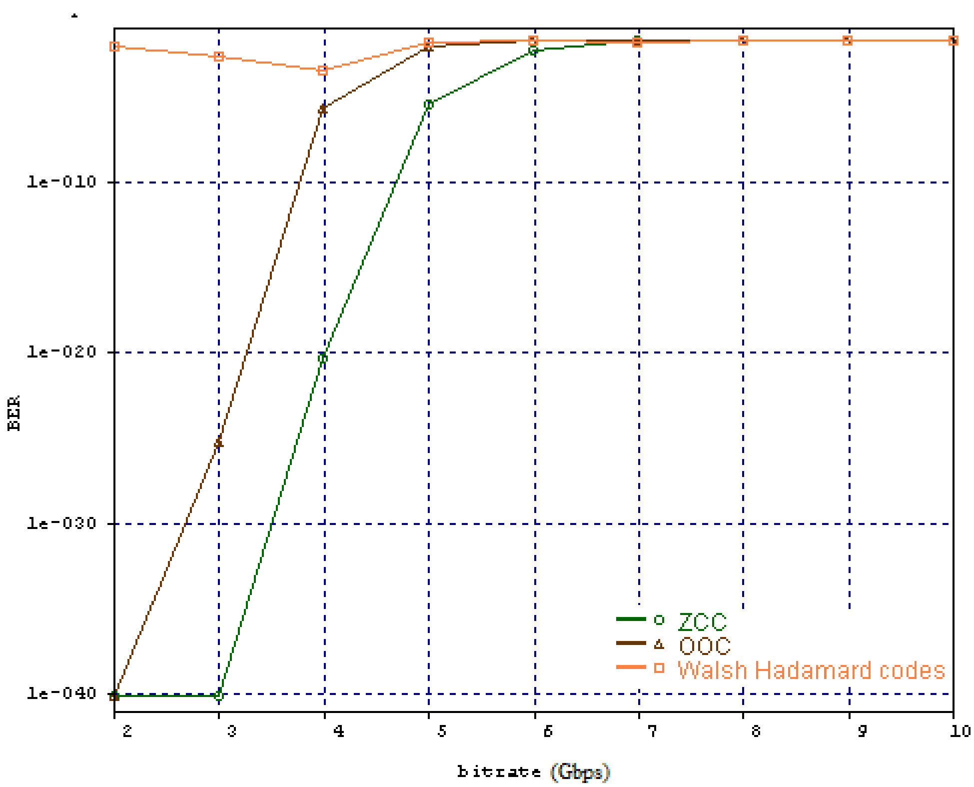


Figure 3.19: BER versus Bit-rate for various 1-D codes

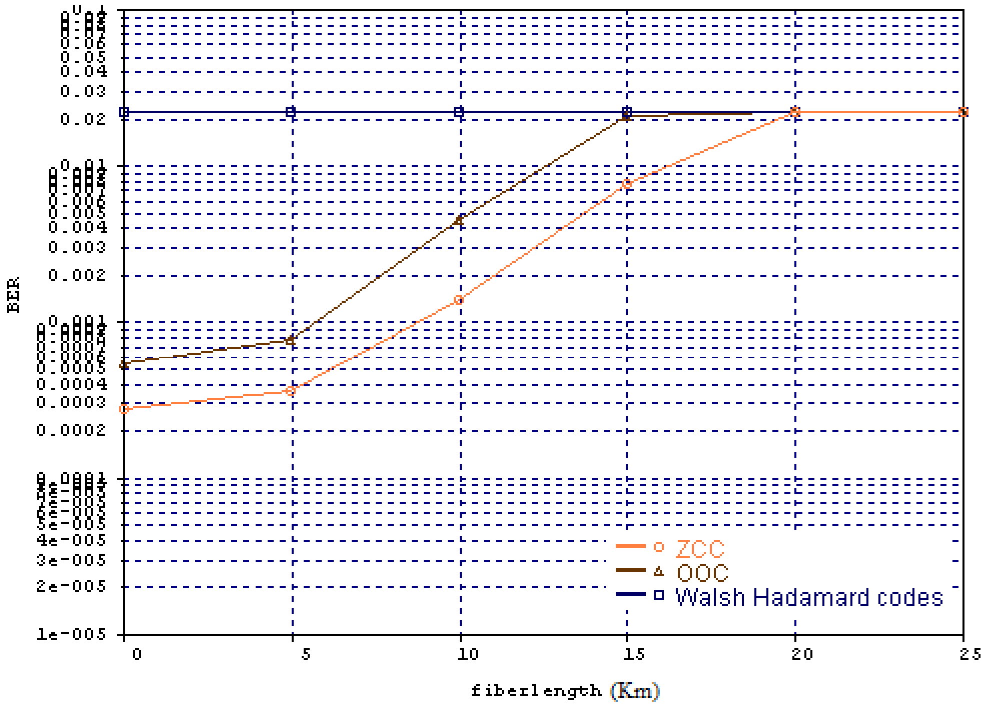


Figure 3.20: BER versus Fiber Length for various 1-D codes

Figure 3.19 shows the variation of BER at different bit-rates and figure 3.20 shows the variation of BER over different fiber length for the three different codes. It can be seen that ZCC has the lowest BER in both the cases. This is because the ZCC codes have zero cross correlation between them while the OOC codes and Walsh Hadamard codes have minimum cross correlation of one.

Figure 3.21 shows variation of received power over fiber length for Walsh Hadamard codes, OOC and ZCC codes using the NRZ raised cosine modulatin format. It can be seen that for all the codes used, power is uniformly decreasing with the increase in fiber length but ZCC has the maximum power.

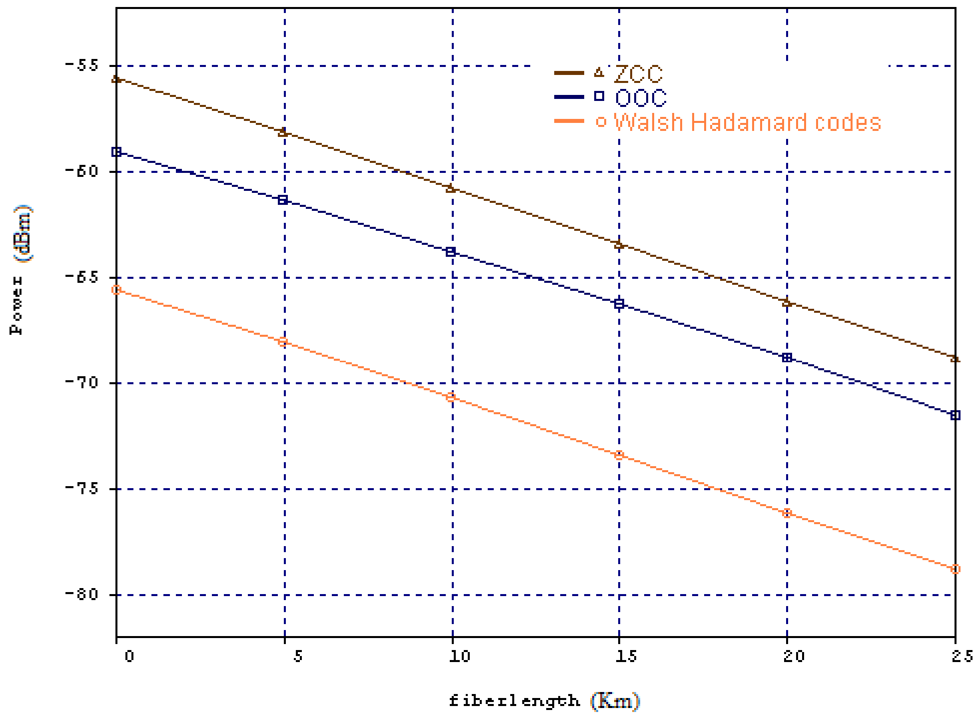


Figure 3.21: Received power versus Fiber length for various 1-D codes

3.6 CONCLUSION

In this chapter, the design, implementation and performance analysis of various one dimensional codes in OCDMA system for different data formats is presented. The comparison of Walsh Hadamard codes, OOC and ZCC using various data formats revealed that the NRZ modulation format has the edge over the RZ modulation format in OCDMA systems. It is found that the NRZ raised cosine has lowest BER value and better system performance. Hence, NRZ raised cosine can be recommended for the distances suitable for local area networks using OCDMA systems at high bit rates. The analytical results revealed that ZCC code has a superior code property of zero cross correlation. It can be seen from the values of the BER, an eye opening and the received power, that the ZCC code gives the best performance compared to Walsh Hadamard and OOC codes. Hence, it is concluded that the ZCC codes are most suitable to be employed in the OCDMA systems using NRZ raised cosine data format.

CHAPTER 4

DESIGN AND IMPLEMENTATION OF TWO DIMENSIONAL WAVELENGTH/TIME CODES FOR OCDMA SYSTEM

In this chapter, two dimensional wavelength/time codes are designed and implemented. The two dimensional (2-D) codes are constructed by a technique based on folding of Golomb rulers. The performance evaluation of OCDMA system based on wavelength/time code has been analyzed by measuring the values of bit error rates and eye diagrams for different number of active users. It is shown that eye opening decreases and BER increases with increase in number of active users. It is also shown that BER further increases with increase in number of active users when number of decoders increases on receiver side. Hence, it is concluded that MAI is the dominant source of BER and there is graceful degradation in system performance when number of simultaneously active users increases. The received optical power is also measured at different transmission distance. It has been observed that received optical power decreases with increase in length of fiber due to attenuation.

4.1 INTRODUCTION

As a core of an OCDMA system, various different types of optical codes have been proposed and studied for various OCDMA technologies: one-dimensional (1-D) codes which spread in time [9] or in frequency [11] and two-dimensional (2-D) codes which spread in both time and wavelength [27]. Wavelength-hopping time-spreading (WHTS) system is a 2-D coding approach that spreads the codes in both the time and wavelength domains simultaneously [28]. The general schematic of an OCDMA network is shown in figure 4.1. The two main elements of the transmitter are the source and the encoder while the receiver consists of the decoder and the receiver electronics. In 2-D OCDMA, pulses are placed in different chips across the bit period and each chip is of different wavelength, thus following a wavelength-hopping pattern, achieving increased code design flexibility as well as code performance. Thus, WHTS codes can be represented as code matrices with time and wavelength as its two axes—the wavelength domain is divided into N_i wavelength channels and the time domain is divided into N_T chips [10]. In this all active users share the same wavelength and time domain space, providing a fair division of the bandwidth. It provides truly asynchronous access, which in turn greatly simplifies network control and management.

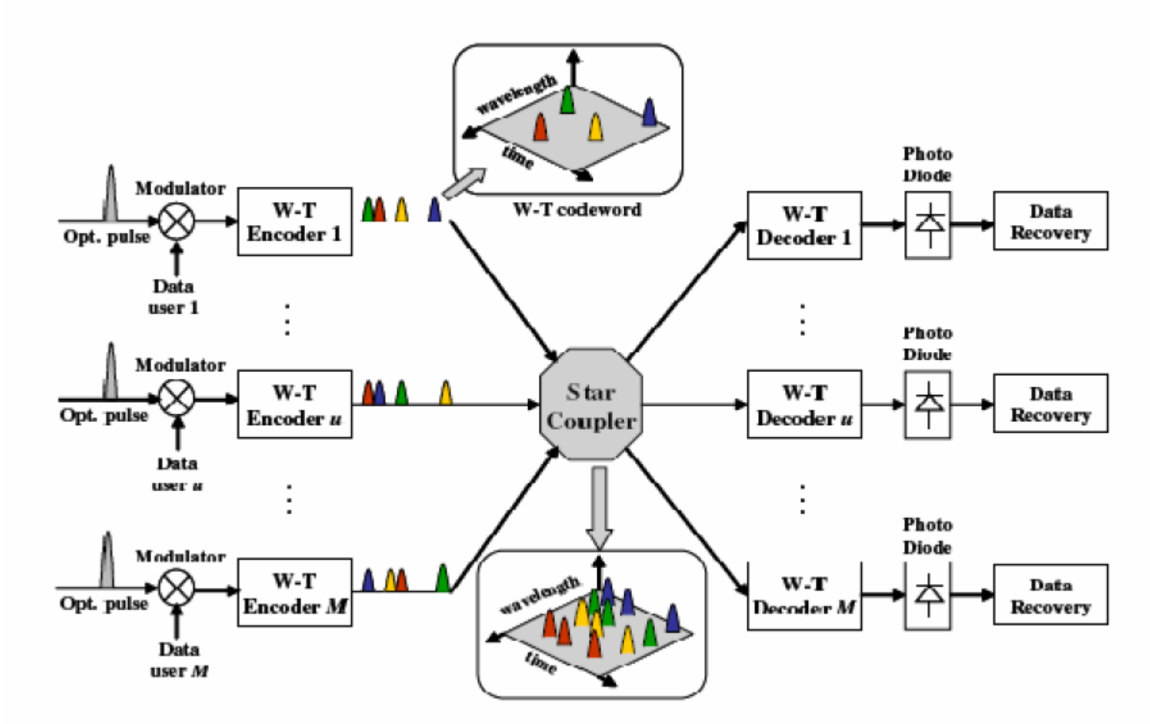


Figure 4.1: A typical wavelength-time OCDMA network [29]

In spite of the use of orthogonal codes, the main effect limiting the effective signal-to-noise ratio of the overall system is the interference resulting from the other users transmitting at the same time, which is called Multiple Access Interference (MAI). MAI is the major source of noise in OCDMA systems [18]. The number of users in a WHTS OCDMA network has a soft limit with a graceful degradation of performance with increasing number of users [10].

Antonio J. Mendez et al. [2] presented a technique for generating PSO matrices from sets of optimum Golomb rulers. It is shown that 2-D codes have higher cardinality and good spectral efficiency, especially when compared to linear or direct sequence code. This paper describes the design and construction of the matrices; analyzes their performance from a communications viewpoint; describes their use as codes for the asynchronous, concurrent communication of multiple users; and analyzes the bit error rate performance based on capturing and modeling a typical network topology and performing a numerical modeling of the system.

S. Yegnanarayanan et al. [27] demonstrated a new technique for implementation of fast wavelength-hopping incoherent OCDMA. The output pulse from a mode locked laser is spectrally broadened through super-continuum generation. This pulse is then encoded into fast wavelength-hopped time-spread waveforms through a wavelength-selective time-delay device. A 1-Gb/s digital transmission experiment through a 15-km dispersion-shifted single-mode fiber link is presented. This technique avoids the need for a fast wavelength tunable optical source.

Mendez et al. [33] demonstrated that 2-D wavelength/time codes have better SE than one-dimensional (1-D) CDMA/WDM combinations (of the same cardinality). Then, the paper described a specific set of wavelength/time codes and their implementation. The 2-D codes have high performance because they simultaneously have high cardinality >>10), per-user high bandwidth (>1 Gb/s), and high SE (>0.10 b/s/Hz). The physical implementation of these W/T codes is described and their performance evaluated by system simulations and measurements on an OCDMA technology demonstrator. This research shows that OCDMA implementation complexity (e.g., incorporating double hard-limiting and interference estimation) can be avoided by using a guard time in the codes and an optical hard limiter in the receiver.

Vincent J. Hernandez et al. [34] described a technology demonstrator for an incoherent optical code-division multiple-access scheme based on wavelength/time codes. The system supports 16 users operating at 1.25 Gsymbols/s/user while maintaining bit-error rate (BER) 10^11 for the correctly decoded signal. Experiments support previous simulations which show that coherent beat noise, occurring between the signal and multiple access interference, ultimately limits system performance.

Up till now, various approaches have been suggested for design of 2-D codes and performance analysis is done for the increase in number of users on the transmitter side only. In this chapter, 2-D matrix codes are constructed using folded Golomb ruler and their performance analysis is done for the increase in number of users at both transmitter and receiver side.

The chapter is divided into different sections. In the first section, the brief introduction about the two dimensional W/T codes is presented. In second section, an analytical model is proposed. In the third section, construction of 2-D matrix codes based on folded Golomb ruler is presented. The fourth section describes the simulation setup for OCDMA system implementing 2-D W/T matrix codes. The fifth section includes the simulation results and the results have been discussed. The sixth section gives the conclusion of this chapter.

4.2 ANALYTICAL MODEL

An (n, w, λ_a, λ_c) optical orthogonal code C is a set of (0, 1) sequences of length n and weight w (the number of ones in every codeword). The size of the code is the number of codewords in C and is called its cardinality. The set is constructed so that it has the following two properties [21].

The Auto-Correlation Property

$$\sum_{t=0}^{n-1} x_t \, x_{t+\tau} \leq \lambda_a$$

for any $x \in C$ and any integer τ, 0 < t < n.

The Cross-Correlation Property

$$\sum_{t=0}^{n-1} x_t \; y_{t+\tau} \leq \lambda_c$$

for any $x \neq y \in C$ and any integer τ.

λ_a is the auto correlation and λ_c is the cross correlation constraints.

The autocorrelation of each sequence in the optical orthogonal code exhibits the thumbtack shape and the cross correlation between any two sequences remain low throughout [21]. Since each sequence *x* has the weight w, the autocorrelation equals w when $\tau = 0$. Thumbtack-shaped auto-correlation enables the effective detection of the desired signal and low-profiled cross-correlation makes it easy to reduce interference due to other users and channel noise.

4.3 CONSTRUCTION OF 2-D MATRIX CODES

A technique based on the "folding" of spanning rulers or optimum Golomb rulers [29] to generate pseudo orthogonal matrix codes is explained is given below.

A spanning ruler or optimum Golomb ruler is a (0, 1) pulse sequence where the distances between any of the pulses is a non-repeating integer. The optimum Golomb ruler **g(1,7)** of cardinality 1, weight 7, and length 26 [31] is shown at the top of figure 4.2. After that a table is shown containing the ruler and three shifted versions (all in bold) of the ruler. To make up the code dimension (CD) of 32 filler zeros are used in the table.

g (1,7)=

1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1

Mi from g(1,7)

	Column 1 (C1)				Column 2 (C2)				Column 3 (C3)				Column 4 (C4)				Column 5 (C5)				Column 6 (C6)				Column 7 (C7)				Column 8 (C8)			
	r1	r2	r3	r4	r1	r2	r3	r4	r1	r2	r3	r4	r1	r2	r3	r4	r1	r2	r3	r4	r1	r2	r3	r4	r1	r2	r3	r4	r1	r2	r3	r4
M1=	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0
M2=	0	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0
M3=	0	0	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0
M4=	0	0	0	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0

M1

	C1	C2	C3	C4	C5	C6	C7	C8
r1	1	1	0	0	0	0	0	0
r2	1	0	0	0	0	0	1	0
r3	0	0	1	0	1	0	0	0
r4	0	0	0	0	0	1	0	0

M2

	C1	C2	C3	C4	C5	C6	C7	C8
r1	0	0	0	0	0	0	1	0
r2	1	1	0	0	0	0	0	0
r3	1	0	0	0	0	0	1	0
r4	0	0	1	0	1	0	0	0

M3

	C1	C2	C3	C4	C5	C6	C7	C8
r1	0	0	0	1	0	1	0	0
r2	0	0	0	0	0	0	1	0
r3	1	1	0	0	0	0	0	0
r4	1	0	0	0	0	0	1	0

M4

	C1	C2	C3	C4	C5	C6	C7	C8
r1	0	1	0	0	0	0	0	1
r2	0	0	0	1	0	1	0	0
r3	0	0	0	0	0	0	1	0
r4	1	1	0	0	0	0	0	0

Figure 4.2: Constructing the four pseudo-orthogonal (PSO) matricesM1. . .M4 from the single optimum Golomb ruler g(1,7) [2].

The CD is determined as follows [2]: The Golomb rulers are shifted as shown in figure 2 which indicates that the result should be a matrix of dimensions CD = r*C, where r*C > L. Here "r" is the number of rows, "C" is the number of columns, and L is the length of the Golomb ruler. Then possible shifts are r*C - L; hence the number of new matrices depends on the two parameters. One is initial Golomb ruler length L and second is the number of shifts permitted by the product r*C. In order to assure that the matrix code set size M is equal to the number of rows in the matrices the following condition should be fulfilled.

$$r * C - L \geq r - 1$$

During the design process, chose the dimension "r" first and it's should be a multiple of two because of optical component (e.g., coupler or WDM multiplexer/ demultiplexer) characteristics.

Returning to figure 4.2, given L = 26 and assuming r = 4 and trials C = 7, 8. When C = 7, then r*C = 4*7 = 28 gives M = 28-26+1 = 3, and for C = 8, r*C = 4*8 = 32 gives M = 32-26+1 = 7. Out of 7, 4 shifts produce new OOC matrices and remaining three shifts that do not produce new OOC matrices due to the cyclic nature of the operation. Hence the value of M is taken as 4. Increasing the CD by increasing the number of columns does not increase M due to cyclic nature of shifting process. Thus, with r = 4, 32 is the optimum CD with C = 8, maximizing both the matrix code set size M.

The headings in Mi of figure 4.2 define the column and row to which the table entries should be transposed. Take the transpose of column 1 of Mi to make the C1 of matrix M1. Similarly transpose the column 2 of Mi to make C2 of matrix M1 and so on. The un-shifted ruler, with column/row algorithm, defines the new matrix M1; the shifted rulers, define M2-M4; these are shown at the bottom of the figure. The resulting matrices are optical orthogonal codes (OOC).

g1(4,4)=

1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1

g2(4,4)=

1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0

g3(4,4)=

1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0

g4(4,4)=

1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0

Mi from g1(4,4)

	Column 1 (C1)								Column 2 (C2)							
	r1	r2	r3	r4	r5	r6	r7	r8	r1	r2	r3	r4	r5	r6	r7	r8
M1=	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
M2=	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
M3=	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
M4=	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
M5=	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
M6=	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0
M7=	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
M8=	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1

	Column 3 (C3)								Column 4 (C4)							
	r1	r2	r3	r4	r5	r6	r7	r8	r1	r2	r3	r4	r5	r6	r7	r8
M1=	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
M2=	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
M3=	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
M4=	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
M5=	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
M6=	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
M7=	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
M8=	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1

Figure 4.3: Constructing 32 PSO matrices M1. . .M32 with eight rows and four columns from the set of four optimum Golomb rulers g1(4,4) . . . g4(4,4) [2].

The ruler-to-matrix transformation [32] enhances cardinality (code set size) and while preserving the OOC property. This transformation increases the cardinality (n versus n*r) from one (1) to four (4).

The concept of folded optimum Golomb rulers is extended by using sets containing more than one optimum Golomb ruler to target matrices with eight time slots and eight wavelengths. A set of optimum Golomb rulers (**g1(4,4)**, **g2(4,4)**, **g3(4,4)**, and **g4(4,4)**) of cardinality four and weight four [31] is shown in the upper portion of figure 3. The ruler **g1(4,4)** thus generates the matrix **M1**, **g2(4,4)** generates **M9**; **g3(4,4)** generates **M17** , and **g4(4,4)** generates **M25** [33]. Cyclic row shifting allows M1 to produce M1…M8 ; M9 produces M10…M16 ; M17 produces M18…M24 and M25 produces M26…M32. The eight shifted versions of **g1(4,4)** are shown in bottom portion of figure 3. Now same method is used with these shifted versions as in the previous example to generate the eight OOC matrices of figure 4.4.

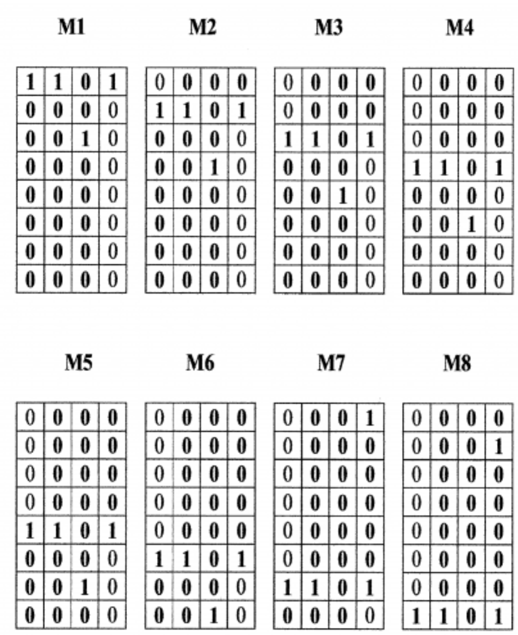


Figure 4.4: The eight OOC matrices M1. ..M8 generated from the optimum Golomb ruler g1(4,4) [2].

The initial set of four optimum Golomb rulers folded into eight-row matrices produces 32 OOC matrices based on the ruler-to-matrix construction. It should be noted that the cardinality goes from four to 32.

TABLE 4.1-THE 32 PSO MATRIX CODES INTERPRETED AS W/T MATRIX CODES

Wavelength	Time Slots(s)			
(W)	1	2	3	4
1	**1**,**9**,17,25	**1**,14,29	19,24,26	**1**,7,10,11,20,32
2	2,10,18,26	2,15,17,30	20,25,27	2,8,11,12,21
3	3,11,19,27	3,16,18,31	**1**,21,26,28	3,12,13,22
4	4,**9**,12,20,28	4,19,32	2,22,27,29	4,13,14,23
5	5,10,13,21,25,29	5,20	3,23,28,30	5,14,15,24
6	6,11,14,22,26,30	6,21	4,17,24,29,31	6,15,16
7	7,12,15,23,27,31	7,17,22	5,**9**,18,30,32	7,16
8	8,13,16,24,28,32	8,18,23,25	6,**9**,10,19,31	8

The PSO matrices are converted to wavelength/time (W/T) codes by associating the rows of the PSO matrices with wavelength (or frequency) and the columns with time-slots, as shown in Table 1. The matrices M1… M32 are numbered 1… 32 in the table, with the corresponding assignment of wavelengths and time-slots. The codes M1 and M9 are shown bold in table. The code M1 is represented as (λ_1; λ_1; λ_3; λ_1) and M9 as (λ_1, λ_4; 0; λ_7, λ_8; 0); here the semicolons separate the timeslots in the code. In code M9 there are two wavelengths (λ_1, λ_4) in time-slot 1 and no wavelength is allotted in time-slot 2 . M1 shows extensive wavelength reuse, and codes M9 shows extensive time-slot reuse. It is the extensive wavelength and time-slot reuse that gives these matrix codes their high cardinality.

4.4 SIMULATION SETUP

The simulation setup for OCDMA system implementing 2-D wavelength/time (W/T) matrix codes [34] is shown in figure 5. The mode locked laser is used for generating pulses of pulse width of 100ps at a repetition rate equal to data rate of the system. The data rate of the system is 1.25 Gbps. The wavelengths range from 1543.74 nm to 1549.34 nm, with 0.8nm wavelength spacing. Eight mode-locked lasers (wavelengths 1 to 8) are used to create a dense WDM multi-frequency light source i.e. carrier signal using OptMUX1. This carrier signal is used to modulate the pseudo random bit sequence (PRBS) data of the user. The PRBS1 and PRBS2 data generators are used to generate random data of length 2^7 bits with 2^5 points per bit. The ElecGen1 is an electrical NRZ signal generator used to convert logical data into electrical signal from PRBS1. An intensity modulator which is ExtMod1 is using on-off keying to modulate the multiplexed 8 wavelengths according to the NRZ electrical data. After modulation an encoder is used for encoding the signal. The modulated signals are distributed to the respective encoders, which have been assigned a unique W/T code respective to each encoder. In an encoder four optical filters and four Shift signal are used to produce the encoded bit stream. The OptFil is used to filter out one spectral wavelength and then the ShiftSig is used to produce a pulse at specified chip. The OptMux2 combines four of the displaced pulses to form an encoded signal. The encoders use delay line arrays providing delays in terms of integer multiples of chip times. The placement of the delay line arrays and the amount of each delay are dictated by the specifics of the user signatures.

The code M9 is (λ1, λ4; 0; λ7, λ8; 0); which is given to encoder1. Here, the semicolons separate the timeslots in the code. This means that wavelength 1 and wavelength 4 are placed in timeslot 1. The time slot 1 provides zero delay of. The wavelength 7 and wavelength 8 are placed in timeslot 3. The timeslot 2 and 4 has no wavelength. The encoder 2, 3 and 4 are using code 21, 10 and 22 respectively.

The encoded data from all users are multiplexed by OptMUX5 and then passed through a 60 km span of standard single mode optical fiber followed by a loss compensating optical amplifier which is OptAmp1. The output signal from a fiber span is then passed through OptSplit1 to split the signal and routed to the user's decoder. The decoder uses optical filters and inverse delay line arrays providing delays in terms of integer multiples of chip times. The decoded signal finally arrives at optical receiver (Reciever1), BERTest1 and EyeDia1. Eye diagram analyzer has been used to take the plot of Eye pattern at the receiver end. Bit error rate values for different number of transmitting users have been taken from BER Tester. The system has been redesigned for different number of users.

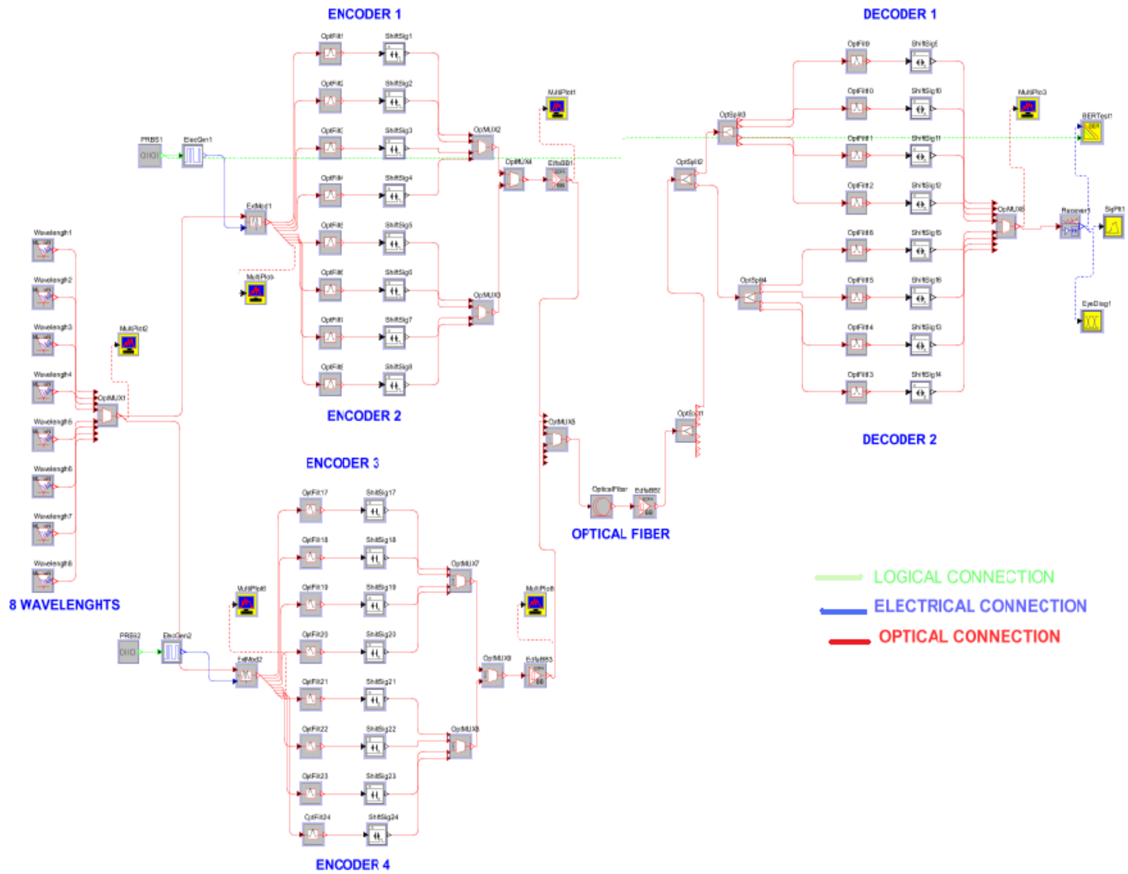


Figure 4.5: An OCDMA system implementing 2-D W/T matrix codes.

4.5 RESULTS AND DISCUSSION

Using simulation setup the value of bit error rate (BER), wavelength spectrum, eye diagrams, optical power are measured. Wavelength spectrum is measured at OptMux1 with the help of Multiplot1. Eye diagrams are measured at receiver end by using an eye diagram analyzer which is EyeDia1. BER is measured at the receiver end by using the BER estimator which is BERtest. With the help of optical power meter, optical power is measured at receiver side.

Figure 4.6 shows the different wavelengths at which various lasers are transmitting before encoding. These eight wavelengths together form a dense WDM multi-frequency light source i.e. carrier signal. This carrier signal is used to modulate the PRBS data of the user. After modulation an encoder is used for encoding the signal.

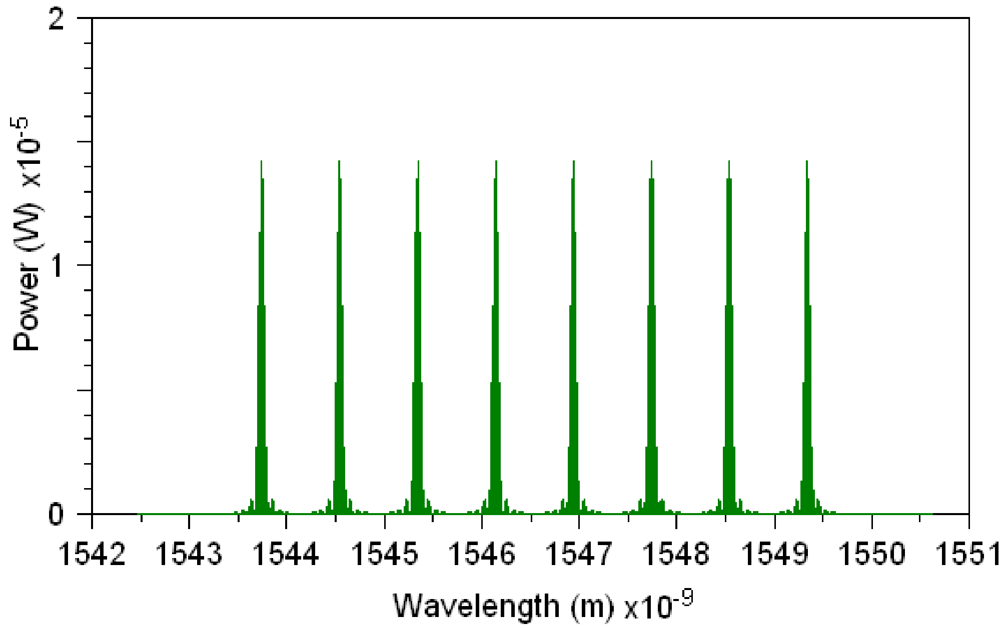


Figure 4.6: Transmit Wavelength Spectrum

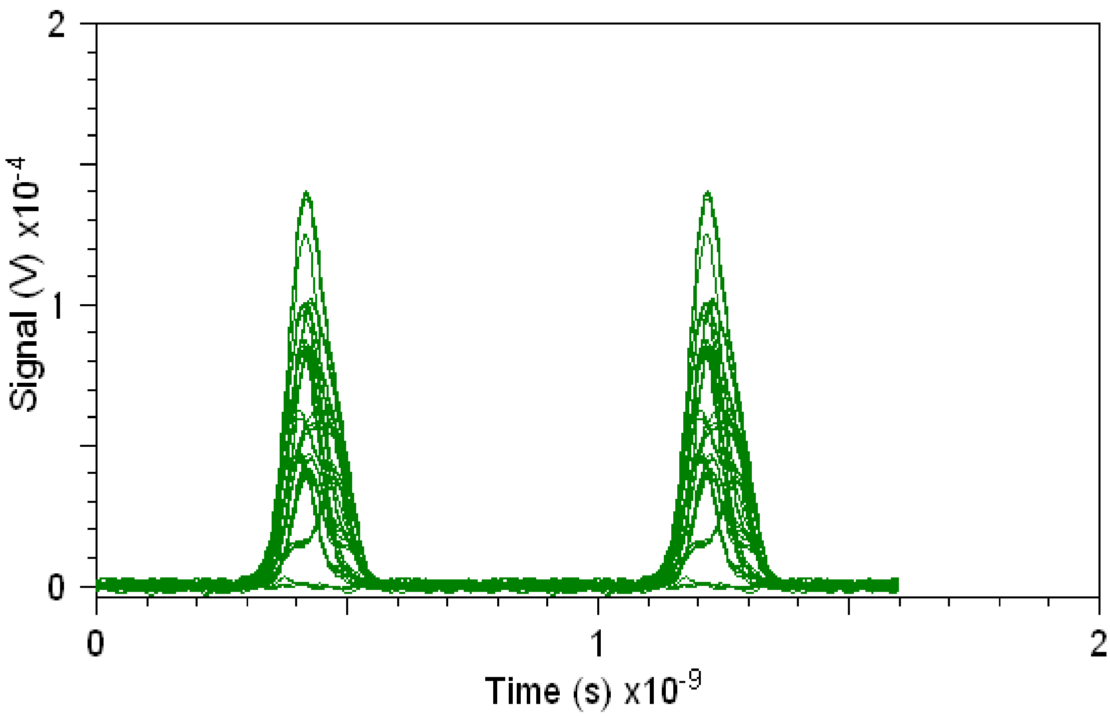


Figure 4.7: Eye diagram when one user is transmitting.

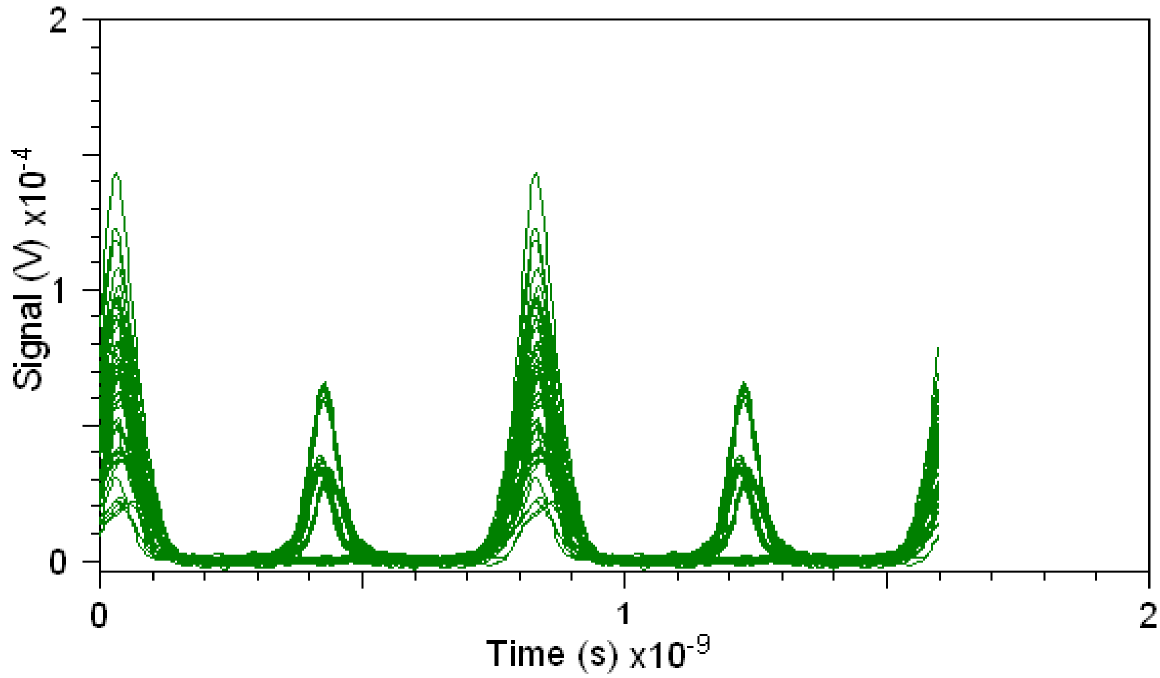


Figure 4.8: Eye diagram when two users are transmitting.

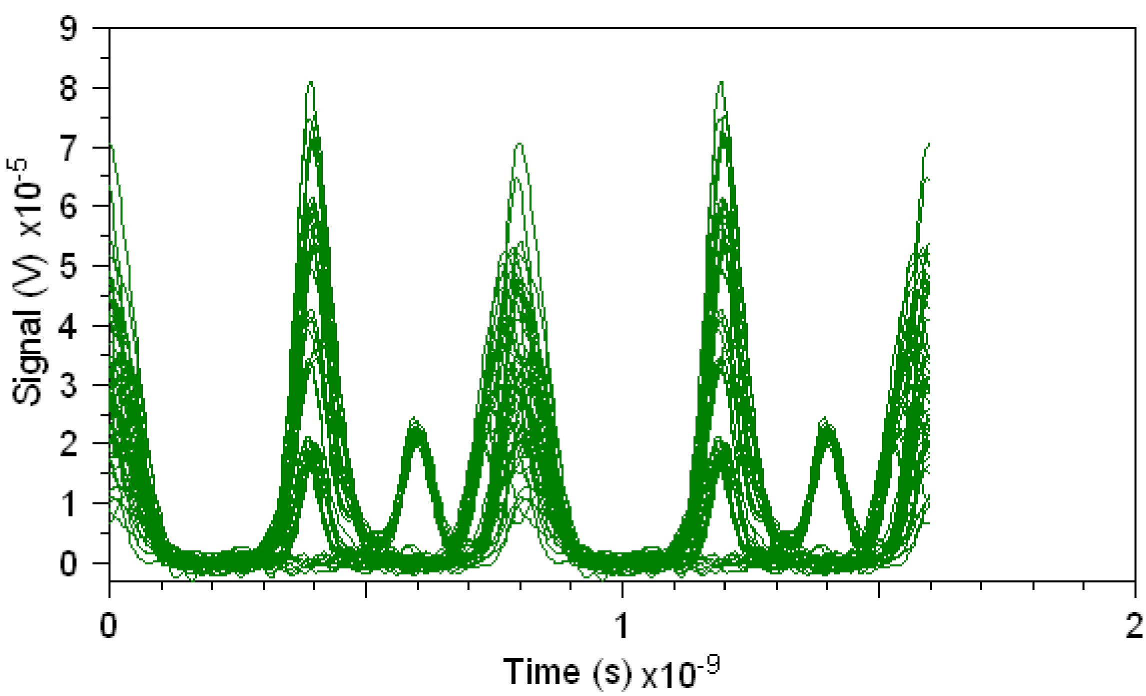


Figure 4.9: Eye diagram when three users are transmitting.

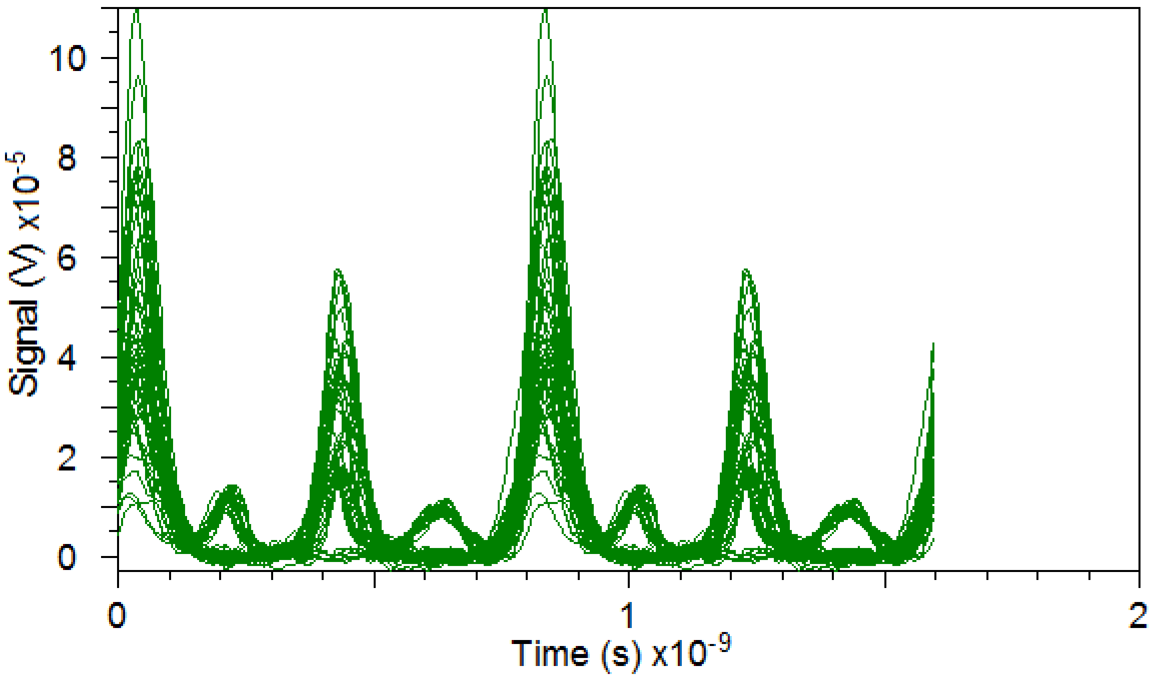


Figure 4.10: Eye diagram when four users are transmitting.

Figure 4.7, 4.8, 4.9 and 4.10 show eye diagrams taken for different numbers of transmitting users with standard single mode fiber length of 60 Km. It can be seen from these diagrams as numbers of transmitting users are increasing eye opening is considerably decreasing. When one user is transmitting eye diagram is clear. With the addition of more users, MAI peaks begin to appear around the decoded signal. This is due to the fact that as numbers of transmitting users are increased, MAI becomes very dominant and eye diagram degrades. MAI is the co-channel interference from other transmitting users and it is the dominant source of bit error rate in an OCDMA system. Hence the performance of the OCDMA system degrades with increase in number of active users.

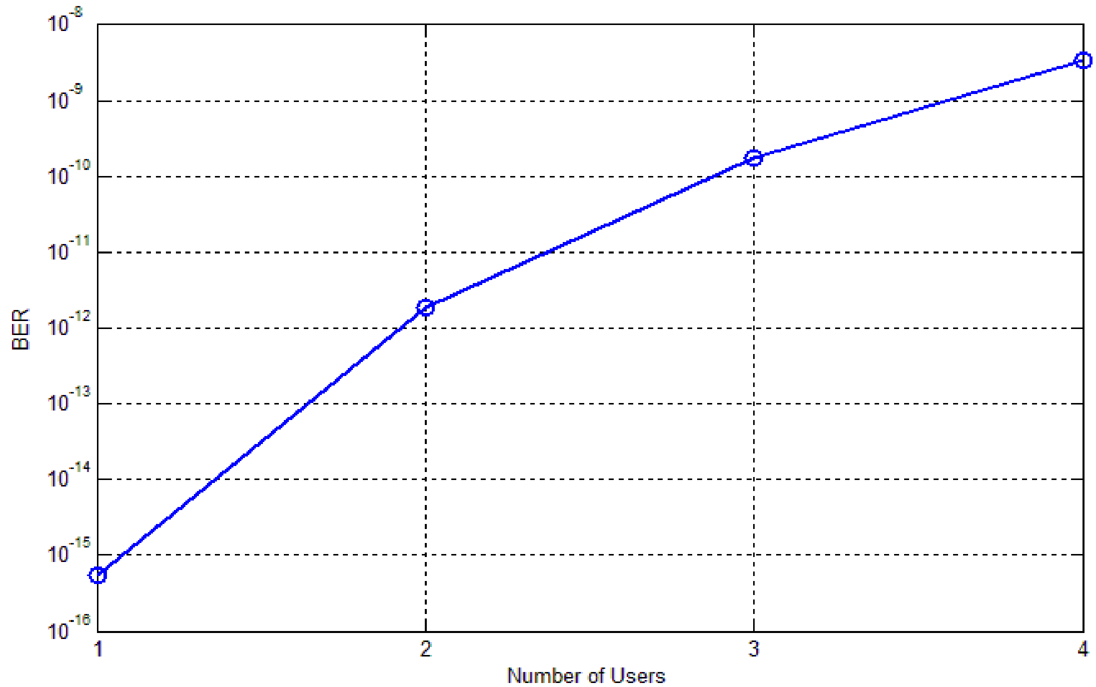


Figure 4.11: BER versus Number of users when only code 9 of decoder is used

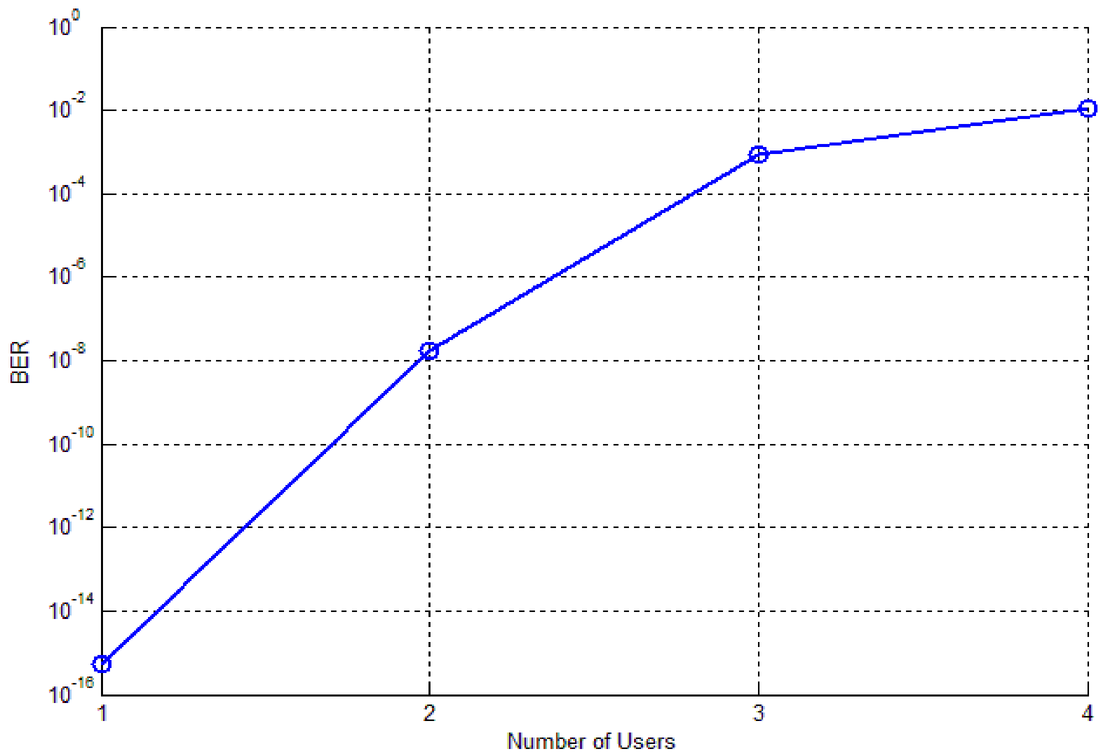


Figure 4.12: BER versus Number of users when code 9 and 21 both are used.

Figure 4.11 shows the BER versus number of users when only code 9 is used in the decoder. Each code uses only four wavelengths out of available eight wavelengths. It can be seen from the figure that as the numbers of active users increases BER also increases. This is because, as the number of users increases they start interfering with each other. This leads to the multiple access interference which causes distortion in the signal. Due to the signal distortion BER increases. Figure 4.12 shows the BER versus number of users when code 9 and 21 both are used in decoder. Code 9 and 21 uses different wavelengths to transmit the signal but the time delay to any wavelength can be same. Here also, BER increases with the increase in number of users due to MAI.

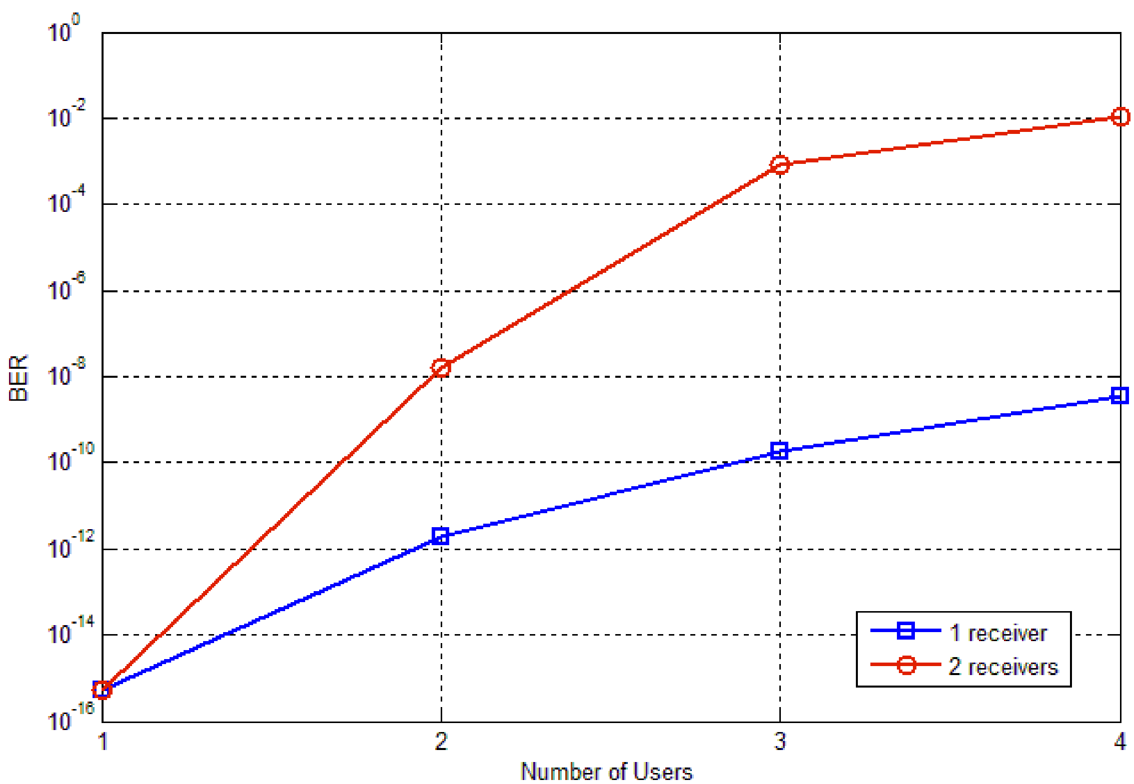


Figure 4.13: Comparison of BER versus Number of users for two codes.

Figure 4.13 shows comparison of BER versus Number of users when only code 9 is used and when both code 9 and 21 are used. It can be seen from the figure that as BER further increases with increase in number of users when both code 9 and 21 are used in the decoder 1. The code 9 uses a set of four wavelengths and the code 21 uses the set of remaining four wavelengths out of available eight wavelengths which makes the codes orthogonal to each other. Each encoder shares the same time slot. Due to this, sometimes time delay to any of the wavelengths can match which make these codes pseudo orthogonal to each other. This will cause multiple access interference and the system performance decreases causing increase in BER.

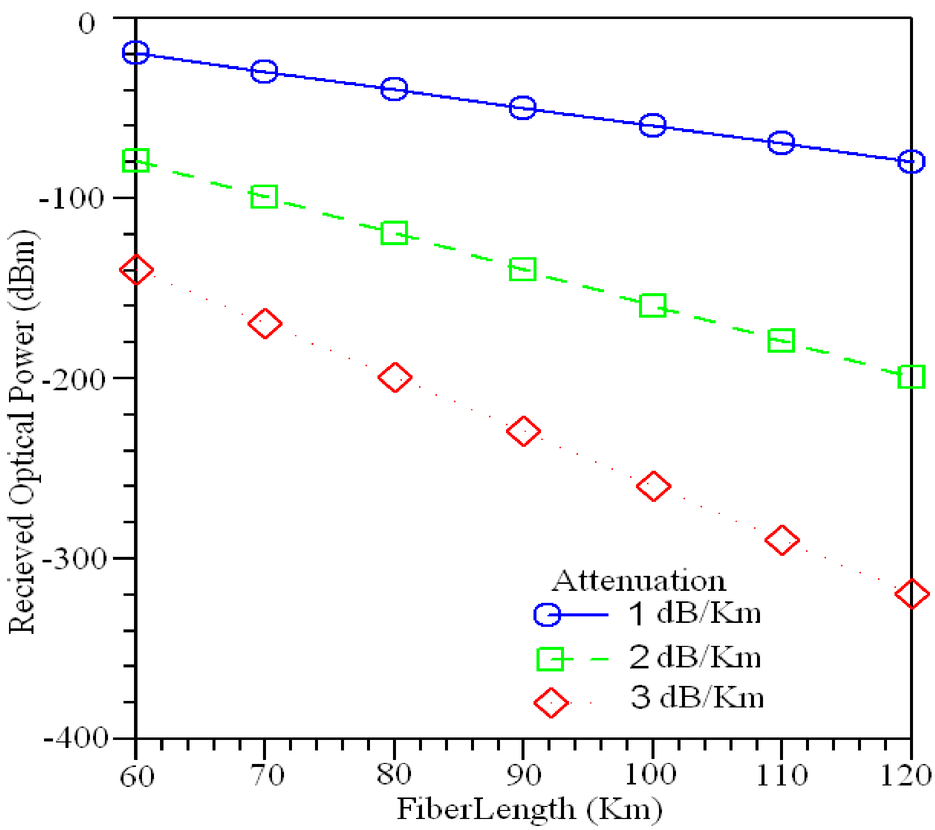


Figure 4.14: Received optical power versus Fiber length

Figure 4.14 shows the received optical power decreases with the increase in distance covered for various values of attenuation. Various factors which can be responsible for this are attenuation, absorption etc. Attenuation is basically a transmission loss of optical fibers and it largely determines the maximum transmission distance prior to signal restoration. Material absorption is a loss mechanism related to the material composition and fabrication process for the fiber, which results in the dissipation of some of the transmitted optical power as heat. Both attenuation and absorption are responsible for decrease in optical power. It can be seen from graph that former one is dominating factor because received power decreases with increase in attenuation.

4.6 CONCLUSION

In this chapter design, implementation and performance analysis of two dimensional wavelength/time codes for OCDMA is presented. A technique based on folding of Golomb ruler for the construction of 2-D is described. It has been observed that cardinality of 2-D codes is high than 1-D codes. The eye diagram degrades and the BER increases as the number of active users increases. The BER further increases with the increase in number of transmitting users when two codes are used at receiver end. It has been shown that MAI is the dominant source of BER. It has been also shown that attenuation causes the decrease in received signal power with increase in optical fiber length. The number of users in a WHTS OCDMA network has a soft limit with a graceful degradation of performance with increasing number of users. Hence, it is concluded that MAI leads to graceful degradation in the system performance when number of simultaneously active users increases at transmitter side as well as at receiver side.

CHAPTER 5

SECURITY ENHANCEMENT OF OCDMA SYSTEM AGAINST EAVESDROPPING USING CODE SWITCHING SCHEME

In this chapter, the security enhanced OCDMA system based on spectral encoding using code switching scheme is analyzed. The security issues are investigated by measuring eye diagrams and received signals for various cases. It has been observed; an eavesdropper based on a simple energy detector can easily read the information being transmitted by a single user using On-Off keying. In order to increase the security a code switching scheme is implemented on OCDMA. It is shown that the eye diagram at the eavesdropper becomes true noise waveform due to code switching scheme and at the receiver end a clear eye diagram is observed. Hence, it is concluded that the code switching scheme shows an immunity of the OCDMA system against eavesdropping and like conventional OCDMA schemes an authorized user clearly decodes an original data when a single user is active in the network.

5.1 INTRODUCTION

The act of surreptitiously listening to a private conversation is known as eavesdropping. It can be done over telephone lines (wiretapping), email, instant messaging, and other methods of communication considered private. The security deals with data that is encoded in such a manner that decoding is difficult or impossible without some secret information, even if the coded or encrypted form of the data is easily read. The confidentiality assures that only the intended receivers of information actually receive the information. It can be compromised to various degrees and in the worst case; an eavesdropper can directly read the data. Even if an eavesdropper cannot read the data, the knowledge that two particular people (or computers) are communicating may compromise confidentiality. A part of information is available to potential adversaries just by knowing the traffic patterns.

The potential adversaries are technologically sophisticated, have significant resources, and know a great deal about the signals being transmitted [35]. In particular, the eavesdropper knows what types of OCDMA signals are being sent: the data rate, the type of encoding, and the structure of the codes—but not the particular code that an individual user employs. This is because it is reasonably easy for a user to change codes in the event his code is compromised. However, the other parameters mentioned, such as the data rates, the types of codes, etc., are difficult to change quickly, and might even require a hardware or software redesign of the communication equipment in the event that they were found out by an adversary. Underestimating an adversary is a poor security practice; one must assume, when doing a security analysis that an adversary may even know hard to change parameters.

Thomas H. Shake [35] examined the degree and types of security that may be provided by OCDMA encoding. A quantitative analysis of data confidentiality is presented for OCDMA encoding techniques. It is shown that increasing code complexity can increase the signal-to-noise ratio (SNR) required for an eavesdropper to “break” the encoding by only a few dB. Rapid reconfiguration of codes can also increase the difficulty of interception. The overall degree of confidentiality obtainable through OCDMA encoding is also compared with that obtainable through standard cryptography.

D.E. Leaird et al. [36] experimentally investigated spectrally phase coded OCDMA with a modulation format based on switching between two codes. The code switching data modulation format enhances security compared to On-Off keying by eliminating a vulnerability to eavesdropping based on a simple energy detector.

Hwan S Chung et al. [40] experimentally demonstrated a security improved optical code division multiplexed access (CDMA) scheme based on spectrally encoded incoherent broadband light source with bipolar coding. The details of coding scheme are shown and security issues have been investigated by measuring eye diagrams and bit error rates for various cases. The analytical and numerical simulation results are presented for secure transmission of spectrally encoded incoherent optical CDMA signal.

Up till now most arguments advocating OCDMA for secure communication in the research literature have been qualitative and vague. Various approaches have been suggested for enhancing the network security mechanisms in order to protect the network from attack by unauthorized users. In this chapter a code switching scheme is implemented for security enhancement and making the OCDMA system less vulnerable to eavesdropping.

The chapter is divided into different sections. In the first section, the brief introduction about the eavesdropping is presented. In second section a descriptive model is proposed for security enhancement of OCDMA system when single user is transmitting. The third section describes the simulation setup for bipolar coding based OCDMA system. The fourth section includes the simulation results and the results have been discussed. The fifth section gives the conclusion of this chapter.

5.2 DESCRIPTIVE MODEL

Up to recent days, various OCDMA schemes have been proposed and demonstrated based on time spreading, phase coding, spectral encoding, or two-dimensional (time-spectral) encoding. All these approaches used On-Off keying (OOK) for data modulation [1] in which a coded transmission is sent during a bit interval to represent a "one," and no energy is sent during a bit interval to represent a "zero." This makes the implementation of optical transmitters and receivers relatively simple. It is also highly vulnerable to relatively simple eavesdropping techniques. The eavesdropper does not need to decode the signal; he can just read the ones and zeros directly. If an eavesdropper can isolate individual user's signals as in figure 5.1, he can use a simple energy detector to detect whether energy is present or not in each bit interval [37]. In this case, there is no need for the eavesdropper to "break" the coding scheme or steal the code; the energy detector output contains the user's data stream.

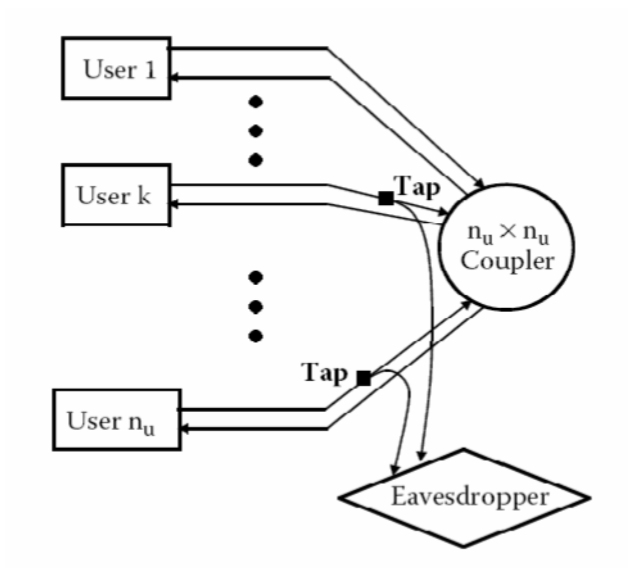


Figure 5.1: An eavesdropper tapping into the optical fiber can isolate an individual user [35].

One of many possible OCDMA schemes is illustrated in figure 5.2. A particular arrangement of different colors is representing a code at different time slots (known as chips) within a single data bit [38]**.** It should be clear that if only one data stream is present, the total energy in each bit time is all the information needed to obtain the data bits. When multiple users are present, deciphering the data bits becomes more difficult—especially, as in the case illustrated, when the data streams are asynchronous.

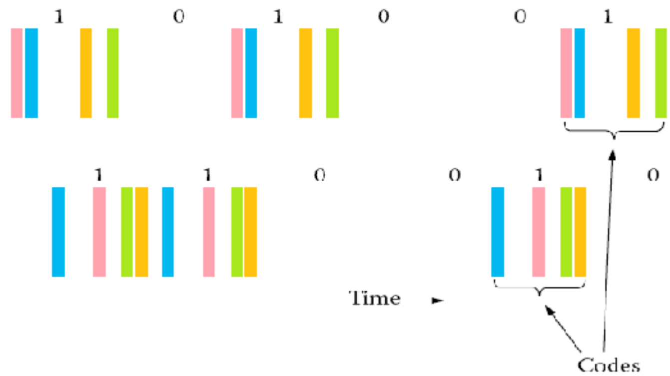


Figure 5.2: Schematic of two, asynchronous incoherent OCDMA channels. On–off key modulation is being used. Note that no decoding is needed if only one channel is present [10].

A solution that relies solely on the properties of the encoding would be to force the modulation technique to send a constant amount of energy for each transmitted bit by transmitting one code sequence for a "one" and a different code sequence for a "zero" as shown in figure 5.3. The user could send out a particular optical code for a "1" and an orthogonal optical code for a "0". This approach is called **2-code keying or code switching scheme** [35]. It is also known as **bipolar coding**. 2-code keying would require distribution of twice as many codes for a given set of users. It would produce significantly more multiple access interference for a given number of simultaneous transmitters compared with On-Off keying based OCDMA, although it would also increase the receiver's average energy per data bit, since energy would be transmitted for both "zeros" and "ones." It would work with most proposed OCDMA technologies and would remove the vulnerability to eavesdroppers with simple energy detectors. Now an eavesdropper (no matter how good the signal-to-noise ratio is) cannot measure the signal. The eavesdropper is now forced to figure out the coding in order to decode the signal and obtain the data, which is a far more complicated and difficult task than tapping the user's signal and detecting the power transmitted during each bit period [36].

This increased security has its costs that are:

• Twice as many codes are needed.

• The increase in codes will increase multiuser interference, which may reduce the number of users.

• The increase in codes adds complexity to the network, which may increase the cost of network management.

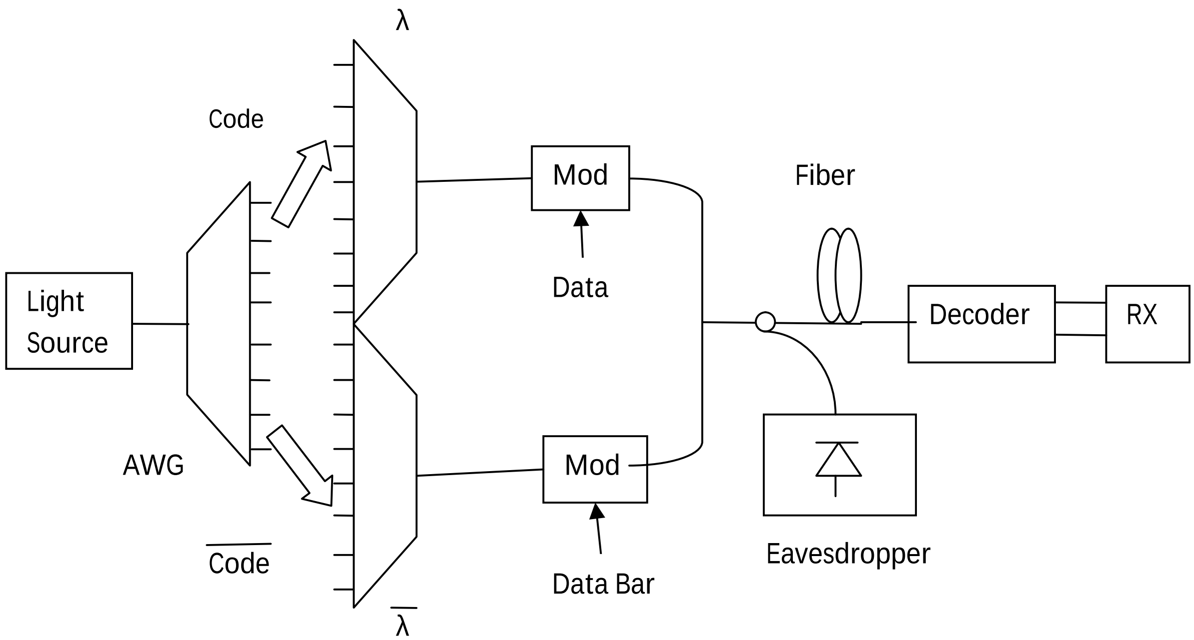


Figure 5.3: Block Diagram of OCDMA system based on spectral encoding with bipolar code.

5.3 SIMULATION SETUP

The simulation set-up for the security enhanced OCDMA system based on spectral encoding with bipolar code and incoherent broadband light source is shown in figure 5.4. In bipolar coding, a particular code is used to transmit the data bit 1 and its complementary code to transmit the data bit zero. The setup that is shown is for the single transmitting user. The optical CDMA code used is a modified PN code [39]. The output of broadband light source which is DMLaser1 is demultiplexed into 32 spectral chips with the help of OptDeMUX1. The wavelengths of chips ranged from 1530.33 to 1554.94 nm with 100 GHz spacing. According to the modified PN code, 16 spectral components are connected to the upper multiplexer (OptMUX1) to make a code, and the other 16 spectral components are connected to the lower multiplexer (Optmux2) to make a complementary code (Code, Code-bar) [40].

The output of each multiplexer is modulated by a intensity modulator employing on-off keying with 1.25 Gbps non-return-to-zero (NRZ) pseudo-random-bit sequence (PRBS) signal. The PRBS1 generates the logical PRBS sequence which is converted into electrical signal by an electrical generator (ElecGen1). The output of PRBS1 is also sent to Boolean operator (NOT) which is acting as NOT gate, converting the data into data-bar. The data and data-bar are assigned to the upper and lower arms, respectively. The two modulated optical outputs are combined by the OptCoup1 which is a 3-dB fiber coupler.

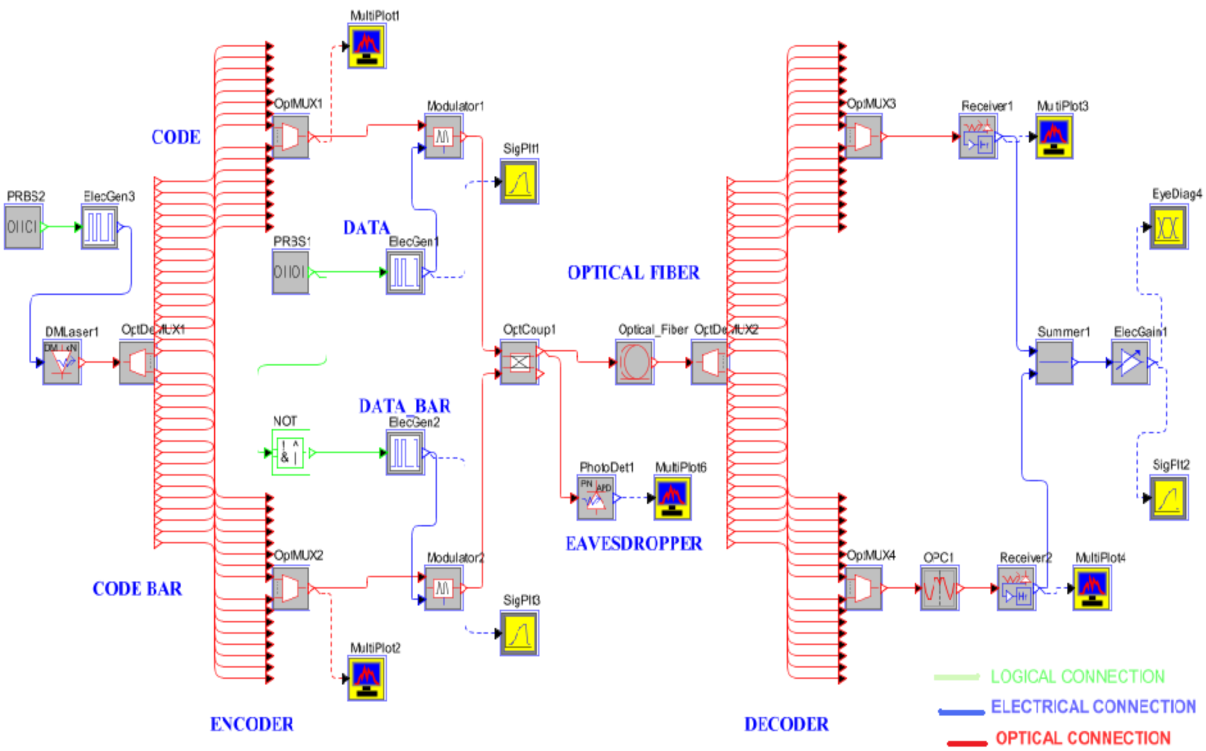


Figure 5.4: Simulation setup for security improved optical CDMA system based on spectral encoding with bipolar code

The NRZ signal patterns as shown in figure 5.6 are complementing each other in time. In this demonstration, an eavesdropper (PhotoDet1) armed with a band limited photo-detector tries to intercept the information data between transmitter and receiver. After 20 km transmission of conventional single mode optical fiber, spectrally encoded signal was decoded by an authorized user sharing the same code with the transmitter. The optical signal was demultiplexed by OptDeMUX2 and then OptMUX3 is set to the Code and OptMUX4 is set to Code-bar, which was used in the encoder. The receivers 1 and 2 are used simultaneously to detect Code and Code-bar. The component OPC1 is an optical phase conjugate which is used to give a phase shift of 180 degrees. It is complementing the data-bar into data in order to detect the information being sent. The two received signals are added by the summer1 and then amplified. In order to measure wavelength spectrum, multiplot1 and 2 are used; for data and received signal, signal plotter is used and for eye diagram, eye diagram analyzer is used.

5.4 RESULTS AND DISCUSSION

Using the simulation setup, the values of input signals, wavelength spectrum, eye diagrams and received signal are measured. Eye diagrams are measured at the eavesdropper and at the receiver end. The received signal is measured at the receiver end. The measurement components used are multiplot for the wavelength spectrum, eye diagram analyzer for an eye diagram and signal plotter for the input signal and the received signal.

The measured wavelength spectrum is shown in figure 5.5 which consists of 32 wavelengths. The bold lines show the 16 spectral components which implement the code and the dashed lines show the remaining 16 spectral components which implement the complementary code, according to the modified PN code. The wavelengths corresponding to one in the modified PN code are transmitted to implement the code and wavelengths corresponding to zero in the same code are transmitted to implement the complementary code.

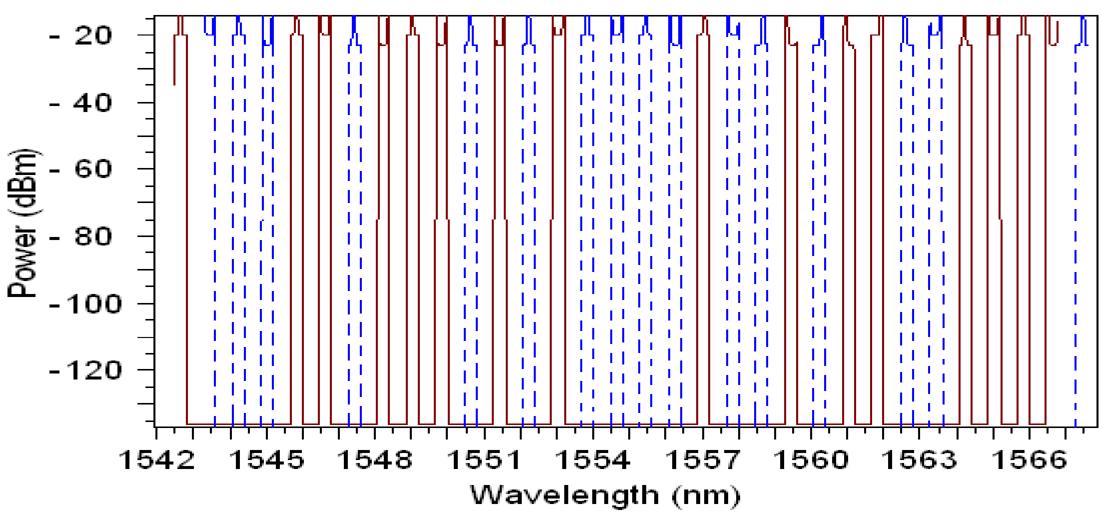
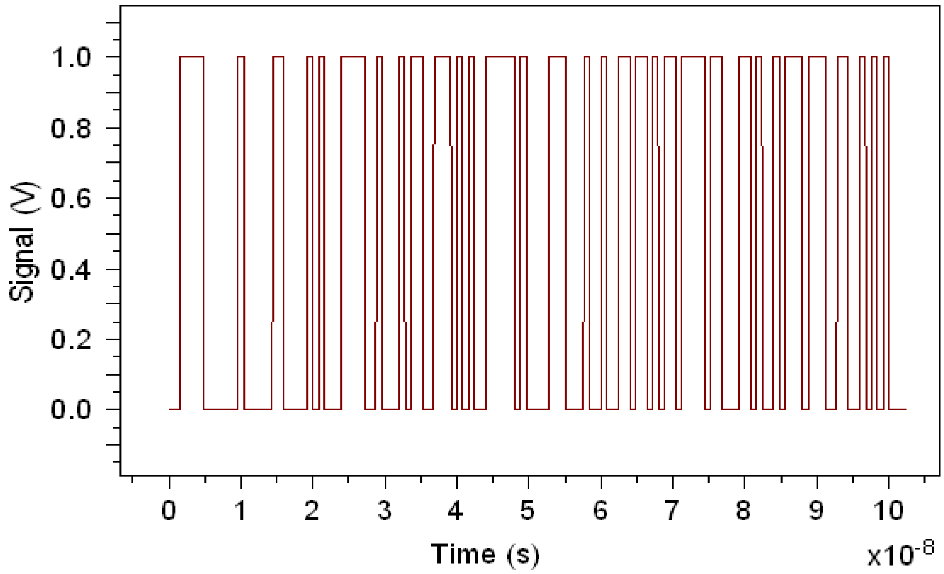
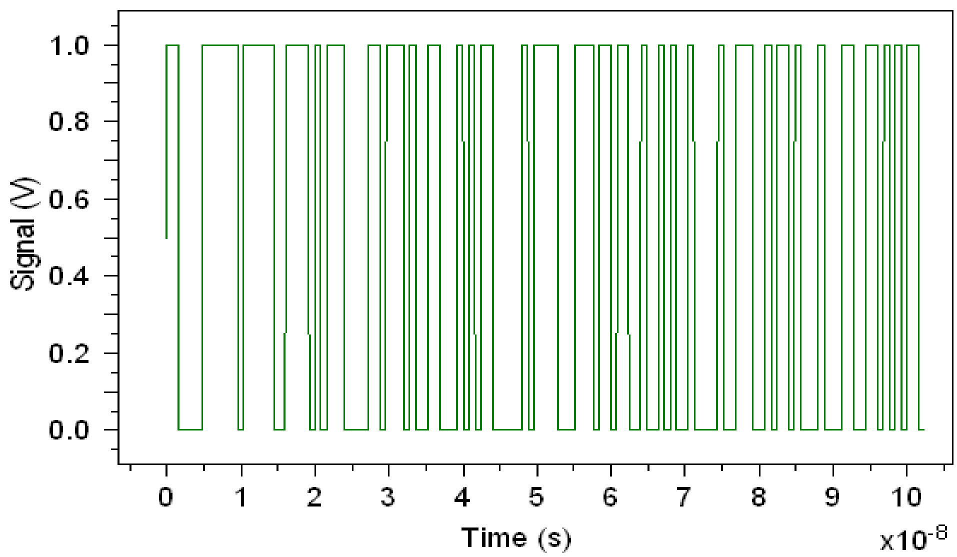


Figure 5.5: Measured spectra after transmitter



a)



b)

Figure 5.6: a) Data b) Data-bar

Figure 5.6 a) shows the data and 5.6 b) shows the data bar. The code is used to modulate the data and code-bar is used to modulate the data-bar in order to implement the code switching scheme in which a code sent for high bit of data and complementary code is sent for low bit of data.

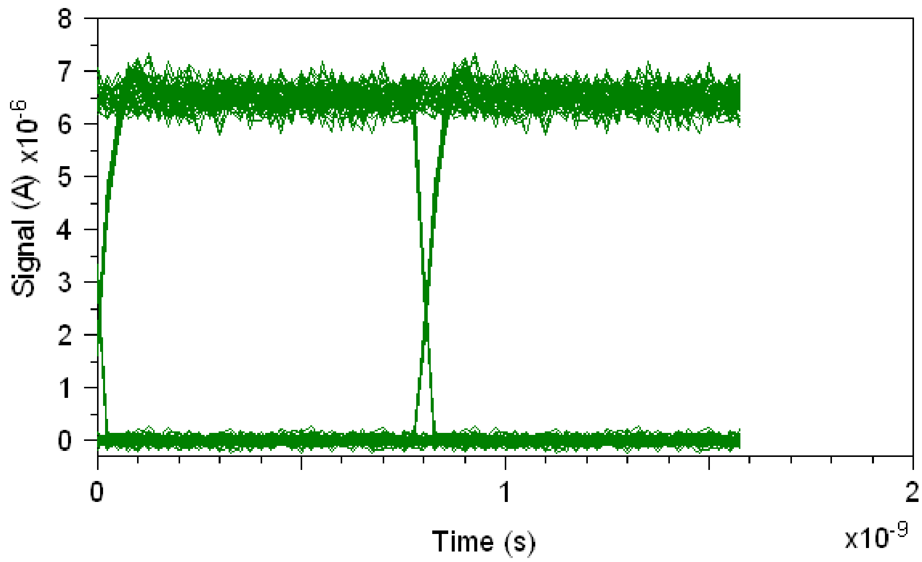


Figure 5.7: Eye diagram without bipolar coding at eavesdropper

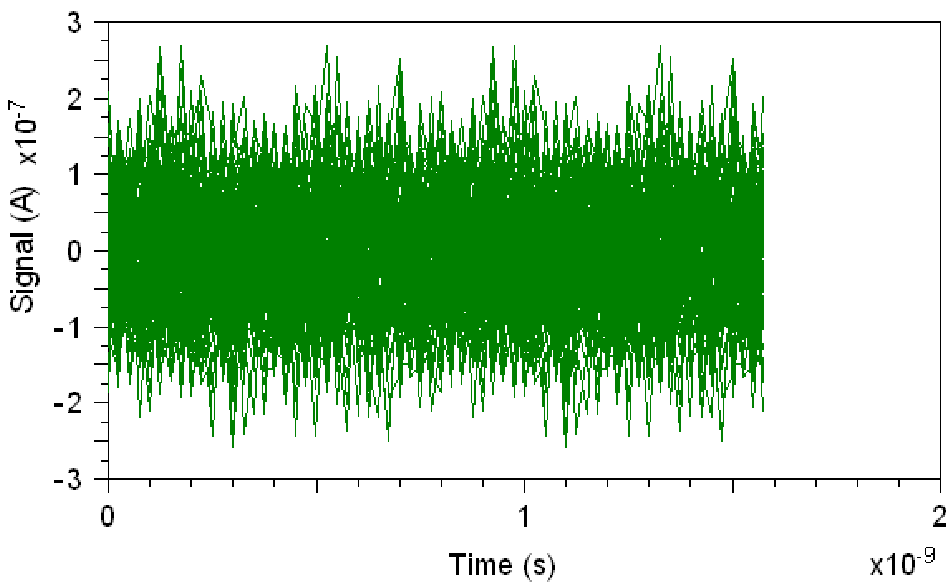


Figure 5.8: Eye diagram with bipolar coding at eavesdropper.

The figure 5.7 shows an eye diagram at the eavesdropper when one user is transmitting. It shows large signal to noise ratio. This means an eavesdropper can easily make out what information is being sent by means of simple energy detector. Hence, this system lacks confidentiality. Alternatively, a code switching scheme is used, where information bit one (1) is encoded by a modified PN code and information bit zero (0) is encoded by a complementary code sequence. This code switching data modulation format enhances the security compared to On-Off keying by eliminating the vulnerability to eavesdropping by a simple energy detector. The figure 5.8 shows an eye diagram at the eavesdropper when one user is transmitting using the 2-code keying. The eye diagram at the eavesdropper becomes true noise waveform (which is required) due to the code switching scheme. This means there is no intelligible signal present at the eavesdropper and there is no eye diagram at all since both bits '1' and '0' are occupied by encoded waveforms, which demonstrates the ability to enhance security through the code-switching scheme. As a result, the information is concealed by the code-switching scheme to resist a simple interception from a malicious eavesdropper.

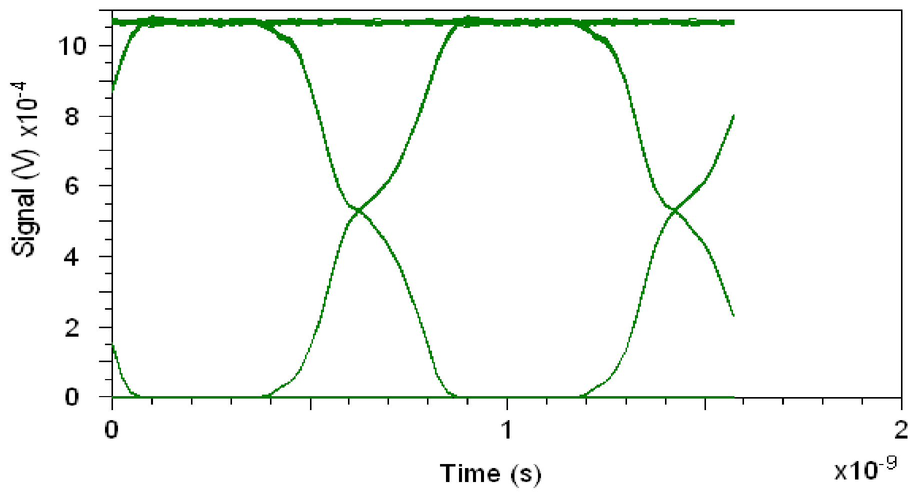


Figure 5.9: Eye diagram at the receiver without bipolar coding.

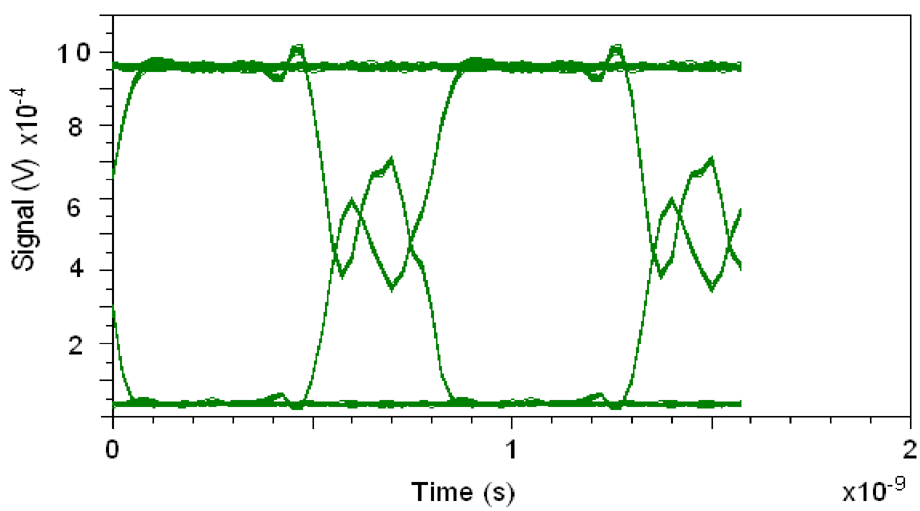


Figure 5.10: Eye diagram at the receiver with bipolar coding.

The figure 5.9 shows an eye diagram at the receiver without bipolar coding for a single user. The eye is opening completely which means that the bit error rate is low. On the other hand, it is important to show that the code-switching scheme still works for an authorized user using conventional OCDMA detection: decoded by a decoder and detected by the photodiode. The figure 5.10 shows an eye diagram at the receiver with bipolar coding for a single user. A clear eye diagram is observed. An authorized user clearly decodes an original data when a single user is active in the network. The received signal as shown in the figure 5.12 is very similar to the received signal without bipolar coding as shown in the figure 5.11. Hence by implementing the 2-code keying there is a strict security against eavesdropping without affecting the received signal.

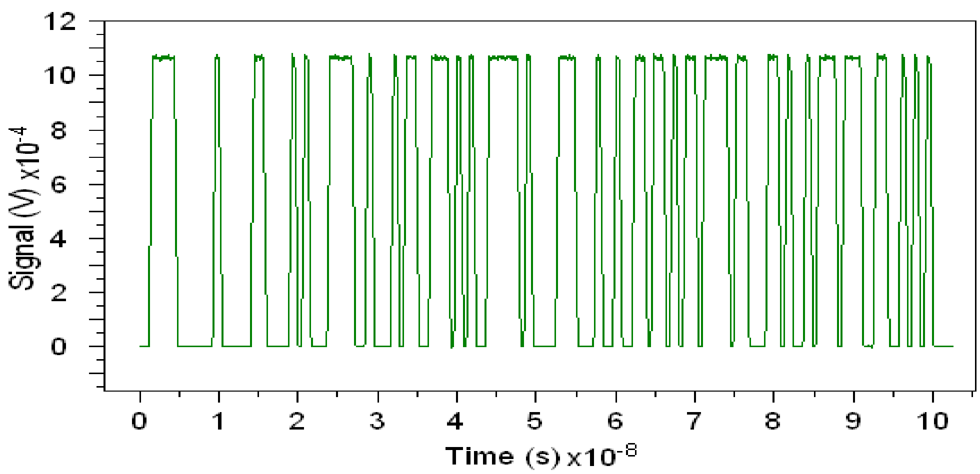


Figure 5.11: Received signal without bipolar coding

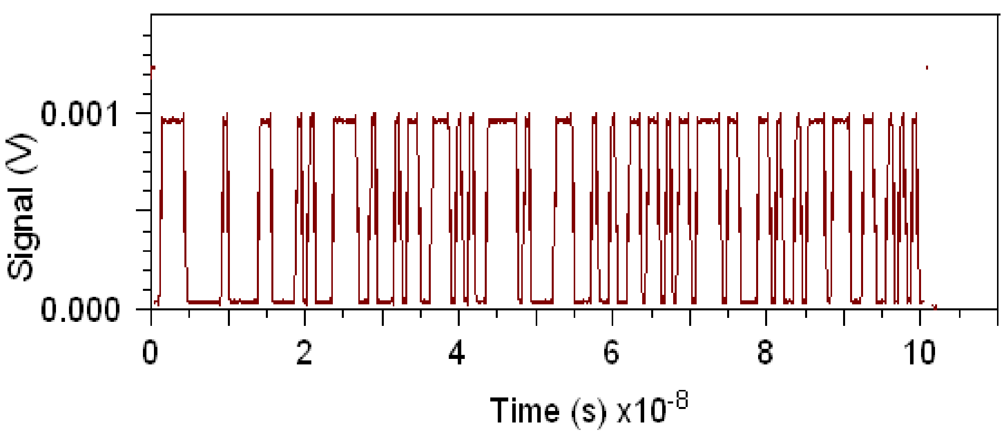


Figure 5.12: Received signal with bipolar coding

5.5 CONCLUSION

In this chapter the security enhanced OCDMA system based on spectral encoding using bipolar code is analyzed. It has been shown that how an eavesdropper can easily read the information being transmitted by a single user. Hence, confidentiality can be compromised to various degrees. In order to increase the security, a code switching scheme is implemented. The code switching data modulation format enhances the security compared to On-Off keying by eliminating the vulnerability to eavesdropping based on a simple energy detector. It has been observed that implementing a 2-code keying is a good alternative for security enhancement. Using the bipolar codes the optical output of the encoder became true noise waveform. This means there is no signal present at the eavesdropper and information is strictly confidential. The code switching scheme shows an immunity of the OCDMA system against eavesdropping without affecting the received signal.

CHAPTER 6
CONCLUSION AND FUTURE SCOPE

This chapter provides a summary of the findings of the study which has been done so far. Also, in this chapter the scope for further research in OCDMA is given.

6.1 CONCLUSION

The first objective of the thesis is the design, implementation and performance analysis of various one dimensional codes in OCDMA system for different data formats. The comparison of Walsh Hadamard codes, OOC and ZCC using various data formats revealed that the NRZ modulation format has the edge over the RZ modulation format in OCDMA systems. It is found that the NRZ raised cosine has lowest BER value and better system performance. Hence, NRZ raised cosine can be recommended for the distances suitable for local area networks using OCDMA systems at high bit rates. The analytical results revealed that ZCC code has a superior code property of zero cross correlation. It can be seen from the values of the BER, an eye opening and the received power, that the ZCC code gives the best performance compared to Walsh Hadamard and OOC codes. Hence, it is concluded that the ZCC codes are most suitable to be employed in the OCDMA systems using NRZ raised cosine data format.

The second objective of thesis is the design, implementation and performance analysis of two dimensional wavelength/time codes for OCDMA system. A technique based on folding of Golomb ruler for the construction of 2-D is described. It has been observed that cardinality of 2-D codes is high than 1-D codes. The eye diagram degrades and the BER increases as the number of active users increases. The BER further increases with the increase in number of transmitting users when two codes are used at receiver end. It has been shown that MAI is the dominant source of BER. It has been also shown that attenuation causes the decrease in received signal power with increase in optical fiber length. The number of users in a WHTS OCDMA network has a soft limit with a graceful degradation of performance with increasing number of users. Hence, it is concluded that MAI leads to graceful degradation in the system performance when number of simultaneously active users increases at transmitter side as well as at receiver side.

The third objective of the thesis is to enhance the security of an OCDMA system based on spectral encoding using bipolar code. It has been shown that how an eavesdropper can easily read the information being transmitted by a single user. Hence, confidentiality can be compromised to various degrees. In order to increase the security, a code switching scheme is implemented. The code switching data modulation format enhances the security compared to On-Off keying by eliminating the vulnerability to eavesdropping based on a simple energy detector. It has been observed that implementing a 2-code keying is a good alternative for security enhancement. Using the bipolar codes the optical output of the encoder became true noise waveform. This means there is no signal present at the eavesdropper and information is strictly confidential. The code switching scheme shows an immunity of the OCDMA system against eavesdropping without affecting the received signal.

6.2 FUTURE SCOPE

In this thesis, the work is limited to 1-D and 2-D codes. Their various aspects like modulation formats and security have been considered. The 3-D codes have not been considered in this work. The present work can be enhanced for 3-D codes. Moreover, multiple access interference is the main limiting factor of the OCDMA systems. It increases with the increase in number of users. Further work can be done to reduce MAI.

The OCDMA system can be applied to future access networks. So, OCDMA system with passive and active access networks can be studied further.

REFERENCES

[1] Tomoaki Ohtsuki and Iwao Sasase, "Optical Synchronous CDMA, Encyclopedia of Telecommunications" Editor: John Proakis, Wiley, 2002.

[2] A.J. Mendez, R.M. Gagliardi, V.J. Hernandez, C.V. Bennett, and W. J. Lennon, "Design and Performance Analysis of Wavelength/Time (W/T) Matrix Codes For Optical CDMA," IEEE Journal of Lightwave Technology, Vol. 21, pp: 2524-2533, November 2003.

[3] M.S.Borella, J.P.Jue, D.Banerjee, B.Ramamurthy, and B.Mukherjee, "Optical Components for WDM Lightwave Networks". Proceedings of the IEEE, Vol. 85, pp: 1274 – 1307, August 1997.

[4] Izhak Rubin, "Message Delays in FDMA and TDMA channels." IEEE Transactions on Communications, Vol. 27, No. 5, May 1979.

[5] Theodore S. Rappaport, "Wireless Communications: Principles and Practice". Second edition, Prentice Hall, 2007.

[6] www.umtsworld.com/technology/cdmabasics.htm.

[7] Paul R. Prucnal, Mairo A. Santoro, "Spread Spectrum Fiber-optic Local Area Network Using Optical Processing". Journal of Lightwave Technology, Vol. 4, No. 5, May 1986.

[8] A. Stok and E.H. Sargent. "Lighting the Local Area: Optical Code-Division Multiple-Access and Quality of Service Provisioning". IEEE Network, Vol. 14, pp: 42–46, November/December 2000.

[9] Bin Ni and James S. Lehnert, "Performance of an Incoherent Temporal-Spreading OCDMA System With Broadband Light Sources" Journal of Lightwave Technology, Vol. 23, No. 7, July 2005.

[10] Paul R. Prucnal, "Optical Code Division Multiple Access: Fundamentals and Applications." CRC Press, 2006.

[11] E. Inaty, H. M. H. Shalaby, P. Fortier, and L. A. Rusch, "Multirate Optical Fast Frequency Hopping CDMA System Using Power Control," Journal of Lightwave Technology, Vol. 20, No. 2, pp. 166–177, February. 2002.

[12] K. Yu, J. Shin, and N. Park, "Wavelength-time Spreading Optical CDMA Systems Using Wavelength Multiplexers and Mirrored Fiber Delay Line," IEEE Photonics. Technology Letters., Vol. 12, No. 9, pp. 1278–1280, September. 2000.

[13] Poorya Saghari, P. Kamath, Vahid R. Arbab, Mahta Haghi, Alan E. Willner, Joe A. Bannister and Joe D. Touch, "Experimental Demonstration of Interference Avoidance Protocol (transmission scheduling) in O-CDMA Networks." Optics Express, Vol. 15, No. 25, December 2007.

[14] P. Saghari, R. Gholizadeh, H. Abrishami, E. Pakbaznia, J. E. McGeehan, S. M. R. M. Nezam, and A. E. Willner, "Experimental and Theoretical Analysis of the Optimum Decision Threshold for Varying Numbers of Active Users in a 2-D Time-Wavelength Asynchronous O-CDMA System," Journal of Lightwave Technology. Vol. 23, pp: 3339-3346, 2005.

[15] P. Kamath, J. D. Touch, and J. A. Bannister, "Algorithms for Interference Sensing in Optical CDMA Networks," IEEE International Conference on Communications (ICC) 3, pp: 1720-1724, 2004.

[16] Kohki Ohba, Takaya Miyazawa, Iwao Sasase, "A Mitigation Technique of High-Power MAI in the Multimedia Optical CDMA System with the Optical Power Selector." IEICE Transaction Communication, Vol. 91, No.3, March 2008.

[17] M.S. Anuar, S.A. Aljunid, N.M. Saad, A. Mohammed, and E.I. Babekir, "Development of a Zero Cross-Correlation Code for Spectral-Amplitude Coding Optical Code Division Multiple Access (OCDMA)." IJCSNS International Journal of Computer Science and Network Security, Vol.6 No.12, December 2006.

[18] S.A. Aljunid, M. Ismail, A.R. Ramli, B.M. Ali and M.K. Abdullah. "A New Family of Optical Code Sequence for Spectral Amplitude Coding Optical CDMA Systems." IEEE Photonics Technology Letters, Vol. 16, No.10, October 2004.

[19] M.I.Hayee and A.E.Willner, "NRZ versus RZ in 10-40-Gb/s dispersion-managed WDM transmission systems," IEEE Photonics Technology Letters, 2003.

[20] H. Sunnerud, M. Karlsson, and P. A. Andrekson, "A comparison between NRZ and RZ data formats with respect to PMD-induced system degradations," IEEE Photonics Technology Letters, Vol. 13, No. 5, pp: 448–450, May 2001.

[21] F. R. K Chung, J. A. Salehi, V. K. Wei, "Optical Orthogonal Codes: Design, Analysis, and Applications," IEEE Transactions on Information Theory, Vol. 35, No. 3, May 1989.

[22] J.A. Salehi. "Code Division Multiple-access Techniques in Optical Fiber Networks Part 1: Fundamental principles". IEEE Transactions on Communication, Vol.37, No. 8, August 1989.

[23] K.J. Horadam, "Hadamard Matrices and Their Applications." Princeton university press.

[24] Fan R.K. Chung, Martin kerner, Mary G. O'Conner, Jawed A. Salehi, Victor K. Wei. "Encoding and Decoding For Code Division Multiple Access Systems." IEEE Transactions on Communication, Patent No. 4,779,266, October 1988.

[25] M. S. Anuar, S. A. Aljunid, R. Badlishah, N. M. Saad, A. Mohammed, and I. Andonomic, "Performance Analysis of Optical Zero Cross Correlation in OCDMA System." Journal of Applied Sciences, Vol. 7, No.23, pp: 3819-3822, 2007.

[26] I.B. Djardjevic and B. Vasic "Novel Combinatorial Constructions of Optical Orthogonal Codes for Incoherent Optical CDMA Systems" Journal of Lightwave Technology, Vol. 21, 2003.

[27] S. Yegnanarayanan, A. S. Bhushan, and B. Jalali, "Fast Wavelength-Hopping Time Spreading Encoding/Decoding for Optical CDMA." IEEE Photonics Technology Letters, Vol. 12, No. 5, May 2000.

[28] L. Tanceski, I. Andonovic, "Wavelength hopping/time spreading code division multiple access systems," Electronic Letters, Vol. 30, No. 9, pp: 721–723, 1994.

[29] Nasaruddin and Tetsuo Tsujioka, “Design of Reconfigurable Multiweight Wavelength-Time Optical Codes for Secure Multimedia Optical CDMA Networks.” IEEE Communications Society ICC, 2008.

[30] J. P. Robinson, “Optimum Golomb rulers,” IEEE Transactions on Computers, Vol. 28, pp: 943–944, 1979.

[31] F. Khansefid, H. Taylor, and R. Gagliardi, “Design of (0,1) Sequence Sets for Pulsed Coded Systems,” IEEE International Symposium, 1990.

[32] A. J. Mendez, J. L. Lambert, J.-M. Morookian, and R. M. Gagliardi, “Synthesis and demonstration of high speed, bandwidth efficient optical code division multiple access (CDMA) tested at 1 Gb/s throughput,” IEEE Photonics Technology Letters, Vol. 6, pp: 1146–1148, September 1994.

[33] A. J. Mendez, R. M. Gagliardi, V. J. Hernandez, C. V. Bennett, and W. J. Lennon, “High-Performance Optical CDMA System Based on 2-D Optical Orthogonal Codes.” Journal of Lightwave Technology, Vol. 22, No. 11, pp: 2409–2419, November 2004.

[34] Vincent J. Hernandez, Antonio J. Mendez, Corey V. Bennett, Robert M. Gagliardi and William J. Lennon. “Bit-Error-Rate Analysis of a 16-User Gigabit Ethernet Optical-CDMA (O-CDMA) Technology Demonstrator Using Wavelength/Time Codes.” IEEE Photonics Technology Letters, Vol. 17, No. 12, December 2005.

[35] Thomas H. Shake, “Security Performance of Optical CDMA Against Eavesdropping”. Journal of Lightwave Technology, Vol. 23, NO. 2, February 2005.

[36] D.E. Leaird, Z. Jiang and A.M. Weiner, “Experimental Investigation of Security Issues in OCDMA: A Code-Switching Scheme” IEE Electronics Letters, Vol. 41, No. 14, 2005.

[37] D.D. Sampson, G.J. Pendock, and R.A. Griffin, “Photonic Code-Division Multiple Access Communications,” Fiber Int. Opt., Vol. 16, pp: 129–157, 1997.

[38] N. Ferguson and B. Schneier, "Practical Cryptography". Indianapolis, IN: Wiley, 2003.

[39] Bong Kyu Kim, Sangjo Park, Younghee Yeon and Byoung Whi Kim, "Radio-Over-Fiber System Using Fiber-Grating-Based Optical CDMA With Modified PN Codes." IEEE Photonics Technology Letters, Vol. 15, No. 10, October 2003.

[40] Hwan Seok Chung, Sun Hyok Chang, Bong Kyu Kim and Kwangjoon Kim, "Experimental Demonstration of Security-Improved OCDMA Scheme Based on Incoherent Broadband Light Source and Bipolar Coding." Optical Fiber Technology, Vol.14, pp: 130–133, 2008.