Performance Evaluation of Optical Code Division Multiple Access System

A Thesis

Submitted in fulfillment of the requirement for the award of the degree

Of

Doctor of Philosophy

Submitted by

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Declaration

I, Himanshu Monga hereby declare that the work which is being presented in this thesis entitled "**Performance Evaluation of 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 Doctor of Philosophy in Electronics and Communication Engineering Department, Thapar University, Patiala, under the guidance of Dr. R.S. Kaler.

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

(Himanshu Monga)

Dated: 5/11/2014

Signature of student

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

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Abstract

This thesis deals with Performance evaluation of Optical Code Division Multiple Access System. The major noise source in Optical CDMA is co-channel interference from other users known as Multiple Access Interference (MAI). The system performance in terms of bit error rate (BER) degrades as a result of increased MAI. It is perceived that number of users and type of code used for optical system directly decides the performance of system. MAI can be restricted by efficient designing of optical codes and implementing it with unique architecture to accommodate more number of users. Hence it is a necessity to design 2-D wavelength-time and 3-D spectral-phase-time codes, which can provide better cardinality and good correlation property. The designing and investigation of efficient 2-D and 3-D coding techniques for different number of users in terms of Bit Error Rate (BER) performance aiming to counter the ill effects of MAI has been presented.

Firstly, a WDM compatible optical CDMA system incorporating 3-D spectral-phase-time encoding/decoding is demonstrated. Coding and decoding using binary [0, π] phase chips is demonstrated for six users at 10 Gb/s, and a single coded signal is separated with acceptable bit-error rate $\leq 10^{-9}$. The coding and decoding method is based on 3-D coding of tightly spaced phase-locked laser lines that is compatible with conventional WDM networking. In our proposed optical CDMA system, encoding and decoding is done by converting Hadamard codes (used for conventional CDMA system) to phase codes. Duo-binary modulation format is reported to be the best with adequate bandwidth compression. Simulation results too confirm better results in terms of BER and MAI. The obtained simulation results have been further verified that achieved bit error rate (BER) by the use of the bipolar coding method is much improved as compared to the unipolar scheme, especially when the received power is large. Hence it is summarized that whenever the system needs good performance to transmit multimedia data, we can use bipolar scheme in the network and if the users only transmit voice data the unipolar method can be employed.

Further, a new optimized class of optical codes known as Message Priority & Fast Routing (MPFR) is presented. We have presented two dimensional code constructions based on message priority and routing at faster rate. Tridiagonal matrix is used for code construction and message

priority is used which enables the priority of messages by simply assigning the priority value in packet header. We have proposed an algorithm based on multiple user environments used in-accordance with the packet header. The message size is increased and priority bit is added which leads to faster and effective data transfer in communication. MPFR code development is based on minimizing code length. Variation in weight due to priority provides fixed data rates but can support various different qualities of service processes and in other case; length variation can provide data variation to cater the user specific needs. An OCDMA environment is created and an interference sensing algorithm is introduced. The results revealed that proposed MPFR codes provide better performance as compared to Flexible Cross Correlation (FCC) codes, Zero Cross Correlation (ZCC) codes and Prime Hop codes (PHC) in term of BER, packet delivery ratio and MAI.

Also we have studied and analyzed the spectrally encoding/decoding OCDMA system for different lengths of fiber in terms of quality factor (Q) and BER performance. The performance characteristics like bit error rate, eye diagrams and eye closure penalty at the output are studied using simulation methods for different lengths of fiber. An upper bound on the bit error probability for phase encoded OCDMA system is maintained under the above considerations. The advantages of this system over the conventional time-encoded system include the availability of larger number of low cross-correlation sequences and the implementation of efficient decoders for low error probability detection.

In addition, we have presented the optical simulation technique of Encoding/Decoding for different lengths & gain in terms of Quality factor and BER performance. The system supports up to sixty four asynchronous users, while maintaining BER < 10^{-11}, for the correctly decoded signal. We have designed and simulated a Tree Network Topology Optical Code Division Multiple Access System, for large number of users using wavelength–time code and then analyzed the performance of the system based on BER and Eye Diagram under the influence of number of simultaneous users with different received powers.

The thesis also highlights the investigative study of proposed Optical CDMA network, by implementing spectral-coding of incoherent broadband optical sources. We have utilized the transmissive spectrum characteristics of FBG (Fiber Bragg Grating) to design encoder/decoder. In this design, we have not used any circulator; thereby reducing the cost as well as power loss. Signal at the receiver is extracted with acceptable bit-error rate ≤ 10^{-9}. The coding and decoding method is based on spectral-amplitude coding of FBG. Here FBG are used to control and modify the amplitude and phase spectrum of broadband incoherent optical signal. The effect of FWM (Four Wave Mixing) is avoided to a larger extent by using this optical CDMA coding technique. Simulation results too confirm better results in terms of Q factor, SNR and bit error rate in favour of NRZ modulation format.

Therefore, this study establishes the design and optimization of Optical CDMA system resulting in the revolutionary growth of data traffic with enhanced supported data rate with acceptable BER.

List of Publications

1. Himanshu Monga, R.S. Kaler, "Spectrally Efficient 3-D Optical CDMA Using Coherent Spatial-Phase-Time Coding/Decoding", *Journal of Russian Laser Research, Springer*, Vol 35, issue 4, August 2014.

2. Himanshu Monga, R.S. Kaler, "Performance Analysis of Multiple User Optical Code Division Multiple Access System", *Optics and Photonics Journal, Scientic Research*, Vol 4, pp.21-25, Feb. 2014.

3. Himanshu Monga, R S Kaler, "Performance Analysis and Improvement Of Spectrally - Amplitude Encoded/Decoded OCDMA System", *Optik - International Journal for Light and Electron Optics Elsevier Science*, vol 122,issue 22, pp. 2006-2010, Nov. 2011.

4. Himanshu Monga, R S Kaler, "Performance Analysis Of a 16-User 2.5 Gigabit Optical-Cdma Using Wavelength/Time Codes", *Optik - International Journal for Light and Electron Optics Elsevier Science*, vol 122,issue 22, pp. 2001-2005, Nov. 2011.

5. Himanshu Monga, R.S. Kaler, "Investigating Wavelength Allocation and Suitable Modulation Format For 2-D W/T And 3-D W/T/S Codes in Order to Enhance System Performance", *Journal of Communications Technology and Electronics", Springer*, Vol 59, issue 11 September 2014.

6. Himanshu Monga, R.S. Kaler, "Analytical Design, Simulation & Evaluation Of Proposed OCDMA With Message Priority Fast Routing Codes", *National Academy of Science Letters, Springer*, vol 37, issue 5, September 2014.

7. Himanshu Monga, R.S. Kaler, Performance Comparison of Proposed 3-D Coherent Spatial-Phase-Time Coding/Decoding With Super Structured Fiber Bragg Grating-Based OCDMA Systems "*Journal of Communications Technology and Electronics", Springer*, vol 59, issue 12, Nov. 2014.

8. Himanshu Monga, R.S. Kaler, "Analytical Performance Evaluation of Proposed Optical Code Division Multiple Access (OCDMA) System", Journal of Communications Technology and Electronics, Springer, Vol 59, issue 11 September 2014.

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List of Acronyms

2-D	Two Dimensional
3-D	Three Dimensional
BER	Bit Error Rate
CDMA	Code Division Multiple Access
EDFA	Erbium Doped Fiber Amplifier
FWM	Four Wave Mixing
LAN	Local Area Network
MAI	Multiple Access Interference
Mux	Multiplexer
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
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
WDM	Wavelength Division Multiplexing
WDMA	Wavelength Division Multiple Access

W/T	Wavelength/time
FBG	Fiber Bragg Grating
FCC	Fixed Cross Correlation
MPFR	Message Priority Fast Routing
ZCC	Zero Cross Correlation
PHC	Prime Hop Codes

Chapter 1

Introduction

1.1 Introduction and Overview

With day-by-day increasing spectrum requirements, various multiple access techniques have come into limelight. Use of multiple access techniques has enabled us to utilize the huge bandwidth of optical fiber communication system to its maximum. With effective use of multiple access schemes, a finite amount of spectrum can be shared simultaneously among various users. Optical CDMA (OCDMA) has knocked the doors of communication world with its great ability to sustain robust conditions, support for asynchronous data traffic and much better response to multiple access techniques. Along with these some of other attained gains by the use of optical fiber communications are low loss, high speed, huge capacity and great consistency by the usage of the wide-ranging bandwidth of the optical fiber [1].

Every user channel in OCDMA network is known by its exclusive signature sequence code and thereby achieved multiplexing gain is high. In comparison with TDMA and WDMA, where the transmission capacity can only be increased once, the total numbers of time or wavelength channels are increased, OCDMA permits flexibility of network design because here effective code generation decides the number of supported subscribers in a network [2].

Optical Code Division Multiple Access with huge bandwidth of the fiber as channel utilizes the benefits derived from CDMA technology to achieve higher speed and bulk data transfer. Hence it uses the same method of unique signature sequences (pseudo noise key) per user having large bandwidth and unique cross and auto correlation properties as that of CDMA system combined with its own advantages has brought new standards in communication by designing a modulator structure based on SAW (Surface Acoustic Wave) induced stark effect [3], [4]. Another great benefit of using this method is that now it is not required to manage and control the connected nodes in terms of time and frequency [5].

Modern communication networks require huge bandwidth for providing seamless connectivity for users and it is achieved in the form of optical medium by adopting different topologies [6]. The WDM light wave systems are investigated for their use with optical amplifiers, so that all the used channels may get amplified at the same time only. The application of these optical amplifiers at the transmitter side enables the transmitting channels to boost up their power and subsequently same amplifier placed at the receiver end compensates for the loss of power [7]. In a classic Optical CDMA system, data bit is distributed into small binary chips, divided into different time slots. Only for chip time interval (according to signature sequence) representing bit "one", a short optical pulse is sent, while no pulse is sent for data bit "zero" for the same duration. This way an optical signature sequence or codeword is generated [8].

The Co-channel interference is identified to be the major source of error, also known as Multiple Access Interference (MAI). It is observed that for an Intensity Modulated (IM) Direct-Detection (DD) optical CDMA type of network, the originating bit error from a bit "0" being understood as bit "1" is a usual case, although the bit error from a data bit "1" getting interpreted wrongly as a data bit "0" is not that common scenario. It is also studied that in spite of adequate received optical power at the receiver, the impact of MAI cannot be ignored because combined optical power inside a communicated pulse is spreaded equally between all of the transmitting active users at that time [9], [10].

The OCDMA network comprises: encoding, decoding, types of codes and nature of codes. Most commonly used codes in communication are bipolar and unipolar. In bipolar type of codes, for the purpose of encoding the data, both negative and positive levels are considered whereas in the case of unipolar scheme only single level i.e. positive level is earmarked. Optical communication systems generally employ unipolar codes because optical power is required to convey the information and the point with optical power is that it can never be made negative. On the other hand RF communication systems generally use the bipolar codes, as voltage levels are used to convey the information and voltage can either be negative or positive.

1.2 OCDMA System: A Review

1.2.1 Introduction to OCDMA

With the help of OCDMA technique, we can combine the gains extracted from CDMA technology and fibers enormous bandwidth, to achieve high-speed seamless connectivity. The last decade has seen huge development in optical based networking, which includes dense optical networking such as Wavelength Division Multiplexing and Code Division Multiple Access. Optical version of these technologies known as OCDMA has left huge impact on the real time networking to satisfy user's needs. Optical CDMA permits various users to access the network resources asynchronously, capability to support flexible data rate and bursty traffic and privacy in communication. [3], [4].

The advantages of Optical CDMA include its easy and smooth functioning and it has emerged as a strong option to ultra-high speed LANs. Here it is never required to have full control over time and frequency components for the communication. In addition to its ability to transmit asynchronously without any overlapping of data, gives it a definite edge over its competitors [5].

Every user channel in OCDMA network is known by an exclusive signature sequence code and as such achieved multiplexing gains are high. As compared to TDMA and WDMA, where the communication capability can only be increased with the increase in total number of time or wavelength channels, OCDMA permits flexibility of network design because here effective code generation decides the number of supported subscribers in a network i.e. approach is soft-limited and hence is more user friendly than TMDA and WDMA [2].

A general optical CDMA system is shown in Fig 1.1.and a basic diagram of multi-user system in which N-number of users can transmit/receive their information bits using signature codes is given in Fig. 1.2.

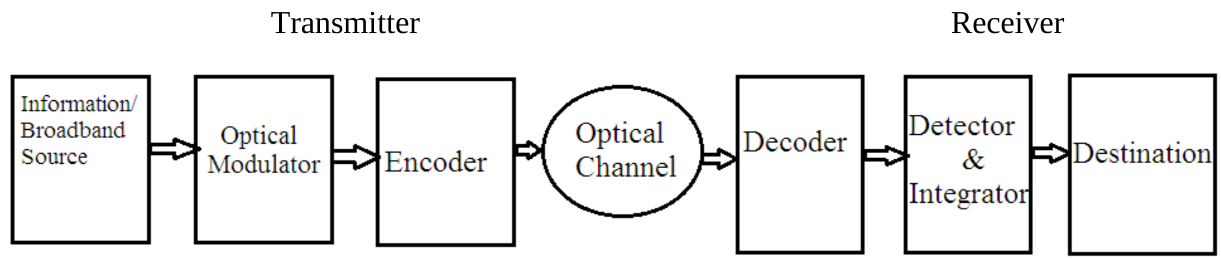


Fig. 1.1: Single user fiber communication network

In any typical OCDMA system, the broadband signal (carrier) from the light source is amplitude modulated with random sequence of digital data (user data). The light pulse for a defined time period is transmitted for data bit "1"; otherwise no power is transmitted. Signals transmitted from all synchronized users will be mixed up in the network by a combiner to constitute a composite signal before it is received by all users. At the receiver, the compound signal is interpreted by a matched decoder. The combined signal in the receiver travels to a photo detector, an integrator and a threshold decision to recover the transmitted data [3].

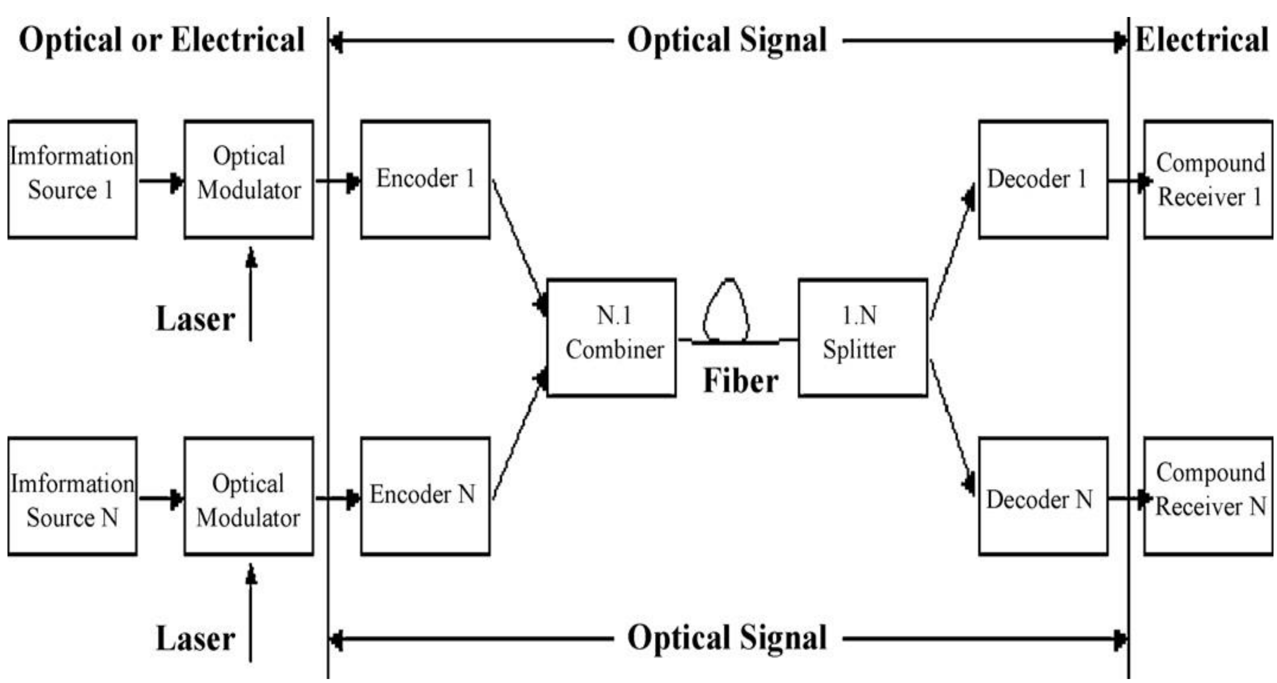


Fig. 1.2: Block Diagram of Optical CDMA systems [3]

In OCDMA technique, the orthogonality of the codes is the important property to minimize MAI. For its implementation, unipolar, (0, 1) codes with throughout low out-of-phase auto-correlation and cross-correlation values are used for asynchronous OCDMA networks. Unipolar codes maintain low out-of-phase auto-correlation and cross-correlation by minimizing the number of coincidences of "ones" rather than by their cancellation as in bipolar codes. So the number of "ones" in a unipolar code is less than the number of "zeros".

Wavelength is combined in any 2-D codes with time as the other dimension of the code. It is apparent that 2-D codes show better results in terms of spectral efficiency. Hence these codes use the available bandwidth in a better way. These 2-D codes are high performing as they simultaneously achieve the following: [12]

- Provision for greater number of subscribers.
- Realize high data rates per user.
- Provides a high Spectral Efficiency

There are several optical orthogonal codes, which are divided into two main groups: bipolar codes involving states "1" and "-1" and the unipolar codes, having status as "0" and "1" which are most often used for the detection purpose.

1.2.2 Advantages and Limitations of OCDMA networks

Enormous known advantages of OCDMA illustrate that; it might be an appropriate access technique to be used in access networks like LANs or WANs. The optical CDMA technology offers advantages as follows: [8]

1. Rational Distribution of Available Bandwidth
2. Easy Network Regulation and Organization

3. Flexibility

4. Security

5. Quality of Service (QoS)

1.2.2.1 Rational Distribution of Available Bandwidth

In Optical CDMA network, the allotted Optical CDMA bandwidth is divided among all the active subscribers in a very rational manner and hence it is operated to get maximum benefits by proper utilization of available spectrum. Hereby, efficient designing of codes enable OCDMA network to have more number of users than available bandwidth by providing the technique of spreading in time domain. The allotted spectrum of the optical fiber link is sub-divided into a number of effective channels, one for each user. Thus availability of these vast numbers of channels in optical network reduces channel conflict. Here each user of the network has its own assigned channel (bandwidth) to communicate, so it does not interfere and block other users data and the network usage is very fair.

1.2.2.2 Easy Network Regulation and Organization

The network control is also very simple and smooth in Optical Systems. Here users can asynchronously transmit their data without the need of any centralized monitoring. This is possible, as users are individually assigned unique codes and transmit their signals, by the use of their own pre-assigned channels, thereby eliminating any requirement of controlling. It is very clear that number of users supported by the system is dependent on availability of optical codes only. The designed codes with special properties enable the users to communicate independently with no need for a centralized node. The additional users can easily be added to the existing network by simply assigning a new code. Some unused codes are kept reserved for future expansion at the time of network deployment. Even if this is not the case, then also optical codes can still be generated and added to existing code structure by either the increase of time or wavelength domain spreading.

1.2.2.3 Flexibility

In addition OCDMA systems have the capacity to be very flexible. With the introduction of 2-D and 3-D codes, designer can design the network as per the need of the user. Two-dimensional Optical CDMA codes use both time and wavelength spreading with acceptable cross-correlation and auto-correlation characteristics. This is the flexibility with users to choose the services, according to their needs and then accordingly the bandwidth is allotted. The third dimension added to 2-D codes goes one step ahead to achieve the mentioned objectives. Hence one more dimension is available to boost the performance and cardinality of the system.

1.2.2.4 Security

The integral security is the biggest advantages offered by Optical CDMA. The Optical CDMA systems bring dual integral security to information data of each user at coding as well as at the media level. Tancvevski et al. have proved that it is not feasible for anyone, who is unauthorized in OCDMA network, to decode the data. [8]. Hence, security is very much ensured in OCDMA systems.

1.2.2.5 Quality of Service (QoS)

Finally, OCDMA introduces the possibility of presenting discriminated service at the physical layer. We can identify different service needs and cater them by designing the suitable codes. We can design the codes supporting low data rates for the services like e-mail and file transfer, while services like transfer of audio and video information can be entertained by designing high data rate codes. There is a facility of quality of services at the fiber level by the use of dynamic coding. In case the network observes high MAI pulses that compromise the earlier selected quality of service, new signature sequences can be assigned to all the nodes to restore the quality of selected service. Each node has the capability to sense the average MAI and once it exceeds the value, each node would switch to a new code word to continue the anticipated QoS limits. No two nodes can share the same code word from the code set.

To summarize the main benefits of using Optical CDMA systems include:

- Equal Distribution of Available Bandwidth.

•Control and Organization of the network.

•Provisioning of Value-Added Services.

•Security.

In spite of their many advantages, OCDMA systems suffer from few limitations, which may be summarized as follows:

•Noise.

•Error Correction.

•Encoding/Decoding.

•Security Integration.

In addition, the main limitation of OCDMA system is Multiple Access Interference (MAI), which affects the BER and the number of concurrent users in the network. It is co-channel interference caused by multiple users, transmitting in the same frequency band at the same time, but using different codes [12]. It is the leading cause of BER in an optical CDMA system. The major source of error in CDMA is co-channel interference from other users, also known as MAI. The BER degrades as the effect of MAI increases.

1.2.3 Types of OCDMA Systems

The optical CDMA systems can be broadly categorized into two main categories:

(i). Coherent OCDMA System.

(ii). Non-coherent or Incoherent OCDMA System.

1.2.3.1 Coherent OCDMA System

In the Coherent OCDMA system, Signature coding is performed electrically, and then the optical carrier of the laser transmitter is modulated coherently. A block diagram of the operation of Coherent optical CDMA receiver is shown in the Fig. 1.3.

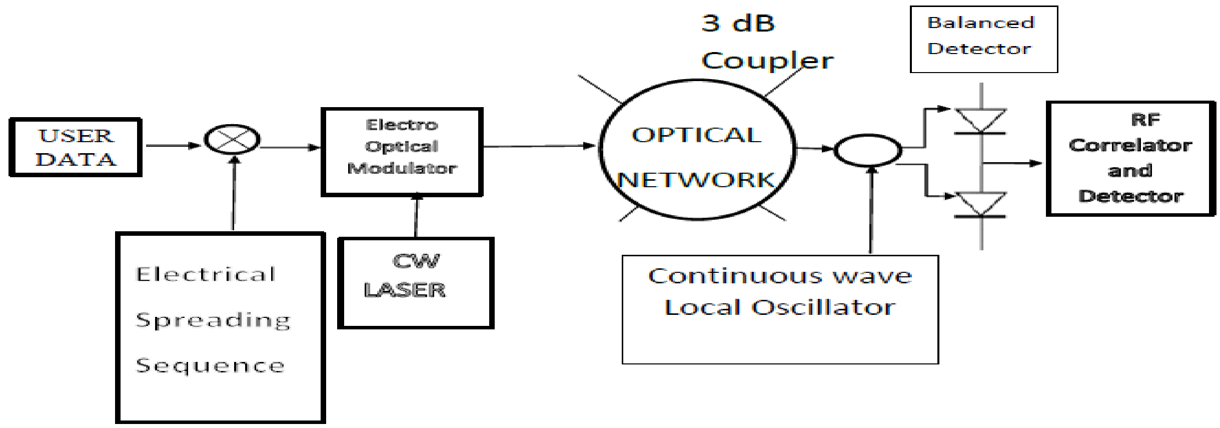


Fig. 1.3: Coherent Optical CDMA (OCDMA) System

1.2.3.2 Non-coherent OCDMA System

A Non-coherent or Incoherent Optical CDMA communication receiver system uses Direct Detection Technique. In Direct Detection (DD), the photo detector gives the output current $I_{D,}$ which is relative to the average power of the received optical (modulated) signal.

1.2.3.3 Comparison of OCDMA Systems

In general the coherent optical system offers two advantages over incoherent system: One is the better receiver sensitivity and the second is frequency selectivity. Because of the high frequency selectivity, great capacity can be achieved by using different carrier frequencies much closer to each other.

An important advantage of the coherent OCDMA systems is that different kinds of modulation methods (e.g. FSK, PSK) can be used. Hence the chip values, as with incoherent system, is not limited to the use of non-negative (unipolar) “0” and “1” levels of the power. So most common and already developed codes for the radio based systems can also be used in optical communication systems.

But the major disadvantage of Coherent OCDMA systems is that they need to use more complex receiving schemes to correctly perform the dispreading at receivers. It needs alignment of polarization vectors, phases of optical pulses with frame and time-slot synchronization between the incoming OCDMA signal and the local signature sequence for the correct detection of transmitted information. Therefore this type of optical systems is more difficult to implement and are expensive too. So in comparison to Coherent, Incoherent (Non-coherent) optical CDMA systems are more practical, simple and economical [13]. The transmission of coherent optical code division multiple access traffic over optical-code-based optical packet switching network has recently been explored with codes having flexible cross-correlation value to reduce the effect of interference thus optimizing the code length. The FCC code can be constructed with simple tridiagonal matrix property and performance validated for packet switched network based on optical coding technique.

1.2.4 Components of Optical CDMA networks

The OCDMA technology is relatively new, that emerged and gained focus for the research community, during the last twenty years. The OCDMA implementation depends on several factors such as, for instance the desired number of users. In OCDMA, the spread signal is subjected to conversion from one format to another like electrical-to-optical, optical-to-optical or optical-to-electrical. The Optical CDMA network comprises of the following components:

1. User Data Originator

2. Optical Encoder

3. Star Coupler

4. Optical Decoder

5. Decision making circuitry

1.3 Multiple Access Interference (MAI) and Its Effects

The performance of OCDMA systems is mainly affected by interference from other simultaneous users called Multi-user Interference (MUI) or Multiple Access Interference (MAI). The Optical CDMA systems adversely suffer from pulses from other simultaneous users. Other asynchronous user pulses may overlap with desired user pulse; it may lead to change in logical meaning of the data. This ill effect of MAI, can be reduced by either using optical Hard-Limiters (Single or double) at the receiver end or by carefully designing the code sequences of a fixed in-phase cross-correlation value. The first approach is appreciable when users count is limited, above a certain number of users, result gets degraded. In recent years, many innovative receivers with optical hard limiter have been developed to suppress MAI.

From some time, numerous interference elimination methods have been presented, aiming at lowering these asymptotic error floors. These interference cancellation techniques are classified into two groups. One is based on the designing of improved codes with required properties of auto and cross-correlation and the other approach is hardware oriented i.e. the use of optical hard-limiters. In hardware approach, to meet this problem, it is identified that it is not possible to completely mitigate the effects of MAI and hence forth it is concluded that the first approach of efficient code designing is a better alternative.Therefore, there is a requirement to use 2-D wavelength-time codes, which can support improved cardinality and decent correlation property than its predecessors. The need is also felt for new optimized communication method for OCDMA aiming to minimize code length. Variation in weight due to priority, provides fixed data rates, but can support various different quality of service processes and in other case, length variation can provide data variation according to users and subsequently support for different quality of services.

1.3.1 Types of Signature Sequences Used in OCDMA

In Optical CDMA systems to encode/decode the data, basically two types of signature sequence codes are used:

(1) Optical Orthogonal Codes (OOC).

(2) Prime Sequence Codes [64]

1.3.1.1 Optical Orthogonal Codes

An Optical orthogonal code (OOC) is a set of (0, 1) sequences with good auto and cross-correlation properties, i.e., the auto-correlation of each sequence displays the “thumbtack” shape and the cross-correlation between any two sequences remain low throughout [11]. The optical system with such codes does not require synchronization and provide support for asynchronous users. The thumbtack shape of the auto-correlation permits the detection of the desired signal, and the low cross correlation decreases the interference from unwanted signals present in the network

In OCDMA systems the encoded signature code of each user should be distinguished from a shifted version of itself and from the shifted versions of the codes of other users. When x_n and y_n are signature codes of two users, the designed code must fulfill the following two conditions of correlation [14], [15].

Auto-Correlation:-

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

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

For τ =0, λ_a = w (weight i.e number of ones in every codeword)

Where λ_a is the auto correlation constraint. So as to allow for the effective recovery of the wanted signal, it should exhibit the thumbtack shape. If λ_a takes on the minimal value, desired user sequence can easily be detected.

Cross-Correlation:-

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

For any $x \neq y \epsilon C$ and for any value of integer τ.

Where $\boldsymbol{\lambda_c}$ is the cross correlation constraint. It should remain low throughout to overcome interference due to simultaneous users. If $\boldsymbol{\lambda_c}$ takes on the minimal value, sequence is easily distinguishable from other code sets.

1.3.1.2 Prime Sequence Codes

In Optical CDMA, each data bit "1" is encoded into a waveform (i.e., a binary code sequence), which represents the destination address of that bit, but data bits "0" is not encoded. Each bit period T is sub-divided into N small units, called chips, in order to accommodate all the elements (i.e., 1's and 0's) of the binary code sequence [18]. The 2^n codes are here defined as a collection of binary N-tuples with weight 2^n. The distribution of the pulses in each generated codeword must be symmetric (i.e., the distribution of the current 2^m pulses highly depends on that of the previous 2^{m-1}pulses, where$1 < m \leq n$) and results in a very preventive pulse-distribution constraint.

1.4 Summary

In this chapter, we have outlined the basic Optical CDMA system by giving its basic block diagram and highlighting the importance and necessity of Effective Coding Technique to achieve desired performance. The various advantages along with few limitations of Optical CDMA are also given. The impairments like Multi Access Interference (MAI), its cause, impact and possible remedies are also shared. The various components constituting the optical CDMA system are discussed. The basics of optical code generation as well as their properties are also explained. The chapter also gives two widely used categories of optical system. It is mentioned that the OCDMA network comprises: encoding, decoding, types of codes and nature of codes. The effective code design is a critical part of any Optical CDMA system. Most commonly codes used in communication are bipolar and unipolar. In bipolar type of codes, for the purpose of encoding the data both negative and positive levels are considered, whereas in case of unipolar scheme only single level i.e. positive level is earmarked. Optical communication systems generally employ unipolar codes because optical power is required to convey the information and the point with optical power is that it can never be made negative. On the other hand, RF communication systems generally use the bipolar codes, as voltage levels are used to convey the information and voltage can either be negative or positive.

Chapter 2

Literature Review

2.1 Introduction

In this chapter, we present a comprehensive literature review of Optical Code Division Multiple Access networks. Its various coding techniques and various impairments are also discussed. In section 2.2, we step back to provide a brief overview of the previous developments in OCDMA. The section 2.3 discusses the recent developments in Optical CDMA Systems. Further, gaps, objectives and thesis outline are presented in section 2.4, 2.5 and 2.6 respectively.

2.2 Literature Survey

2.2.1 Evolution of OCDMA

The code construction techniques provide a big advantage for OCDMA communication and utilize various code families of time spreading and wavelength hoping codes. Security in 2-D codes is always better than the normal single dimensional codes and the maximum values for cross correlation is also reduced by implementing these codes. In communication through optical codes, many issues, such as Multiple Access Interference and Bit Error Rate occur, which degrades the quality of communication through optical network. MAI is the major issue accountable for the degradation of the performance of optical network and it is even more significant in case of large optical networks and it is further enhanced by thermal noise while propagating through optical link.

A. J. Mendez et al. [3] investigated that, for Direct Detection of AM (on/off) keying type optical signals, a spread spectrum multi-access system gives better results. The research is performed by designing codes and strategies for its applications to dense, high-speedoptical network. The performance of the network is examined and reported.

Fan R.K.Chung et al. [11] proposed and demonstrated an Optical CDMA network architecture using Optical Orthogonal Codes with required co-relation properties in terms of auto and cross co-relation. In this work, various previous literatures on similar terms were also discussed and a performance analysis of introduced codes is also performed.

Kwon et al. [12] utilised an Avalanche Photodiode (APD) to design and analyse the performance of a correlation receiver by the use of a hard-limiter in a system. For modelling of the received signal a Gaussian process was used. In another experiment, hard limiter was not considered for practical experimentation. It is proved that prior utilisation of hard limiter before the correlator at the receiver side improves the system performance, compared to the optical system, employing hard limiters after the correlator receiver. Optical systems under the impact of OHL (Optical Hard Limiter) placed both before and after the correlator are examined and then performance wise compared. In continuation to his work in optical domain, further observations suggested that use of Gaussian approximation for the receivers involving PIN diode, is not the best choice for modelling the optical systems, when it comes to analysis of low power optical signals.

Salehi et al. [16] examined the optical system considering channel impairments and proved the usability of Optical Orthogonal Codes, in actual interference driven systems. It was suggested by them that the proper use of optical hard limiter in optical system, can eliminate major interference, causing bit being interpreted correctly. They have analytically shown that improvement in optical systems can be achieved against multi user interference by the suggested method. In their proposed method, the assumptions were made considering only the channel interference. The complete system is examined for co-channel interference and its suppression by the use of optical hard limiters.

H.M.Kwon [17] derived a system capable of transmitting data at a high rate of multi-bits per sequence-period. The constructed system was derived by exploring the correlation properties of the OCDMA code sequence, and making a decision for the detected bit, based on the Maximum Search Algorithm, rather considering threshold value. This approach yielded better results, compared to the earlier researches on similar domains, in terms of supported data rate.

Kwong [18] introduced a unique cluster of 2^n codes, named 2^n prime-sequence codes. These codes were constructed based on a conceptual algorithm to improve the cardinality of optical network. The basic features and outcomes of the suggested codes were also presented. For designing Optical CDMA networks, these proposed codes, having the mathematical characteristics of prime-sequence codes, new optical receiver/correlator were introduced aiming for enhanced network performance.

Chang et al. [19] constructed and generated two-dimensional codes for validation of their performance in terms of BER, for utilization in typical OCDMA networks. The generated codes were expanded in dual dimensions of time and wavelength to achieve the desired cardinality. It is experimentally demonstrated that instead of using unanimously utilized SUM type of detection and replacing it with AND detector, the optical channel capacity can be increased for a given data rate, number of active users, and bit error rate.

Han [20] examined the relationship between various Optical CDMA communication techniques w.r.t applied optical orthogonal codes. Various Simulations were performed to illustrate and highlight the desired features of these optical codes and their utility in optical CDMA is reported. Resultant simulation results verified the properties of optical CDMA and evaluated the probability of errors.

Kwong et al. [21] invented a group of variable-length, constant-weight 2-D wavelength-time optical orthogonal codes. The proposed codes are shown to support multimedia services with capability of catering to different quality-of-service requirements and signalling rates in optical CDMA networks with the effective installation of fiber-Bragg-grating array type of encoders/decoders at the receiver.

Shalaby [22] discussed the designing of correlation receiver in optical system along with its hardware implementation using optical hard limiters (Both single and double) is demonstrated. A comparative reporting of system performance in terms of the bit error rate and the throughput for both chip-level and correlation systems (without hard limiters) is reported. The obtained results of comparison showed inclination towards chip-level receivers. These were found to be much simpler to implement and their performances are even at par with that of traditional correlation receivers employing double optical hard limiters in optical systems.

F. Gutleber et al. [23] experimentally demonstrated and brought into limelight, that one can achieve increase code weight and therefore cardinality (users) by slight increase in conditional value of maximum cross-correlation from one to two. The interesting findings also validated the assumption and subsequent work done in this regard and newly introduced code structure showed that even by relaxing the laid condition on cross-correlation, generated 2-D codes outperformed the earlier reported optical orthogonal codes, for better value addition.

Tien et al. [24] developed a new class of 2-D optical codes, which possess the maximum cross-correlation value of two and validated for its performance under the effect of fiber impairments. The newly designed system supported bigger code set and weightier code (i.e., more Simultaneous users) without subsequent compromise on the code length. The designed 2-D Optical CDMA system performance was computed, compared to other optical codes satisfying the laid cross correlation criteria.

Galli et al. [25] expressed the necessity of achieving better efficiency in terms of utilization of available spectrum in a general asynchronous optical CDMA network; a novel *M*-ary modulation scheme to achieve this is also discussed and proposed.

2.2.2 Literature Survey on various Coding methods and impairments

In recent years, to counter the unwanted effects of MAI in Optical networks, distinct receiver structures with optical hardlimiter have been introduced. The ill-effects of increased MAI ultimately lead to degrading the BER and in turn are hampering the overall performance of optical network. The effective code designing is considered to be a good way to deal with this issue.

Heo et al. [26] experimentally proved that Two-dimensional (2-D) optical code employed for Optical CDMA (OCDMA) systems outperforms linear or direct sequence codes in the cardinality and efficient use of available bandwidth. They gave 2-D Wavelength-hopping /Time-spreading codes with balanced detection type of correlator at receivers and analytically analyzed the features of the proposed optical system. The achieved results from proposed code structure yielded enhanced performance and accommodated more number of asynchronous users in contrast to differential detection scheme employed with even 3-dimensional codes for similar performance matrix.

Ohtuski et al. [27] extended and investigated the work on the performance evaluation of Optical CDMA receiver using double Optical Hard Limiter (OHL). They calculated and presented an OCDMA system with hardware implementation of double OHL in the presence of fiber impairments and considered the effects of received optical power. Their analysis related the results in terms of BER to received optical power and finally conclusion is drawn that there is phenomenal improvement in bit-error-probability of OCDMA systems in case of increased received optical power.

Mendez et al. [28] highlighted that when it comes to differential detection, 2-D wavelength/time codes outperforms one-dimensional (1-D) Optical CDMA system of similar cardinality. Then, the paper described and developed set of 2-D wavelength/time codes and experimentally demonstration was performed. These 2-D codes exhibited good results i.e. high cardinality, high bandwidth, and high Spectral Efficiency (SE). Their research proved that OCDMA system can be hardware implemented by introducing double hard limiter at the receiver side and guard time can be employed between the codes to avoid interference.

Shivaleela et al. [29] constructed the basic implementation structure for in-coherent fiber optical OCDMA system, introducing entirely new family of wavelength/time multiple-pulses-per-row codes with increased cardinality, maintaining minimum cross correlation value and even with improved spectral efficiency. In addition, an analytical description on the upper limit on achievable user count of W/T MPR codes supported with derived code structure was demonstrated. The added feature of derived 2-D W/T Multiple Pulse per row codes is its adjustable aspect ratio, by a simple relation between wavelength and temporal lengths. Various simulation parameters like wavelength dimensions, weight of the code, time etc. were considered for the Performance evaluation of the introduced 2-D W/T MPR codes and their practical limitations against channel constraints were taken in to account.

Hernandez et al. [30] proposed an experimental set-up for Optical CDMA system built on two dimensional (2-D) codes. For developing 2-D W/T codes, optimum Golomb ruler was taken as the basic seed. The code set was designed and performance evaluated for acceptable results for defined number of users.

Hernandez et al. [31] derived a practical design for an incoherent Optical CDMA system and extended the previous work on 2-D wavelength/time codes by implementing the same for increased number of optical channels. The proposed system gave acceptable results for 16 asynchronous users operating at a 1.25 Gsymbols/s/user. Experiments were supported by many simulations, addressing and presenting issues like coherent beat noise (mostly present in the channel) and MAI, those put upper bound on optical network performance.

Wang et al. [32] examined the coherent Optical CDMA against the application of various data formats. In particular, practicability of Differential Phase Shift Keying data format in (DPSK-OCDMA) had been recommended for its better performance against different types of noises in the OCDMA system. It is further studied that this adopted technique in optical network provides less complexity at receiver end for deciding its threshold level, thereby even increase the system confidentiality against tempering.

Zou Wei et al. [33] identified and analyzed that MAI is the main cause of decline in network performance, whenever users count is more. In a spectral-amplitude-coded optical CDMA network functioning for a assumed cardinality and a code length, MAI can only be determined by the present values of in-phase cross correlation among the address sequences.

R.S.Kaler et al [34] highlighted the impact of EDFA power on optical systems, also explained the performance of optical communication systems with subsequent increase in different types of fibers used in optical systems; it is further highlighted the need of proper matching between the EDFA power and length of the fiber for optimum performance.

Tai-Chien Wang et al. [35] reported that O-CDMA is getting the attraction of many, due to the rapid growth of the 2-D wavelength-time coding technique. The applied Wavelength-time codes in optical networks increased the number of channels and supported many users transmitting asynchronously by making use of both the coding dimensions simultaneously, rather than the previous approach of code implementation with only one coding dimension. Earlier reported one-dimensional (1D) codes were found to have this drawback that their length is required to be increased, to provide acceptable code performance, which limited the use of optical system to a great extent. The concept was demonstrated and this deficiency was addressed by the proposed work on 2-D wavelength-time coding technology.

Shalaby et al. [36] highlighted the basic requisite of conditional auto and cross-correlation properties in conventional optical ON–OFF keying (OOK) CDMA systems. Use of Double hard limiter based receiver structure with its importance was also presented. [35].

D.E. Leaird et al. [37] experimentally proved the spectral-amplitude-phase encoded OCDMA system with different modulation schemes implementing the code switching technique, between two codes to combat the effects of MAI and investigated the security issues involved.

Jawad A.Salehi [38] presented and investigated the application part of latest class of signature sequences as optical codes, named; Optical Orthogonal Codes (OOCs). Also discussed their importance in context to optical networks for acceptable BER values.

Anuar et al. [39] constructed new code architecture applicable for Spectral-Amplitude Coded Optical OCDMA system using almost zero cross-correlation and also gave its analytical model considering various channel impairments.

Chung et al. [40] introduced the new class of Optical Orthogonal Codes and investigated for their performance validation in long haul communication systems citing the importance of these codes.

Yang et al. [41] reported that two dimensional optical codes can be constructed based upon coding in spatial/frequency domains. They mathematically constructed a 2-Dimentional M-Matrices structure and verified its better performance using proposed optical network set-up.

Eltaif et al. [42] introduced a technique for Interference Mitigation by the use of successive interference cancellation technique in Optical CDMA Systems. The obtained results were discussed and were shown to be better than previously suggested techniques on interference reduction.

2.3 Developments in OCDMA

The major developments in the field of Optical CDMA are presented in tabular form. The researches have contributed heavily in terms of effective code designing, reduction of MAI and other impairments and to achieve acceptable BER.

Table 2.1: Progress/Developments of OCDMA network

OCDMA	Work done	Authors, Year
Foundation of OCDMA	Showed CDMA can be implemented on optical fibers using optical delay lines	Prucnal, Santoro, and Fan[77] , 1986
	Demonstrated the frequency domain manipulation of coherent ultra-short light pulses to implement CDMA in Optical domain	Weiner, Heritage, and Salehi[78] , 1988
	Presented the concept of adding and dropping the signals by using optical add drop multiplexers (OADMs)	Bhatia, Kaler, & Rajneesh Randhawa [96], 2013
OOC and 1-D codes	Introduced optical orthogonal codes for OCDMA and their representation as optical disk patterns.	Jawed A. Salehi [79] , 1989
	Derived the BER of OCDMA system with OOC's, Introduced optical hard limiter to reduce the MAI.	Salehi and Brackett [80], 1989
2-D codes	Proposed 2-D multi-wavelength time spread OCDMA system and reported their performance evaluation.	K. Yu, J. Shin, and N. Park [81] , 2000
	Extended the concept of generation of 2-D codes from Prime sequence orthogonal codes from existing sets of optimum Golomb rulers and derived its cardinality.	Antonio J. Mendez et al. [82] , 2003
	Demonstrated the semi-graphical method of generation of Two-dimensional codes by matrix structure from pseudo orthogonal (PSO) sequences.	Antonio J. Mendez, et al. [28] , 2009
	Studied and Proposed an orthogonal modulation scheme applicable with differential phase-shift keying (DPSK) and code-shift keying (CSK) to enhance data transmission ability of the optical CDMA system.	Bo Dai, et al. [91], 2011
	Reported a method based on genetic algorithm to design and develop optical CDMA address code sequences. Also derived the analytical model for the same.	D. Sadot, U. Mahlab et al.[90], 2009
	Designed Flexible Cross Correlation Code for SAC-OCDMA System and explained its	C.B.M. Rashidi et al. [44] , 2012

	advantages to optical systems.	
	Derived the modified prime-hop codes for opticalCDMA systems and its performance evaluation are carried out.	Wen et al. [89], 2003
	Presented the Enhancement of Zero Cross Correlation Code for Optical CDMA Network.	Anuar et al.[39] ,2012
	Introduced the Code Length Optimization technique Using Flexible Cross Correlation Code in OCDMA Networks.	C.B.M. Rashidi et al. [45] ,2012
3-D codes	Presented and extended the work on OOC codes, thereby spreading the 2-D wavelength-Time codes by working with another dimension i.e. space. This way obtained 3-D optical codes were reported for their improved performance.	Sangin kim, Kyungsik Yu, and Namkyoo Park [87], 2000.
	Experimentally demonstrated 3-D OCDMA system to encode data in time, wavelength, and polarization.	J. E. McGeehan et al. [88], 2004.
	Simulated wavelength converter for future broadcast networks at 40 Gb/s using low-cost semiconductor optical amplifiers.	Rajneesh Randhawa, Surinder Singh, Kaler et al. [97], 2009.
	Poposed Lubi transform based encoding technique for free space optics and presented the obtained results in terms of SNR.	Muralidharan Kulkarni et. al. [95],2012
Concerns of OCDMA		
Crosstalk /FWM Investigation	Studied the influence of increase in word length of a pseudo-random bit sequence on nonlinear crosstalk.	Yamamoto et al. [92], 2004.
	Reported an all-optical multiple-channel optical system under the adverse impact of four-wave mixing (FWM) in a single mode nonlinear fiber and its remedy is also highlighted.	Majumder et al. [84], 2011.
To reduce/study the non-	Highlighted the importance of interleaving in time domain to avoid Interchannel crosstalk and generation of FWM.	Amarpal Singh et al. [85], 2006.

linarites In Optical Networks	Investigated the role of interleaving in time domain for multi-user system based on higher-order FWM in a Single Mode fiber.	P.Teh et al. [86], 2001.
	Experimental demonstrated the security-improved OCDMA with bipolar coding to improve system performance.	Al-khafaji et al. [93], 2011.
	Design of Ultrafast Encryption and Decryption Circuits for Secured Optical Networks is demonstrated. Proposed network is reported to be secure, reliable and fast.	R. S. Kaler el al. [94], 2010.

2.4 Gaps in Present Study

This section lists the common limitations encountered while dealing with Optical CDMA systems. This would realize the importance of these drawbacks and explicate the reasons for attempts to attain solutions to these problems.

Based on the research literature, it is observed that there is a continuous need of the OCDMA systems, which can operate at higher user data rates with large cardinality. The impact of MAI and FWM on optical CDMA systems using different coding techniques and modulation formats have not been investigated. Even limited work had been carried out for the priority based fast routing of data packets in multiple user environments, which could be managed by packet header in Optical CDMA networks for its better performance. It is perceived that number of users and type of code used for optical systems directly decide the performance of system. MAI can be restricted by efficient designing of optical codes and implementing it with unique architecture to accommodate more number of users. Various codes have been offered to remove the MAI effect. However these codes suffer from various limitations by one way or another. The code constructions are either with a too long code length, or having variable cross- correlation. So as to improve survivability of optical system, more work needs to be carried out to implement different architectures based on vast available network topologies by designing better codes. Till now, investigation of OCDMA system using effective coding method has been carried out at relatively low bit rates and higher channel spacing. Hence there is need to identify a WDM compatible Optical CDMA system that can operate at higher data rates to facilitate different types of user data to be communicated faithfully with acceptable BER and reduced MAI.

2.5 Objectives

Keeping in view the above mentioned aspects, the objectives of research were formulated which are listed as follows:

1. To analyze and investigate techniques to reduce the Multiple Access Interference in OCDMA system.
2. To improve the system performance in terms of bit error rate by designing the code for OCDMA system.
3. To design a new family of Unbalanced Two-Dimensional Wavelength-Time Codes in order to enhance system performance.
4. To investigate Wavelength Allocation and suitable modulation format to reduce effects of FWM in OCDMA system.

2.6 Outline of Thesis

The thesis has been organized into seven chapters. Contents of each chapter are briefly described as under:

Chapter 1 covers the introduction to Optical Code Division Multiple Access network and its types, components and major concerns.

Chapter 2 of this work gives a comprehensive literature review of various existing techniques of effective code designing and subsequent reduction in MAI of OCDMA system and their limitations. The objectives of the thesis are crystallized.

Chapter 3 deals with the first objective of the thesis which is to analyze and investigate techniques to reduce the Multiple Access Interference in OCDMA system. A WDM compatible Optical CDMA system incorporating 3-D spectral-phase-time encoding/decoding is displayed. Coding and decoding using binary $[0, \pi]$ phase chips is demonstrated for six users at more than 6 Gbps, and a single coded signal is separated with acceptable bit-error rate of $\leq 10^{-9}$.

Chapter 4 deals with the second objective of the thesis which is to improve the system performance in terms of bit error rate and number of users by designing the code for OCDMA system. To achieve this objective, we have divided the work in two sections, in the first section, we have designed Optical CDMA system based on spectral encoding technique with application of bipolar code and second section presents a new optimized class of optical codes known as Message Priority and Fast Routing (MPFR). This work explained optimized optical codes based on message priority with fast routing method. Codes for MPFR are generated based on simple tridiagonal matrix which enables multiple user environments and managed by packet header. Evaluation of the proposed network codes is done by comparing proposed work with flexible cross correlation code construction, zero cross correlation code construction and prime hop code construction concepts. Proposed work provides improvement with less code length, bit error rate, packet delivery ratio and multiple access interference.

Chapter 5 deals with the third objective of the thesis i.e. to design a new family of Unbalanced Two-Dimensional Wavelength-Time Codes in order to enhance system performance. In this chapter, we have also proposed architecture for Optical CDMA using a Tree Topology where the transmitter uses developed 64 users 2-D PSO (W/T) codes for their enhanced performance.

Chapter 6 deals with the fourth objective of the thesis which is to investigate Wavelength Allocation and suitable modulation format to reduce effects of FWM in OCDMA systems. The proposed Optical CDMA network is implemented by spectral-coding of incoherent broadband optical sources. We have utilized the transmissive spectrum characteristics of FBG (Fiber Bragg Grating) to design FBG encoder/decoder. In our design, we have not used any circulator so there is reduction in the cost as well as power loss to a great extent.

Finally, chapter 7 covers the summary/conclusions drawn, recommendations on the basis of results obtained in chapters three to six and the scope of future work has been presented.

Chapter 3

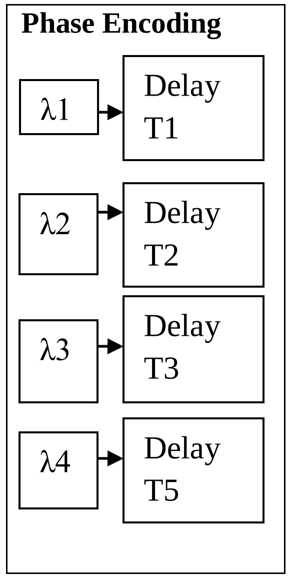
Reduction of MAI in Optical CDMA system

3.1 Introduction

This chapter focuses on the first objective of the research work that is to propose a technique to reduce the MAI originating in OCDMA systems. As we have pointed out in previous chapter that earlier some work is done on phase encoding, but it is restricted to very limited number of users. As the numbers of users are increased with intended data rate, the system performance degrades. In addition, earlier work on phase encoding used FBG's (Fiber Bragg Grating) by varying its refractive index profile, which has the limitation of requirement of precision of the FBG fabricating device. Further there is a need to find the suitability of modulation schemes with suitable bandwidth compression to overcome the physical constraint of optical bandwidth. The encoding/decoding in our proposed Optical CDMA system is demonstrated by converting the famous Walsh Hadamard codes, mainly employed for conventional CDMA systems to phase codes. First of all, this work demonstrates and analyzes dual unipolar and bipolar coded configurations of Spectral Amplitude Coded (SAC) OCDMA systems by making use of simulation methods [47], [49], [50]. The prime advantage of implementing code sequences of a fixed in-phase cross-correlation value with SAC-OCDMA system is that multiple access interference (MAI) can be reduced. In the same network use of balance detection schemes at receiving end also contribute to the same cause. The simulation results show that obtained bit error rate (BER) by use of bipolar coding method is better than the unipolar scheme, particularly when the received effective optical power is great. Whenever system needs good performance to transmit multimedia data, we can use bipolar scheme in the network. If the users only transmit voice data, the unipolar method can be employed. The eye diagram also reveals that network with bipolar encoding structure displays a broader opening than by using unipolar encoding structure.

3.2 Spectrally Efficient 3-D Optical CDMA Using Coherent Spectral-Phase-Time Coding/Decoding Technique

This work investigates dual unipolar and bipolar spectral-amplitude-coding optical code division multiple access (SAC-OCDMA) systems along with phase coding (unipolar and bipolar) with the use of simulation method. The important feature of the SAC-OCDMA systems along with phase coding in time domain is that multiple access interference (MAI) can be removed by employing code sequences of a fixed in-phase cross-correlation value [51], [53]. So far our work is concerned, we have implemented Walsh-Hadamard codes as signature codes for the unipolar and bipolar schemes and then compared the obtained results with other available coding schemes for the same proposed simulation set-up. The simulation results of unipolar/bipolar coding structures are first presented by commercial simulation obtained using VPI Transmission Maker software and later it is compared with other coding techniques for same proposed simulation setup. The proposed idea to implement the 3-D (Spatial/Phase/Time) OCDMA system is illustrated with the help of block diagram in Fig. 3.1.



Here proposed system is implemented by the use of broadband light sources acting as carrier. Different set of wavelengths are isolated in space or plane, by creating different groups of frequency channels. The number of wavelengths are divided among different frequency channels accordingly the number of time slots or unique delays are provided. This way at the transmitter side, wavelength specific delay is provided. These group of wavelngths after modulation with carrier is fed to encoder. Hence at the transmitter end, spreading in the space domain takes place. The encoder further provides the actual encoding by separating each of these frequency slots, shifting its phase, in this case by 0 or π as per selected code, and then recombining these frequency bins to produce the coded signal. At the receiver side, decoder performs the reverse opertaion to that of transmitter, providing similar but negative delays and inverse phase changes.

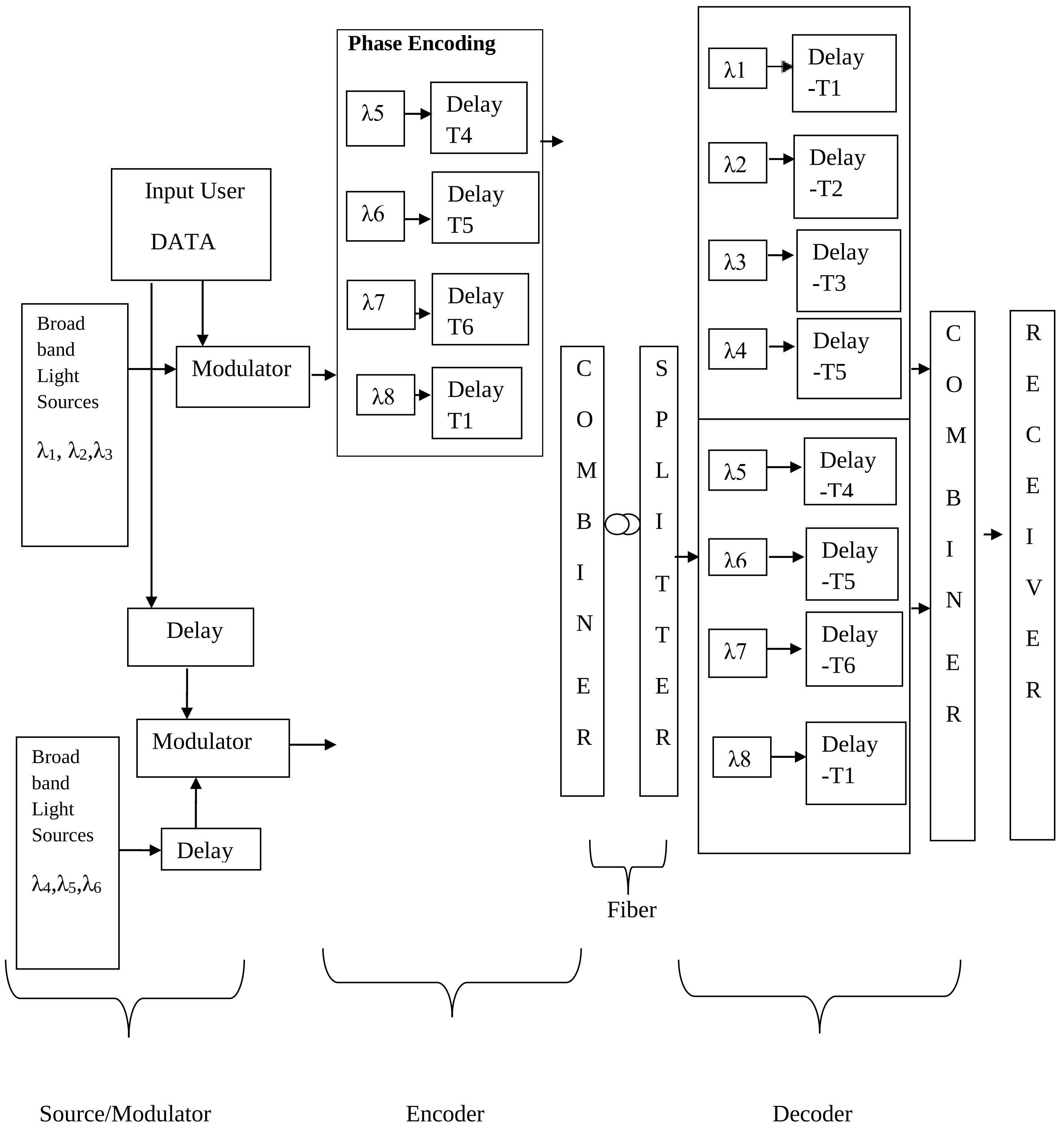


Fig. 3.1: Block Diagram of Proposed 3-D Spatial/Phase/Time Encoding/Decoding Technique

We have reported a 3-D Optical CDMA system with increased data rate i.e. 10 Gbps and even with increased number of users and achieved a spectral efficiency of more than 12.5% (6×10 Gbps in an 40-GHz tunable window for each source). Spectrum spreading is further limited by the preferred use of single-sideband modulation over on-off key modulation. Results thus obtained in terms of eye-diagram and BER indicate that for six simultaneous users transmitting at 10 Gbps and using a wisely selected set of codes among the set 16 Hadamard codes of length 16, up to 12 ps of comparative delay is acceptable with a power loss inside 1 dB at a BER of ≤ 10^{-9}**.** We have displayed the possibility of WDM-compatible Optical-CDMA system using 16 PLL/MLL (Phase Locked Laser/Mode Locked Laser) lines within 40 GHz tunable window as frequency bins/chips. In actual it is the phase coding (0 or π) of these various frequency chips, as agreed by the choice of used codes and later recombining these individual frequency chips to compose the encoded signal. Our system is different from conventional WDM in a sense that in WDM, each one of the 16 users would be statistically allocated one dedicated line whereas in our OCDMA system, each user can utilize all the 16 lines having different phase encoding combined with two other dimensions i.e. time and space (as given in simulation set-up).

Table 3.1: Used Simulation parameters for proposed 3-D OCDMA system

Parameter	Value
Bit rate (Data rate)	10 Gbps
Number of optical sources	16 mode-locked lasers
Wavelength range	1550–1551.2 nm
Wavelength spacing	0.1 nm
Repetition rate of laser pulses	10 Gbps
Input power	1 –10 mW
Drive type of electric generator	On-off (AM)
Signal type of electric generator	Voltage
Modulation type	Phase modulation (with a phase shift of π)
Codes used	Walsh-hadamard Codes

Code weight	4
Code Length	16
Fibre length	25 km
Attenuation	0.25 dB/km

3.2.1 Proposed Simulation Model of encoding/decoding technique

The simulation setup for optical CDMA shown in Fig. 3.2 implement phase coding by constructing a matched decoder pair from the Hadamard-16 code set. In order to give proper demonstration, we have used 6 equally spaced Phase Locked Laser (PLL) lines within 40 GHz tunable window as frequency slots. We have utilized the advantages of distinct frequency chips and small available tunable window and then phase encoding technique is employed over each slot using a encoder based upon Hadamard codes and ultra-high resolution optical demultiplexer. The WDM-DEMUX demultiplexes 6 WDM channels. It is a galaxy which contains 6 optical band pass filters, an optical attenuator and a logical fork to split the signal having the physical parameters like Bessel's transfer function and stop bandwidth is equivalent to eight times the bit rate. In our OCDMA system, every users uses all the lines but with different phase encoding. It can be shown that this encoder encodes the data both in wavelength and in time domain. Therefore allows more number of users than in the static WDM case. The simulation set-up is shown in Fig. 3.2.

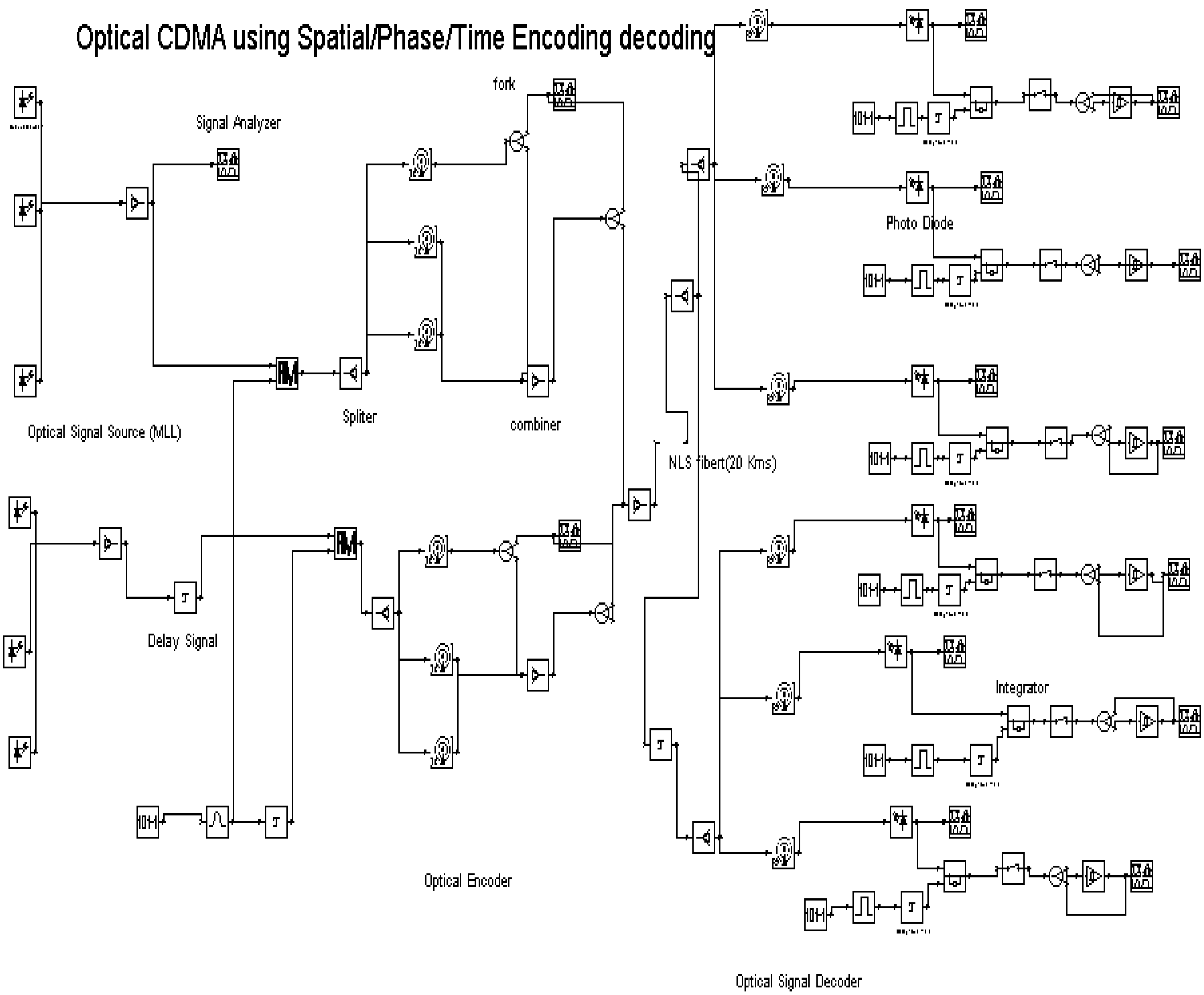


Fig. 3.2: Proposed Architecture of OCDMA system using spectral/phase frequency encoding/decoding

At the encoder in Fig. 3.3, a WDM Demux demultiplexes the WDM channels and then delay signal module simulates a propagation delay of optical signal by applying a time shift of the signal waveform. After this a WDM Mux module, multiplexes WDM channels which further passes these to modulator where again delay signal module is introduced.

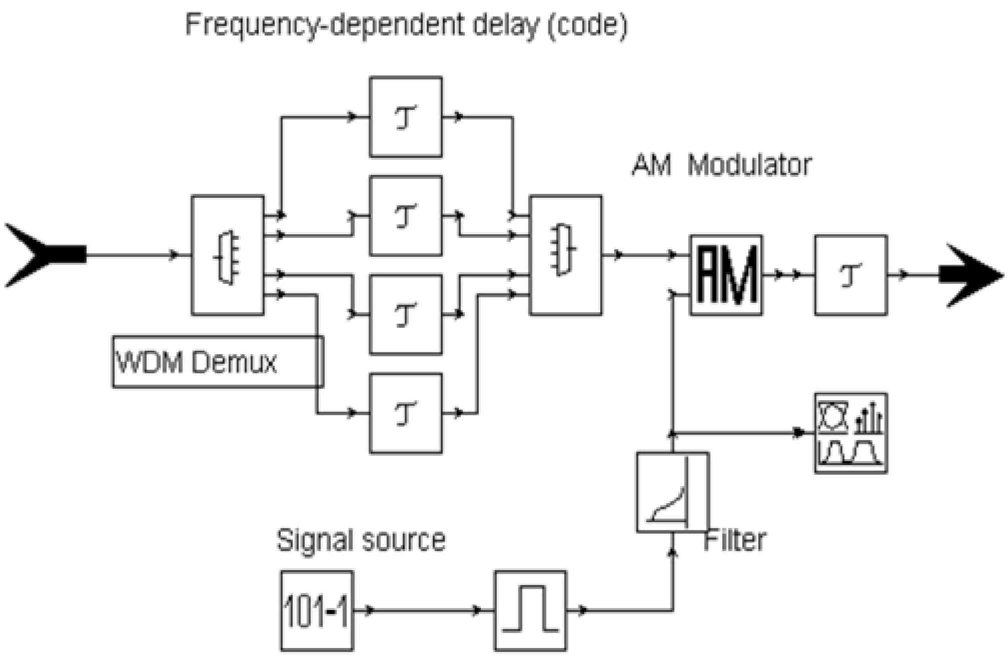


Fig. 3.3: OCDMA Encoder

Decoding shown in Fig. 3.4 is accomplished by using optical power splitter which equally splits the incoming signal on each output port and uses matched complementary codes at OCDMA decoder. For the binary Hadamard codes used here, these codes have their own compliments and therefore both encoder and decoder are similar. Decoder is nothing but just the inverse of encoder, it consists of the same components, filter and time delay. In decoder, the delay module simulates a propagation delay of optical signal by applying a time shift of the signal waveform (sampled signals). For optical signals, a delay-induced phase shift is simulated for relative signal frequency.

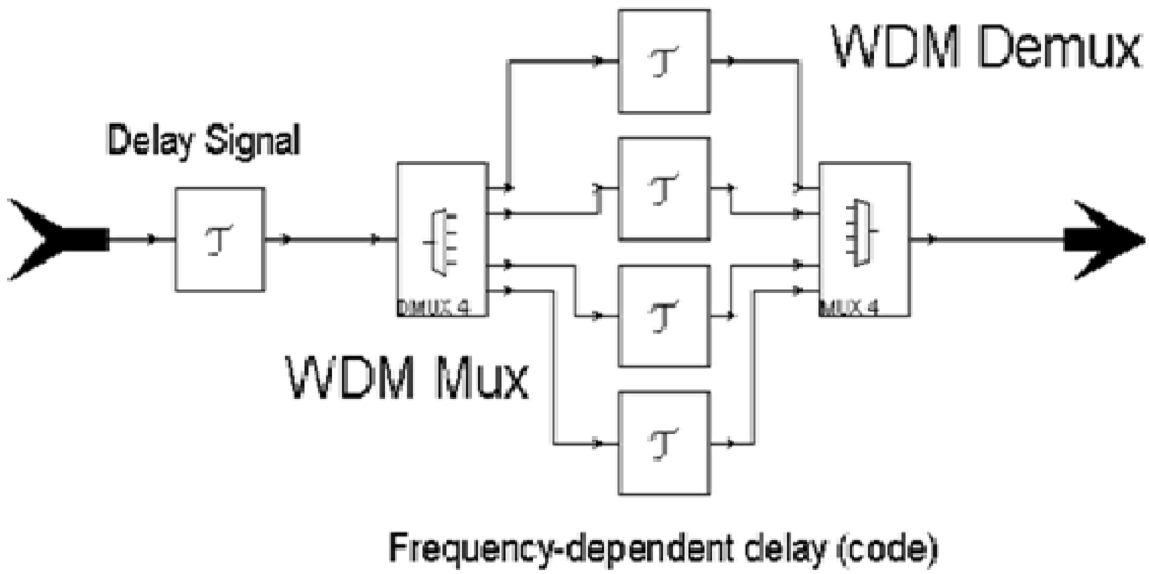


Fig. 3.4: OCDMA Decoder

Output of the six individual coders is combined and then after amplification fed to a fiber with the help of a decoder at the receiver which is capable of changing its code to match any one of the six transmitters. Output of the decoder is time gated to select the proper sender and reject the MAI from the other five users which in turn is fed to an optical-electrical receiver. The desired decoded signal can be detached from composite signals by the use of optical time gating.

The transmitted composite electrical spectrum is given in Fig. 3.5. The transmitted and decoded data for user1 is shown below in Fig. 3.6 and 3.7; using 5 GHz frequency slots to code up to 10 Gbps data. It clearly shows that frequency slots are sufficiently wide to transmit this data rate. Similar waveforms are obtained for other users.

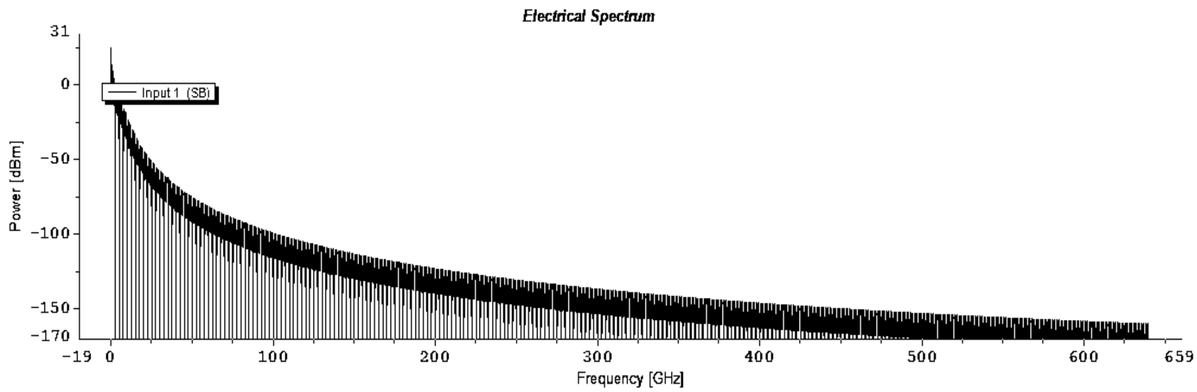


Fig. 3.5: Electrical spectrums at the transmitter

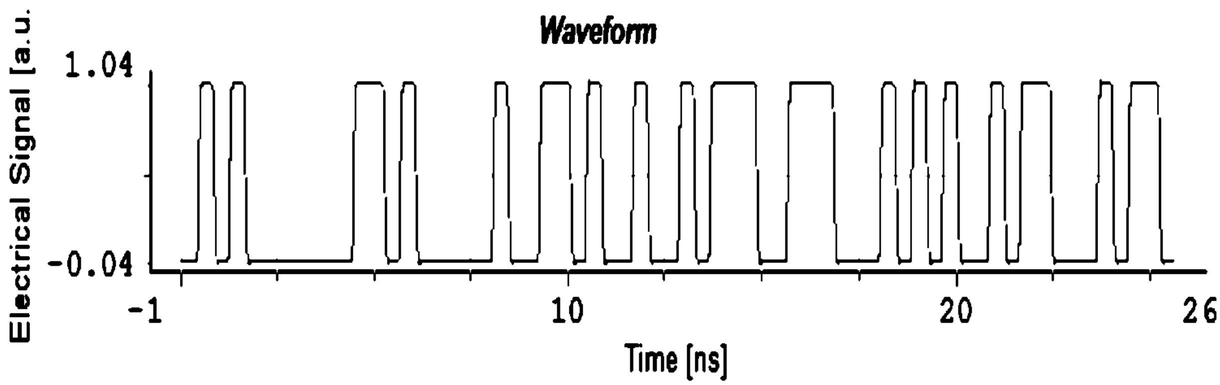


Fig. 3.6: Transmitted waveform for channel 1

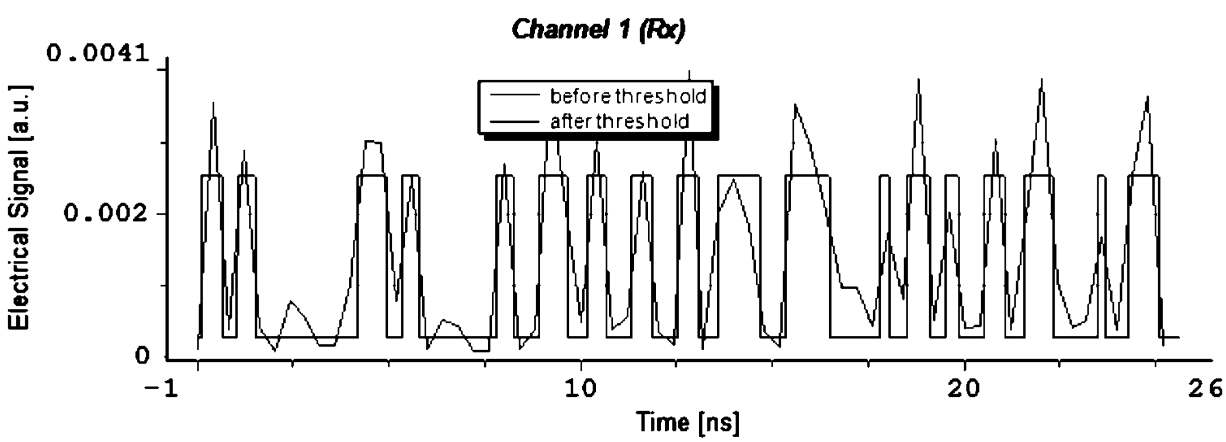


Fig. 3.7: Detected waveform for channel 1

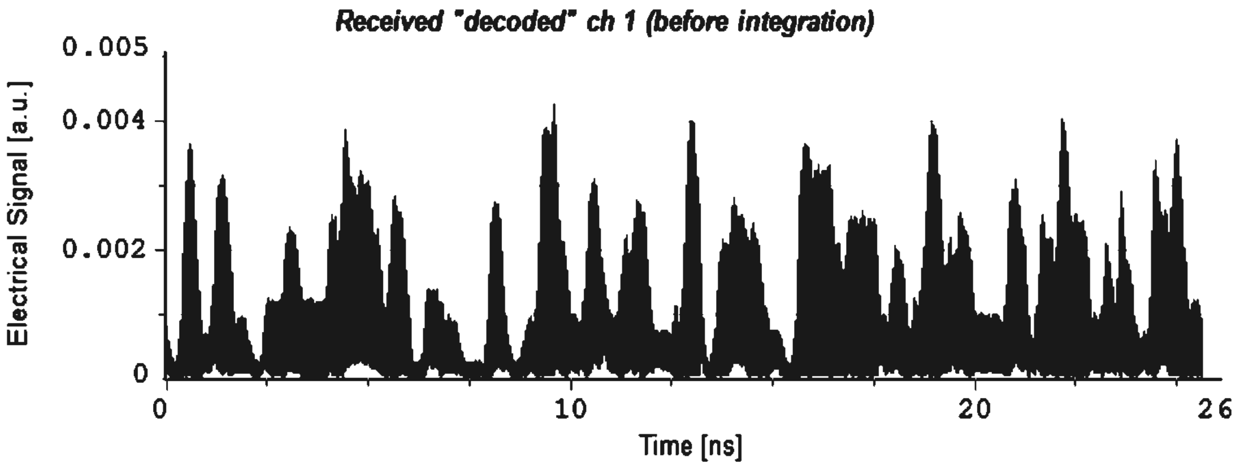


Fig. 3.8: Detected waveform for channel 1(before integration)

The above Fig 3.8 shows received waveform for channel 1 prior to integrator. It is the decoded electrical waveform for the desired user in presence of other co-propagating users. In this case, the optical power linked with the neighboring users is existent but it is isolated in time domain from the desired user's decoded data, which alone gives a clear eye. After this the detected electrical signal passes through an integrator, which is a lossy integrator for electrical signals, in which a portion of previous output is added to new input to give an output. If upper limit is not equal to lower limit, the integrator will saturate at the upper limit and lower limit, or will wrap-around (when beyond these limits). Fig 3.9 and 3.10 below show the eye diagrams at the receiver side for the Optical system using On/Off key (AM) modulation, Single Sideband (Duo binary) for uniform length of fiber i.e. 25 Kms for 6 active users transmitting at 10 Gbps whereas for other modulation types like Electro-absorption and Mach-Zehnder modulation the obtained eye-diagram is entirely distorted one.

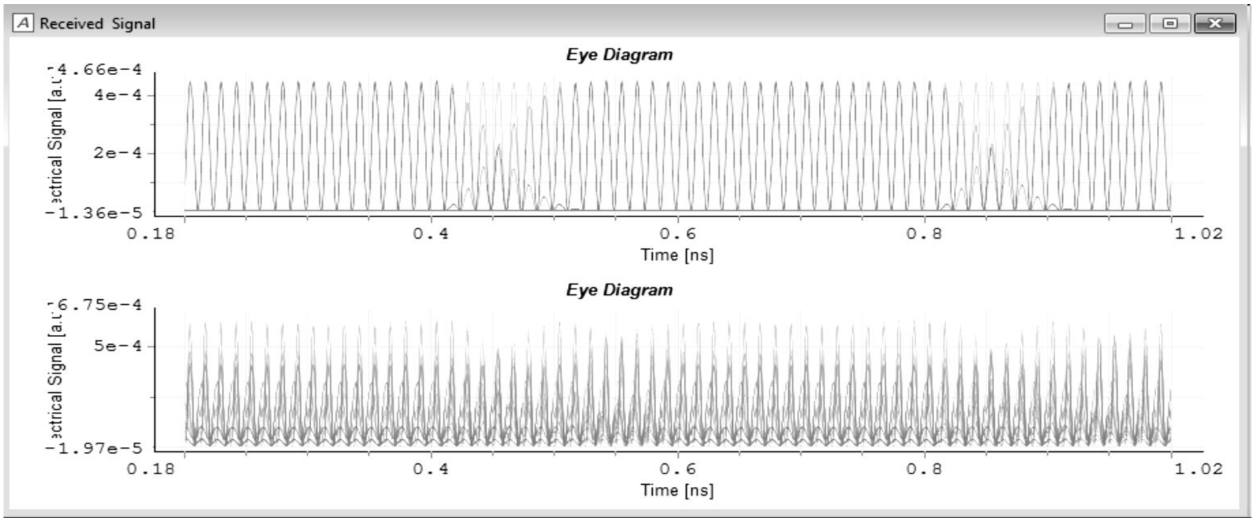


Fig. 3.9: Eye-diagram for AM modulation

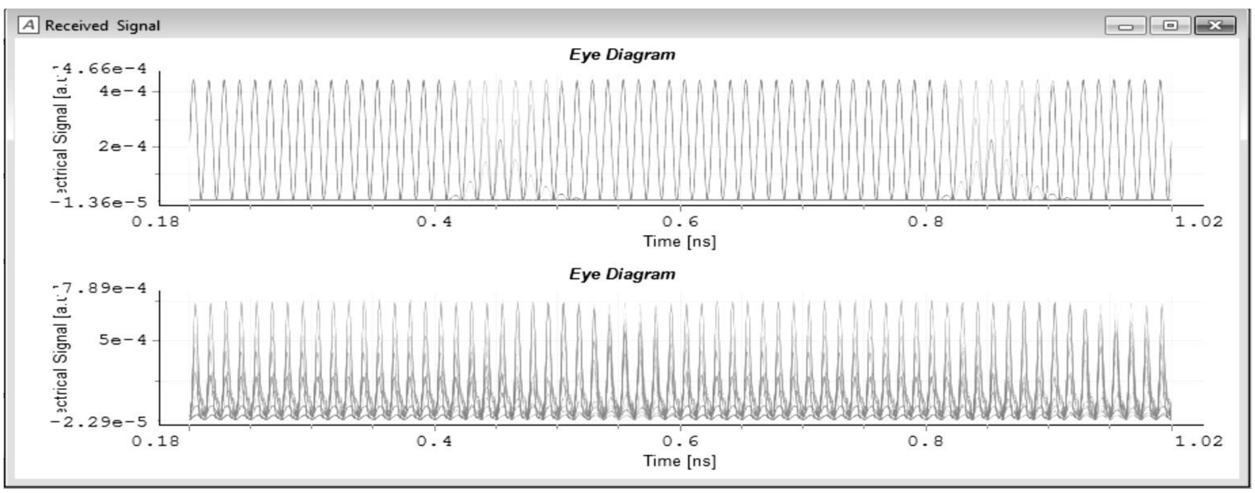


Fig. 3.10: Eye-diagram for duo-binary modulation

3.2.2 Walsh-Hadamard code generation as signature codes for the unipolar and bipolar schemes

As stated earlier, actual encoding process comprises of separating each of these frequency slots, fluctuating their phase by 0 or π as prescribed by the unique selection of code per user, and recombining the frequency chips to compose the composite encoded signal. When the relative phases of the frequencies are shifted and later their recombination results in a different temporal pattern per user. So each OCDMA code is well-defined by a unique choice of phase shifts according to exclusive choice of codes within the available codeset.

We have selected the customary Walsh Hadamard codes in our proposed system, which are by nature orthogonal. Six simultaneous users transmitting at data rate of up to 10 Gbps employing Hadamard codes of length 16 is used in this system. This choice of Hadamard codes is based on the goal of achieving high spectral efficiency and subsequent reduction in MAI. Unlike many optical coding schemes which have been proposed, this offers true orthogonally in the sense that MAI is zero at the time when the decoded signal strength is maximum. The number of frequency bins is decided by the choice of number of orthogonal codes used in system design. Hence, high spectral efficiency is possible. A Z-component Walsh Hadamard code is a particular row obtained from $Z \times Z$ orthogonal Hadamard matrix, having $(1, -1)$ appreciated binary entries. The $Z \times Z$, Hadamard matrix HM (Z =2^{M}) is produced by the code matrix:

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

For the value of M = 2, the Hadamard matrix is extended as shown below [29]:

$$H_{2}=\begin{bmatrix} H1 & H1 \\ H1 & \overline{H1} \end{bmatrix}=\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

Hadamard matrix HM demonstrated for unipolar type of Optical system must possess following characteristics:

- Value of M must exceed 2 in all cases
- The length of codes is decided by the relationship, N=2^{M}
- Code weight is given by W = 2^{M-1}
- Total number of supported users is given by (User K = 2^{M}-1)
- The relation of $W/\lambda = 2$ is needed to be maintained (Where λ denotes cross-correlation property)

A $(Z \times Z)$ Hadamard matrix of 1's and -1's has the unique characteristics that any two rows differ from each other in exactly $Z/2$ positions. The sequence $(1, 0)$ is for unipolar Hadamard code implementation. For example, if $Z = 4$ [29], [41].

$$H_2=\begin{bmatrix}1 & 1 & 1 & 1\\ 1 & 0 & 1 & 0\\ 1 & 1 & 0 & 0\\ 1 & 0 & 0 & 1\end{bmatrix} \quad \text{and so on....}$$

Hence the number of subscribers is related to the above mentioned relationship. MATLAB coding is done to generate Walsh-Hadamard codes and later MATLAB code is generated for Optical CDMA system using these Hadamard codes for sixteen users. 16 Users generated Walsh Hadamard Codes are given in Table 3.2.

Table 3.2: MATLAB generated 16-User Hadamard codes for proposed OCDMAsystem

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

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

We have demonstrated an OCDMA system, for six simultaneous users transmitting up to 10 Gbps and using Hadamard codes of length 16. A matched encoder /decoder pair is constructed.

3.2.3 Comparison of dual unipolar and bipolar coded configurations of Coherent Spatial-Phase-Time coding/decoding by the use of simulation method

We have compared the performance in the simulation set-up of the unipolar and bipolar schemes for the SAC-OCDMA systems with phase encoding/decoding by VPI Transmission Maker software. The transmission link is a signal mode fiber with no attenuation, and without the dispersion influence. The central wavelength of the optical fiber is set at 1550 nm and transmission distance is 25 km. The wavelength spacing is equal to 0.1 nm. There are six simultaneous active users to analyze the performance of unipolar/bipolar encoding structures in proposed SAC-OCDMA network with 3-D S/P/T codes. With the unipolar encoding structure for the SAC-OCDMA system, the user specific spectra are sent to the spectral component whenever the data bit is “1”. However, when the data bit is “0”, it does not communicate any spectral component. A comparison between these two configurations shows that the eye opening for the SAC-OCDMA system with the bipolar encoding structure is significantly greater and the results obtained in terms of BER for various parameters like fiber Length, data rate, number of simultaneous users and power received in Fig. 3.11 to 3.14, are in favour of bipolar encoding configuration. Based on the simulated results, conclusions have been drawn in favour of bipolar encoding structure for the different kinds of data to be transmitted and their usefulness.

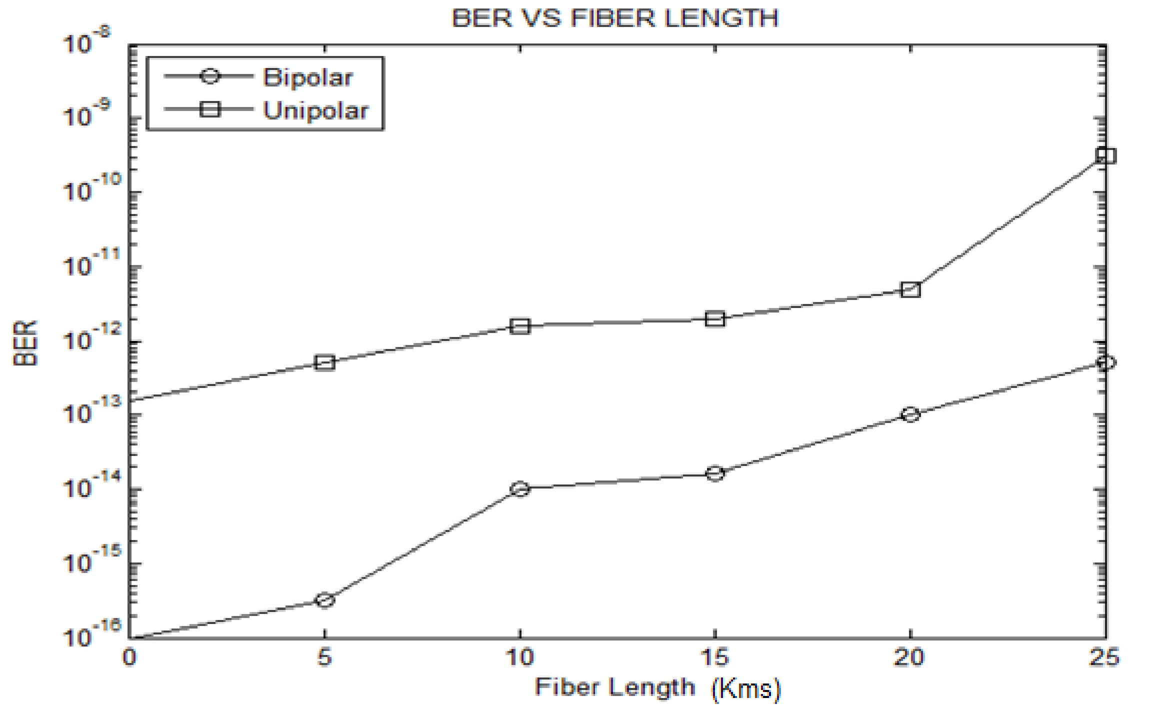


Fig. 3.11: BER Vs Fiber Length for proposed 3-D OCDMA System for Bipolar and Polar Encoding techniques

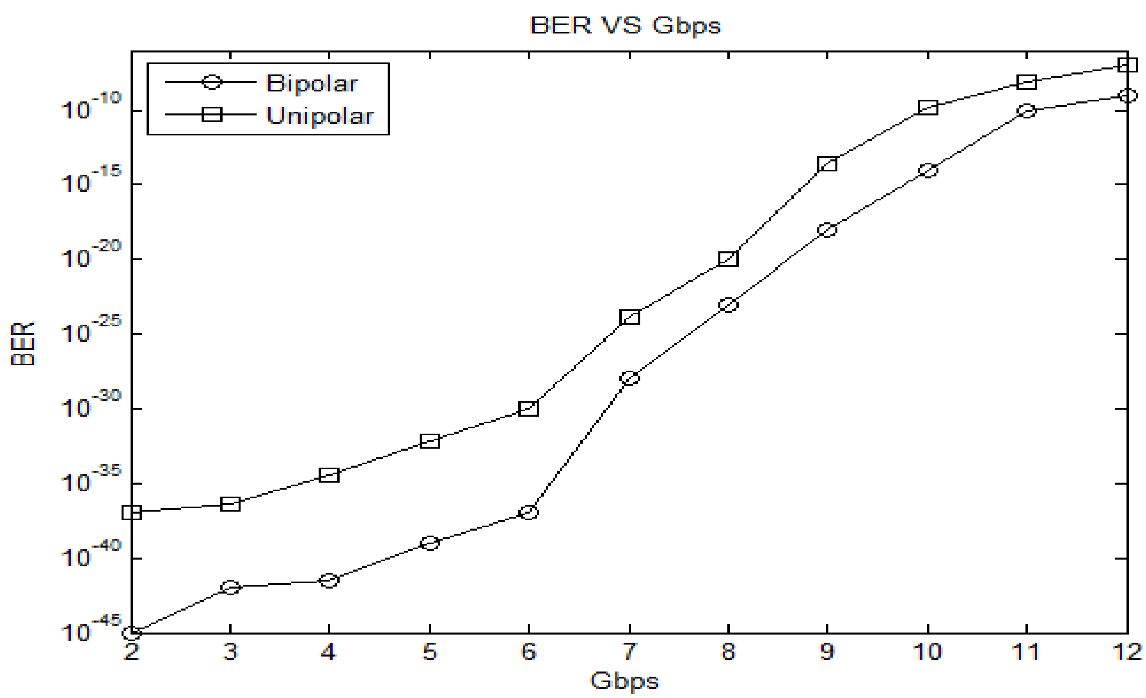


Fig. 3.12: BER Vs Data Rate (Gbps) for proposed 3-D OCDMA System for Bipolar and Polar Encoding techniques

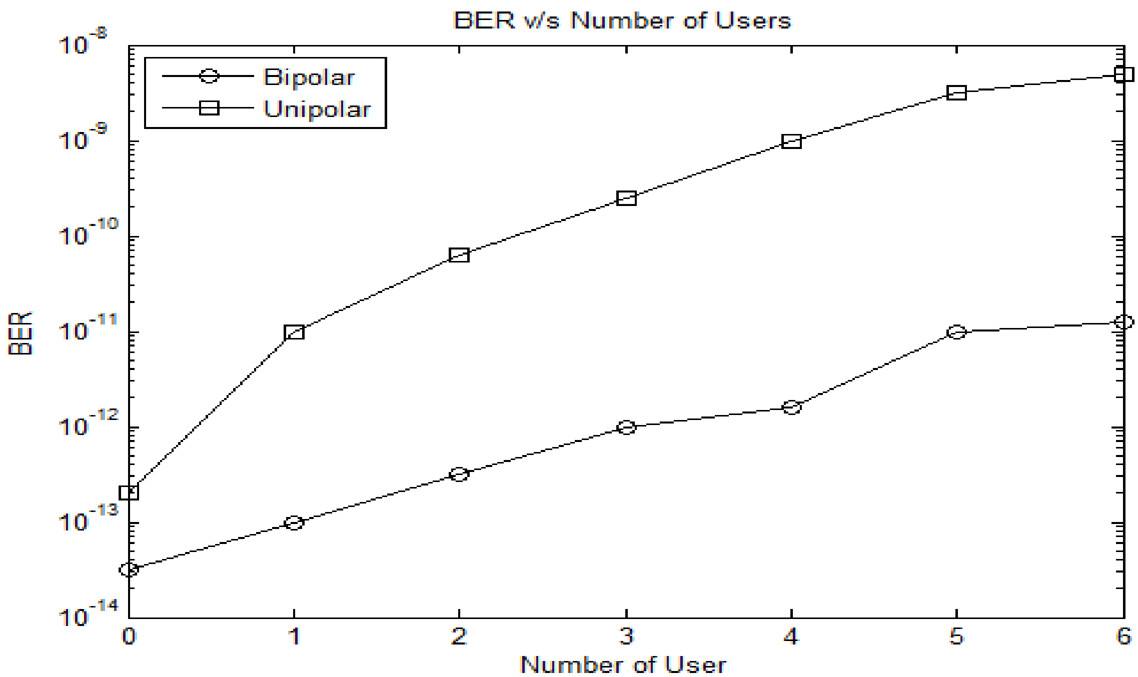


Fig. 3.13: BER Vs number of Users for proposed 3-D OCDMA System for Bipolar and Polar Encoding techniques

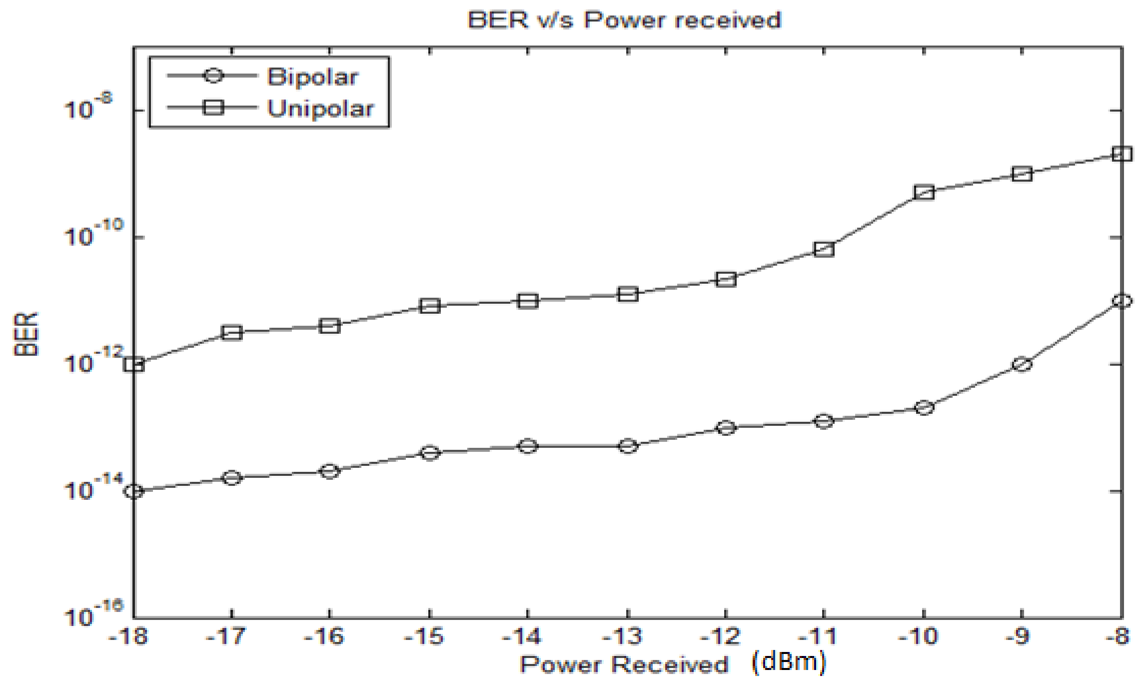


Fig. 3.14: BER Vs Received power for proposed 3-D OCDMA System for Bipolar and Polar Encoding techniques

The obtained results clearly indicate that, for bipolar encoding structure of the SAC-OCDMA system with phase encoding, BER performance is superior to that of the unipolar method. The advantage of the system is that user can choose either bipolar or unipolar coding method, depending on the data format (Voice, video or multimedia) to be transmitted.

3.3 Results and Discussion in terms of BER and MAI for 3D-Coherent Spatial-Phase-Time OCDMA system

Multiple access interference (MAI) elimination by code sequences of a fixed in-phase cross-correlation value (Walsh Hadamard Codes) and its comparison with other coding techniques is reported. The comparison is done on the basis of obtained values of BER and MAI for the same simulation set-up for different parameters like Fiber length, data rate, number of active users and received power. The obtained results are clearly in favour of OOC codes [46], [48] followed by Walsh Hadamard codes demonstrated from Fig. 3.15 to 3.22.

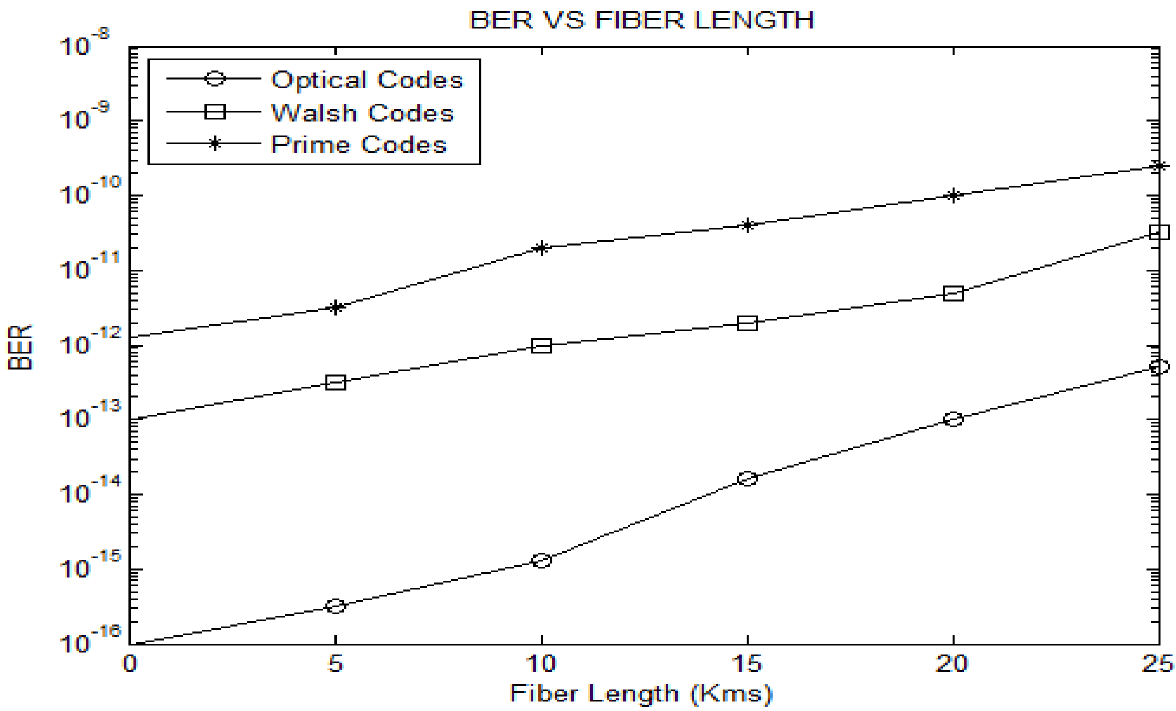


Fig. 3.15: BER Vs Fiber Length for proposed 3-D OCDMA System for Various coding schemes (comparative Analysis)

This Fig. 3.15 shows the BER for different codes compared upto a distance of 25 Kms. It is evident that the obtained BER is least in case of OOC codes followed by Walsh Hadamard Codes of same length

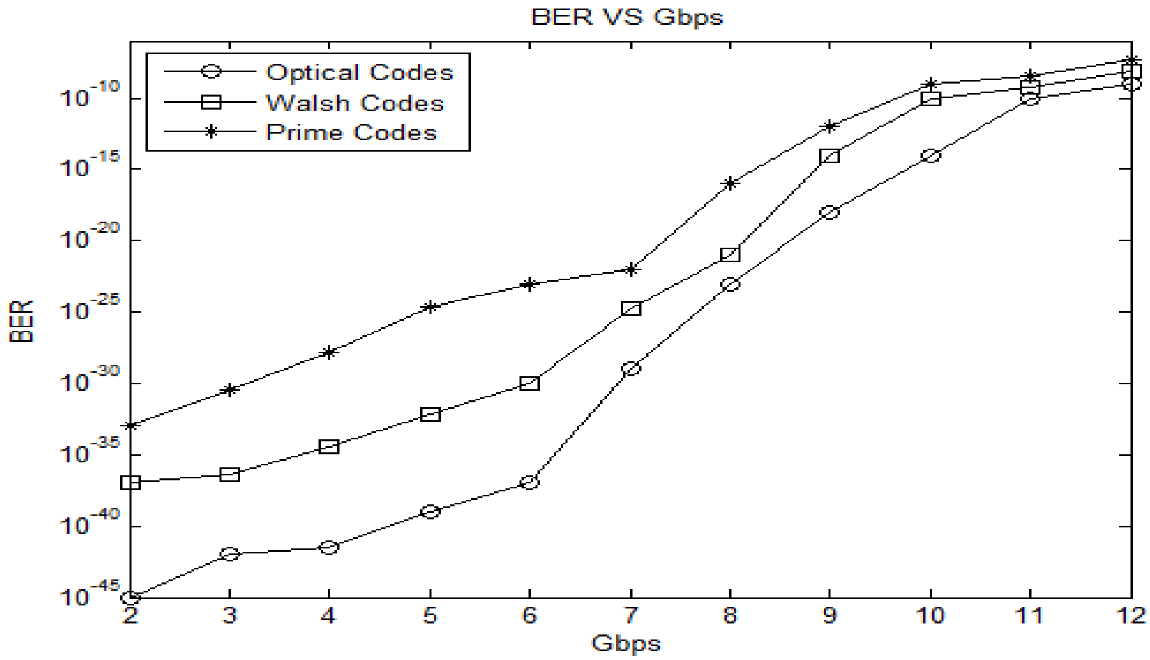


Fig. 3.16: BER Vs Data Rate (GBPS) for proposed 3-D OCDMA System for Various coding schemes (comparative Analysis)

The Fig. 3.16 gives the comparative results of three coding techniques for supported data rates. Here we have considered data rate upto 12 Gbps. It is observed that the Walsh Hadamard Codes perform well upto 10 Gbps afterwards its performance in terms of BER degrades. Similar is the trend for other coding techniques but it is slightly better for OOC codes for proposed optical setup.

Simillar pattern for obtained BER against number of users and received optical power in favour of OOC codes are depicted in the following Fig. 3.17 & 3.18.

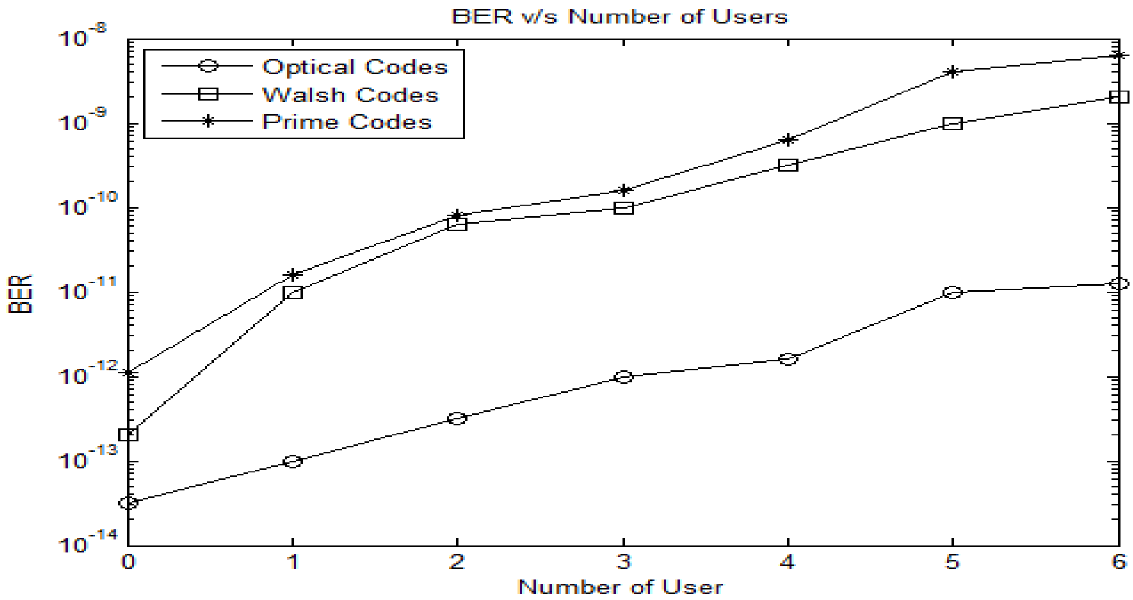


Fig. 3.17: BER Vs Number of Users for proposed 3-D OCDMA System for Various coding schemes (comparative Analysis)

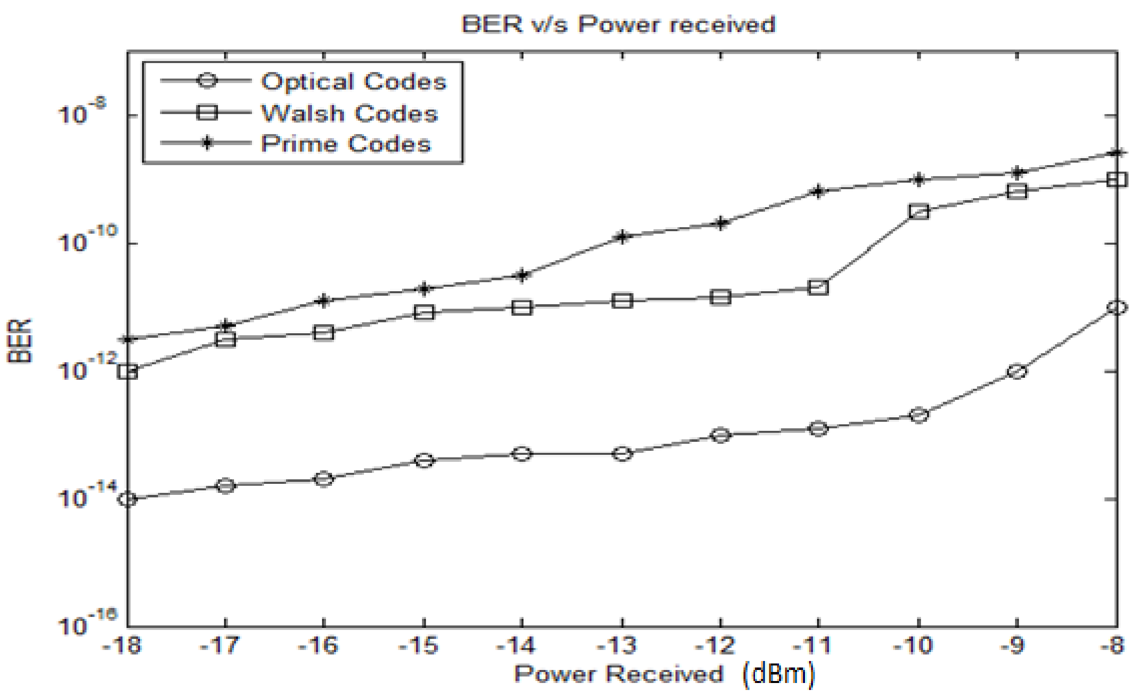


Fig. 3.18: BER Vs Received Power for proposed 3-D OCDMA System for Various coding schemes (comparative Analysis)

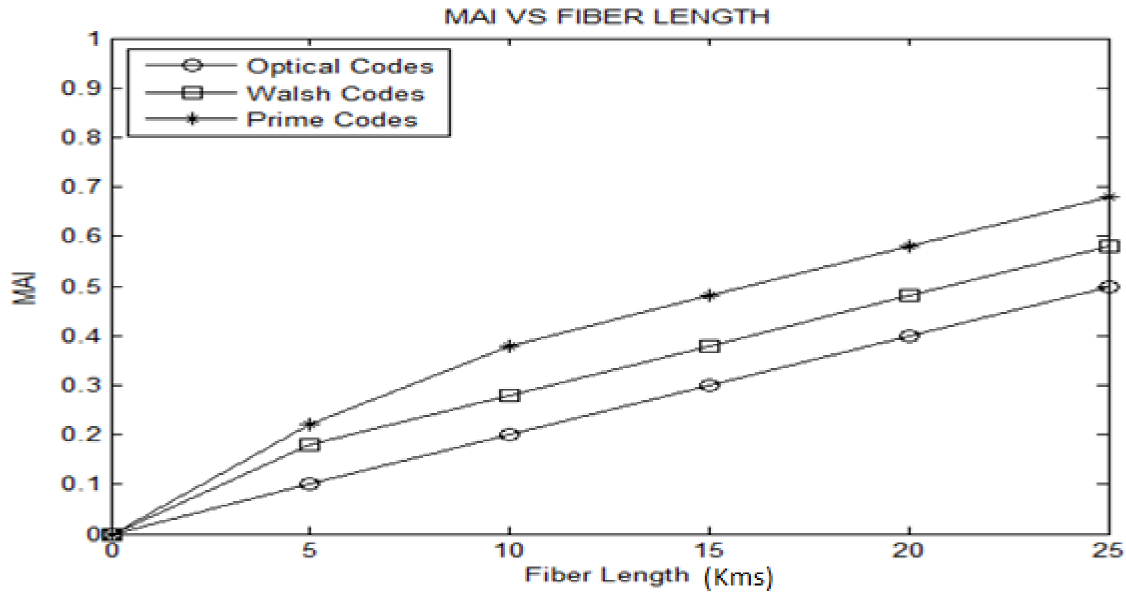


Fig. 3.19: MAI Vs Fiber Length for proposed 3-D OCDMA System for Various coding schemes (comparative Analysis)

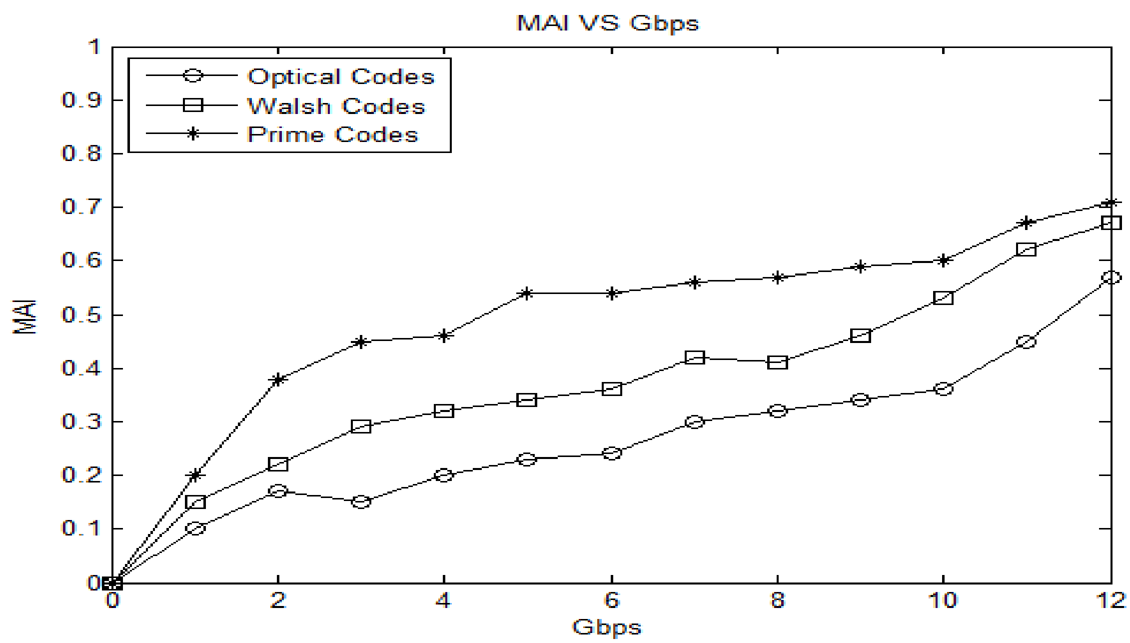


Fig. 3.20: MAI Vs Data Rate (Gbps) for proposed 3-D OCDMA System for Various coding schemes (comparative Analysis)

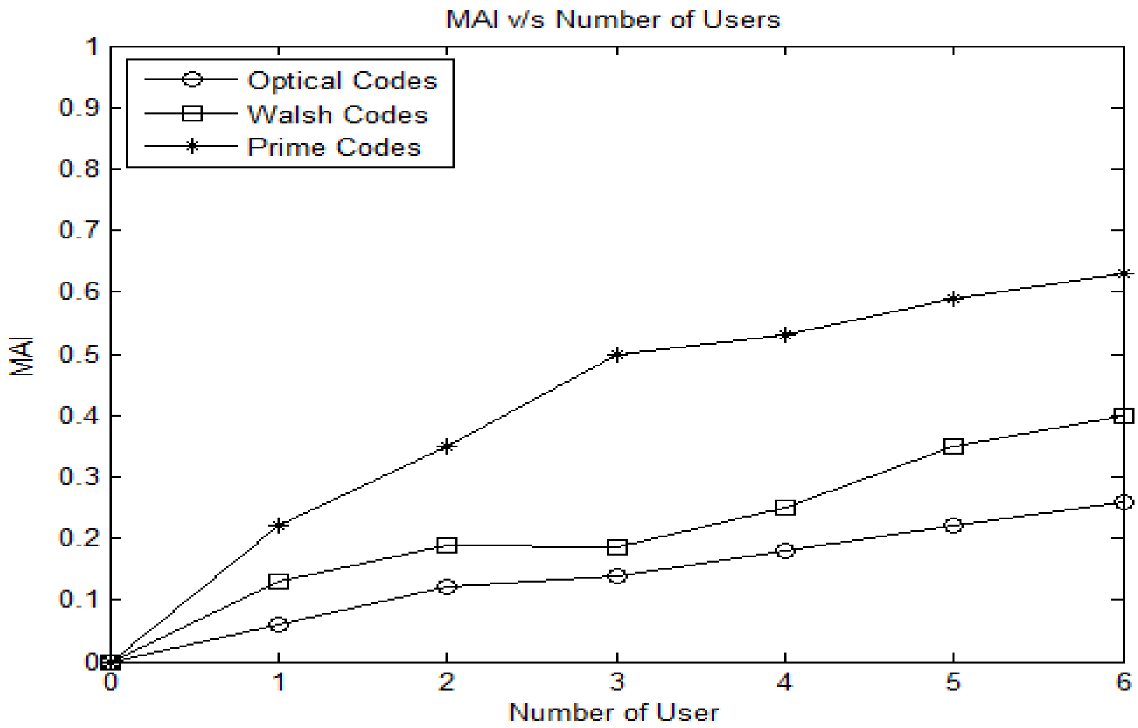


Fig. 3.21: MAI Vs Number of Users for proposed 3-D OCDMA System for Various coding schemes (comparative Analysis)

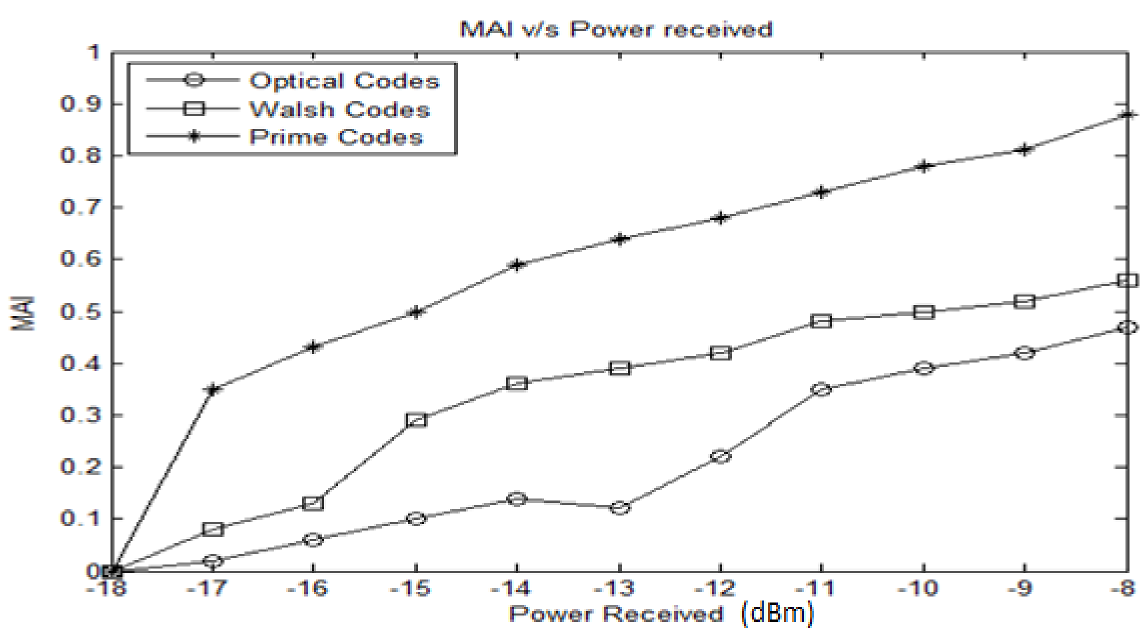


Fig. 3.22: MAI Vs Received power for proposed 3-D OCDMA System for Various coding schemes (comparative Analysis)

The above shown Fig. 3.19 to Fig. 3.22 gives the comparative analysis of received MAI for various coding techniques. It is observed that for our proposed setup prime codes exceeds the acceptable limit of MAI and hence is not recommended whereas OOC codes gives best results.

3.4 Conclusion

We have demonstrated a six-user OCDMA system operating at 10 Gbps with a low-power requirement per user, which exhibits potential for scaling of OCDMA at multi Giga-bit-per-second data rates to accommodate significantly higher user counts. The coding and decoding method used is based on 3-D coding of tightly spaced phase-locked laser lines that is compatible with conventional WDM networking. Six channels (10 Gbps per channel) are encoded on 6 different frequency components within a 40 GHz tunable window frequency slots. The narrower spectral extent of the coded signal also limits the effects of transmission impairments such as dispersion. Our proposed system is better in a sense that here we have chosen Hadamard codes, which are orthogonal and binary in nature for phase coding but we have the luxury of choosing any other bipolar codes to achieve even higher spectral efficiency. The result obtained for the proposed technique is compared with the conventional schemes already existing in literature. The results show that for six simultaneous users transmitting at 10 Gbps and using a suitably chosen set of codes among the set 16 Hadamard codes of length 16, up to 12 ps of relative delay can be tolerated with a power penalty within 1 dB at a bit-error rate (BER) of $\leq 10^{-9}$. As the spectrally-phase encoded signals do not loose orthogonality, the effect of MAI is minimal. Here it is ensured that coded signals are fully synchronized (maintains orthogonality), lead to lower MAI. For this, we used Walsh-Hadamard codes as signature codes for both unipolar and bipolar schemes. The obtained simulation results show that BER and MAI, by the use of bipolar coding method are superior to unipolar scheme, especially when the received effect power is large. Whenever Optical CDMA system is designed for good performance to transmit multimedia data, we can use bipolar scheme in the network. If the users only transmit voice data, the unipolar method can be employed.

Chapter 4

Designing the code for OCDMA system

4.1 Introduction

In this chapter, we take the second objective of the thesis i.e. to improve the system performance in terms of bit error rate by designing the code for OCDMA system In this work, first section deals with implementing a code structure (Modified PN sequence) for proposed SAC-OCDMA network with "0" in-phase cross-correlation. One very important property of such code is that the peak cross-correlation will always be zero, which implies that both MAI and PIIN (Phase Induced Intensity Noise) will get reduced. The impact of MAI is considerably lowered by the use of basic properties of applied spectral amplitude codes. We have compared our obtained simulated results in terms of Bit error rate performance with different modulation formats. Also we have simulated an Optical CDMA network based on a topology to spectrally isolate the channels. Then, we have investigated the behaviour of the proposed architecture considering the combined effect of various factors like variable fiber span, supported data rate and received optical power for various modulation formats.

In second section, codes for MPFR (Message Priority Fast Routing) are generated based on simple tridiagonal matrix with less size of the header bit reduction. In the proposed algorithm, multiple user environments have been used in accordance to the packet header. The message size is increased and priority bit is added which leads to faster and effective data transfer in communication. The transmitter uses 2D codes, which is further added an extra priority bit for priority based fast transmission. This stuffing of priority bit and corresponding algorithm for interference sensing enable better results in terms of BER and number of users, which is our second objective.

4.2 Spectrally encoded/decoded OCDMA system

In this work, the spectrally encoded/ decoded OCDMA system with bipolar coding technique using Modified PN is demonstrated for varied distance along the Single Mode Fiber (SMF) for the measurement of various performance parameters like BER and received optical power. The achieved benefits realized by our proposed system over earlier similar reported systems are its easy access to available low cross correlation sequences and decoder can be effectively implemented for the detection of bits with low error possibility. The spectral encoding technique along with proper use of bipolar codes is implemented and incoherent broadband light source is adopted to generate carrier frequencies in the optical domain. Data in the form of binary bits i.e. “ones” and “zeros” is transmitted by a technique in which a data bit “one” is replicated by a particular assigned code, whereas the complement of the similar code is used to denote data bit “zero”. For our demonstration purpose, we opt for Modified PN codes [74] . We have the luxury of choosing any other existing codes too. The block diagram given below in Fig. 4.1 illustrates the proposed OCDMA system. Here the user data is spectrally encoded and twice modulated and later it is converted into data and data bar at the transmitter side and the encoded into optical data before it is fed to optical fiber.

The unique feature of proposed system is that data maintains its acceptable BER value and integrity by dividing the data in to code and code-bar by the use of Boolean operator (NOT) at the transmitter side whereas recovering the data at the receiver side by the use of phase conjugate. The modulation is performed twice before the user data is fed to demultiplexer and then to multiplexers to decompose it into two halves of eight bit each i.e. data and data-bar. This even maintains the security of the system and avoids the data to be wrongly interpreted at the decoder side [59], [60].

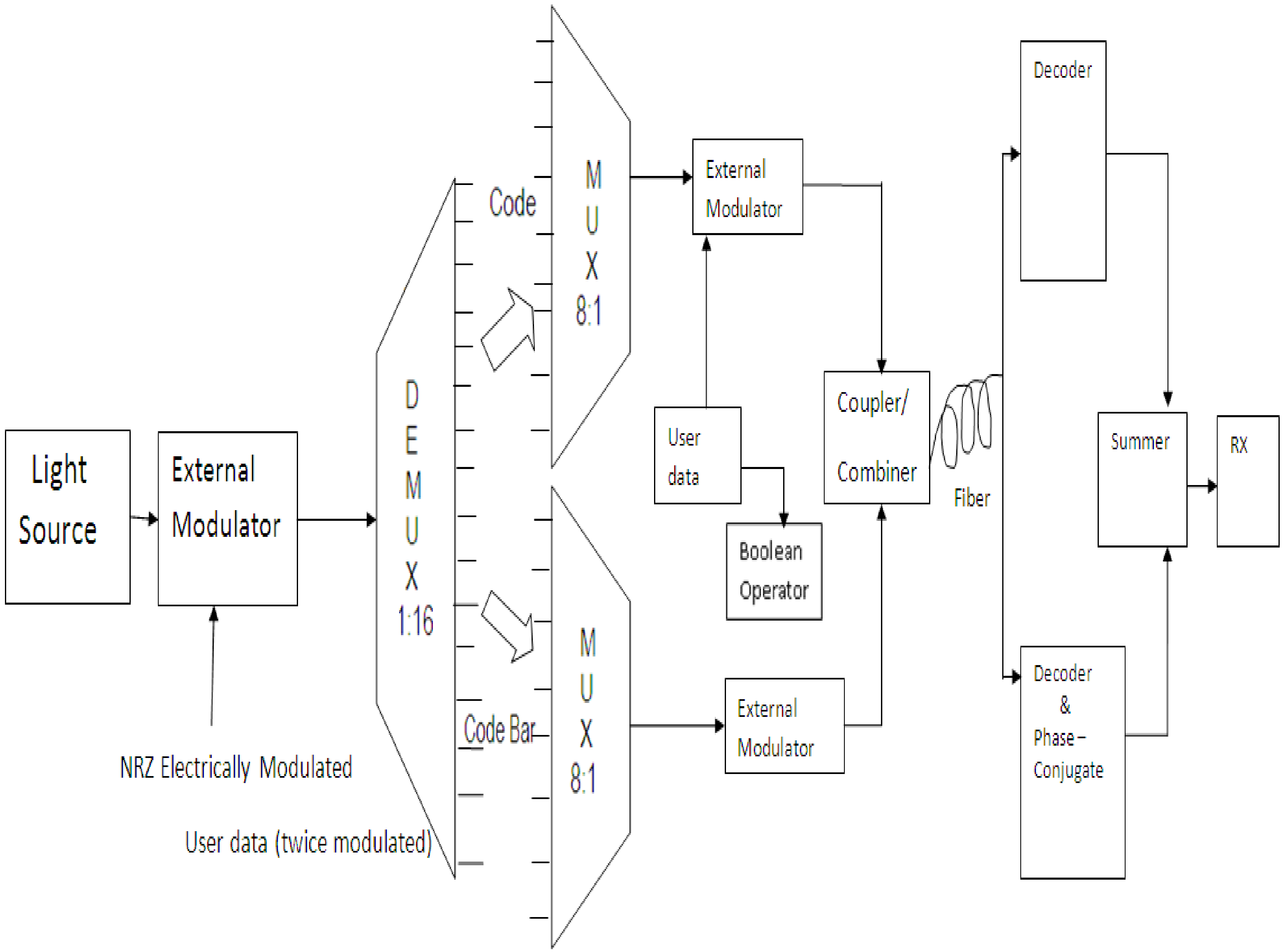


Fig. 4.1: Pictorial demonstration of spectral- amplitude encoded/decoded optical system

The block diagram of proposed OCDMA set-up built on the concept of spectral amplitude encoding/decoding with bipolar codes and incoherent broadband light source is designed and is depicted in Fig 4.1. In this, as stated earlier a unique(user specific) signature code is used to convey the data bit “1” present in a data sequence and its complimentary code denotes transmitted bit “0”. Here the resultant output from broadband light source (acting as career) after modulation with randomly generated user data from pseudo random bit sequence (PRBS), is further demultiplexed in to 16 spectral chips with the help of optical demultiplexer. The utilized wavelength of chips ranges from 1530.33 to 1554.94 nm, having spacing of 100 GHz. Now according to the choice of used coding technique, 8 spectral amplitude components are connected to the upper multiplexer (OptMUX1) creating a code and rest of 8 spectral amplitude components are given to lower multiplexer (Optmux2) to form a complementary code. The intensity modulation technique is employed, employing on–off keying(modulation) with 1.25 bps non-return-to-zero (NRZ) pseudo-random bit sequence (PRBS) signal to once again provide the modulation for the output of each multiplexer. The pseudo-random bit sequence generates the binary sequence which is then converted into electrical signal by an electrical generator (ElectGen). The output of PRBS is also fed to Boolean operator, which is acting as NOT gate, converting the obtained data at its input to data bar. The data and data bar are simultaneously fed to the upper and lower arms, respectively. The optical coupler, modeled as a 3-dB fiber coupler, is used to combine the twice-modulated and separately transmitted optical outputs from the user.

After travelling a distance of 120 Km through optical fiber, spectral encoded signal is received and decoded by receiver having the same code as is available with the transmitter. The optical signal is demultiplexed by a demultiplexer at the receiver to split the combined signal and then OptMUX3 is used to recover the code and OptMUX4 is set to detect code-bar, similar to that was used in the encoder. Both the receivers simultaneously receive the data as well as data bar. The phase shifting of 180^0 is provided by a component OPC1, which is an optical phase conjugate. It is applied to complement the data bar into data at receiver, in order to enable user’s decoder at the receiver to recover the information being sent. The two parallel received signals are combined by the summer 1 and the amplification is provided. The wavelength spectrum is studied with the help of multiplot component 1 and 2. For user data and corresponding detected signal, signal plotter is used whereas for measuring performance in terms of opening of eye, eye diagram analyzer is used. Results obtained in the form of achieved BER and Q factor for varied distances of fiber span is witnessed. The OCDMA system constructed in such manner has technically improved the performance in terms of quality factor and bit error rate for NRZ raised cosine data format, whenever system is comparatively analyzed for different data formats.

4.2.1 An Architecture Description of System

The architectural setup of OCDMA system based on spectral-amplitude encoding/decoding employing bipolar optical codes and incoherent broadband optical source is shown in Fig.4.2. The setup shown is for a user transmitting data at the rate of 10 Gbps.

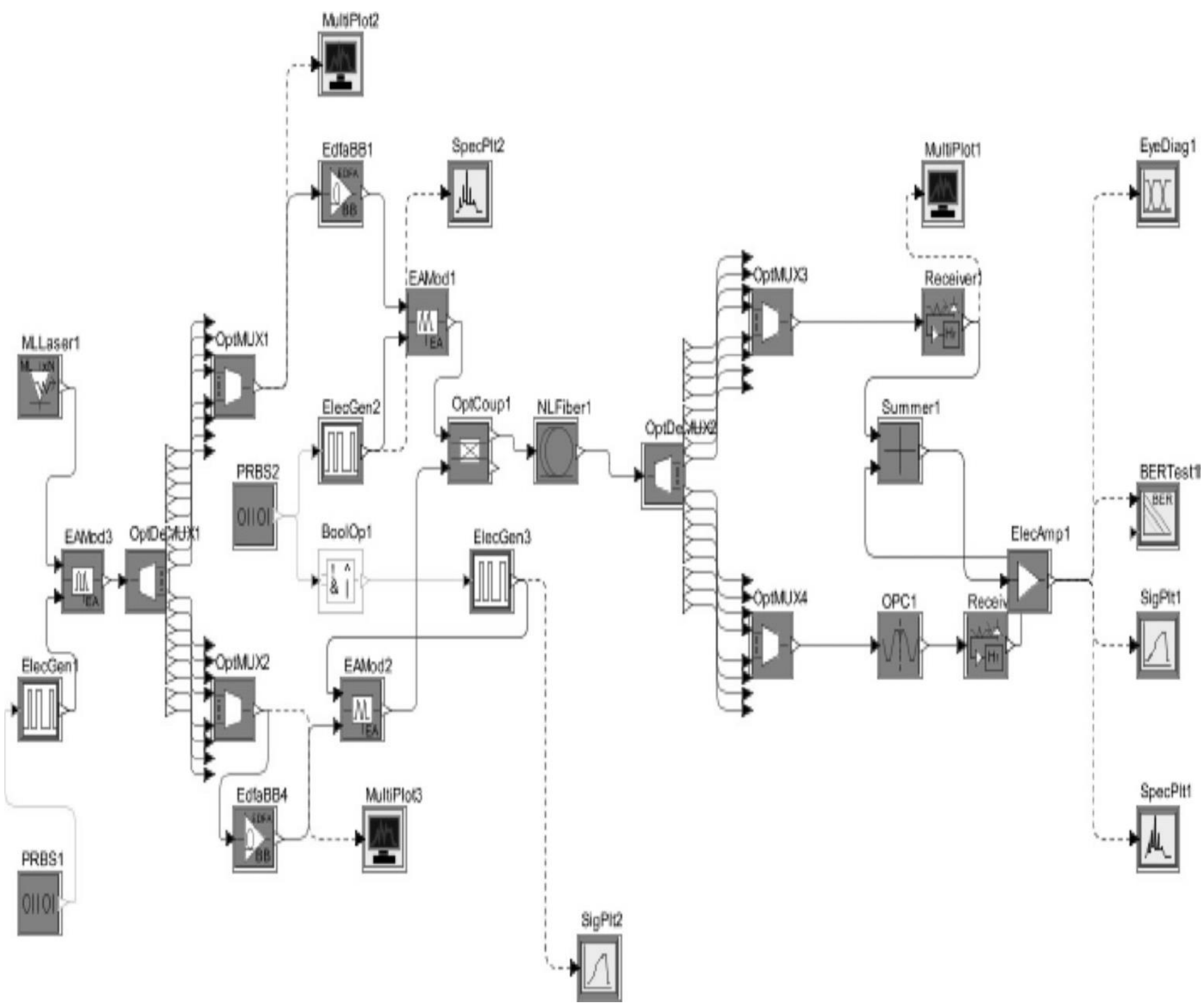


Fig. 4.2: Architecture of Proposed OCDMA system using spectral-amplitude encoding/Decoding

The proposed system has shown acceptable results in terms of BER for the data rate in excess of 10 Gbps. The proposed system performance is analyzed for various modulation formats and their comparative study reveals that NRZ raised cosine format emerges as the best and is recommended for optical systems due to its performance.

4.2.2 Results and Discussion for proposed spectrally amplitude encoded/decoded OCDMA System

By the use of proposed architectural setup of optical system, all the resultant simulated quantities like input signals, wavelength spectrum, eye diagrams and received signals are examined. The decoded signal is analyzed at the decoder and conclusions are drawn. Eye opening is monitored and diagram is studied at receiver side with the help of analyzer for both the extreme lengths of used optical fiber. The obtained spectrum is shown in Fig. 4.3 and 4.4, which clearly shows a frequency spectrum consisting of 32 wavelengths. The thick lines denote the 16 spectral components which implement the code and the dotted lines give the remaining 16 spectral components which represent the complementary code. The assigned wavelengths corresponding to “one” in the used modified PN code are transmitted to practically implement the code whereas wavelengths corresponding to “zero” in the same code length are prorogated with the help of complementary code for implementation .

Fig. 4.5(a) gives the obtained data and (b) shows the data bar once the above mentioned code is implemented for all the user data bits. The applied code is again used for modulation with career signal. Here for modulation purpose, a code is sent for propagating high bit of data and complementary code is sent for low bit of data. The obtained Figs. 4.6, 4.7 and 4.8 give the received spectrum for the fiber lengths of 75 and 120 Kms respectively. Eye diagrams at the receiver side with 95Km and 120 Km fiber for proposed OCDMA system is obtained and shown in Figs. 4.9 and 4.10 for the same extremities of selected fiber length. It is observed that there is a remarkable improvement in the received signal and even the obtained BER is of the order of 10^{-9}. Fig 4.11 illustrates the simulated BER value for single user over 120 Kms fiber length.

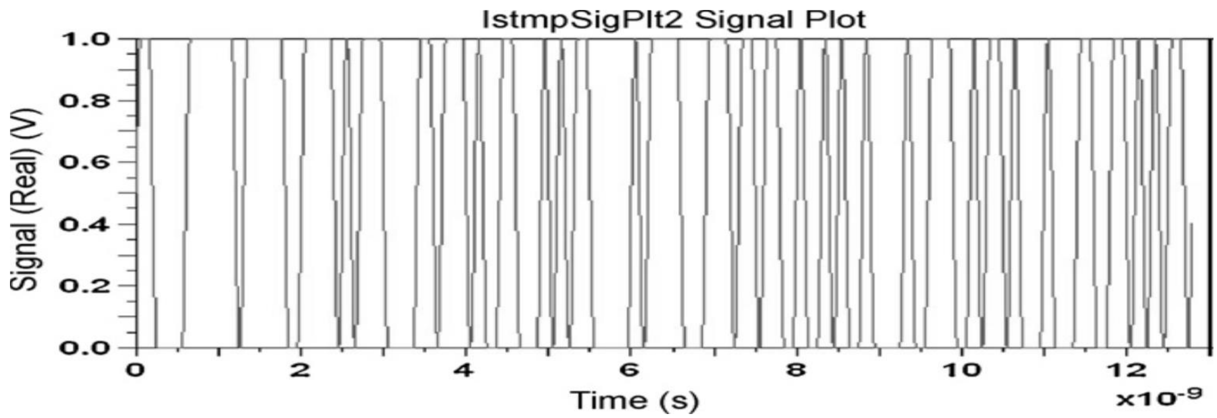


Fig. 4.3: spectra obtained after transmitter

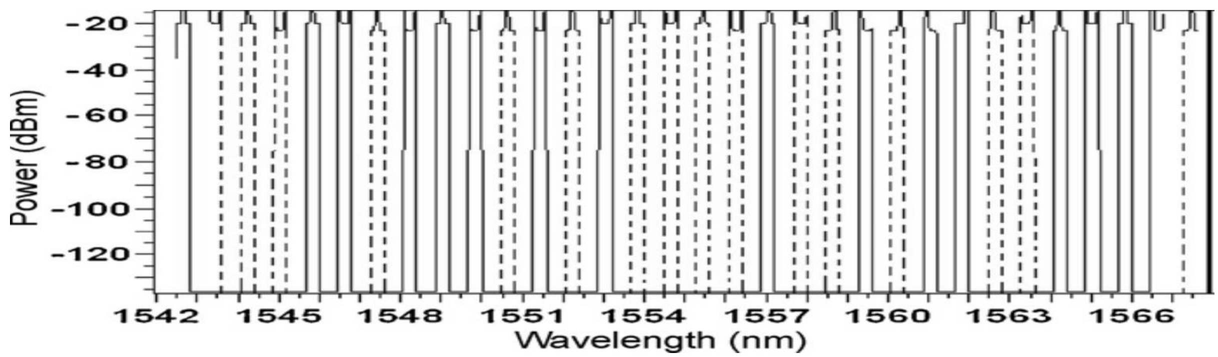


Fig. 4.4: NRZ signal data (Electrical Data)

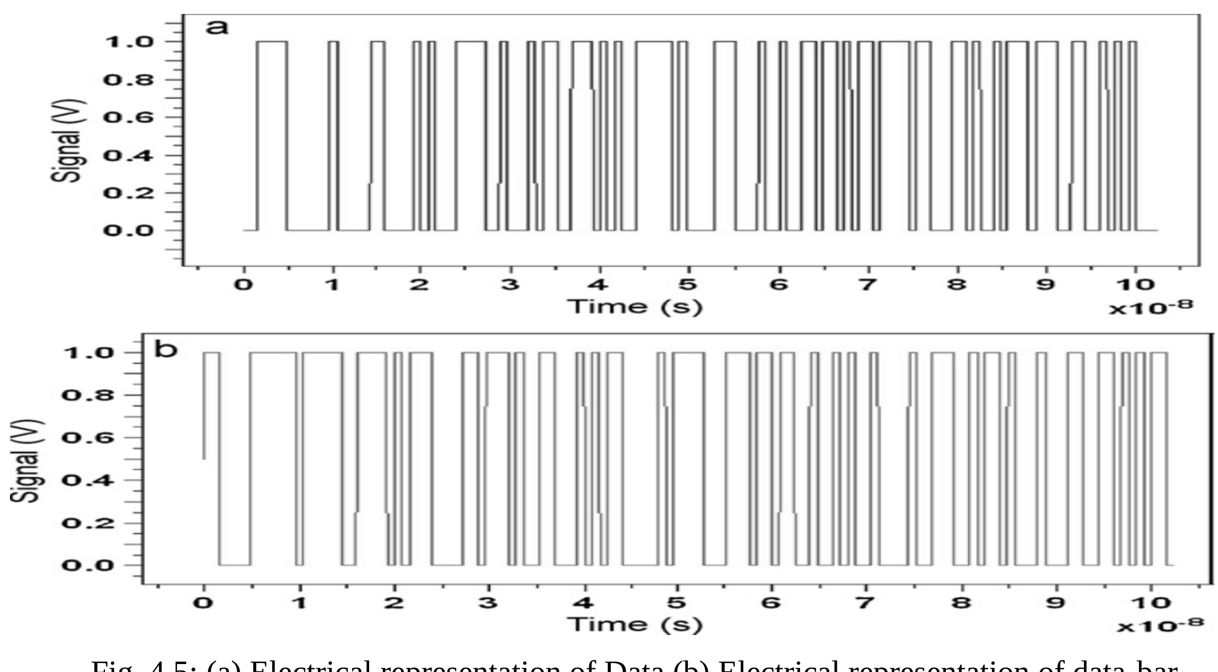


Fig. 4.5: (a) Electrical representation of Data (b) Electrical representation of data-bar

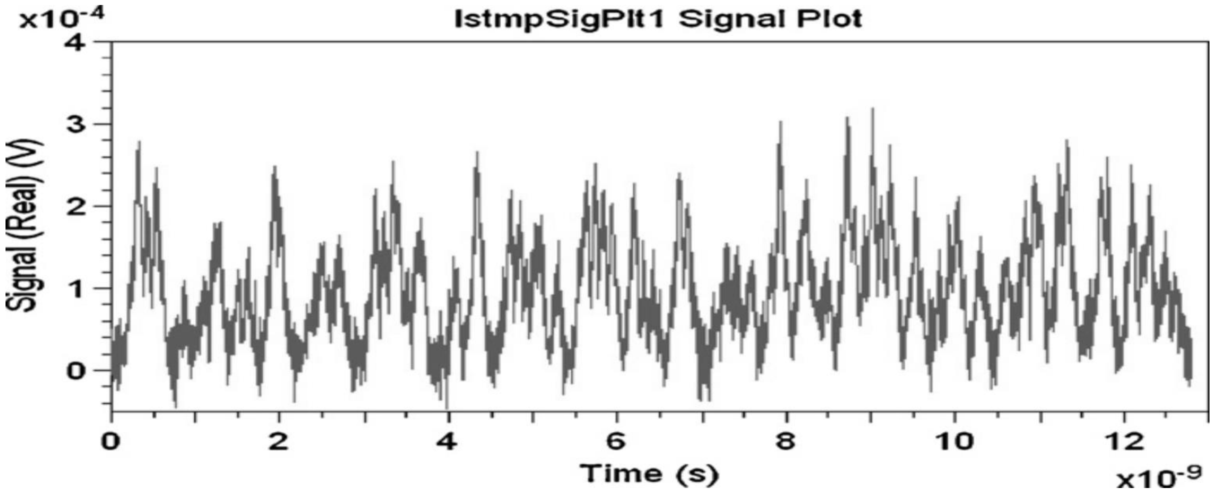


Fig. 4.6: Electrical Signal plot (output for 120 Km fiber)

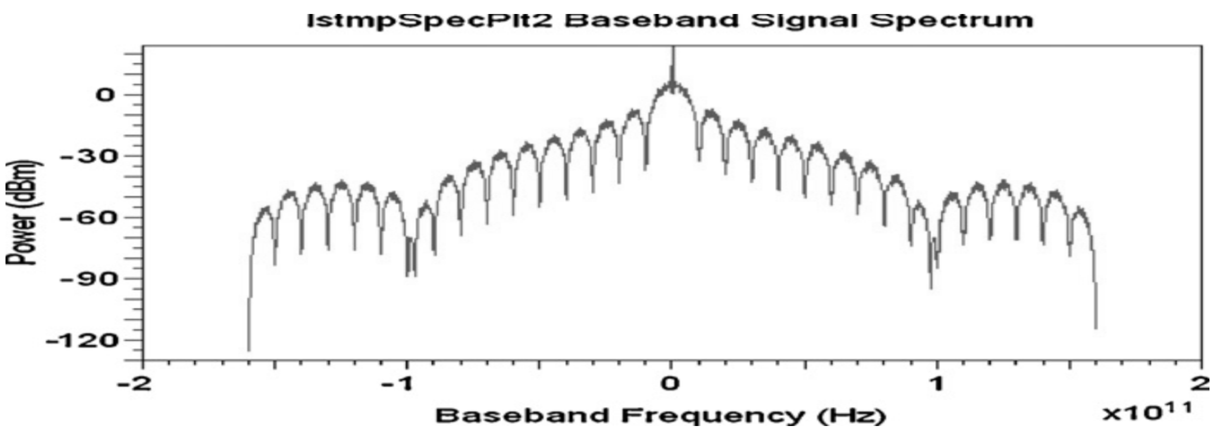


Fig. 4.7: Spectrum analyzer Result (after 75 Kms fiber span)

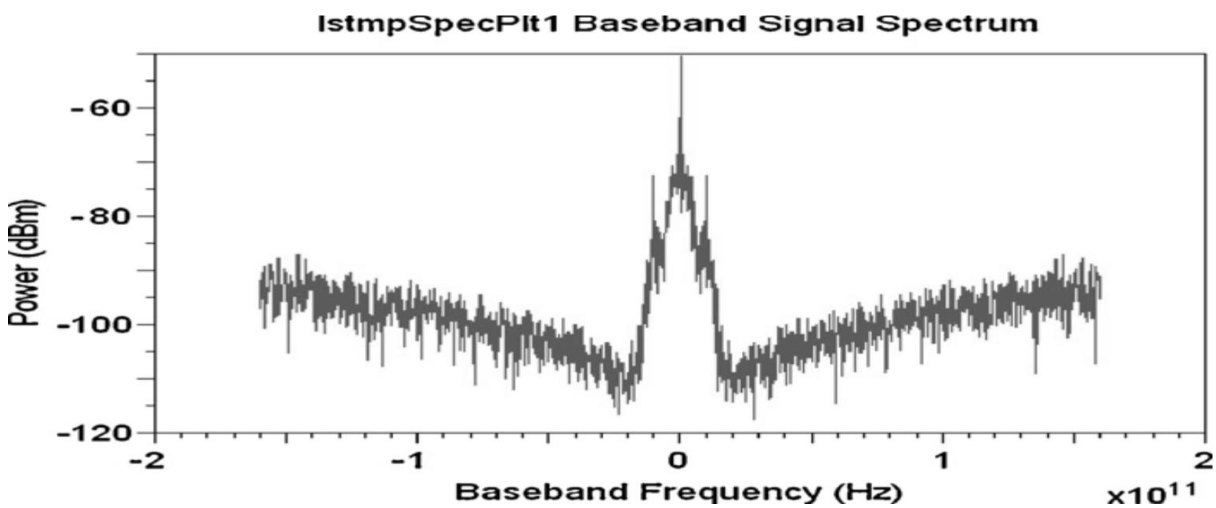


Fig. 4.8: Spectrum analyzer Result (after 120 Kms fiber span)

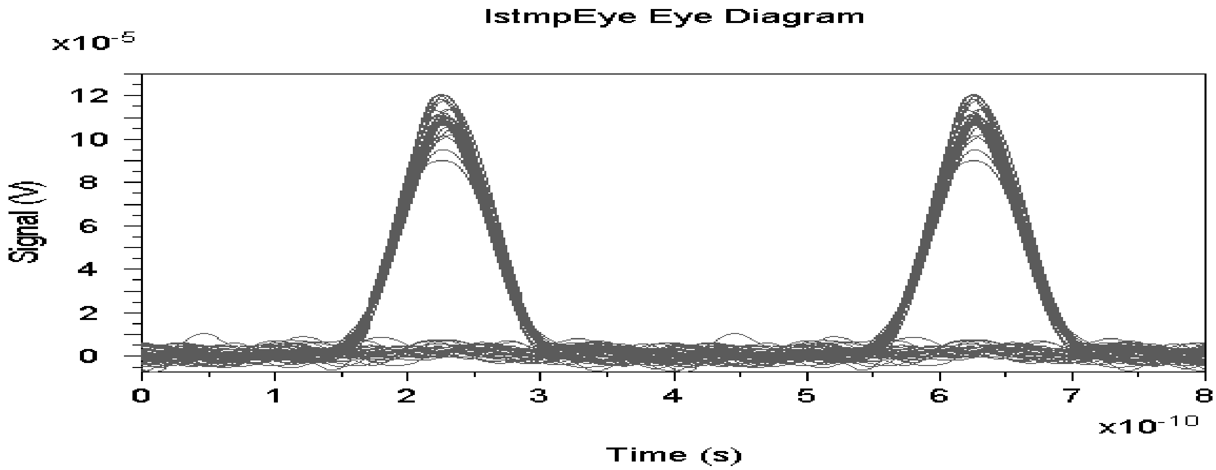


Fig. 4.9: Eye diagram for 75 Km span of fiber

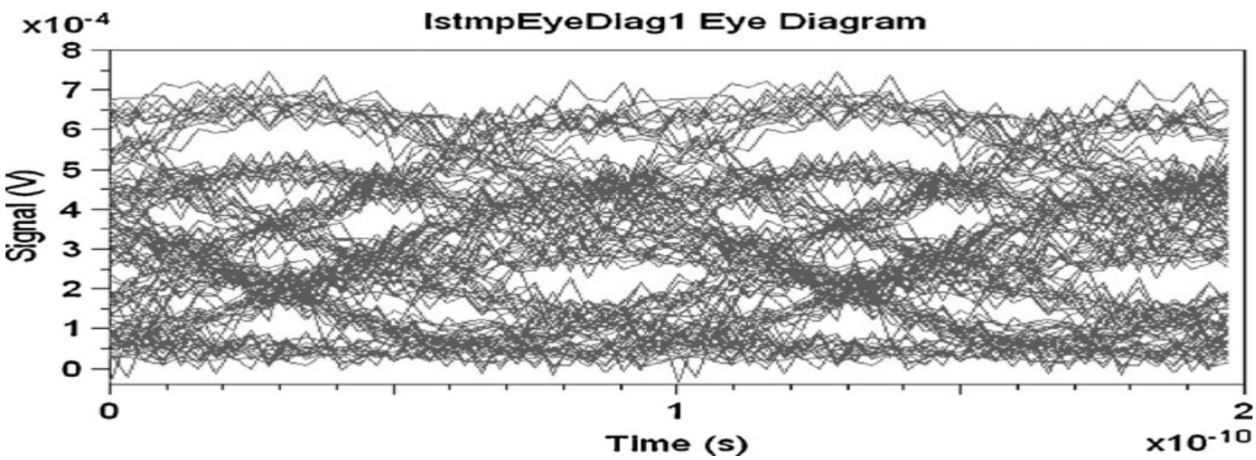


Fig. 4.10: Eye diagram for 120 Km span of fiber

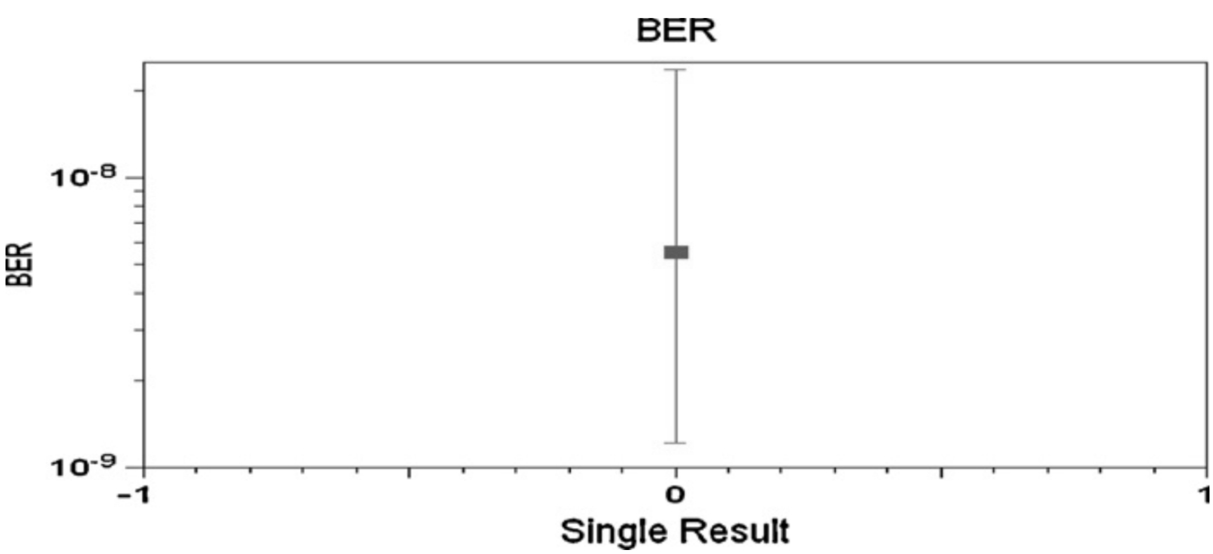


Fig. 4.11: Obtained BER result

The proposed OCDMA system is examined for fiber length of 120 Kms and data rate of more than 10 Gbps with different modulation formats for acceptable BER. The obtained simulated results are discussed for various modulation formats. The results for proposed system for a fiber span of 120 Kms are found to be in line with the acceptable limits of BER.

Here to conclude, we have proposed optical CDMA system code/topology architecture with negligible in-phase cross-correlation value for the spectral encoding/decoding type optical CDMA networks, which means that multi-access interference (MAI) is within limit and even bit error rate (BER) performance is also reported to be acceptable for various data formats and their comparison is given. It can physically be verified that the hardware complexity is bare minimum when it comes to designing and simulation of the proposed optical system. The resultant system is economical as well as proved to be well within the acceptable limits for implementation in optical systems.

The simulated results for the proposed architecture for fiber length up to 120 Kms is shown below in Fig 4.12, Figs. 4.13 to 4.15 presents the comparative results for various modulation formats in terms of supported data rate, fiber length and received power for different data formats. One can clearly visualize the dominance of NRZ raised cosine data format and is recommended for future OCDMA networks.

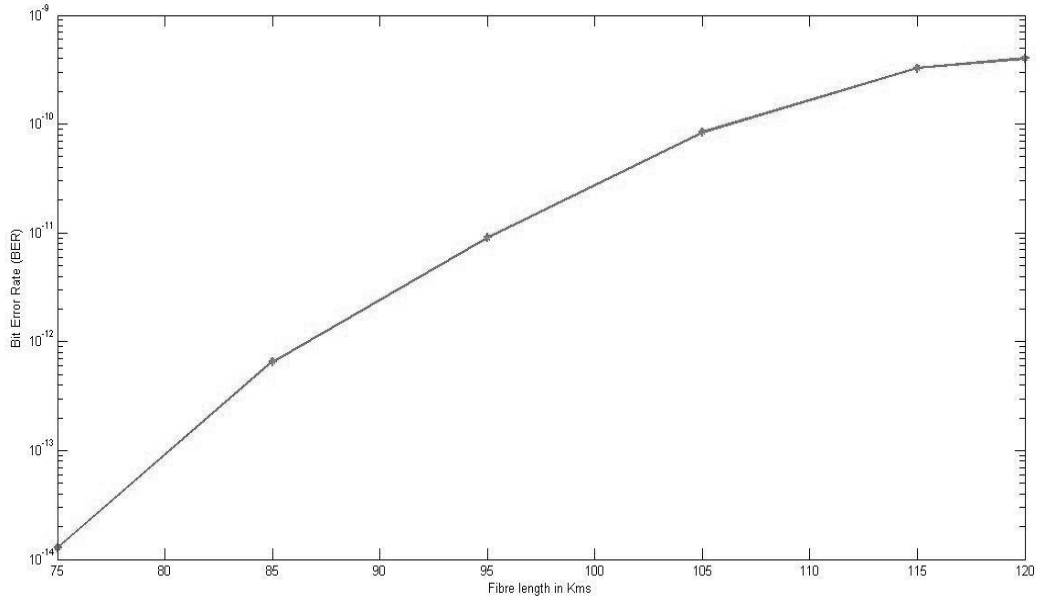


Fig. 4.12: Obtained BER for different length of fibers

These simulated results demonstrate that BER performance is acceptable for fiber length up to 120 Kms. Beyond this the BER value abruptly goes high.

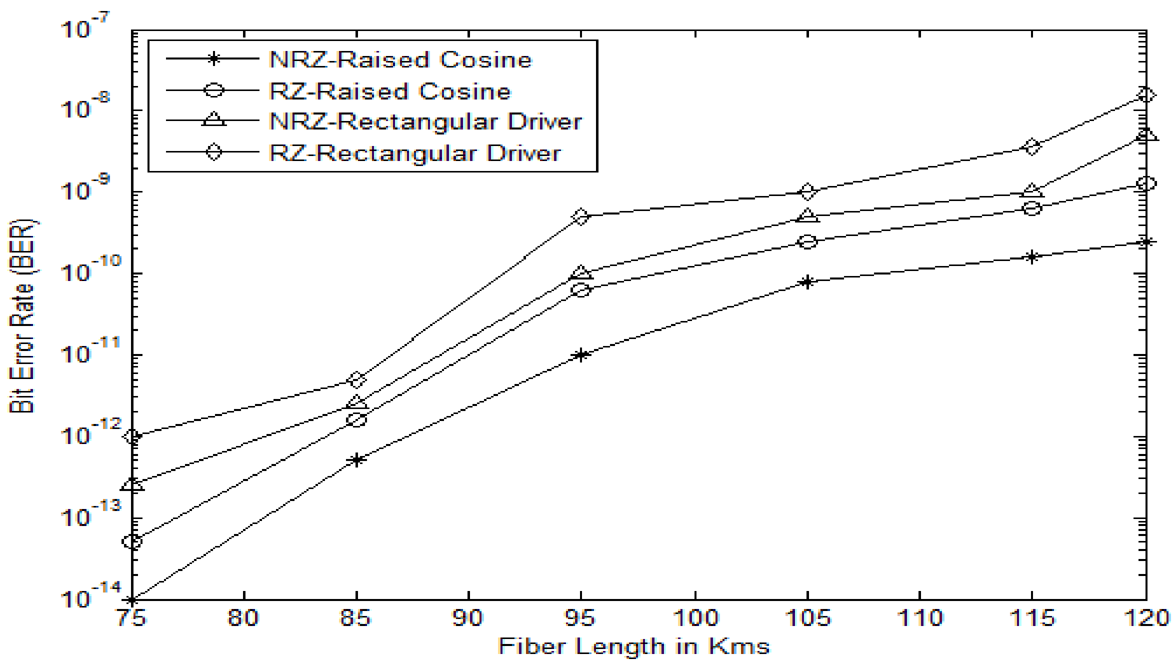


Fig. 4.13: Comparative BER Vs Fiber lengths for various modulation schemes

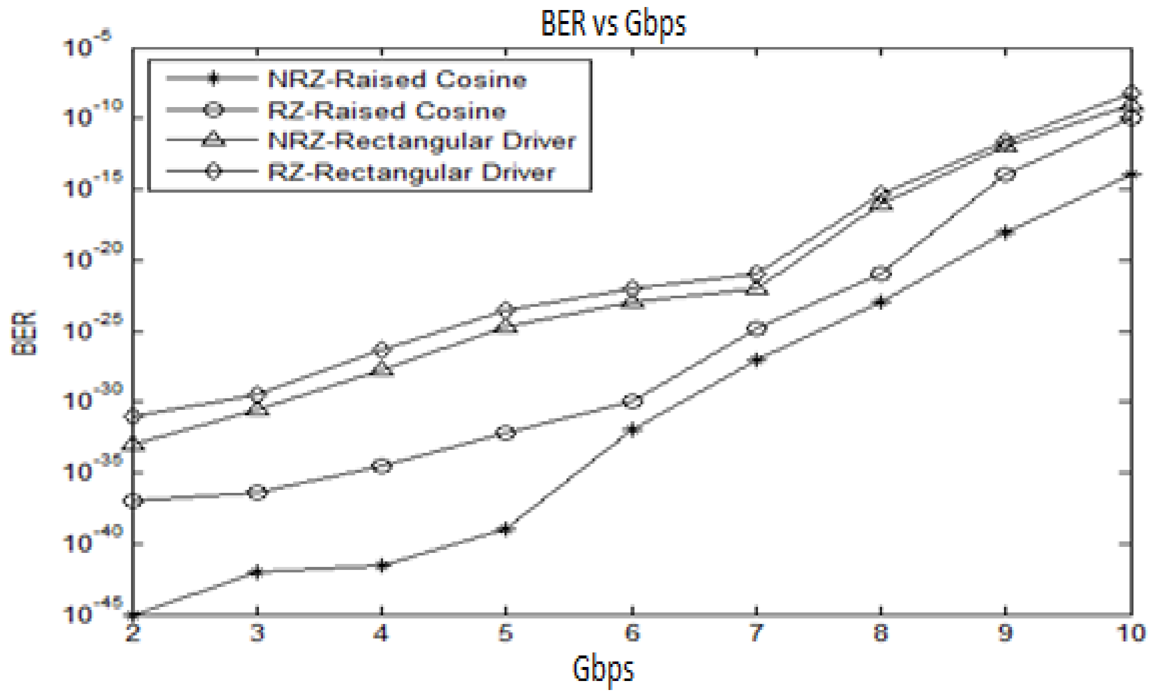


Fig. 4.14: Comparative BER Vs Supported Data rate for various modulation schemes

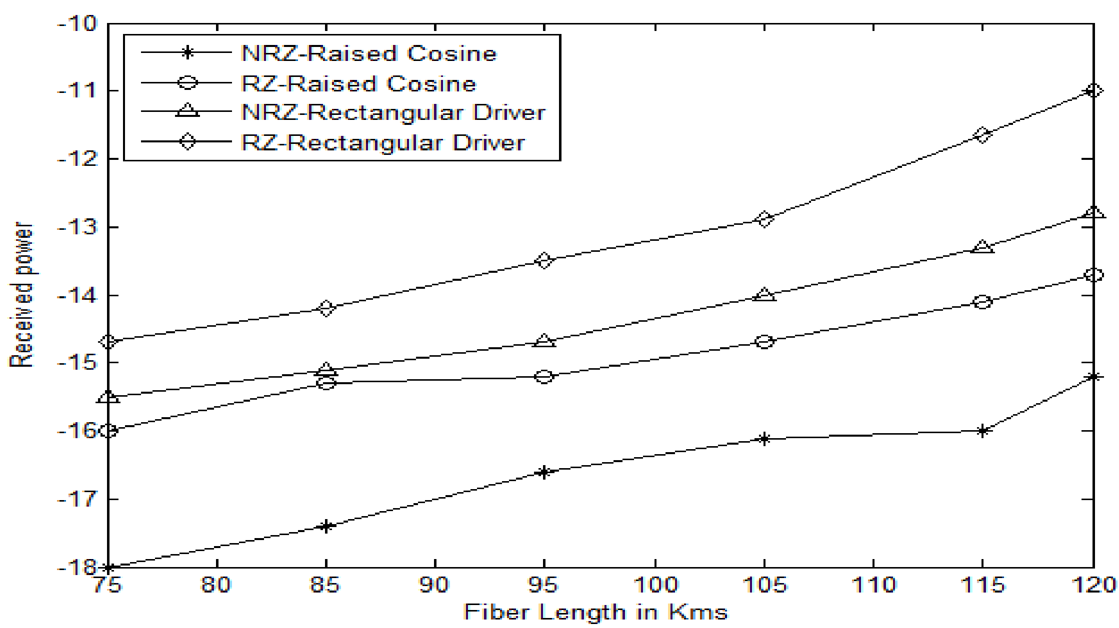


Fig. 4.15: Comparative Received Power Vs Fiber lengths for various modulation formats

4.3 An Optimized Optical Code Division Multiple Access Mechanism for Faster Routing MPFR (Message Priority and Fast Routing) Mechanism in OCDMA

A new optimized class of optical codes known as Message Priority and Fast Routing (MPFR) is presented. MPFR code is essential in the priority based communication of OCDMA for multiple user environments since these codes effectively control the multiple access interface delay by cancellation technique. In proposed work, codes for MPFR are generated based on simple tridiagonal matrix with lesser size of the header and incorporating priority based method. In the proposed algorithm, multiple user environments have been used in accordance to the packet header. The message size is increased and priority bit is added which leads to faster and effective data transfer in communication. The transmitter uses 2D codes, which is further added a priority bit for priority based transmission. Our obtained results revealed that proposed MPFR codes provide better results as compared to Flexible Cross Correlation (FCC) codes, Zero Cross Correlation (ZCC) codes and Prime Hop codes (PHC) in term of bit error rate, packet delivery ratio and multiple access interference. MPFR code is developed considering basic tridiagonal matrix structure and it can support large number of users in multiple simultaneous communications. Proposed work provides better performance than FCC, ZCC and basic PHC codes in term of Multiple Access Interference. While proposing a good scheme for OCDMA network routing and improvement in code length for better communication, “header attributes” have been considered for experimentation

4.3.1 Coding Concept and Header structure of Proposed OCDMA

With the inclusion of priority bit to the codeword the overall length of header is reduced, and length is also controlled at the transmitter side for overall communication. Figure 4.16 below shows the basic header structure for proposed work. PB is the priority bit set in the header.

0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4

<table>
<tr><td colspan="4">Code Length</td><td>Code sequence number</td><td colspan="3" rowspan="2">Repeat</td></tr>
<tr><td>Code Type</td><td colspan="2">V-Time</td><td>PB</td><td>Code Byte Size</td></tr>
<tr><td colspan="7">Originator Address (Hexadecimal)</td><td></td></tr>
<tr><td colspan="2">Time to live</td><td colspan="2">Hop Count</td><td colspan="2">Code Sequence Number and count</td><td></td><td></td></tr>
<tr><td colspan="8">MESSAGE</td></tr>
</table>

Code Type	Vtime	Code size		
Originator Address				
Time to live	Hop Count	Message Sequence Number		

Code Length			Code sequence number	Repeat	
Code Type	V-Time	PB	Code Byte Size		
Originator Address (Hexadecimal)					
Time to live	Hop Count		Code Sequence Number and count		
MESSAGE					
Code Type	Vtime		Code size		
Originator Address					
Time to live	Hop Count		Message Sequence Number		
Message					

Fig. 4.16: Header Structure for proposed MPFR code scheme

For proposed MPFR protocol, the message size is increased which leads to fast routing and while communicating packets of data the priority is assigned, which leads to effective packet transfer. The major attributes used in construction of whole code scheme are code length and priority bits. MPFR codes provide better routing performance by incorporating the priority bit in header. Code size is increased and the header passing time is reduced. The code size is being increased and priority bit is being added which leads to faster data transfer rate (due to lesser processing time) and effective data transfer in OCDMA. A solution involving MPFR code generation for an increase in the routing performance, which can effectively enhance data transfer in optical communication is presented.

Optical CDMA based codes are taken as a group S (represent the S users) with binary (0, 1) string sequences of length Q, weight based on priority y, for variation of cross correlation, £max and £min values are used as maximum and minimum values respectively. Optimized code set based optical network can support the maximum number of users without an increase in code length and have almost acquire every required cross correlation property.

Let $C = \{jn\}$ and $D = \{ln\}$ as the different sequences of length such that: pi is priority bit.

$\{j_e\} = \text{“0” } or \text{ “1”}, e = 0, --------, Q-1\ (pi)$ -------- (4.1)

$\{l_i\} = \text{“0” } or \text{ “1”}, e = 0, --------, Q-1\ (pi)$ ------------ (4.2)

Functions based on auto and cross correlations for sequences are explained below with the help of equations 4.3 and 4.4 respectively.

$£_j\ (\mu) = \sum_{n=0}^{Q-1} j_e\, j_{e+\mu}$-- (4.3)

$£_{jl}\ (\mu) = \sum_{n=0}^{Q-1} j_e\, l_{e+\mu}$-- (4.4)

Now here in is $(0, 1)$ binary arrangement, so the peak value $£_j\ (\mu)$ in Eqn. (4.3) is by considering $\mu = 0$ which is equivalent to priority y, weight based on priority for sequence is explained as:

$£_j\ (0) = y$--- (4.5)

Priority is added and optical codes based on it can also be explained as per eqn. 4.6:

$£_{jmax} = £_j\ (0) = \sum_{n=0}^{Q-1} j_e\, j_e = y$ --------------------------------- (4.6)

Where “y” is also used to represent weight for auto correlation.

Now there must be S number of codes available to be distributed among same S number of users. The earlier given codes in equation (4.1 and 4.2) can also be explained in vector form as given below:

$C = \{j_e\}\ for\ e = 0, \dots \dots .., Q-1\ (pi)$ --------------------- (4.7)

$D = \{l_e\}\ for\ e = 0, \dots \dots .., Q-1\ (pi)$ --------------------- (4.8)

This all possible members of codes in an S x Q matrix C_Y^s are represented as:

$C_Y^s(pi) = (j_{ef}$ = "0" or "1", $e = 1, 2 \dots. s, j = 1, 2, \dots \dots Q\}$ -------- (4.10)

Where pi = priority bit

s = number of rows in the code matrix, equal to number of users

All the generated rows must represent a unique user for this C_Y^s should have rank S. Moreover, to achieve this condition is that

$$Q > S \text{ ------------------------------------ (4.11)}$$

$$C_Y^s = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The code length Q increases with respect to the number of users, the relationship between S and Q is defined in equation 4.11. The example for code sequence is given by table 4.1 below:-

Table 4.1: Example of generated codes for OCDMA structure using MPFR scheme

S users	M1	M2	M3	M4	M5	M6
1	0	1	1	0	0	0
2	1	1	0	0	0	0
3	0	0	0	0	1	1
4	0	0	1	1	0	0

Where M is the column for the code position and S determines the number of users.

4.3.2 Code Construction

Code construction in proposed work for OCDMA communication has flexibility to support large number of users and also provides efficient fixed cross correlation value. While adding a new user in same network, priority of user and wavelength assignment is done according to the available wavelength.

Modified MPFR codes is implemented as

$$\mathrm{MPFR}_{m-j} = \begin{bmatrix} W & X \\ Y & Z \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots.... (4.12)$$

Code construction is explained in matrix form with entities $W, X, Y,$ and Z. These entities have been processed with addition of priority bit and with lesser cross correlation between two codes for better communication. Two dimensional codes construction is initiated by choosing optical orthogonal codes of length S and are considered to be time spreading based code.

£max is denoted as maximum cross correlation for optical codes. £max is fixed to 0 or 1 based on the priority of the user. In a typical scenario where new user needs to immediate join optical communication network for communication, then priority bit is set to 1, hamming weight is also adjusted and priority bit in added to hamming bit only.

In code generation with $N = 5$ users, hamming weight m, having value $m = 2$

Then normal traditional matrix is given as shown below.

$$\text{Traditional Matrix} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Matrix1: Traditional Matrix with 5 active users and weight is 2

Here number of users are 5 and assigned weight is 2. Here cross correlation value $£max$ is 0. Now same traditional matrix can be redefined with priority bit which enables the increase of weight in code generation process. Matrix 2 below presents MPFR code construction process for five users actively participating having weight “two” and it also possess priority value.

$$\text{MPFR Matrix} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}$$

Matrix 2: MPFR Matrix with 5 active users having weight "two" and possessing priority bit

In case partial priority is given to users, for example users 2 and 4 are given the priority for communication; the code construction is shown as given in matrix 3 below.

$$\text{MPFR Matrix} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Matrix 3: MPFR Matrix with 5 active users having weight "two" and priority with user 2 and user 4

In the construction process of normal traditional matrix, we have followed cross correlation scheme and value of the $£max$ is 0, but when priority is assigned then £max value becomes 1. Code construction is extendable to any given number of users which are represented as N and weight assigned is shown as m. This way we have constructed cross correlation based codes, those occupy minimum length, and thus can support better communication with introduction of priority bit.

Code length S is given in below equation 4.13

$$S = weight\ (users) - maximum\ cross\ correlation\ (user - 1)$$
$$= m \times N - £max\ (N-1) \text{----------------- (4.13)}$$

Now according to our process, after addition of the message priority to user's matrices, value of the weight is increased. Hence equation 4.13 is modified and is given in equation 4.14.

$$S = (m+1) \times N - £max\ (N-1) \text{------------ (4.14)}$$

Code length is minimum as per Matrix1, where cross correlation value is 0 and given code length is based on equation 4.14 (calculated value is 10). Code length is also same in Matrix 2. In this priority is assigned to users and thus value of the weight is increased by 1 (calculated value becomes 11).

However the code length varies in accordance with assigned priority to particular user and code length also varies accordingly. However auto-correlation is done automatically in each case to provide optimized code construction while adding a new user in same network.

4.3.3 Architecture/Structure of OCDMA Network for MPFR Technique

The simulated laser setup is used for creating and initiating pulses with a width of 90 ps at a repetitive rate, which is equal to the data rate of network. The proposed system is analyzed with message priority and fast routing with OCDMA. Network Simulator is used with MAI, BER, SNR and PDR as parameters to evaluate the overall performance of the optical system. MPFR codes are developed based on the code development structure of the FCC scheme [43], [44] which is also based on traditional code matrix. The proposed structure is implemented and analyzed with transmitter and multiple receivers.

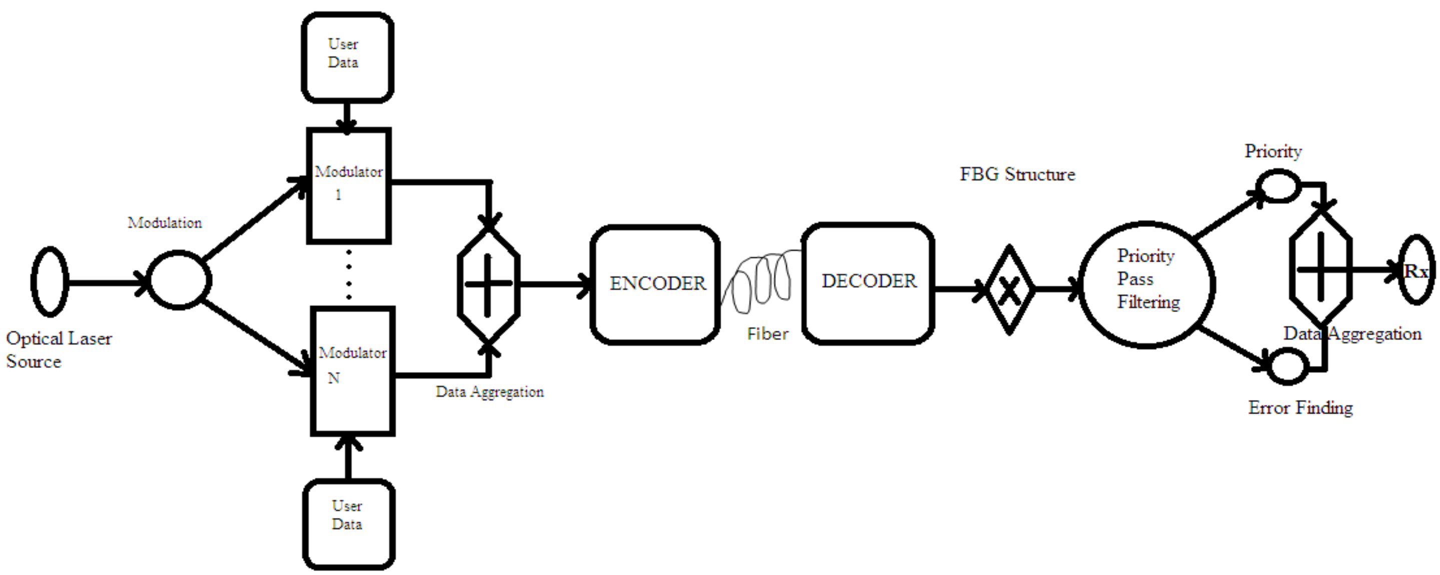


Fig. 4.17: Simulation Set-up (MPFR Technique) for OCDMA structure implementation

Simulation setup for MPFR based on an OCDMA architectural system with the implementation of 2-D wavelength/time matrix codes shown in Fig. 4.17 is self-explanatory. The simulated laser setup is used for creating and initiating pulses with a width of 90 ps at a repetitive rate, which can be equal to the data rate of network. The suggested scheme is analyzed with message priority and fast routing with OCDMA. The architecture of the proposed scheme is shown in figure 4.16.

Network Simulator is used with MAI, BER, SNR and PDR as parameters to evaluate performance. MPFR code is designed based on the code developed structure of the FCC scheme [43], [77] with addition of priority bit and decreased header bit length, which is also, based on traditional code matrices. The suggested structure is implemented and analyzed with multiple transmitters and receivers. In proposed work, receiver senses the interference and provides detection for intrusion. The receiver is processed in accordance with the codeword for data packets being sent or received. There is a limitation of finite propagation delay based on the intermediate medium, estimation of interference sensing is not much accurate as many nodes could sense at the same time of interval [76].

An interference sensing algorithm is developed and implemented in proposed MPFR section. Detection mechanism if done efficiently could provide fast interference and if it is detected, then transmission is aborted and deferred. In proposed work, receivers sense the interference and provide detection for interference. The receiver is processed in accordance to the codeword for packets sent and received.

x_t ←Code processing through codeword

Checker count for retry $C_r \leftarrow 0$

4.3.4 Algorithm for interference sensing:

Start sensing in accordance with priority on sensing mode

Record the position of the sensing line

Do Release fresh instant $t_r \leftarrow 0$
While $(t_r \leq A)$
If ((instance and $x_t \neq x_t$*) AND (weight (instance*$\mid x_t) \leq thresh_o$*) AND (peak height of overlap* $\leq thresh_h$*)) Then immediate break*

Process inverse x_t *by single chip*
Process $t_r ++$
If $t_r \leq A$
Wait up to final instance t_r
Process Data scheme
If $t_r > A$
$C_r ++$
If $(C_r <$ *Limit of reprocess)*
Wait in accordance to wait process

Repeat the algorithm
Else process packet inversely to subsequent advanced layer

Where $thresh_o$the threshold for overlap is count and $thresh_h$ is the threshold of magnitude limit.

4.3.5 Results and Discussion for proposed message priority and fast routing mechanism

The proposed structure is implemented and analyzed with transmitter and multiple receivers. Network Simulator is used with MAI, BER, SNR and PDR as parameters to evaluate performance. The suggested structure is implemented and analyzed with transmitter and multiple receivers. The proposed work described message priority and fast routing mechanism for OCDMA which provide least MAI and BER as compared to FFC, ZCC and PHC based OCDMA networks. MPFR code development is based on decreasing code length and increased message containing capacity and hence enhances the performance of the network.

The upper limit on the number of supported user is also given by equation 4.15

$$M = [(G-1)]/S(S-1) \text{ ----------------------- } (4.15)$$

Where G denotes code length and S is the code weight

4.3.5.1 Performance Evaluation in terms of MAI and BER

The proposed work describes message priority and fast routing mechanism for OCDMA which provide least MAI and BER as compared to FCC, ZCC and PHC based OCDMA networks. The proposed MPFR scheme is also evaluated on the bases of bit error rate with 60 active users.

Various parameters which are used for performance evaluation of proposed work are validity time (time after reception of packets) which is defined as

$$VT = S \times (1 + m/16) \times 2^n \text{ ----------------- } (4.16)$$

Where S =scaling factor used for the calculation of validity time

m is the higher order bit

n Is the lower order bit

As validity time decreases, we need to process the packet very quickly with the help of priority, so that we can increase the performance. Bit error rate, packet delivery fraction, signal to noise ratio and average end to end delay are used for better understanding of results.

$$PDF = \frac{\text{Number of Received Packets}}{\text{Number of Sent Packets}} \quad \text{-----------------} \; (4.17)$$

$$AED = \frac{\sum(\text{Time Received} - \text{Time Sent})}{\text{Total data Packets Received}} \quad \text{-----------------} \; (4.18)$$

$$\text{SNR} = \frac{1}{\left(\frac{16\sigma^2}{R^2 I^2 S^2 (P+2)^2}\right) + \left(\frac{(M+2)(M-1)}{2(P^2-P)(P+2)}\right)^2} \quad \text{-----------------} \; (4.19)$$

Optical CDMA based codes are taken as a group S (represent the number of users) with binary $(0, 1)$ string sequences of length Q, weight is based on priority y and for variation of cross correlation, whereas £max and £min values are used as maximum and minimum values respectively. Optimized code set based on optical network can support maximum number of users without increase in code length and has almost every cross-correlation property.

The system is thoroughly investigated for its performance for acceptable BER with corresponding increased number of users at the transmitter side. The proposed system has shown acceptable and better results in terms of MAI and BER for up to ninety users.

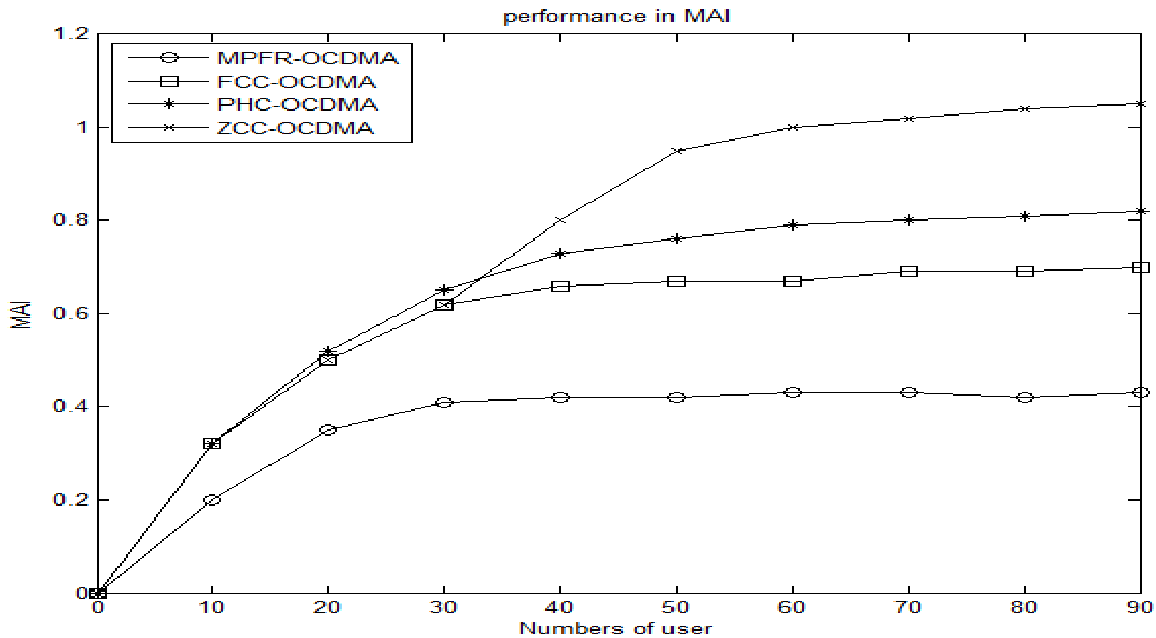


Fig. 4.18: MAI Vs Number of Users for proposed MPFR mechanism based OCDMA System for Various coding schemes (comparative Analysis)

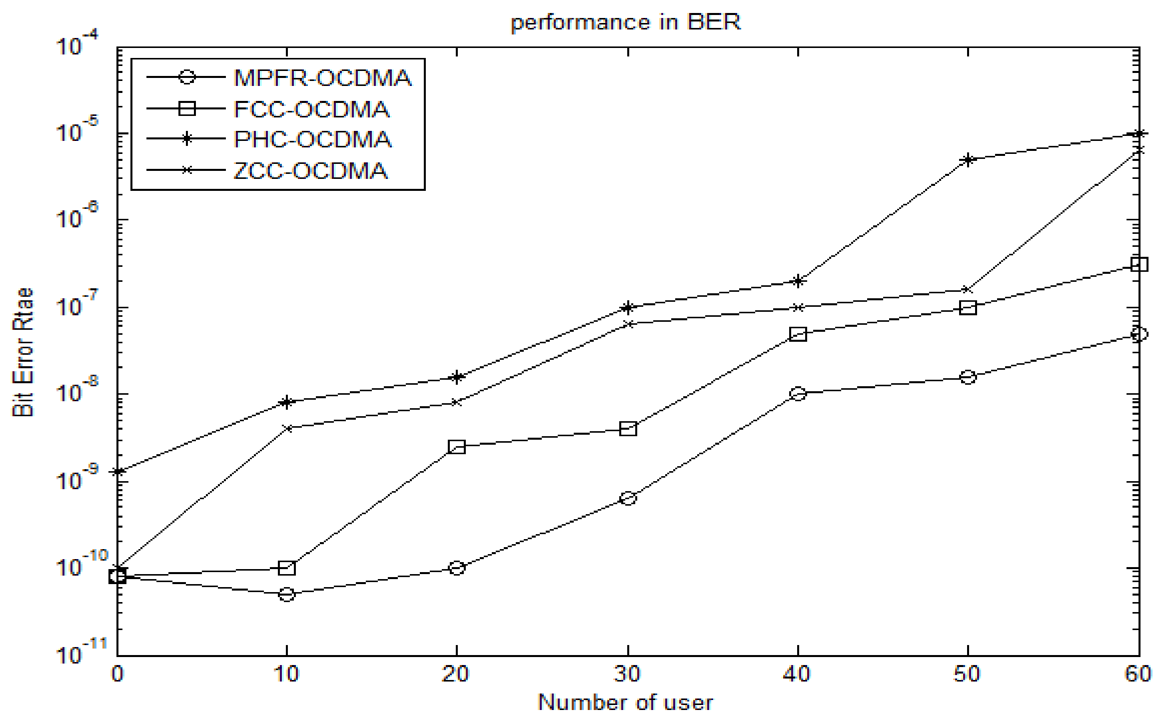


Fig. 4.19: BER Vs Number of Users for proposed MPFR mechanism based OCDMA System for Various other coding schemes (comparative Analysis)

Proposed work introduces MPRF mechanism for OCDMA, which provides least BER compared to BER provided by FFC, ZCC and PHC based OCDMA networks as shown in Fig. 4.19. BER for the proposed employment is low in the beginning of the communication and even throughout maintains a lower value compared to other code schemes. Obtained results for proposed message priority and fast routing mechanism for OCDMA provide less MAI compared to FCC, ZCC and PHC based OCDMA networks illustrated in Fig. 4.18.

4.3.5.2 Performance Evaluation in term of SNR and PDR

SNR is one of the parameters, which is required to be calculated for the optimization judgment for proposing any technique. Our work proposes message priority and fast routing mechanism for OCDMA, which provides better signal to noise ratio value as compared to FCC, ZCC and PHC based OCDMA networks presented in Fig. 4.20.

The performance of the proposed mechanism is also compared on the bases of packet delivery ratio, so that optimized traffic flow can be judged. Fig. 4.21 shows the packet delivery ratio of the proposed work which is very high as compared to existing scheme for communication in OCDMA network.

We have introduced a new optimized communication method known as MPFR for OCDMA. MPFR code development is based on minimizing code length. Variations in weight due to priority provides fixed data rates but can support various different quality of service processes and in other case length variation can provide data variation according to user.

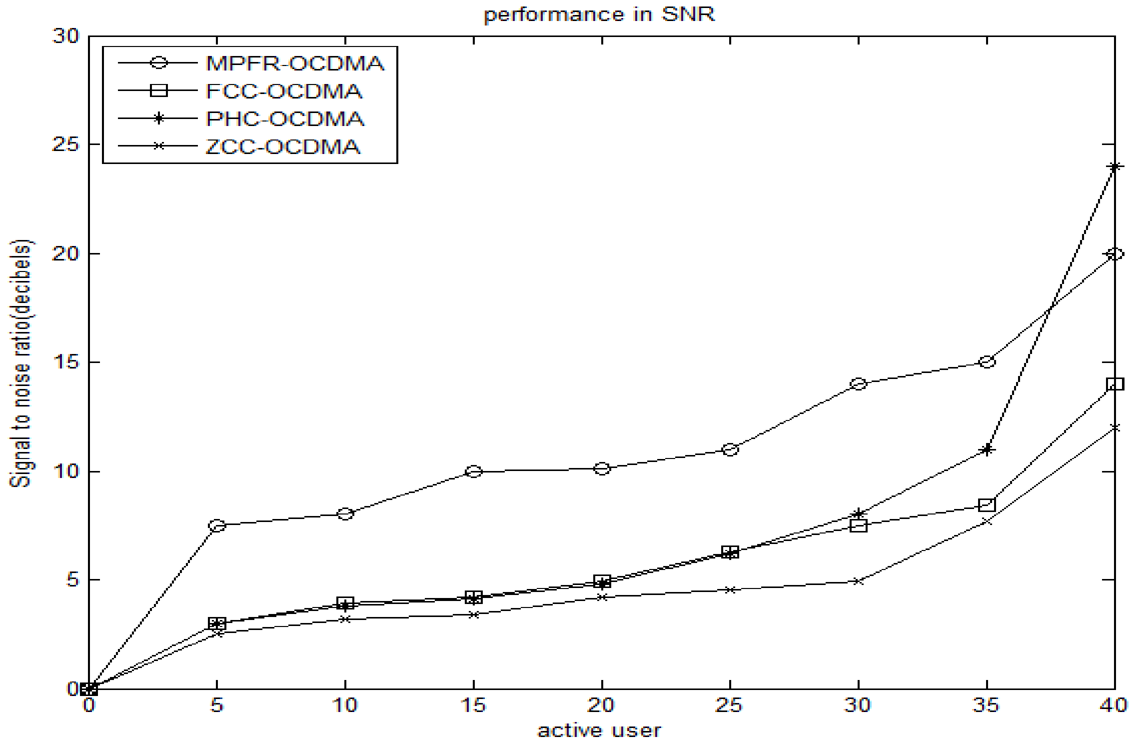


Fig. 4.20: SNR Vs Number of active Users for proposed MPFR mechanism based OCDMA System for Various other coding schemes (comparative Analysis)

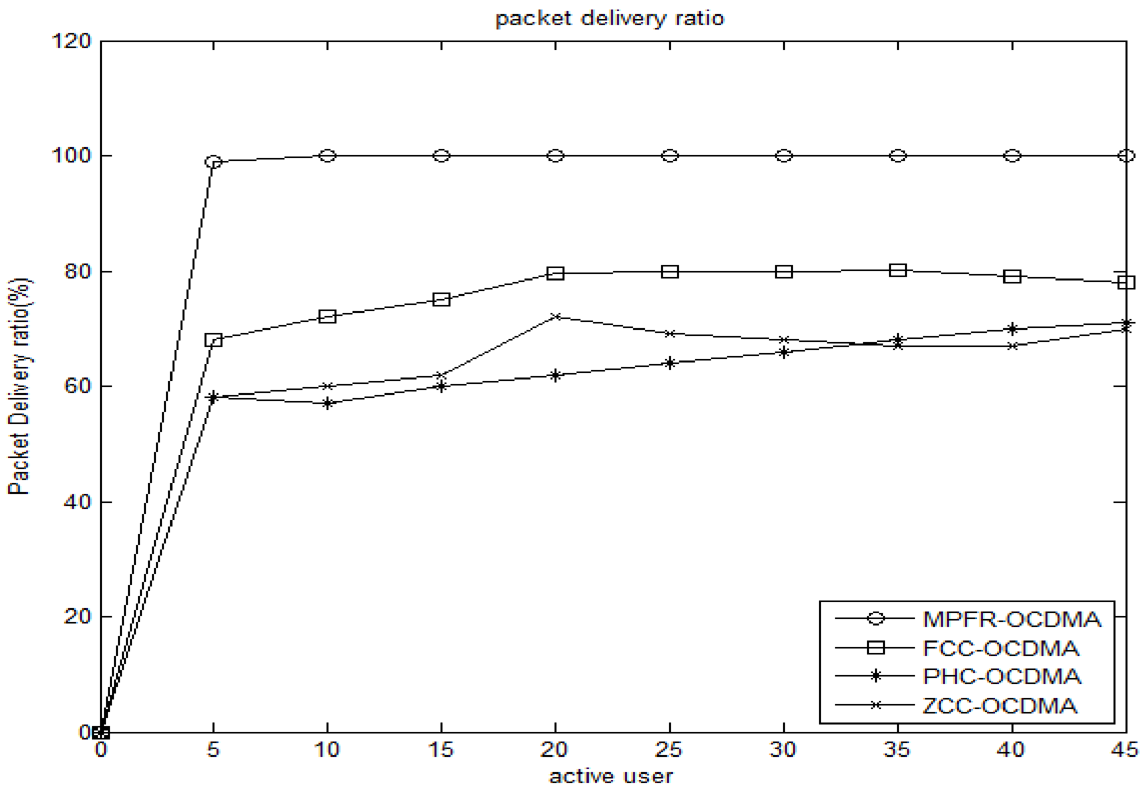


Fig. 4.21: PDR Vs Number of active Users for proposed MPFR mechanism based OCDMA System for Various coding schemes (comparative Analysis)

4.4 Conclusion

The simulated Optical CDMA system for proposed architecture has resulted in better performance in terms of BER for fiber span of 120 Kms and data rate of 10 Gbps. Moreover while simulating the proposed architecture and performing its validation in optical simulator, various practical optical impairments are considered, which has made these results realistic. The proposed architecture reduces the system complexity while keeping the system performance at an acceptable level. Its outstanding performance in terms of BER is obvious from our comparative analysis. The reduction of system complexity greatly lowers the cost of network establishment. Moreover the objective of shown receiver with phase conjugate is to effectively separate and remove the interfering signal from the received composite signal to enable the detection of desired signal without co-channel interference. The proposed system suggests NRZ data format as the best among other counterparts for its better performance.

We have also introduced the new optimized communication method based on priority to provide faster routing for OCDMA. Tridiagonal matrix is used for code construction and message priority is used which enables the priority of messages while communication by simply assigning the priority value in packet header. MPFR code development is based on decreasing code length and increase of message containing capacity and hence enhances the performance of the network. The proposed OCDMA code design shows an efficient code delivery at the receiving end and also results in lower values of BER and MAI.

Chapter 5

Design of Unbalanced Two-Dimensional Wavelength-Time Codes

5.1 Introduction

This Chapter deals with the design of a new family of Unbalanced Two-Dimensional Wavelength-Time Codes to increase the performance of optical system, which is the third objective of the research work. It has been endeavored to explain the complete design of the proposed Optical CDMA system in this section. We have proposed architecture for Optical CDMA using a Tree Topology where the transmitter uses 2-D PSO codes for the coding of transmitted signal. The advantages carried by MATRIX codes for optical code-division multiple access (OCDMA) are manifold. Some of these to mention here are their natural high cardinality, high information spectral density and acceptability to realize WDM capable components for their conceptualization. OCDMA finds its major share of applications in local area and access networks. For its inherited ability, matrix codes have over shadowed other linear optical codes, like direct sequence codes, for its application to Optical CDMA systems.

The technique for constructing the matrix codes extends from either crossing extended quadratic congruence (eqc) sequences with prime sequences or by the use of proposed computational "depth first search algorithms". In this chapter,we are developing pseudo-orthogonal matrix codes based on the "folding" of available spanning rulers or optimum Golomb rulers [1], [54] to produce the matrix codes for Optical CDMA networks. Here we will describe a semi-graphical procedure to create PSO matrix structure for OCDMA system. Our motive is to design the matrix codes those are compatible with optical orthogonal codes (OOC) for its characteristics. It is also desired that for all the column shifts (time shifts), the cross-correlation value between any pair of codes is maintained to "unity" for further extension to code set. Here column represents the time domain and rows correspond to wavelengths.

5.1.1 Designing of the Proposed Wavelength/Time Matrix Codes

An optimum Golomb ruler is defined to be a binary pulse sequences, the entries in the ruler are such that pulses occurring once, after any integer value in the matrix, never repeat the same for further generation of matrix elements. It suggests that the pulse entries are found to be at a unique integer distance apart, and this integer value throughout remains to be unique. Once it is applied to generate the pulse, it cannot be used for providing further pulse at similar integer position in the matrix [54], [55].

While expanding/designing the matrix, it is further taken into consideration, that pulses occurring at two different points in the ruler are differentiated with respect to each other by unique entries. Then only the obtained ruler can be termed as optimum. Apart from being used in mathematical applications in real life, these rulers have interesting property that they are used as starting material/seed for generation of two-dimensional codes, as shown in the following figure 5.1.

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	1

$g_1(4, 4)$

	Col 1 (C1)				Col 2 (C2)				Col 3 (C3)				Col 4 (C4)				Col 5 (C5)				Col 6 (C6)				Col 7 (C7)				Col 8 (C8)			
M1 =	**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**
M2 =	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	1	1	0	0	0	0	0
M3 =	0	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	1	1	0	0	0	0
M4 =	0	0	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	1	1	0	0	0
	0	0	0	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	1	1	0	0

Expended Mi from g_1 (4, 4)

M_1

	C1	C2	C3	C4	C5	C6	C7	C8
R1	1	0	1	0	0	0	1	0
R2	0	0	0	0	0	0	1	0
R3	0	0	0	0	1	0	1	0
R4	0	0	0	0	0	0	0	0

M_2

	C1	C2	C3	C4	C5	C6	C7	C8
R1	0	0	0	0	0	0	0	0
R2	1	0	1	0	0	0	1	0
R3	0	0	0	0	0	0	1	0
R4	0	0	0	0	1	0	1	0

M_3

	C1	C2	C3	C4	C5	C6	C7	C8

M_4

R1	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**
R2	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
R3	**1**	**0**	**1**	**0**	**0**	**0**	**1**	**0**
R4	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
R1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
R2	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**
R3	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
R4	**1**	**0**	**1**	**0**	**0**	**0**	**1**	**0**

Fig. 5.1: Obtained PSO matrix ($M_{1,}M_{2,}M_3 and\ M_4$) from golomb ruler $g_1(4,4)$ [52]

The top of Fig. 5.1 gives the one of the Golomb ruler $\boldsymbol{g1}\ (\mathbf{4},\mathbf{4})$ having cardinality 4, weight 4 and length 26 [1], [55]. This ruler is extended to increase the code dimensions up to 32 with the addition of “zeroes” and then shifting it by a single bit position. As discussed earlier, the chosen matrix code structure has inherited property that correlation property remains intact once golomb ruler is transformed into matrix. This way even row wise shifting to the generated matrix can give birth to additional matrices, which also preserve their orthogonality. Hence we may say that the large number of so forth generated matrices is also called PSO matrices. This way one sequence can produce large number of matrices by either row shifting or column shifting; those can be used to obtain desired cardinality.

By using same procedure, different codes can be generated for OCDMA system. The Code dimension (CD) is determined as follows:

The above cited phenomenon of shifting the ruler and obtaining the matrix of desired dimension is decided by $Cx\ R$. Where CxR should be greater than the value of length of initially taken Golomb ruler. Here “R” represents number of rows and “C” is number of columns present. It can also be shown that with such combination, the possibility of shifts is equal to $R * C - L$. So these are the essential elements while deciding the cardinality of the optical system and therefore must be chosen in the beginning and with utmost care.

During the design process, the number of rows i.e. “R” is selected first and it is usually taken to be a multiple of two $(2, 4, 8, 12, 16, 32, 64\ etc.)$ due to the condition put by physiognomies of available optical component (e.g. $1\ x\ N$, Optical multiplexer, demultiplexer and coupler).

The column entries of table of Fig. 5.1 correspond to time and rows specify the wavelength entries. Now the entire table entries are altered according to their shifted versions and this way extended set of matrices is obtained. The unshifted ruler in its fundamental shape, with column and row entities, expresses the initial matrix M_1 whereas all the shifted rulers produce matrix ranging from M_2 to M_4. The entries in the resulting (shifted) matrices are also OOC, because the process of transposition in either the column or row preserves the characteristics of initially selected optimum ruler [33].

It is worth to note that this ruler-to-matrix transformation has increased the cardinality (code set size) from one (1) to four (4) and the Information Spectral Density (ISD) (= cardinality/CD) from $1/26$ to $4/32 = 1/8$.

$$Information\ Spectral\ Density = \frac{\text{(Throughput performance)}}{\text{Required Bandwidth of channel}}$$

$$= \frac{(Cardinality * data\ rate\ of\ system)}{\frac{1}{T_b} * Bandwidth}$$

$$= \frac{(N * r * D)}{(D)(CD)}$$

$$= \frac{(N * r)}{(CD)} \qquad \text{-------------- (5.1)}$$

Where D =data rate of the system

T_b = Bit duration

N = cardinality of the code set

r = Number of rows in the resultant matrix

$T_b = 1/R$ (AM modulation)

If the selected value of $r = 1$, code dimension reduces to the fundamental Golomb ruler of length L. The achieved greater cardinality by extension/shifting algorithm and ISD, while maintaining the correlation properties, are major benefits of the ruler-to-matrix transformation.

5.1.2 Construction and Block Diagram of 2-D W/T OCDMA system

The designing and providing subsequent shifting in both the time as well as wavelength dimensions to optimum Golomb ruler results into 2-D W/T codes of increased cardinality. The optimum Golomb ruler is then taken as the foundation material in matrix code generation process. A Golomb ruler is one which can measure all the lengths up to its own length. Though it is not a mandatory condition, but if it does then it can be termed as the perfect ruler [45], [66].

5.1.2.1 Optimum Ruler for initiating code formation

The following table 5.1 contains all known available optimal Golomb rulers to be used for the purpose of code generation. The table is inclusive of all the chips entries for order 24.

Table 5.1: Available optimal Golomb rulers [55]

order	length	Chips Positional value
1	0	0
2	1	0 1
3	3	0 1 3
4	6	0 1 4 6
5	11	0 1 4 9 11 0 2 7 8 11
6	17	0 1 4 10 12 17 0 1 4 10 15 17 0 1 8 11 13 17 0 1 8 12 14 17
7	25	0 1 4 10 18 23 25 0 1 7 11 20 23 25 0 1 11 16 19 23 25 0 2 3 10 16 21 25 0 2 7 13 21 22 25
8	34	0 1 4 9 15 22 32 34
9	44	0 1 5 12 25 27 35 41 44
10	55	0 1 6 10 23 26 34 41 53 55
11	72	0 1 4 13 28 33 47 54 64 70 72 0 1 9 19 24 31 52 56 58 69 72
12	85	0 2 6 24 29 40 43 55 68 75 76 85
13	106	0 2 5 25 37 43 59 70 85 89 98 99 106
14	127	0 4 6 20 35 52 59 77 78 86 89 99 122 127
15	151	0 4 20 30 57 59 62 76 100 111 123 136 144 145 151
16	177	0 1 4 11 26 32 56 68 76 115 117 134 150 163 168 177
17	199	0 5 7 17 52 56 67 80 81 100 122 138 159 165 168 191 199
18	216	0 2 10 22 53 56 82 83 89 98 130 148 153 167 188 192 205 216
19	246	0 1 6 25 32 72 100 108 120 130 153 169 187 190 204 231 233 242 246

20	283	0 1 8 11 68 77 94 116 121 156 158 179 194 208 212 228 240 253 259 283
21	333	0 2 24 56 77 82 83 95 129 144 179 186 195 255 265 285 293 296 310 329 333
22	356	0 1 9 14 43 70 106 122 124 128 159 179 204 223 253 263 270 291 330 341 353 356
23	372	0 3 7 17 61 66 91 99 114 159 171 199 200 226 235 246 277 316 329 348 350 366 372
24	425	0 9 33 37 38 97 122 129 140 142 152 191 205 208 252 278 286 326 332 353 368 384 403 425

For the purpose of developing 2-D W/T codes for 64 users, the expanded group of rulers used is the set $\{gi\ (4,4)\}, i = 1, 2, 3$ and 4, having weight four. These eight rulers' sets are as given by:-

$g1\ (4,4)\ =$

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

$g5\ (4,4)\ =$

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

$g6\ (4,4)\ =$

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

$g7\ (4, 4)\ =$

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

$g8\ (4, 4)\ =$

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

After affixing stuffing "zeros", it enables these rulers to extend the obtained code length equal to $(CD\ =\ f\ *\ s)$, the rulers can be extended to get a shape of a matrix [15], [21]. The fundamental ruler $g1(4,4)$ thus produces the matrix M_1, $g2(4,4)$ produces M_9, and $g3(4,4)$ creates M_{17}, and $g4(4,4)$ creates M_{25} and $g5(4,4)$ creates M_{33}. Similar generation continues for remaining sets of matrices. Recurring row shifting allows M_1 to crop $M_2 \ldots M_8$; M_9 harvests $M_{10} \ldots M_{16}$; M_{17} produces $M_{18} \ldots M_{24}$, and M_{25} gives birth to $M_{26} \ldots M_{32}$ and so on prolonged up to M_{62} [1].

The ideal form of matrix to be used for recurring row shifting operation is square one, and is denoted by the matrix operator P is shown as

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

And then the matrices M_{ij} are produced by

$M_{ij} = \left(P^i\right) * M_1$ (like wise... $M_{9,} M_{17,} M_{25,} M_{33}$ ... ... M_{62}) ----------------------- (5.2)

This way the desired codes having the correlational properties are obtained. This is valid for majority of the cases excluding some instances where there is a shifting of "1" in P from the last row to the first row of the resultant matrix code structure. In those limiting cases, the resulting matrix is needed to be "fixed". It is achieved with the help of an operator used to provide the desired shift to the cells except mentioned exceptional case.

$$M1j = M1j + 1$$

(Where $M1j$ is an element present in the first row of the matrix obtained after operator P shifts it from the former row of the previous matrix). The full lists of 64 valid OOC matrices generated by MATLAB coding and generated code matrices are used for proposed optical network.

It is owing to this wide spread wavelength and time-slot reuse that stretches these matrix codes to achieve large cardinality [1], [62], [63], [65].

The 2-D codes obtained can be extended to a conceptual model of 3-D codes by appending a third dimension, generating another type of 3-D prime space-wavelength-time codes. The added third dimension to 2-D codes provides enhanced cardinality as now one additional dimension is there for code expansion. But definitely it will require additional components for their implementation. For their implementation of these codes, network will require polarization maintaining fibers and polarization sensitive components at encoder as well as decoder side, a complex polarization control at all stages in the network is compulsory, making it a very intricate and expensive concern.

The 3-D codes can generate a large number of code sets and therefore can contribute to increase in cardinality of the optical system. The different type of proposed 3-D codes is space-wavelength-time (SPP and MPP) codes, founded on prime sequence algorithm. The 3-D SPP codes are shown to provide better performance compared to the 3-D MPP codes [56].

Differential detection technique is applied for the reduction of MAI and it provides acceptable BER at the receiver. Here two codes are paired up to encode the bits '1'and '0' for each user. Using 3-D SPP codes for Balanced Coding/Differential Detection (SPP-BCDD), we can produce a very large code set with 1-D Golomb ruler sequences. The high spectral efficiency and greater system performance are the added advantages of adding the third dimension and maintaining only a single pulse per matrix structure obtained by earlier discovered matrices [56].

The 3-D SPP codes created on the earlier given concept of golomb ruler are derived for any weight to fulfill the off-peak auto-correlation of '0' and cross-correlation restriction of '1', as confirmed using wide-ranging simulations. A general illustration of 3-D SPP code designed on the basis of expansion to golomb ruler of order '4' resulting in a weight of '4' and displaced in four spatial planes is shown below [56], [57], [58].

$$[2 \quad 5 \quad 7 \quad 9]$$

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

An example of 3-D codes of weight 4

$$\begin{bmatrix}2&0&0&0\\0&5&0&0\\0&0&7&0\\0&0&0&9\end{bmatrix}$$

Alternate Depiction of the pulses in the 3-D SPP code [58]

Phase Shift →

Code No I II IV

$$\begin{bmatrix}2&0&0&0\\0&5&0&0\\0&0&7&0\\0&0&0&9\end{bmatrix}\begin{bmatrix}9&0&0&0\\0&2&0&0\\0&0&5&0\\0&0&0&7\end{bmatrix} \quad \ldots\ldots\ldots \quad \begin{bmatrix}5&0&0&0\\0&7&0&0\\0&0&2&0\\0&0&0&9\end{bmatrix}$$

Code No V VI VIII

$$\begin{bmatrix}3&0&0&0\\0&6&0&0\\0&0&8&0\\0&0&0&10\end{bmatrix}\begin{bmatrix}10&0&0&0\\0&3&0&0\\0&0&6&0\\0&0&0&8\end{bmatrix} \quad \ldots\ldots\ldots \quad \begin{bmatrix}8&0&0&0\\0&10&0&0\\0&0&3&0\\0&0&0&6\end{bmatrix}$$

↓ Wavelength Shift

..

..

..

Code No XIII XIV XVI

$$\begin{bmatrix}5&0&0&0\\0&8&0&0\\0&0&10&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&5&0&0\\0&0&8&0\\0&0&0&10\end{bmatrix}\quad \dots\dots\dots \quad \begin{bmatrix}8&0&0&0\\0&10&0&0\\0&0&1&0\\0&0&0&5\end{bmatrix}$$

Example: Procedure for generating the other codes in the set [58]

This way, another dimension can be provided to the 2-D codes, for their implementation to optical CDMA systems for increased number of advantages in terms of wavelength utilization, cardinality and overall performance against channel impairments.

We have also reported the performance comparison of 2-D Matrix codes with 3-D SPP codes and conclusions are drawn. Moreover the complete analysis in terms of eye-diagrams, BER Tester are carried from Eye diagram analyzer and BER Tester for varied number of simultaneous users and received optical powers for both systems. It is observed that attained BER and the Q-factor have a direct relationship, i.e. as the number of user’s increases; the bit error rate and Q- factor both degrade at the same time. As the number of simultaneous users is increased at the transmitting end, the error performance of the optical system shows a deteriorating tendency. This can also be noticed that as the number of users increase, the system performance starts to get poorer and MAI rises at the output. The Optical CDMA system has been designed to support 2.5 Gbps data rate for different values of received power and the conclusions on this basis are drawn for sixty four users. For our work we have simulated the result for ten users and observed the obtained trends, based on these inferences are drawn. For proposed coding, It is observed that even at 2.5 Gbps the planned system can work up to 64 users to offer BER ($<10^{-11}$). As the number of user increases, the amount of MAI is even more than the wanted user pulse. It is further established that there is a trade-off between supported data rate and received optical power for acceptable values of BER at receiving end. The NRZ raised cosine modulation format is reported to be the best among other modulation formats and hence is recommended for optical networks. For other modulation formats, the requirement of receiver optical power increases for acceptable results in terms of BER.

The block diagram of proposed simulation topology for proposed codes is demonstrated with the help of block diagram given below in Fig. 5.2. Here we have a set of eight light sources composing a group each of them differs by a unique wavelength and correspondingly each one is provided to a user. In totality, we have eight groups corresponding to 64-users. Here one group of broadband light sources combining and emitting/operating at different wavelengths are provided different delays and is applied to the external modulator as career frequency. This generated career after modulation with user specific data is fed to the encoder, where wavelength specific delays are provided. This is repeated for remaining set of light source groups. Each group has four numbers of encoders and it makes thirty two (32) encoders for eight (08) groups of broadband light sources. All the encoded data is then given to a combiner and send over a single mode optical fiber. So we are having eight space channels with sixty four numbers of closely spaced wavelengths, where a channel/group is having a set of eight wavelengths. A PN sequence is generated in the form of logical data from the PN sequence generator. The logical data is then converted into electrical data using NRZ driver. Similarly for the second channel/group, their data is also fed but delayed by same value as given to that particular wavelength, to the electrical input of the modulator. Similar pattern is followed for remaining channels. The modulator of each channel modulates the optical signal (carrier) according to the input data of user. After the modulator, encoder is placed to encode the data. The particular encoder encodes the data in time and wavelength domain. So the output of encoder gives the spreading of data in all three directions with the help of applied 2-D W/T codes. After that SMF of 90 Kms is used.

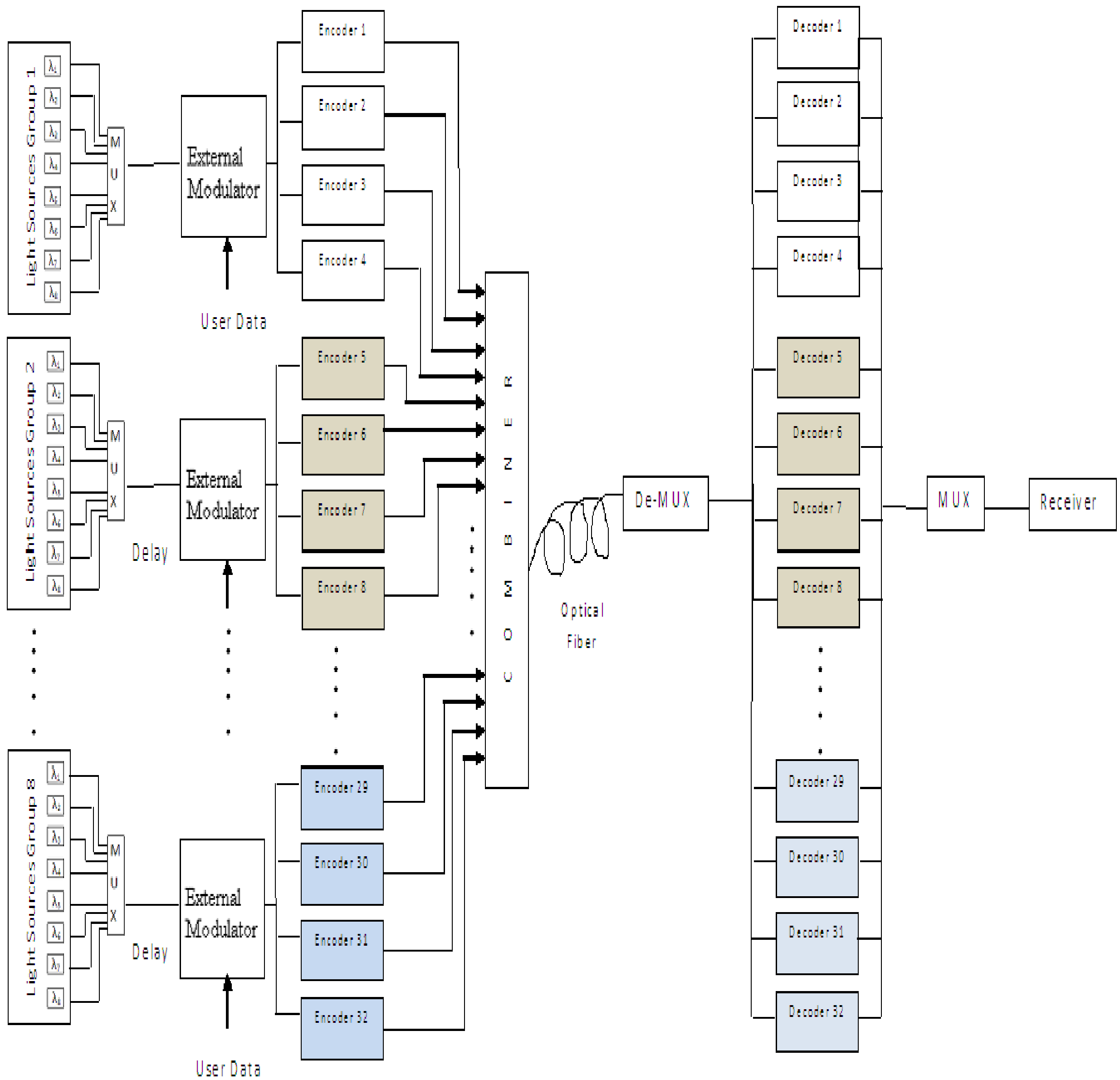


Fig. 5.2: Block Diagram of 64-Users 2-D W/T Encoding/Decoding OCDMA topology.

At the receiver, decoder is implemented by inverting the encoder for first channel and negative delays are provided to the wavelengths of subsequent channels at decoder corresponding to the delays provided at their encoders. After that, receiver is placed which will convert the optical signal into electrical one. Eye diagram analyzer, BER tester and electrical signal plotter are used to analyze the various outputs.

We have the choice of two modulation formats. One is non-return-to-zero, in which an endless power is spread through fiber during the entire bit period, and other is return-to-zero, in which power is conveyed only for a portion of the bit duration. It is observed that the NRZ pulses possess a fine optical spectrum. It is well known that in OCDMA systems, the system performance is dependent on bandwidth effectiveness of the used optical codes, which in turn is linked to error prospect of optical codes and also on the modulation format of the input data.

We have displayed an incoherent OCDMA system based on 2-D wavelength-time coding technique to accommodate large number of users at 2.5 Gbps. The 2-D W/T code has been reformatted by the use of 8 wavelengths and 8-time slots per group comprising of 8 users. Eight channels per group modeling a WDM network has been used for creating the carrier signal. This carrier signal is positioned to modulate the randomly generated (PRBS) data of the user. Modulator is followed by an encoder structure, providing wavelength specific delay to individual users in the optical network. There are eight such groups used for simulation of OCDMA network. Carrier signal is modeled with the help of a group of Mode locked lasers, producing pulses of pulse width of less than 100 ps at a repetition rate equal to supported data rate of the system. The chosen wavelengths spectra range from 1550 to 1551.2 nm, with less than 0.04nm wavelength space between them. The various results related to simulation are shown below in Fig 5.3 to 5.6.

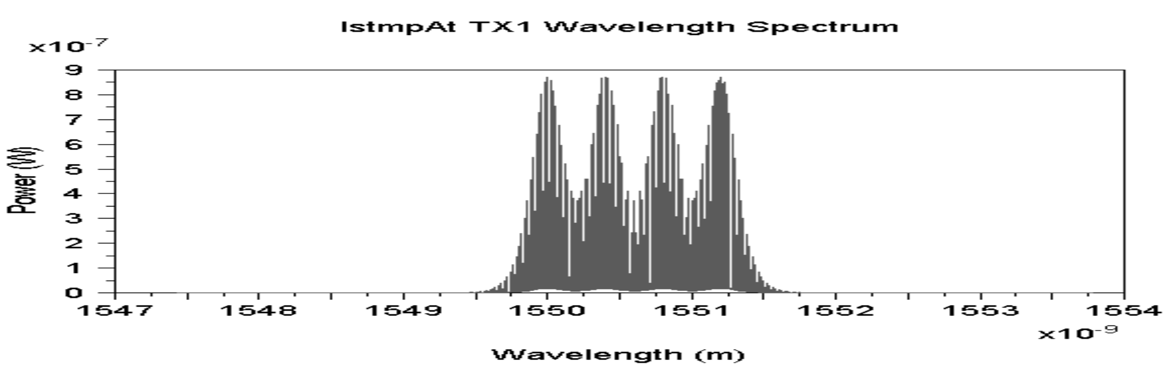


Fig. 5.3: Electrical Spectrum at multiplexer output (one group)**.**

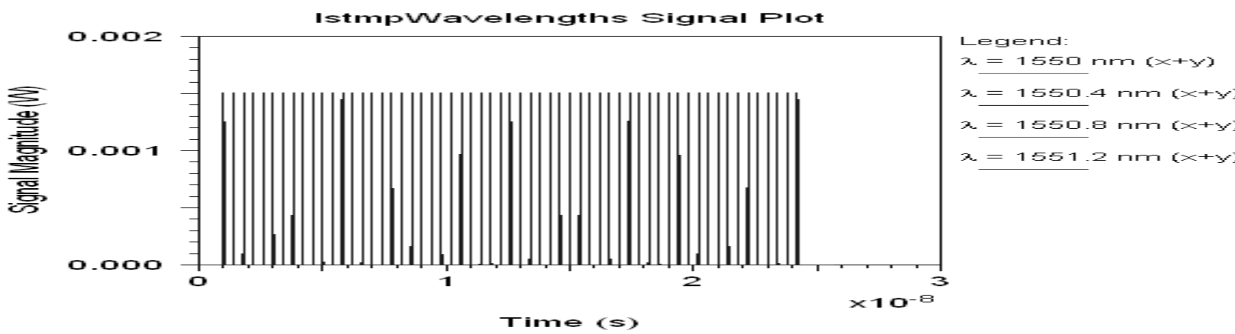


Fig. 5.4: Optical output of carrier (one group)**.**

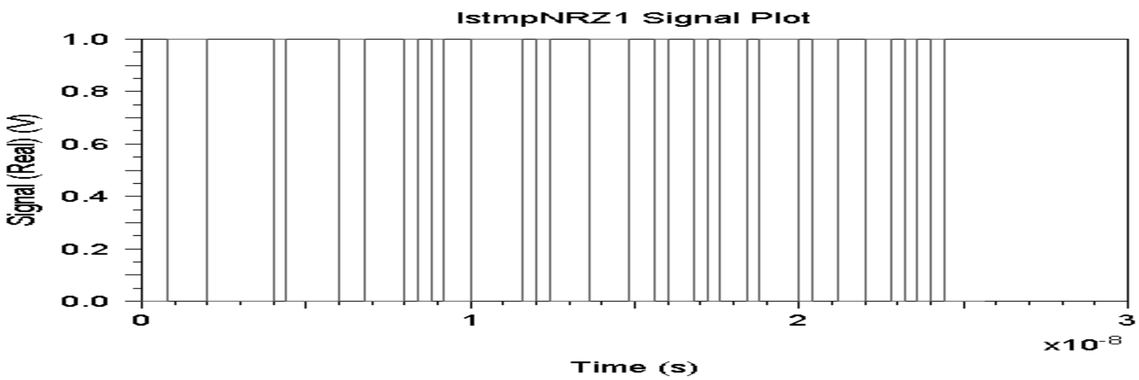


Fig. 5.5: NRZ modulated Electrical data.

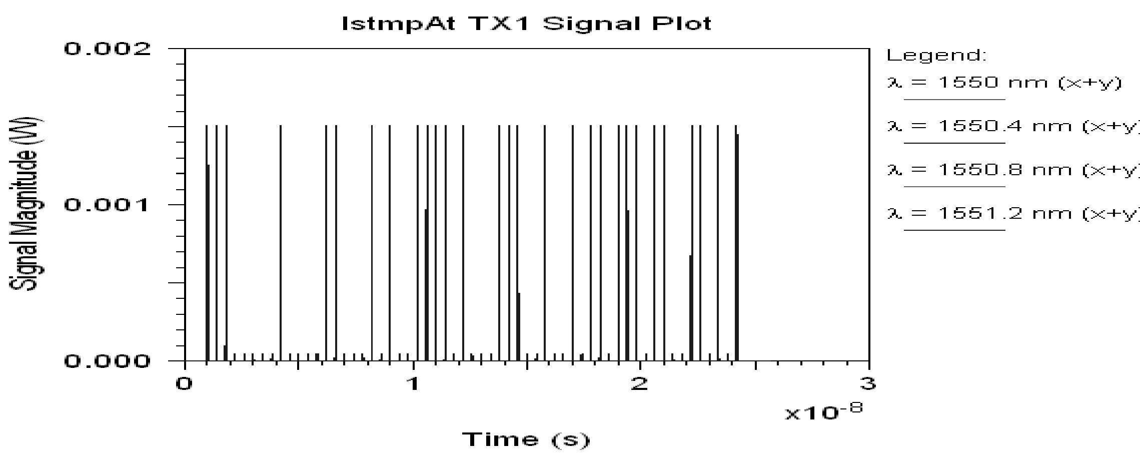


Fig. 5.6: Modulated data prior to encoder (User 1)

The separately modulated signals from all the channels are dispersed to the individual encoders, which is allocated a unique W/T code corresponding to the each encoder. Each Encoder contains four optical filters and four shift signals to yield the encoded bit stream, and later a combiner combines four of the displaced pulses to form an encoded signal. The encoded data in the form of composite signal from all users are multiplexed and then delivered through 90 km span of single mode fiber followed by a loss compensating optical amplifier. The composite signal from fiber span via splitter is then given to the user's decoders. The decoder, tuned to the same structure as the corresponding encoder, but with negative delays as matched to encoder recovers the user specific data.

Eye opening is recorded with the help of in-built component of simulator called Eye diagram analyzer, whereas recorded Bit error rate for varied received optical power has been observed with the aid of a component named BER Tester. The system performance has been restructured for different users for various optical received powers. To verify these for the analysis purpose, intensive simulations are performed.

5.2 Results and Discussions

The performance of an OCDMA network is judged by some pre-defined parameters like type of code, data rates, number of simultaneous users and attenuation factor, etc. In our analysis, we placed ten encoders out of thirty four for simplicity and conclusion is drawn on the basis of BER for received powers for different data modulation formats.

In this work we have located encoders for ten users out of 32, for the ease of representation and to observe the trend. Encoders and decoders respectively use delay and inverse delay line arrays and shift signals, providing delays in terms of integer multiples of chip times. The location of the delay-line arrays and the amount of individual delay per channel are governed by the specifics of the user signatures sequences.

The comprehensive analysis of OCDMA System based on two-dimensional W/T code for different optical received power per user in terms of BER has been done. Finally the performance of proposed 2-D codes is compared with previously reported 3-D OCDMA codes.

5.2.1 Analysis for different number of user with diverse received powers

Eye diagrams were taken from simulator using a component Eye diagram analyzer at receiver side and received signal is also examined. The Eye diagrams demonstrating the one, two, three, four and five users for different required optical power to achieve acceptable results are shown below.

5.2.1.1 Eye Diagram for one User at (-12dBm) received optical power

Eye diagram and received signal for one user has been shown below. Simulation results show no MAI pulses for single user case. The eye opening at receiver for this validates the system performance. In this instance User 1 for the mentioned received power at the decoder has shown no sign of MAI. Figures 5.7 and 5.9 show eye diagram for the user 1 and corresponding electrical detected signal respectively. The discovered signal Q-factor and BER are found as: Q = 22.9 dB, BER = 6.1e-045.

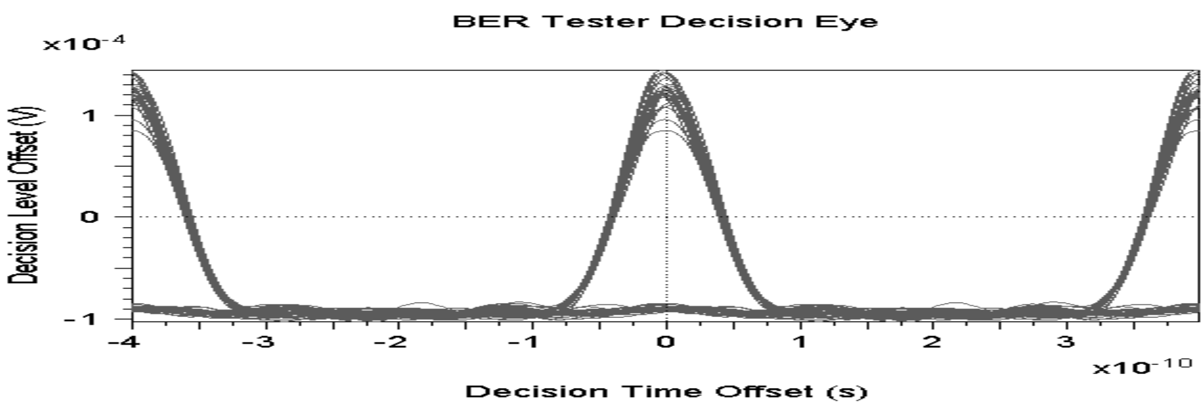


Fig. 5.7: Eye Diagram Analysis for single user, -12 dBm optical power

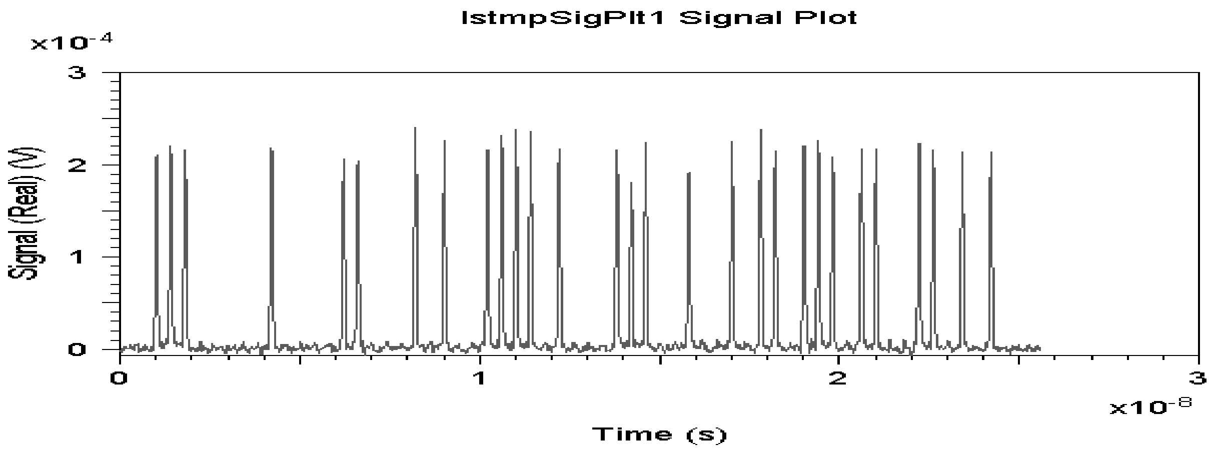


Fig. 5.8: Detected Electrical signal for single user, -12 dBm optical power

5.2.1.2 Eye Diagram for one User at (-15dBm) received optical power

Eye diagram and received signal for one user has been shown below. Simulation results show no MAI pulses for single user case. The eye opening at receiver for this validates the system performance. In this instance User 1 for the mentioned received power at the decoder has shown no sign of MAI. Fig. 5.9 shows eye diagram for the user 1 and corresponding electrical detected signal is given in Fig.5.10. The discovered signal Q-factor and BER are found as: Q = 21.3 dB, BER = 2.2e-031.

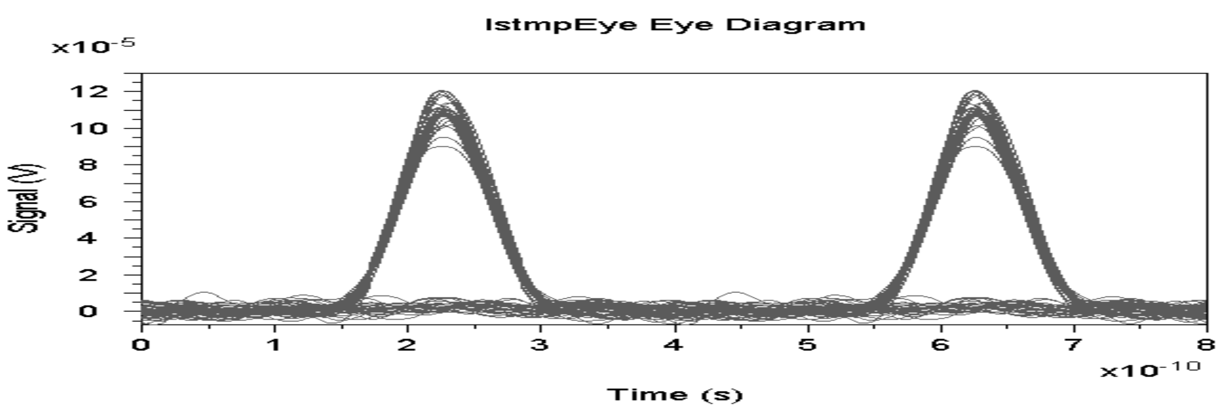


Fig. 5.9: Eye Diagram Analysis for single user, -15 dBm optical power

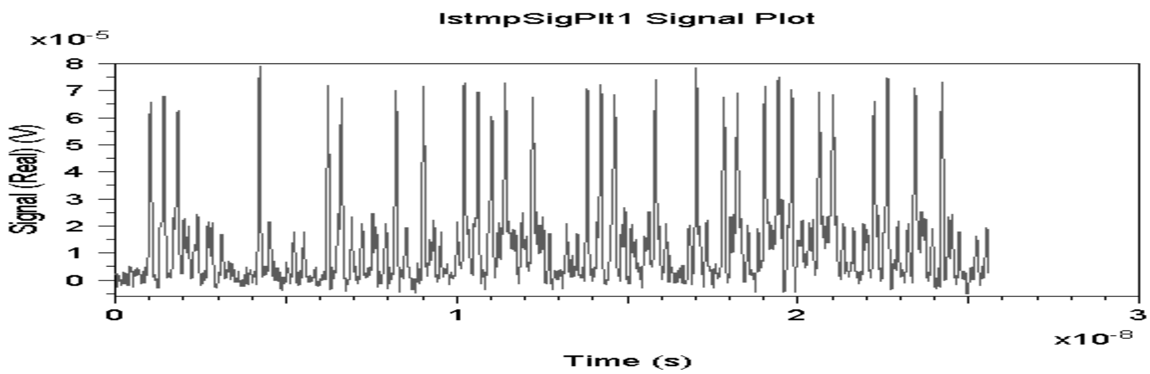


Fig. 5.10: Detected Electrical signal for single user, -15 dBm optical power

5.2.1.3 Eye Diagram for one User at (-18dBm) received optical power

Eye diagram and received signal for one user has been shown below. Simulation results show no MAI pulses for single user case. The eye opening at receiver for this validates the system performance. In this instance User 1 for the mentioned received power at the decoder has shown no sign of MAI. Figures 5.11 and 5.12 show eye diagram for the user 1 and corresponding electrical detected signal respectively. The discovered signal Q-factor and BER are found as: Q=18.4 dB, BER=3.9e-017.

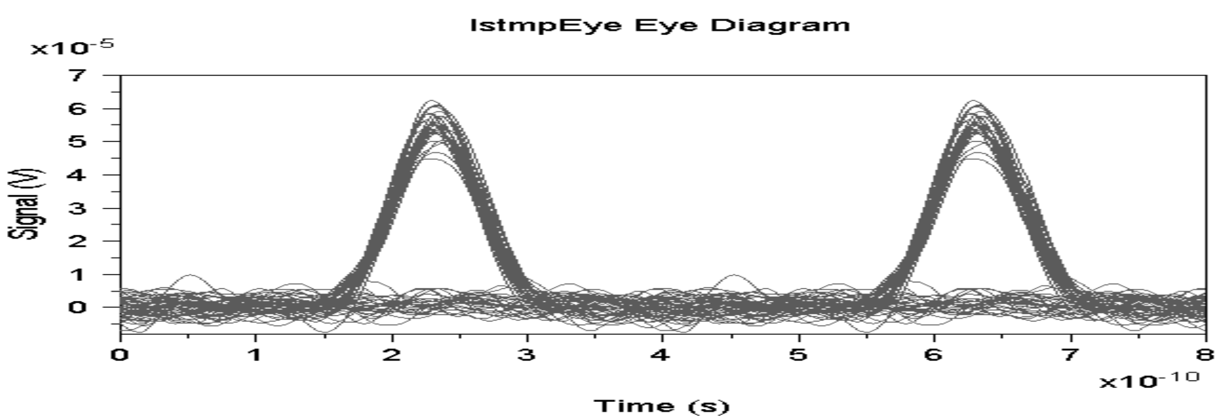


Fig. 5.11: Eye Diagram Analysis for single user, -18 dBm optical power

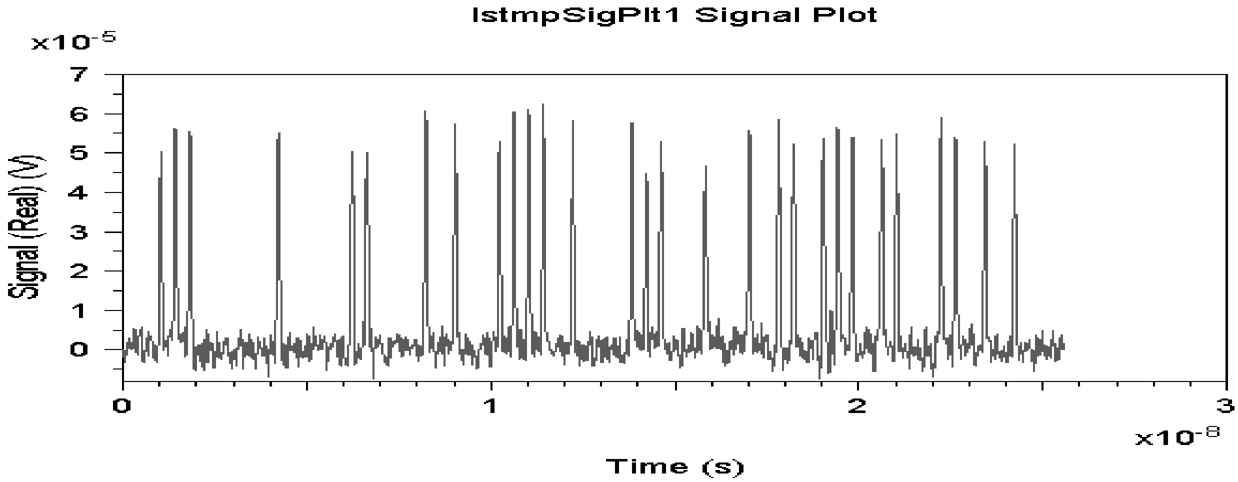


Fig. 5.12: Detected Electrical signal for single user, -18 dBm optical power

5.2.1.4 Eye Diagram for one User at (-21dBm) received optical power

Eye diagram and received signal for one user has been shown below. Simulation results show no MAI pulses for single user case. The eye opening at receiver for this validates the system performance. In this instance User 1 for the mentioned received power at the decoder has shown no MAI. Figure 5.13 and 5.14 shows eye diagram for the user 1 and corresponding electrical detected signal respectively. The discovered signal Q-factor and BER are found as: Q=14.2 dB, BER=1.4e-007.

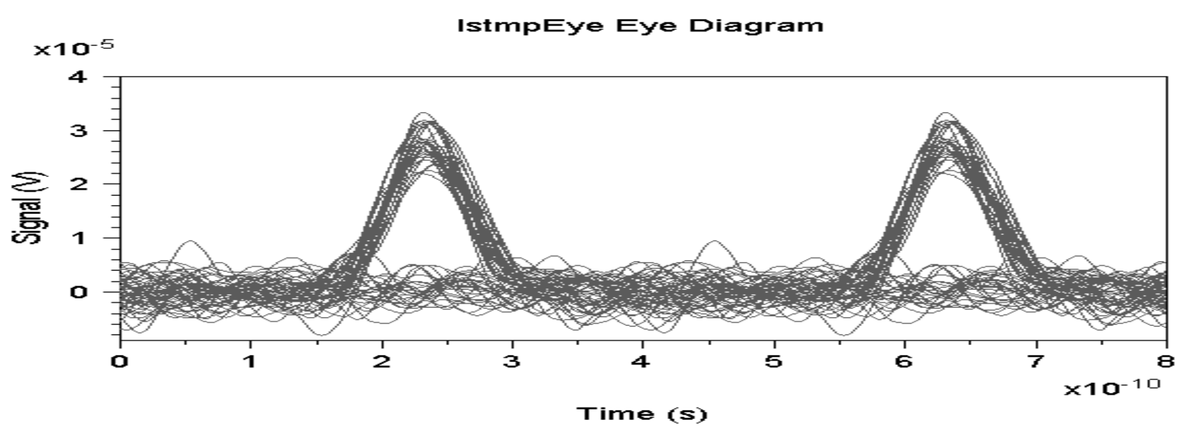


Fig. 5.13: Eye Diagram Analysis for single user, -21 dBm optical power

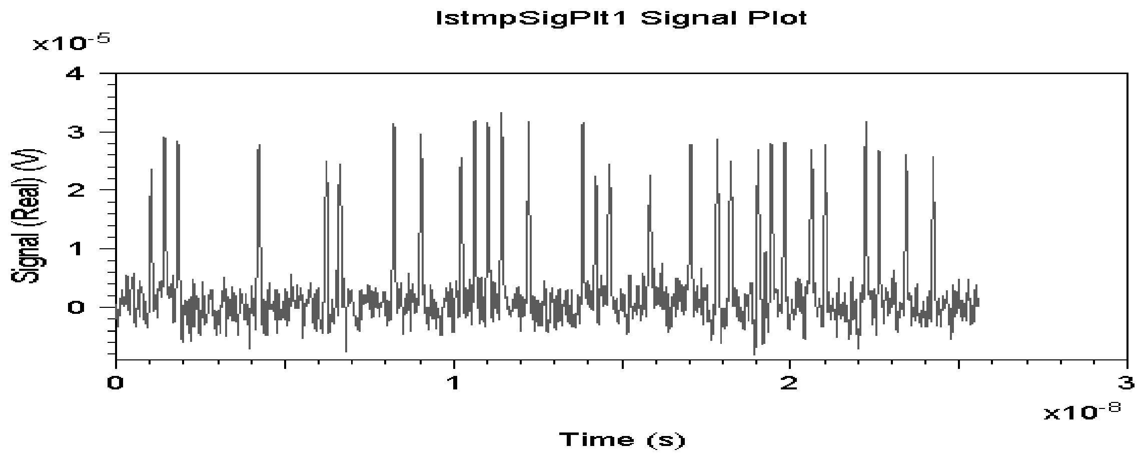


Fig. 5.14: Detected Electrical signal for single user, -21 dBm optical power

5.2.1.5 Eye Diagram for two Users at (-12dBm) received optical power

Eye diagram and received signal for two asynchronous usershave been shown below. Simulation results show very small MAI pulses for single user case. The eye opening at receiver for this validates the system performance. In this instance Usersfor the mentioned received power at the decoder has shown no sign of MAI. Figure 5.15 and 5.16 respectively shows the eye diagram for the user 1 in presence of MAI from other user and corresponding electrical detected signal. The discovered signal Q-factor and BER are found as: Q=22.7 dB, BER=1.2e-43.

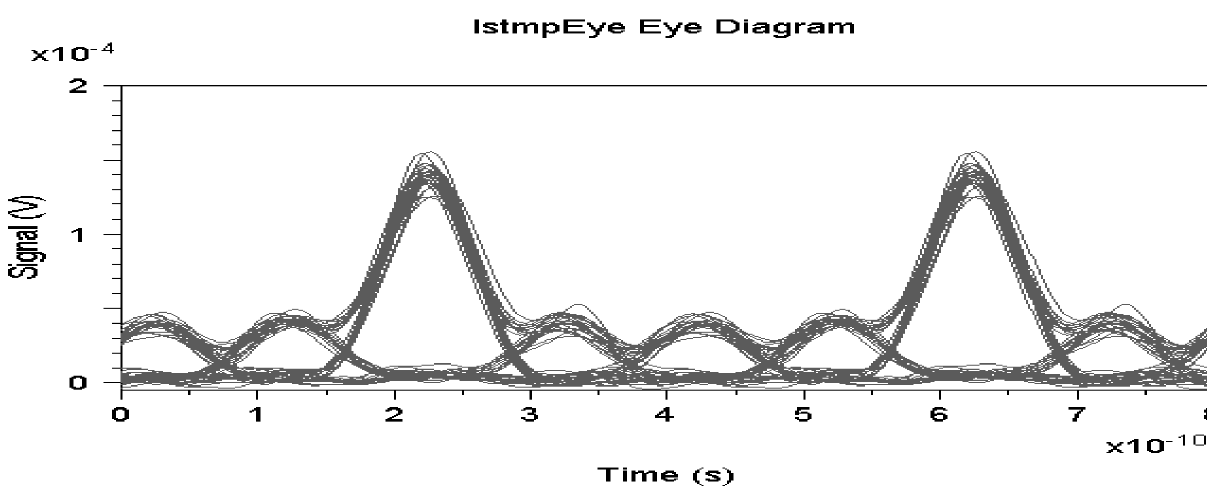


Fig. 5.15: Eye Diagram Analysis for two concurrent users, -12 dBm optical power

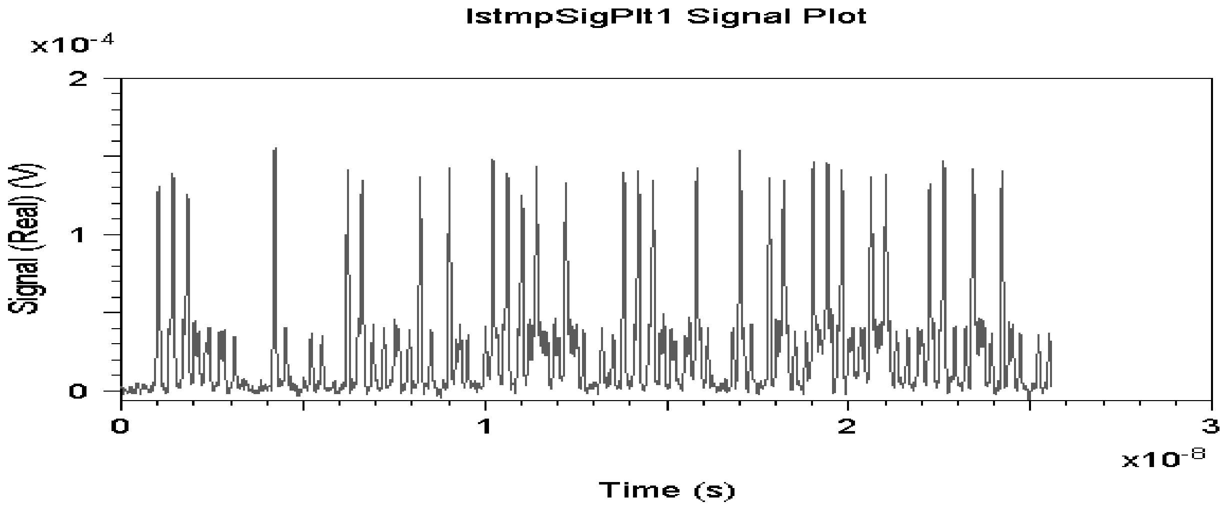


Fig. 5.16: Detected Electrical signal for two simultaneous users, -12 dBm optical power

5.2.1.6 Eye Diagram for two User at (-15dBm) received optical power

Eye diagram and received signal for two asynchronous users have been shown below. Simulation results show very less MAI pulses for two user cases. The eye opening at receiver for this validates the system performance. In this instance User 1 for the mentioned received power at the decoder has no MAI. Figure 5.17 and 5.18 respectively show the eye diagram for the user 1 and corresponding electrical detected signal. The discovered signal Q-factor and BER are found as: Q=20.2 dB, BER=5.5e-25.

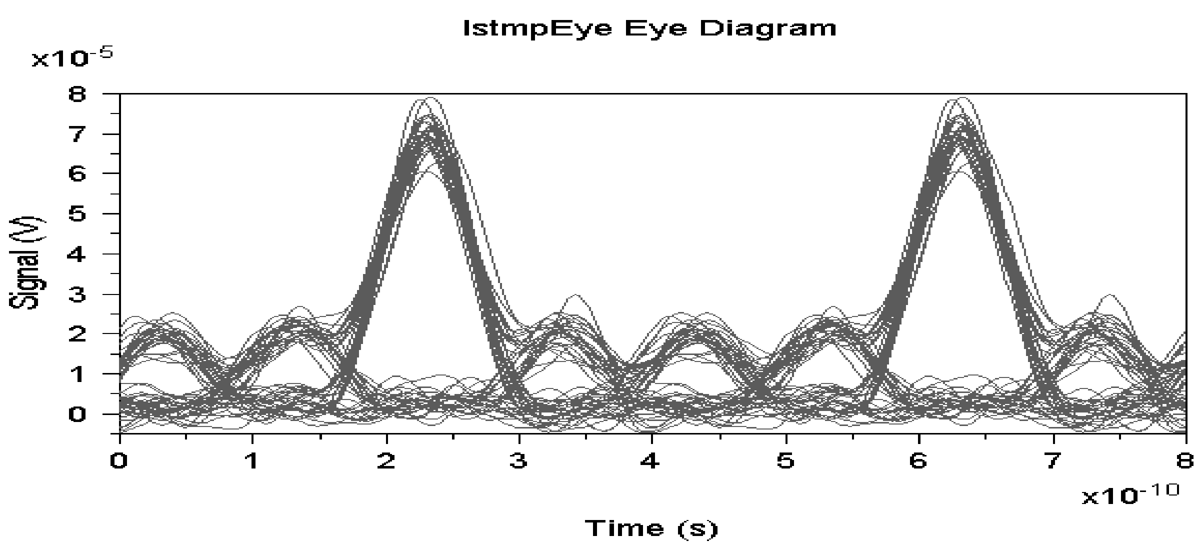


Fig. 5.17: Eye Diagram Analysis for two concurrent users, -15 dBm optical power

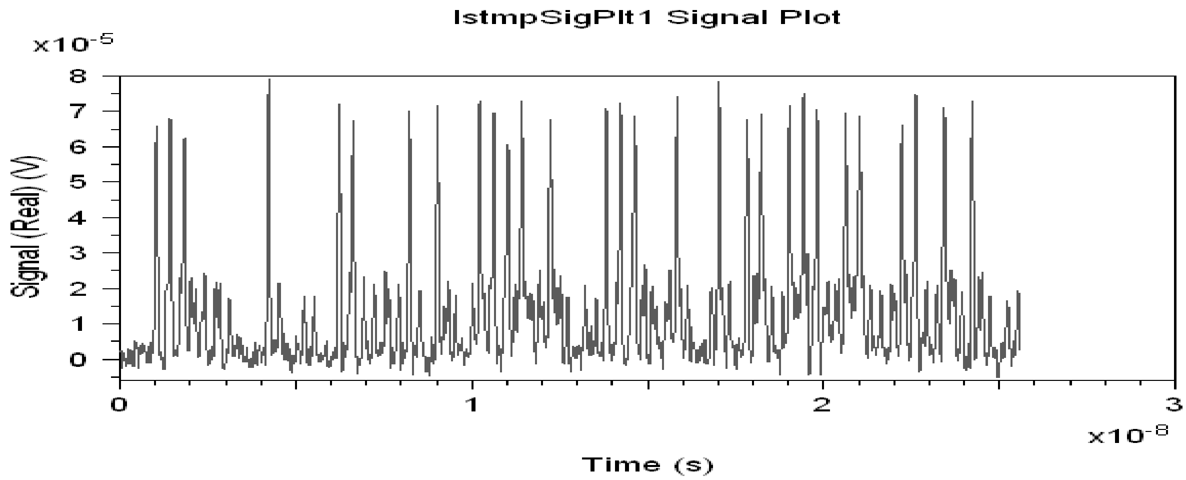


Fig. 5.18: Detected Electrical signal for two simultaneous users, -15 dBm optical power

5.2.1.7 Eye Diagram for two User at (-18dBm) received optical power

Eye diagram and received signal for two asynchronous users have been shown below. Simulation results show very little MAI pulses in the case of two asynchronous users. The eye opening at receiver for this validates the system performance. In this instance User 1 for the mentioned received power at the decoder has no MAI. Figure 5.19 and 5.20 below shows the eye diagram for the user 1 and corresponding electrical detected signal. The discovered signal Q-factor and BER are found as: Q=16.0 dB, BER=1.03e-010.

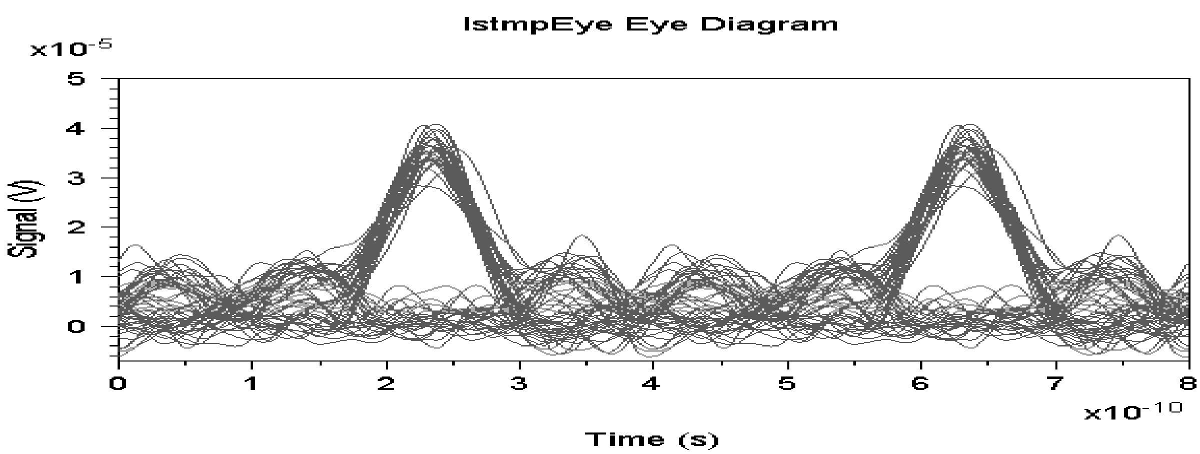


Fig. 5.19: Eye Diagram Analysis for two concurrent users, -18 dBm optical power

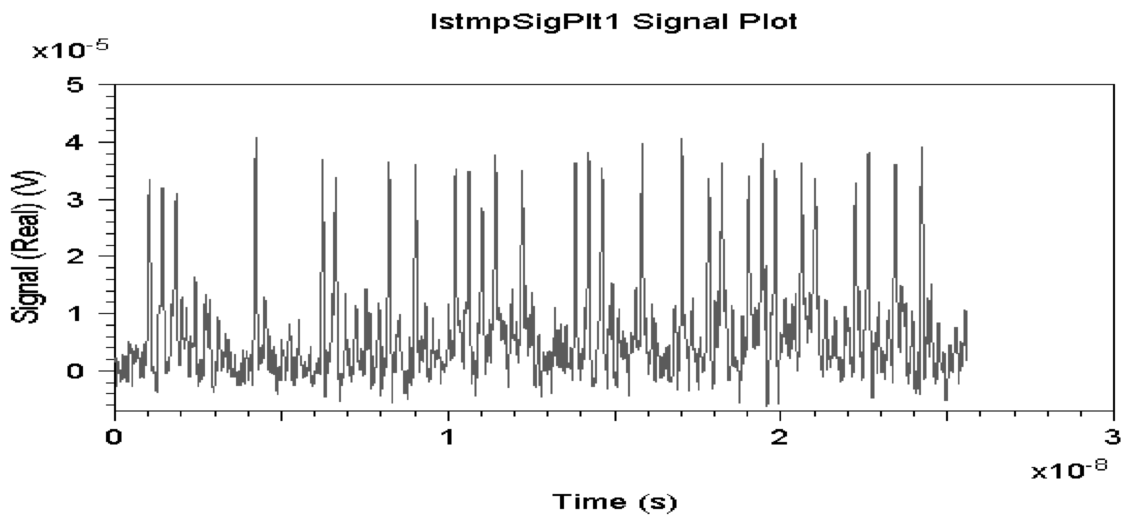


Fig. 5.20: Detected Electrical signal for two simultaneous users, -15 dBm optical power

5.2.1.8 Eye Diagram for two User at (-21dBm) received optical power

Eye diagram and received signal for two asynchronous users have been shown below. Simulation results show no MAI pulses in the case of two asynchronous users. The eye opening at receiver for this validates the system performance. In this instance User 1 for the mentioned received power at the decoder has shown no sign of MAI. Figure 5.21 and 5.22 shows eye diagram for the user 1 and corresponding electrical detected signal. The discovered signal Q-factor and BER are found as: Q=10.7 dB, BER=2.9e-004.

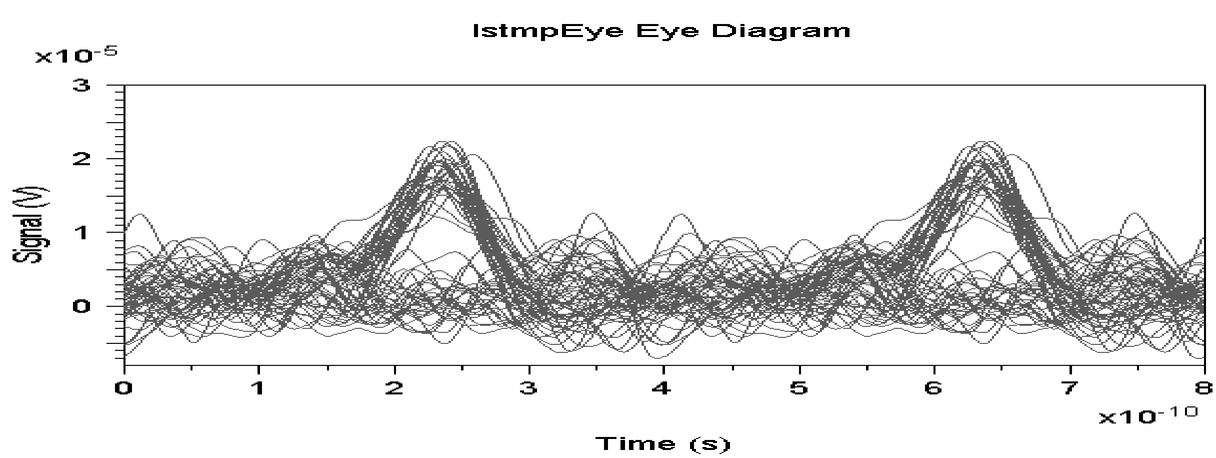


Fig. 5.21: Eye Diagram Analysis for two concurrent users, -12 dBm optical power

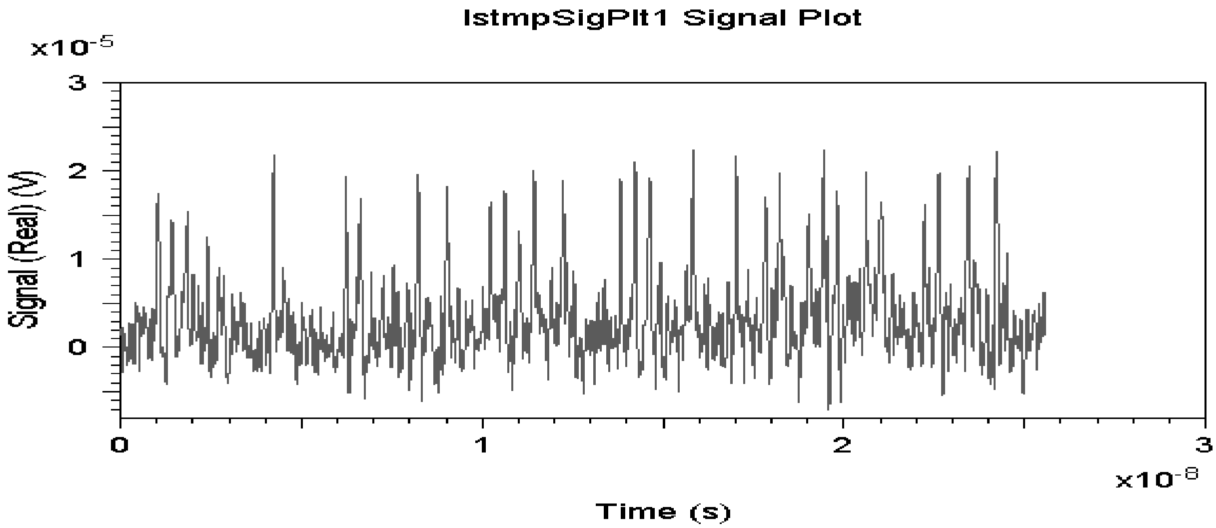


Fig. 5.22: Detected Electrical signal for two simultaneous users, -15 dBm optical power

5.2.1.9 Eye Diagram for three User at (-12dBm) received optical power

Eye diagram and received signal for three users have been shown below. Simulation results show no MAI pulses in the case of three asynchronous users. The eye opening at receiver for this validates the system performance. In this instance User 1 for the mentioned received power at the decoder has shown no MAI in presence of other two transmitting users. Figure 5.23 and 5.24 shows the eye diagram for the user 1 and corresponding electrical detected signal. The discovered signal Q-factor and BER are found as: Q=18.4 dB, BER=3.4e-029.

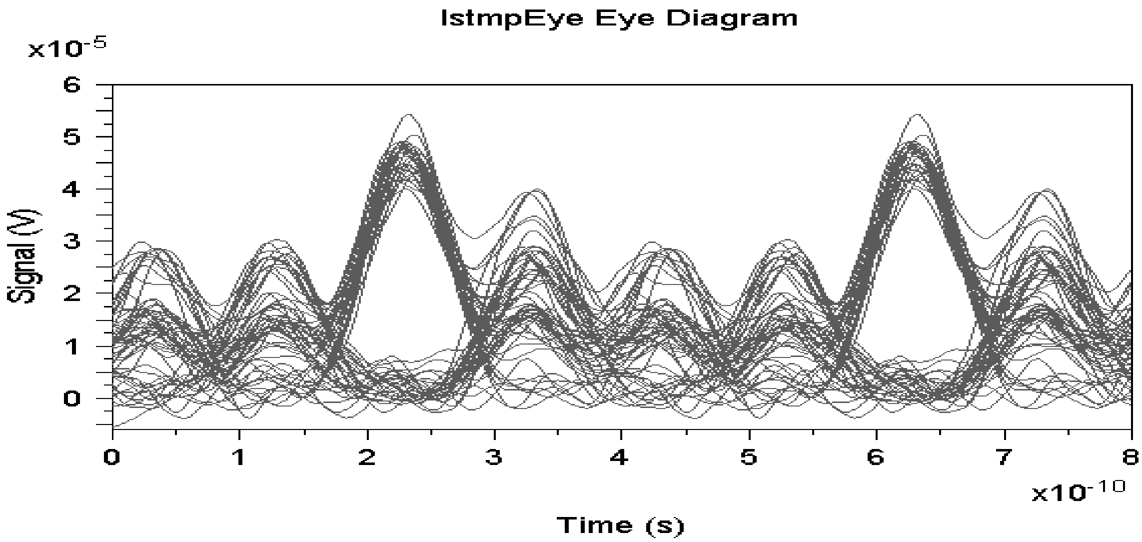


Fig. 5.23: Eye Diagram Analysis for three concurrent users, -12 dBm optical power

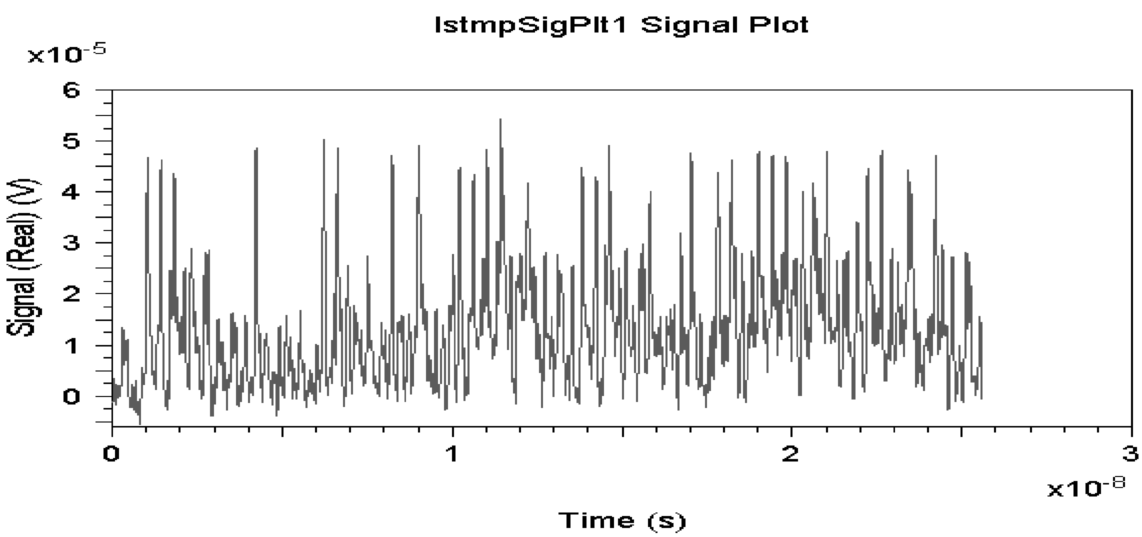


Fig. 5.24: Detected Electrical signal for three simultaneous users, -12 dBm optical power

5.2.1.10 Eye Diagram for three User at (-15dBm) received optical power

Eye diagram and received signal for three users have been given in fig 5.25 and 5.26 respectively. Simulation results show MAI pulses for three user case is increased compared to 2 users. The corresponding Q-factor and BER are: Q=18.4 dB, BER=3.4e-017.

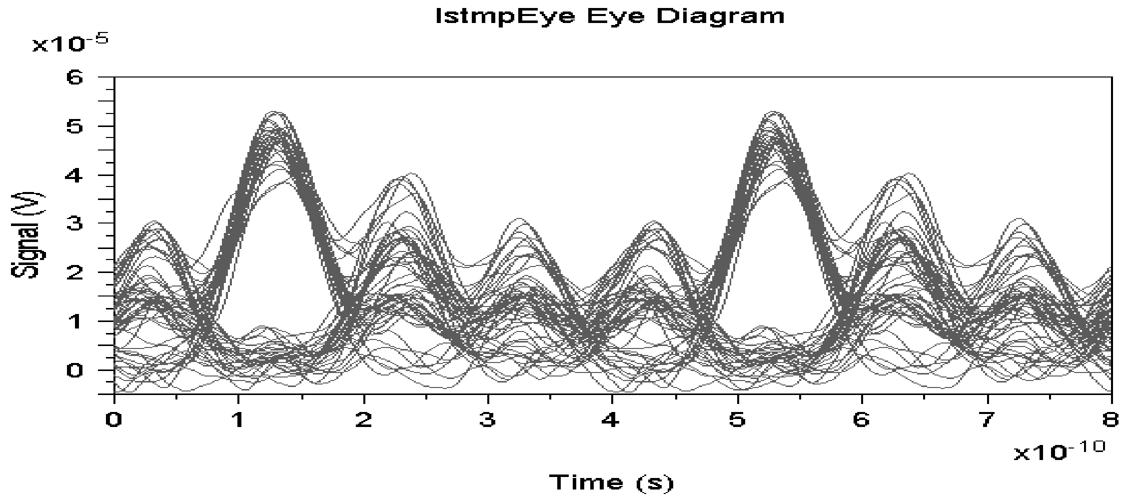


Fig. 5.25: Eye Diagram Analysis for three concurrent users, -15 dBm optical power

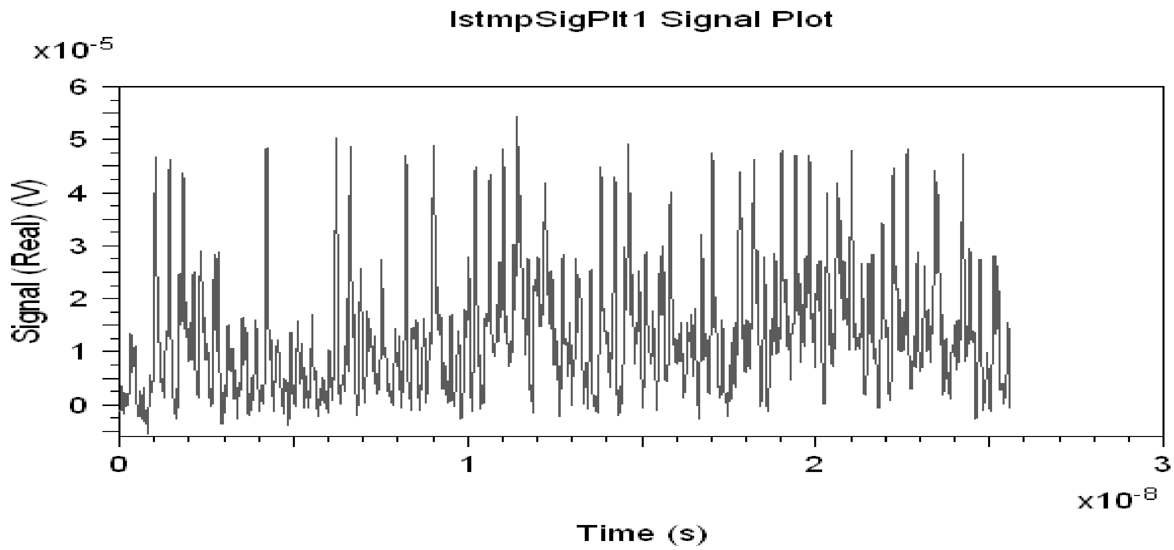


Fig. 5.26: Detected Electrical signal for three simultaneous users, -15 dBm optical power

5.2.1.11 Eye Diagram for three User at (-18dBm) received optical power

Eye diagram and received signal for three users have been given in fig 5.27 and 5.28 respectively. Simulation results show MAI pulses for three user case is increased compared to two users. The corresponding Q-factor and BER are: Q=77.3 dB, BER=9.9e-009

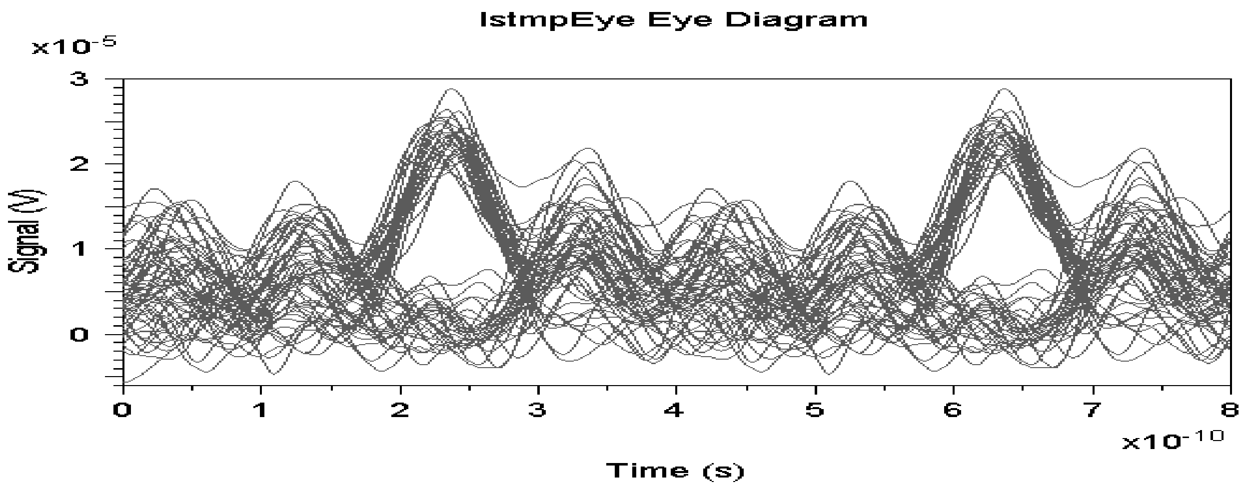


Fig. 5.27: Eye Diagram Analysis for three concurrent users, -18 dBm optical power

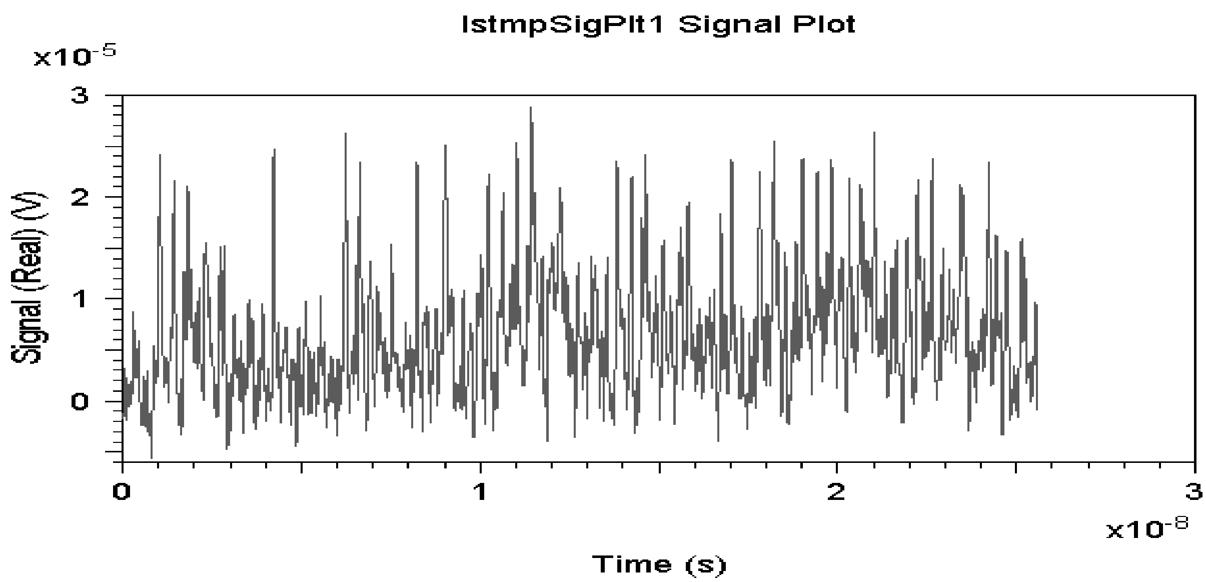


Fig. 5.28: Detected Electrical signal for three simultaneous users, -18 dBm optical power

5.2.1.12 Eye Diagram for three User at (-21dBm) received optical power

Eye diagram and received signal for three users with -21 dBm received power have been given in fig 5.29 and 5.30 respectively. Simulation results show small but acceptable MAI pulses for three user case with some noise due to increased attenuation factor .The corresponding Q-factor and BER are: Q=32.1 dB, BER=7.3e-002

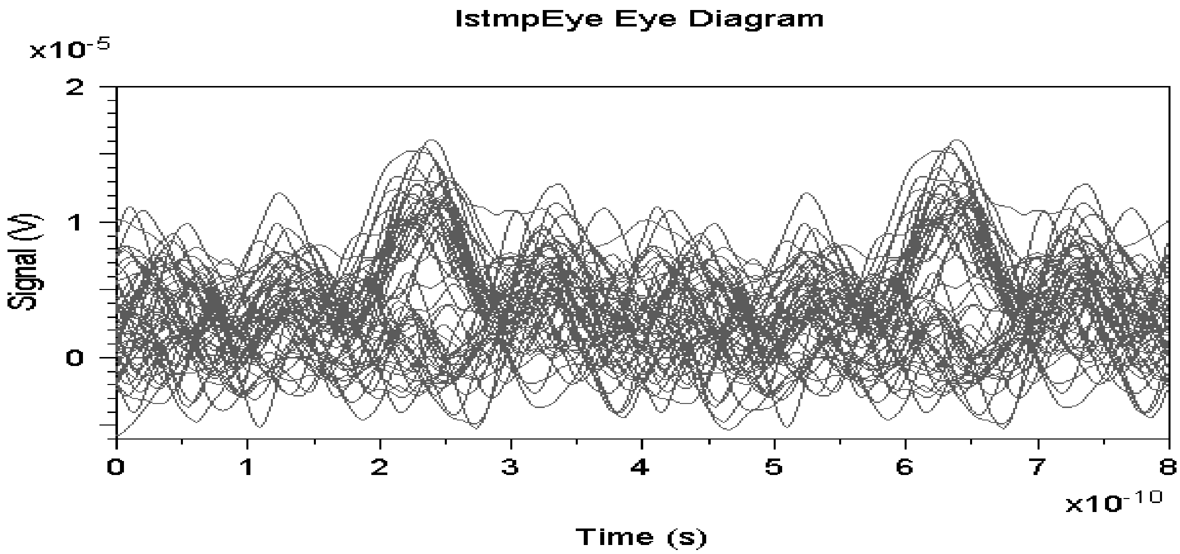


Fig. 5.29: Eye Diagram Analysis for three concurrent users, -21 dBm optical power

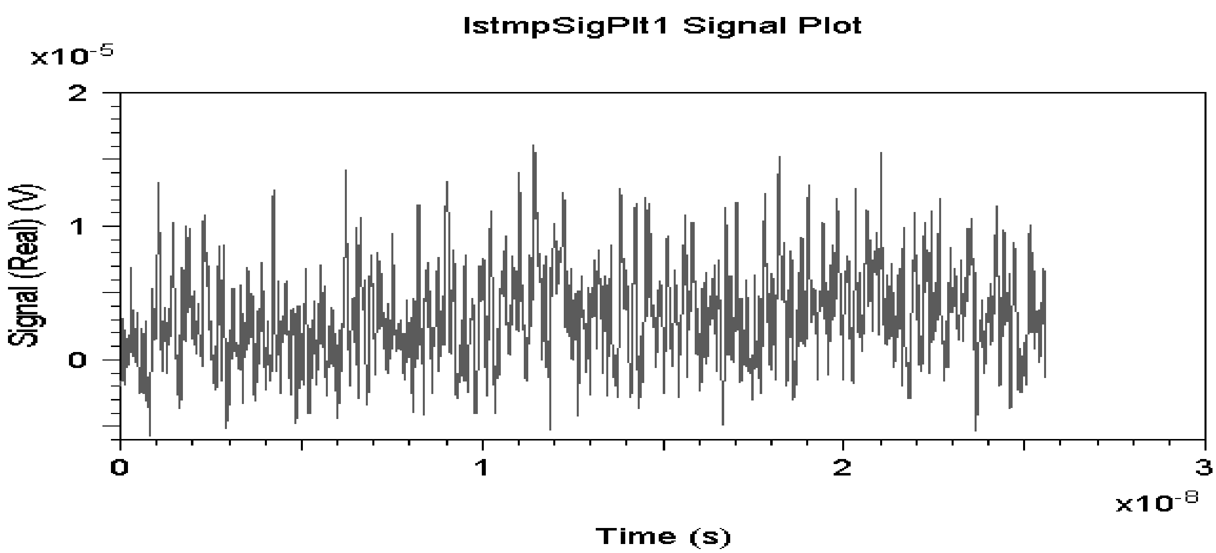


Fig. 5.30: Detected Electrical signal for three simultaneous users, -21 dBm optical power

5.2.1.13 Eye Diagram for four User at (-12dBm) received optical power

Eye diagram and received signal for four users with -12 dBm received power have been given in fig 5.31 and 5.32 respectively. Simulation results show MAI pulses for four user case are increased as compared to previous simulation for three users. The corresponding Q-factor and BER are: Q=46.8 dB, BER=4.3e-017

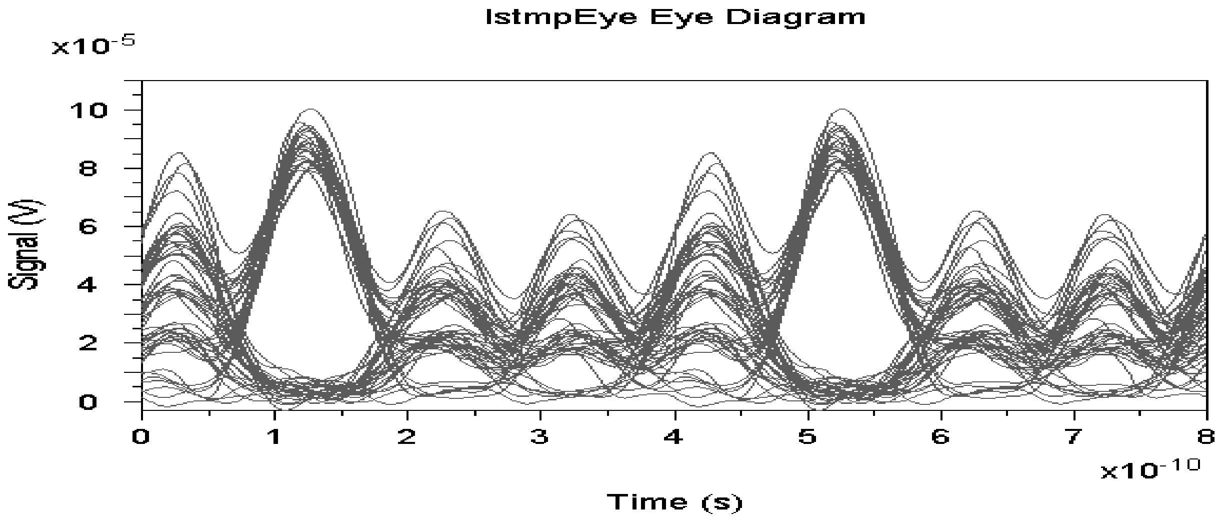


Fig. 5.31: Eye Diagram Analysis for four concurrent users, -12 dBm optical power

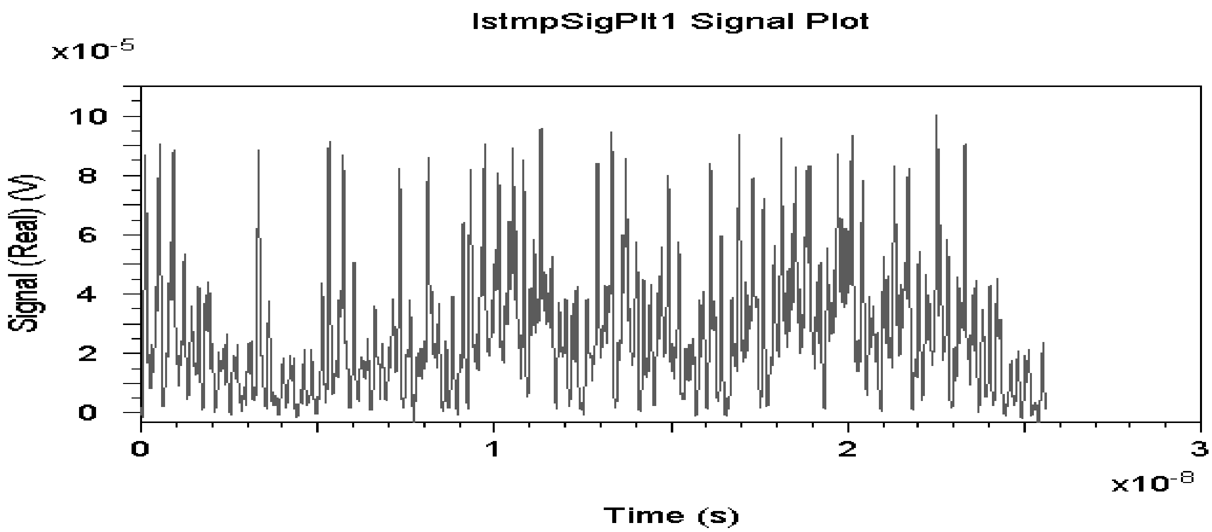


Fig. 5.32: Detected Electrical signal for four simultaneous users, -12 dBm optical power

5.2.1.14 Eye Diagram for four User at (-15dBm) received optical power

Eye diagram and received signal for four users with -15 dBm received power have been presented below in fig 5.33 and 5.34 respectively. Simulation results show some MAI pulses for four users. The corresponding Q-factor and BER are: Q=57.5dB, BER=2.6e-014.

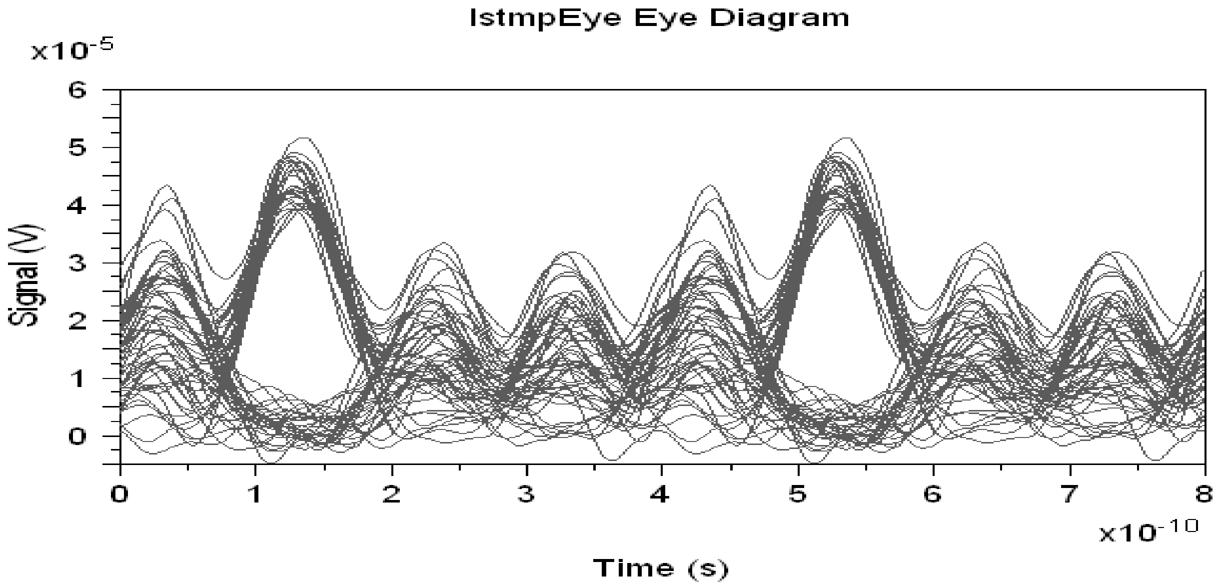


Fig. 5.33: Eye Diagram Analysis for four concurrent users, -15 dBm optical power

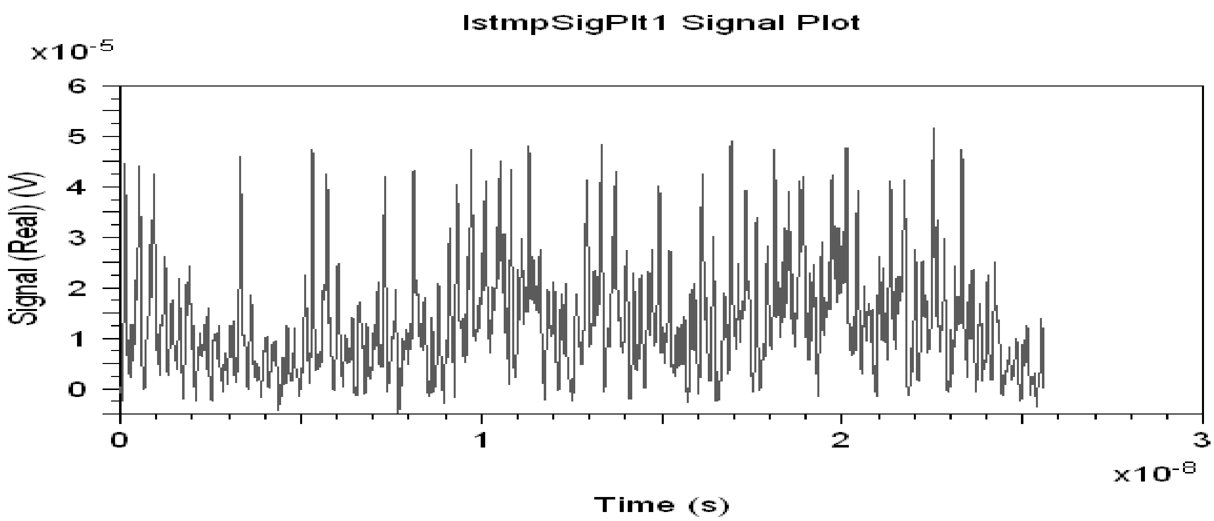


Fig. 5.34: Detected Electrical signal for four simultaneous users, -15 dBm optical power

5.2.1.15 Eye Diagram for four User at (-18dBm) received optical power

Eye diagram and received signal for four users have been given in fig 5.35 and 4.36 respectively. Simulation results show MAI pulses for four users case is increased as compared to three users and noise is increased due to increased attenuation factor. The corresponding Q-factor and BER are: Q=12.3dB, BER=1.8e-007.

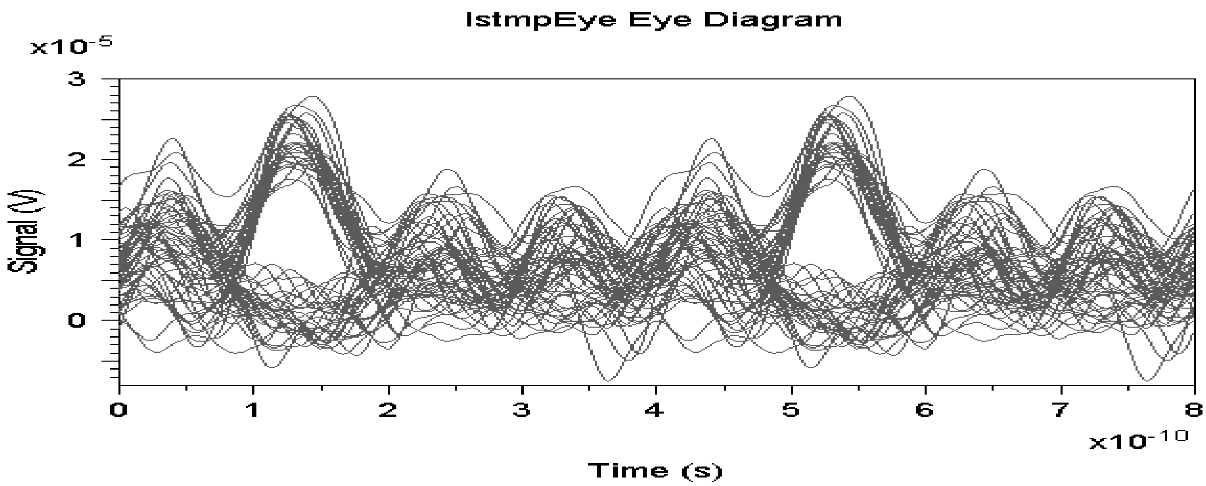


Fig. 5.35: Eye Diagram Analysis for four concurrent users, -18 dBm optical power

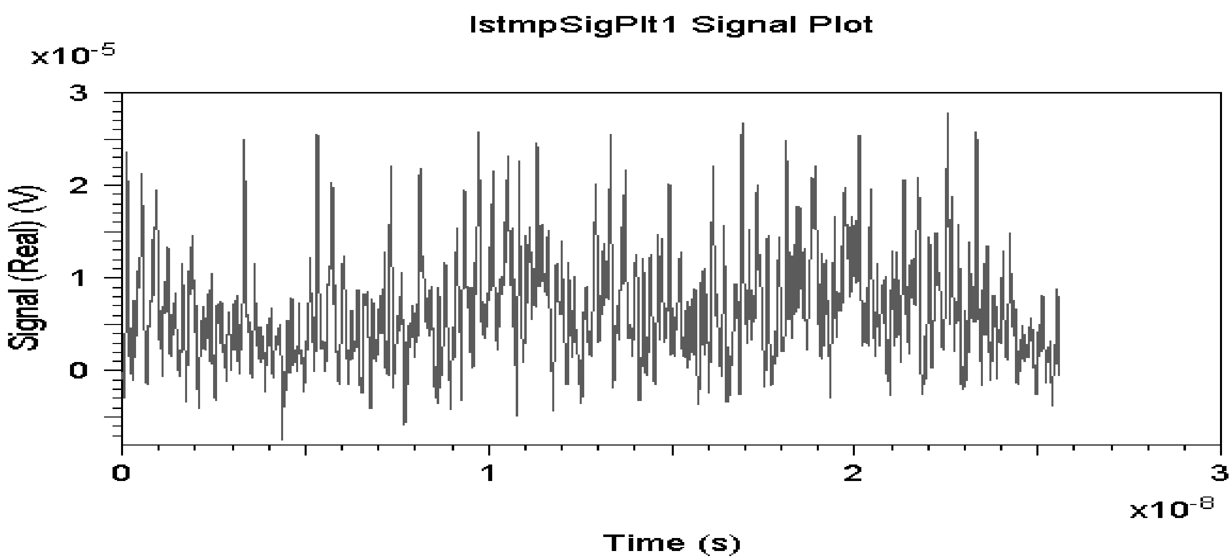


Fig. 5.36: Detected Electrical signal for four simultaneous users, -18 dBm optical power

5.2.1.16 Eye Diagram for four User at (-21dBm) received optical power

Eye diagram and received signal for four users have been given in fig 5.37 and 5.38 respectively. Simulation results show MAI pulses for four users case is increased as compared to three users and disturbance is increased as the attenuation factor is increased compared to previous simulation. The corresponding Q-factor and BER are: Q=60.3dB, BER=2.2e-002.

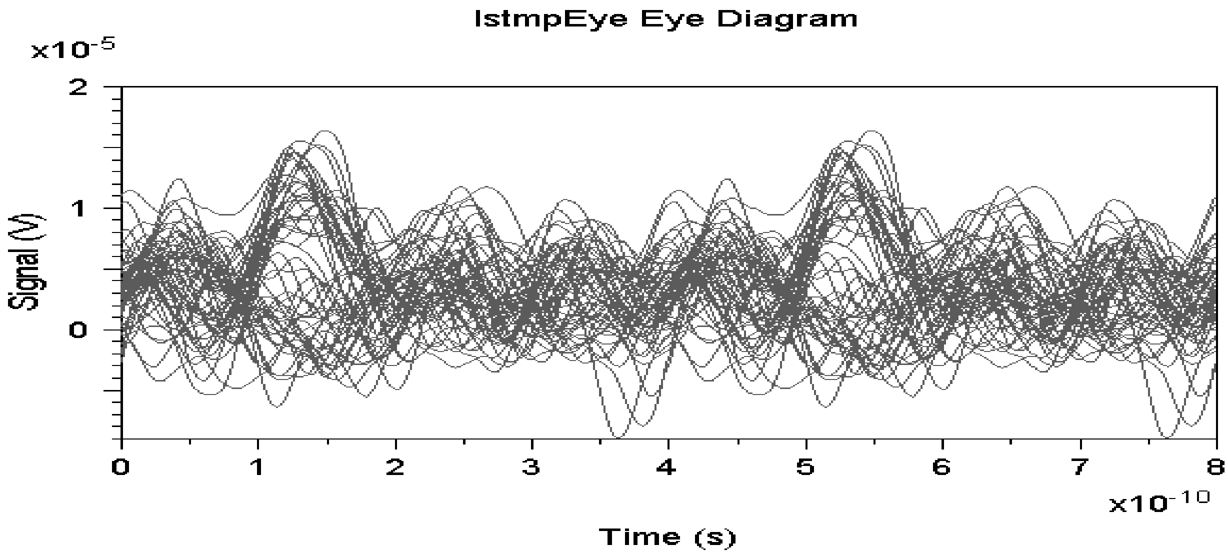


Fig. 5.37: Eye Diagram Analysis for four concurrent users, -21 dBm optical power

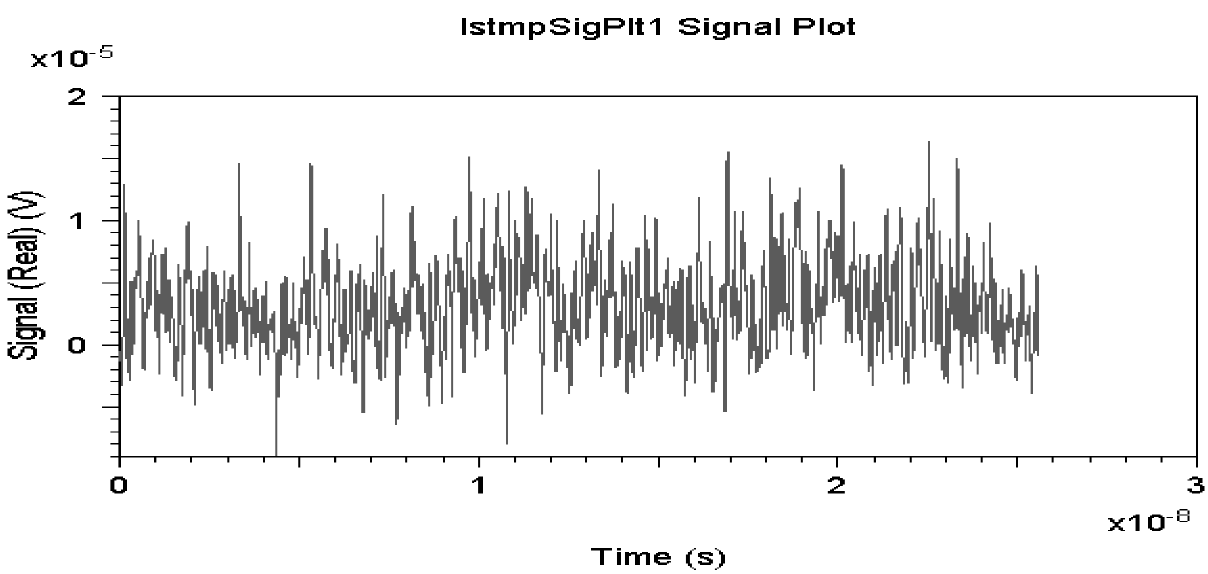


Fig. 5.38: Detected Electrical signal for four simultaneous users, -21 dBm optical power

5.2.1.17 Eye Diagram for five User at (-12dBm) received optical power

Eye diagram and received signal for five users with -12 attenuation factor have been presented in fig 5.39 and 5.40 respectively. Simulation results shows MAI pulses for five users are increased compared to four users. The corresponding Q-factor and BER are: Q=84.8dB, BER=3.9e-013.

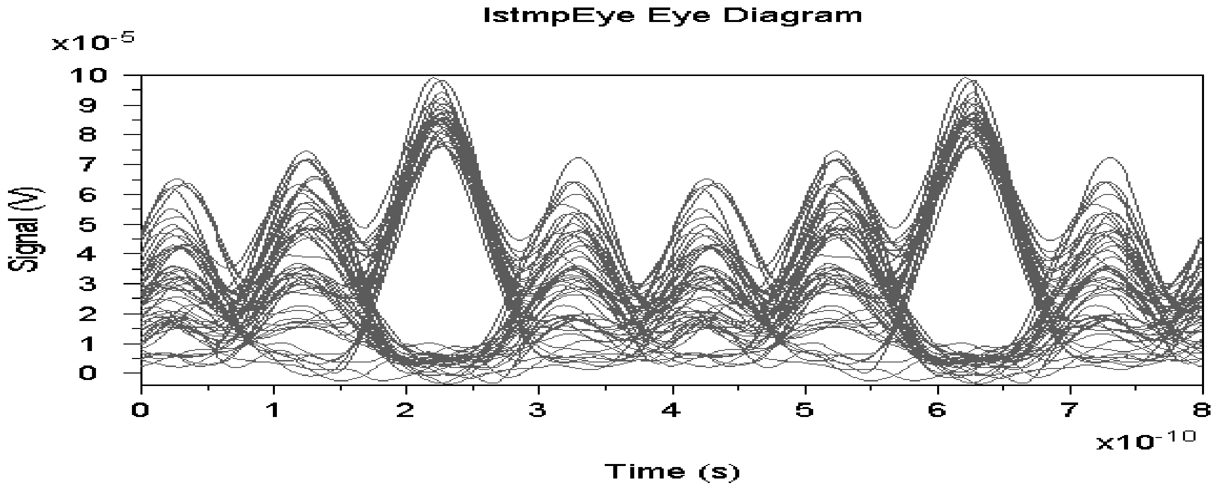


Fig. 5.39: Eye Diagram Analysis for five concurrent users, -12 dBm optical power

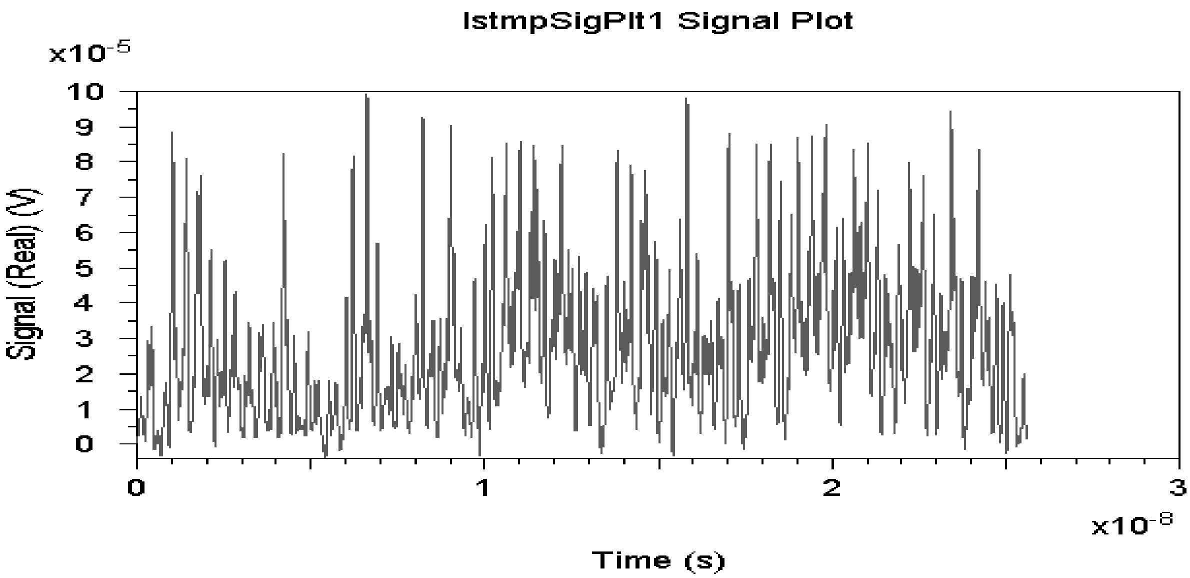


Fig. 5.40: Detected Electrical signal for five simultaneous users, -12 dBm optical power

5.2.1.18 Eye Diagram for five User at (-15dBm) received optical power

Eye diagram and received signal for five users with -15 dBm received power have been given in fig 5.41 and 5.42 respectively. Simulation results shows MAI pulses for five users with little disturbances. The corresponding Q-factor and BER are: Q=92.4dB, BER=1.8e-011.

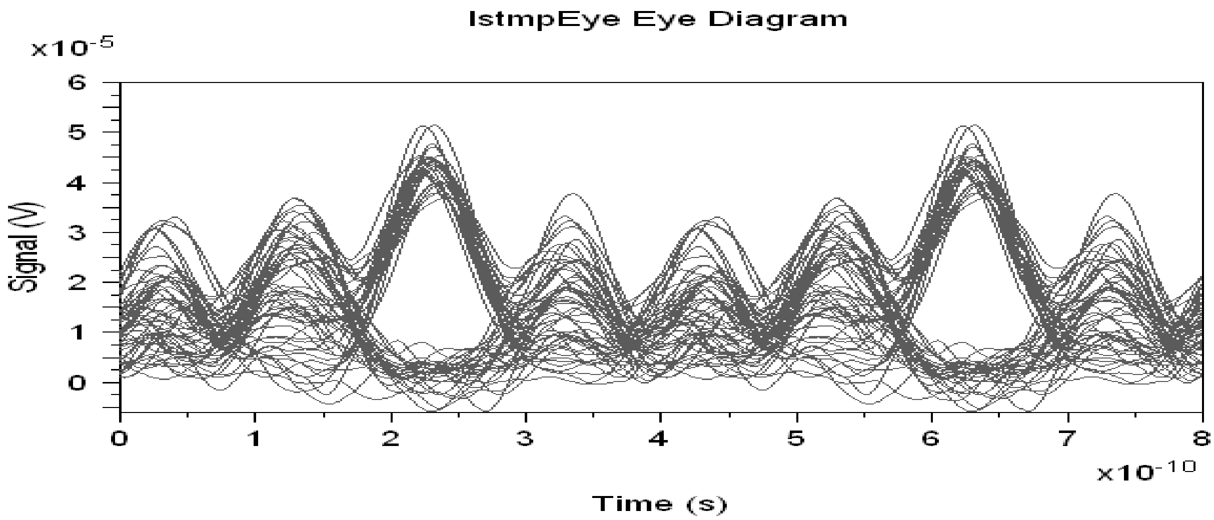


Fig. 5.41: Eye Diagram Analysis for five concurrent users, -15 dBm optical power

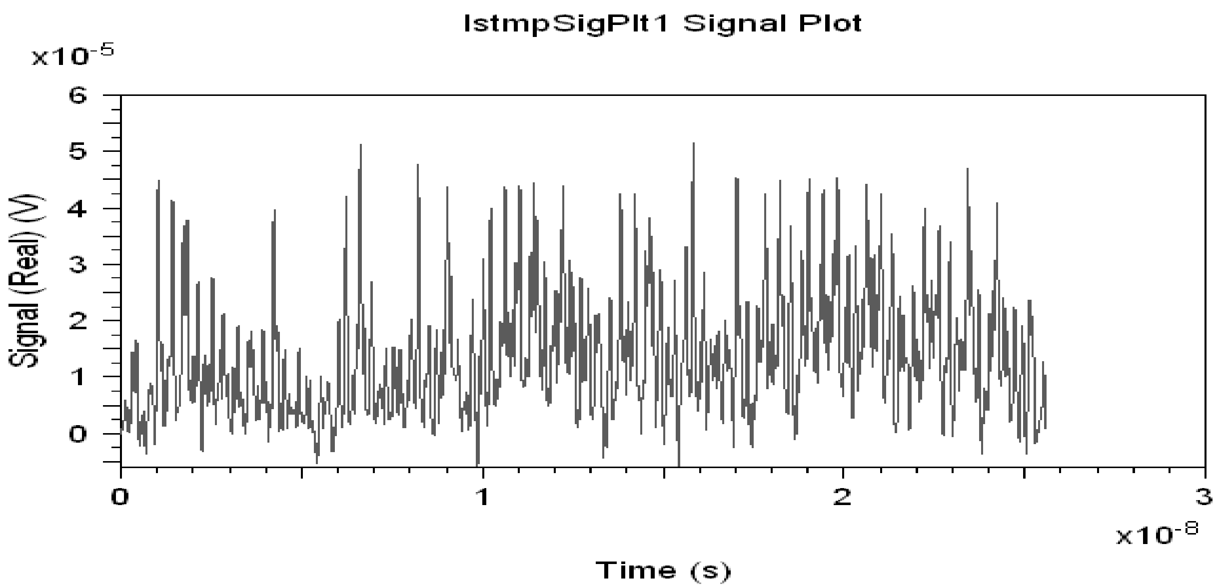


Fig. 5.42: Detected Electrical signal for five simultaneous users, -15 dBm optical power

5.2.1.19 Eye Diagram for five User at (-18dBm) received optical power

Eye diagram and received signal for five users have been given in fig 5.43 and 5.44 respectively. Simulation results indicate that MAI pulses for five users case is increased compared to four users and subsequent disturbance is also increased. The corresponding Q-factor and BER are: Q=78.9dB, BER=6.5e-005.

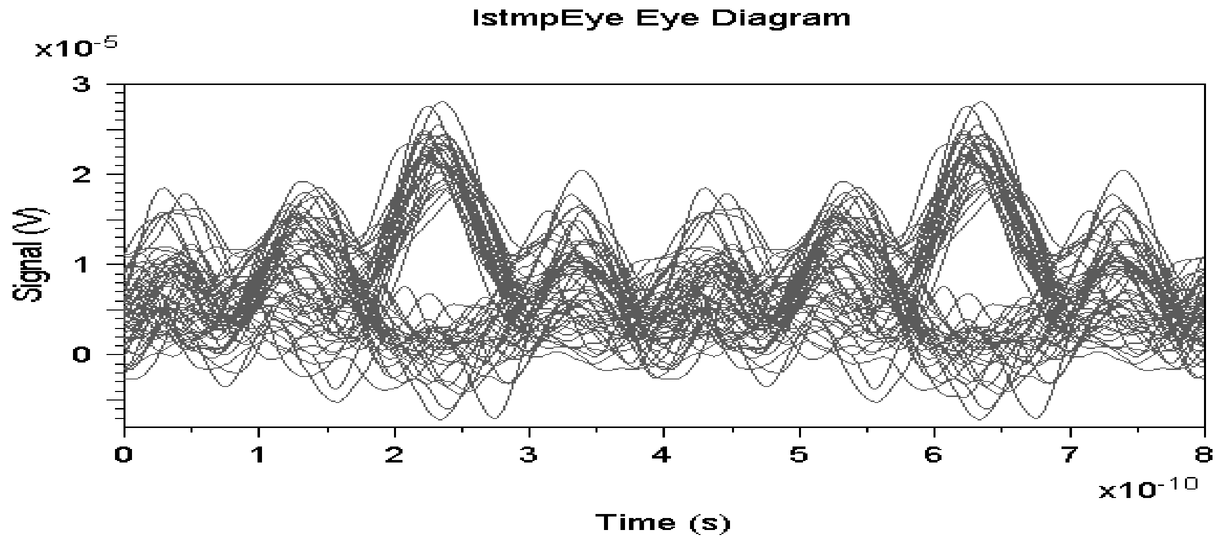


Fig. 5.43: Eye Diagram Analysis for five concurrent users, -18 dBm optical power

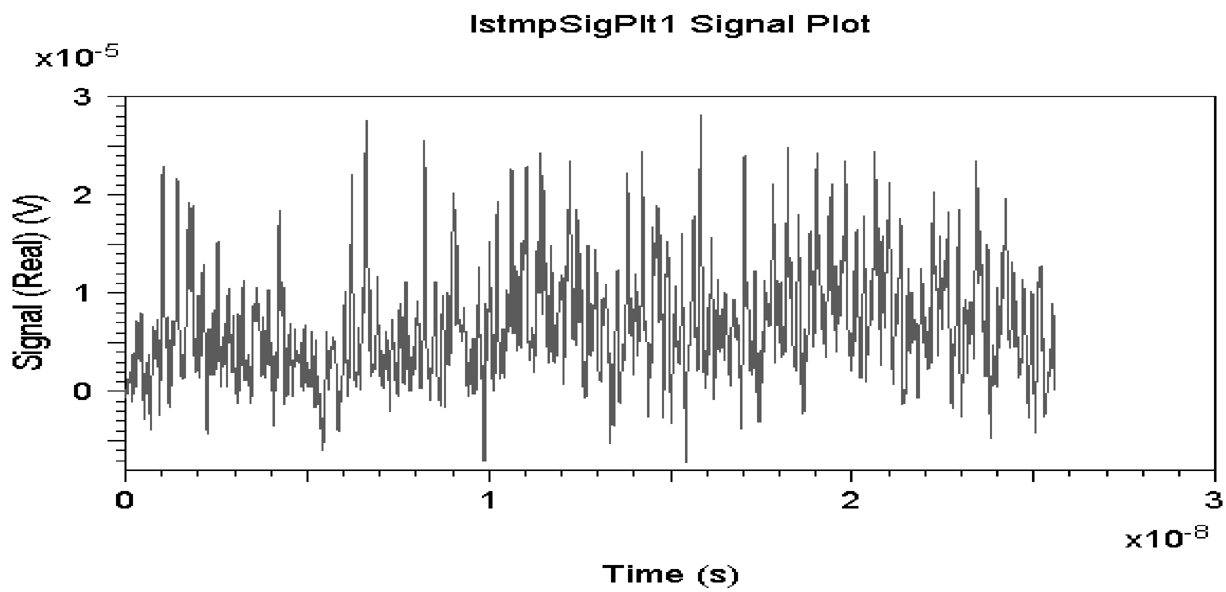


Fig. 5.44: Detected Electrical signal for five simultaneous users, -18 dBm optical power

5.2.1.20 Eye Diagram for five User at (-21dBm) received optical power

We have connected encoders for five Users to the multiplexer and the value of attenuation factor is also increased and then re-run simulation. The corresponding Q-factor and BER are: Q=55.2dB, BER=2.9e-001.

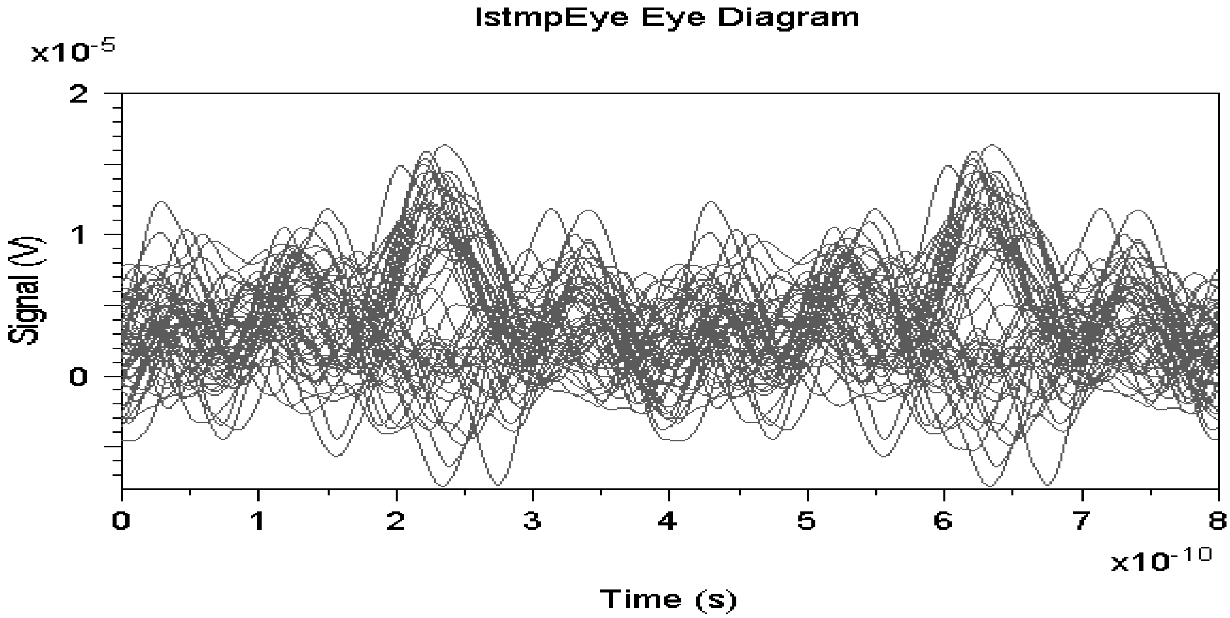


Fig. 5.45: Eye Diagram Analysis for five concurrent users, -21 dBm optical power

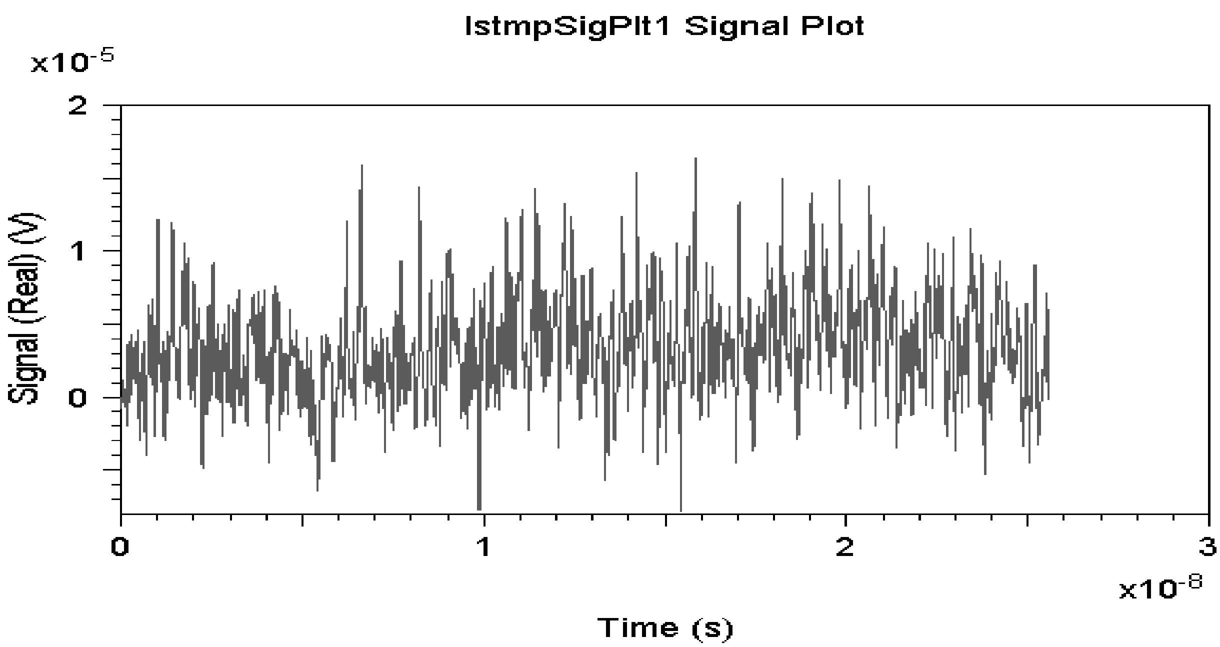


Fig. 5.46: Detected Electrical signal for five simultaneous users, -21 dBm optical power

All the simulated obtained results for ten numbers of asynchronous users are given below in tabular form. Based on these results conclusions are drawn

Table 5.2: Q -Factor and BER values for different received power for user one

Received power (dBm)	BER	Q- Factor (dB)
-12	6.1e-045	22.9
-15	2.2e-031	21.3
-18	3.9e-017	18.4
-21	1.4e-007	14.2

Table 5.3: Q-Factor and BER values for different received power for two users

Received power (dBm)	BER	Q-Factor (dB)
-12	1.2e-43	22.7
-15	5.5e-025	20.2
-18	1.03e-010	16.0
-21	2.9e-004	10.7

Table 5.4: Q-Factor and BER values for different received power for three users

Received power (dBm)	BER	Q- Factor (dB)
-12	3.4e-029	18.4
-15	3.4e-017	18.4
-18	9.9e-009	73.3
-21	7.3e-002	32.1

Table 5.5: Q-Factor and BER values for different received power for user four

Received power (dBm)	BER	Q- Factor (dB)
-12	4.3e-017	46.8
-15	2.6e-014	57.5
-18	1.8e-007	12.3
-21	2.2e-002	60.3

Table 5.6: Q-Factor and BER values for different received power for user five

Received power (dBm)	BER	Q-Factor (dB)
-12	3.9e-013	84.8
-15	1.8e-011	92.4
-18	6.5e-005	78.9
-21	2.9e-001	55.2

Table 5.7: Q-Factor and BER values for different received power for user six

Received power (dBm)	BER	Q-Factor (dB)
-12	5.4e-012	84.8
-15	2.9e-011.5	76.5
-18	2.5e-003	66.2
-21	1.2e-001	45.2

Table 5.8: Q-Factor and BER values for different received power for user Seven

Received power (dBm)	BER	Q-Factor (dB)
-12	2.4e-13.2	88.2
-15	6.8e-11.3	90.2
-18	3.2e-002	68.9
-21	1.02e-001	53.2

Table 5.9: Q-Factor and BER values for different received power for user Eight

Received power (dBm)	BER	Q-Factor (dB)
-12	9.2e-13	82.1
-15	2.1e-11.2	90.2
-18	9.2e-003	72.1
-21	5.9e-001	49.2

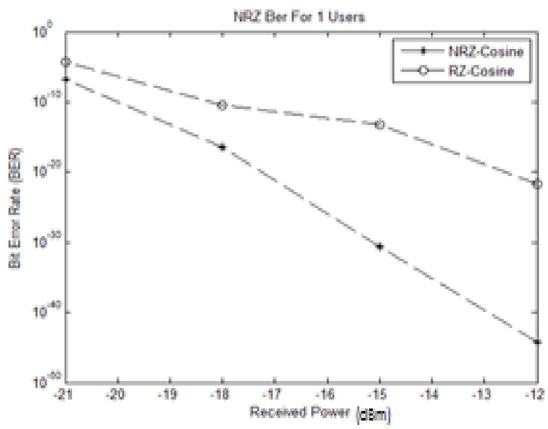
Table 5.10: Q-Factor and BER values for different received power for user nine

Received power (dBm)	BER	Q-Factor (dB)
-12	2.9e-011.8	78.2
-15	1.8e-011	88.4
-18	2.5e-003	65.2
-21	1.9e-001	50.2

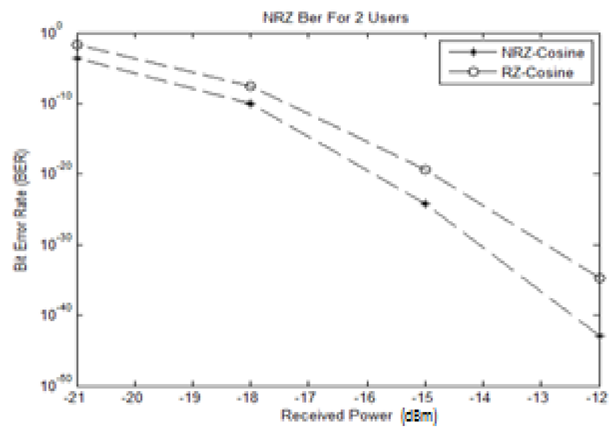
Table 5.11: Q-Factor and BER values for different received power for user ten

Received power (dBm)	BER	Q-Factor (dB)
-12	3.9e-013.6	97.12
-15	1.8e-011	87.2
-18	5e-003	81.2
-21	6.9e-001	60.2

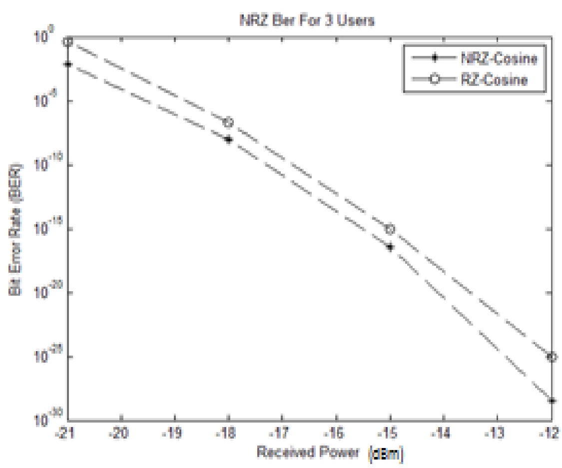
The comparative performance of NRZ raised cosine modulation format against RZ raised cosine up to five users is reported below in Fig 5.47.Inferences has been drawn on the basis of number of asynchronous users and required value of received optical power for desired results.



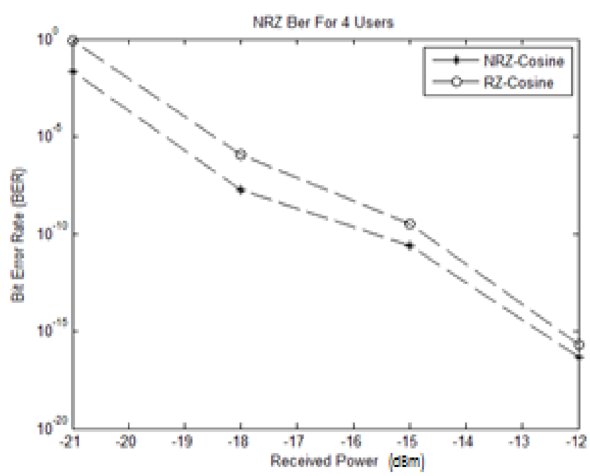
a. User 1



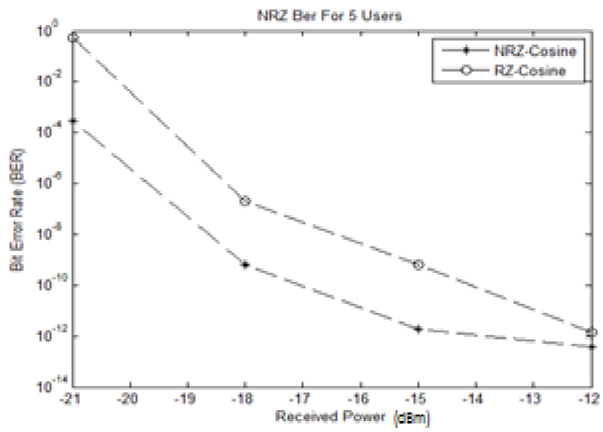
b. User 2



c. User 3



d User 4



e User 5

Fig. 5.47: Simulated Comparative BER Vs Received power for two best modulations formats

From the obtained simulated results, it is concluded that for NRZ raised cosine modulation format resultant BER value is least for required similar received power than RZ raised cosine modulation for all the users. The proposed 2-D W/T codes are compared with 3-D codes for BER Vs received power and comparison is reported in Fig 5.48. In this 3-D SPP matrix codes slightly outperformed the 2-D Optical matrix codes of same cardinality.

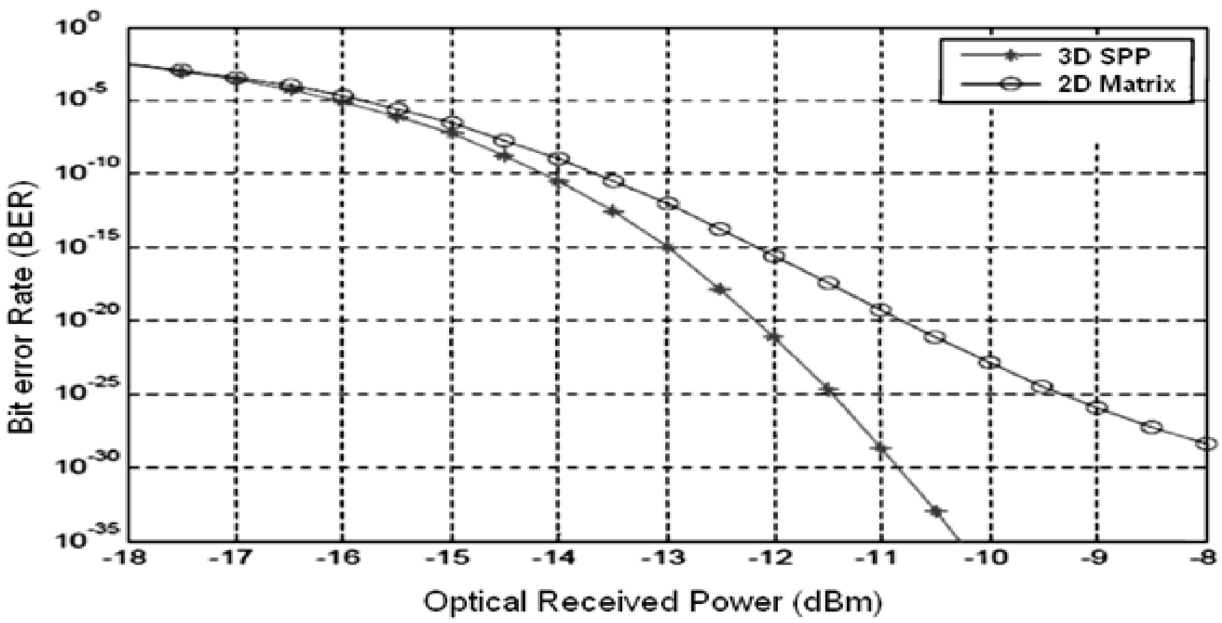


Fig. 5.48: Comparison of 2-D W/T codes with 3-D SPP codes for required received optical power

5.3 Conclusion

In this chapter, we have outlined the obtained simulated results and presented them in the form of eye diagrams and tabular form. The proposed system has shown negligible effect of MAI up to ten users for different optical received power at the receiver.All the obtained simulated results in terms of received power in dBm for acceptable values of BER and Q-factor (dB) are tabulated and careful study of the obtained results signifies important findings for design of optical CDMA system. It is concluded that to achieve desired results in terms of BER, the received power should at least be 15 dBm for proposed 2-D optical system employing NRZ raised cosine modulation. The same is then observed for other modulation formats and it is very much evident that for other modulation formats received power requirement is more. As an alternate RZ raised cosine may be used as second choice. Hence we may conclude that to achieve acceptable system performance in terms of BER and Q-factor, we require healthy amount of received optical power at the receiver (minimum 15 dBm) for fiber length in excess of 90 Kms and simulated results have verified that this is best achievable with NRZ modulation format. It is further investigated that the 3-D codes are better in performance in terms of BER than 2-D codes for the same received optical power within the same fibre span.

Chapter 6

Wavelength Allocation and suitable modulation format to reduce effects of FWM

6.1 Introduction

This chapter deals with the last objective of the thesis which is to investigate Wavelength Allocation and suitable modulation format to reduce effects of FWM in OCDMA systems. In general, three co-disseminating waves through fiber yield additional optical side band waves at diverse frequencies. Whenever these newly produced frequencies overlap with the broadcast window of novel frequencies, optical system becomes unstable.The desired linear response of optical fiber channel is adversely affected due to the propagation of high power light signals and subsequent generation of these unwanted new optical sidebands at different frequencies. This undesired effect in optical network causes degradation of system performance in terms of BER. FWM is an effect, present due to changes in refractive index profile within optical fiber, is also called Kerr effect. The proposed Optical CDMA network is implemented by spectral-coding of incoherent broadband optical sources. We have utilized the transmissive spectrum characteristics of FBG (Fiber Bragg Grating) to design FBG encoder/decoder [61], [70], [73]. The proposed system is designed to identify the suitable modulation format which can reduce the FWM to some extent.

6.2 System Description

Our proposed OCDMA system is presented in the form of a block diagram in fig 6.1. This system is based upon spectral-amplitude coding of incoherent broadband optical sources via FBG coder/decoder. Here this design illustrates a 3-user spectral- amplitude-coded OCDMA with two users transmitting data and the other is offline. In this system based on FBG, each user has bits of information that modulates the broadband incoherent optical carrier to achieve the electrical to optical conversion. We have used OOK modulation format. A series of FBGs are applied inside the fiber to control the amplitude spectra of the broadband coherent optical signals. For spectral coding, every user of OCDMA system is assigned a unique signature sequence incorporated with the help of FBG, with spectral frequency chips centered about the grating frequency. Here the coding is done in wavelength domain. Different wavelengths represent different codewords and here presence of wavelength shows "1" while its absence means "0". The precise spectral filtering achieved with the help of FBGs, input spectrum will cause spectral components to be either reflected or transmitted from the designed logic "1" or logic "0". Here the obtained codes are completely orthogonal between each user in OCDMA network. In ideal case all the code sequences should be mutually orthogonal and each receiver could extract the desired data with matched signature sequence. Here, we have used Hadamard code as users address codes in our optical CDMA system as it has the property i.e. $R_{xy}\,(k) - R_{xy'}(k) = 0$. For our system we have chosen 4×4 Hadamard matrix codes that contains rows of $(1,1,1,1), (1,0,1,0), (1,1,0,0)$,and$(1,0,0,1)$. The first row cannot be applied for coding as it does not come under on/off keying of all the wavelengths. So the likely central wavelengths of the FBG coders are considered from the code matrix $(\lambda_1, \lambda_2, \lambda_3, \lambda_4)$. Each one of the selected wavelength matrix vector is either logic "1" or logic "0". In our simulation we have used broadband LED source and later it is modulated by randomly generated user specific data sequence $(0, 1, \dots)$ and then is forwarded to FBG encoder. The obtained spectrum before encoder will have different amplitude as the optical sources used are broadband LED and its non-flattened.

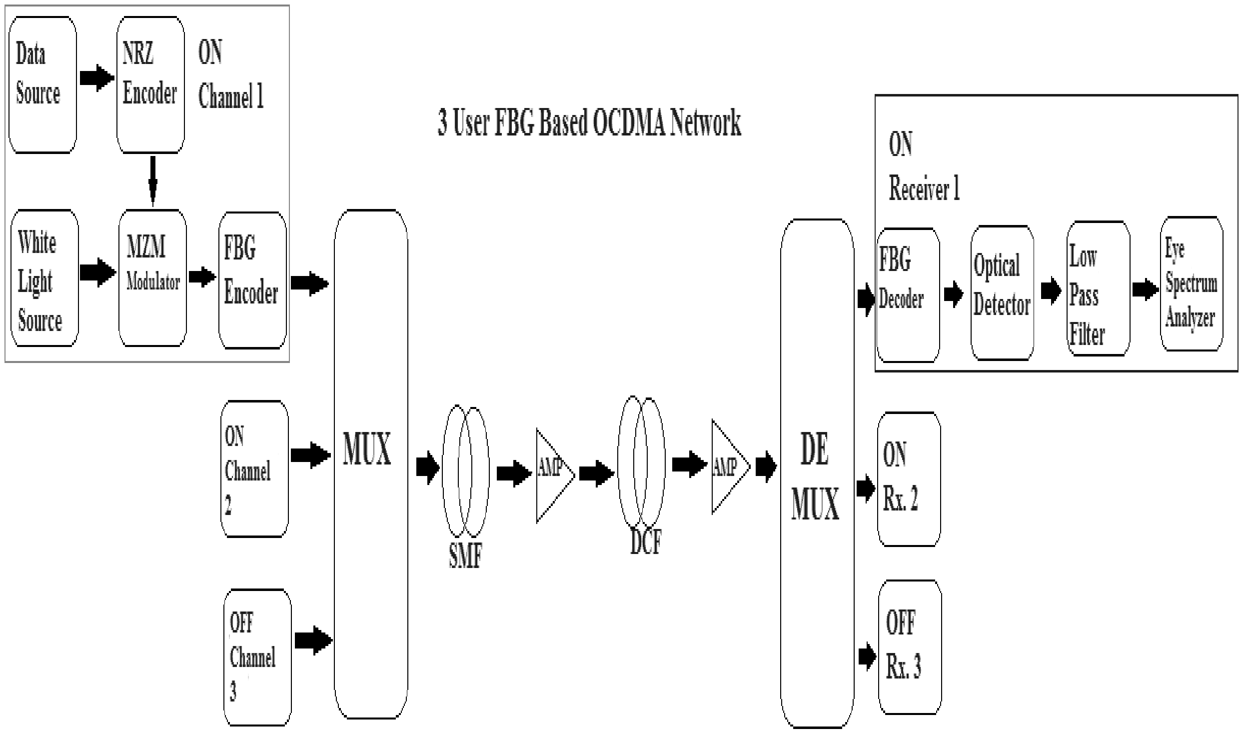


Fig. 6.1: Block diagram of Proposed Simulation Set-up

The unique signature code per user is assigned to a series of complementary FBGs. These FBGs are then placed in the encoder structure as shown in Fig. 6.2. The optical signal obtained after modulation, is given to a series of FBGs having central wavelengths of specified code sequence to accomplish the encoding process. Here, we are removing the logic "0"information and preserving the logic "1" information. The transmissive characteristics of Fiber Bragg Gratings are utilized to construct the encoder/decoder. Users in this proposed Optical CDMA network are assigned different signature codes. Therefore the arrangements of FBG encoder are according to assigned address codes for each user. Each user sends his data stream by modulating its own signature codes into the star coupler (network). A star coupler is used for the summation of all the transmitting users and broadcast to all the receivers in the Optical CDMA network [14]. The optical signals of all the active users are summed in the star coupler and broadcast to all the receivers in the OCDMA network. An isolator is placed to prevent the chips, reflected from the decoder, from entering in to the transmitter end since star coupler is a bidirectional device.

Broadband LED Source Multiple FBGs

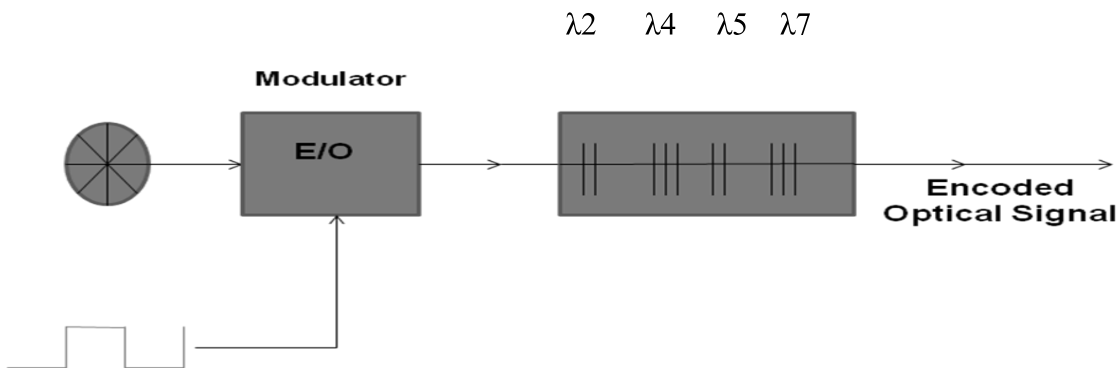


Fig. 6.2: Proposed FBG based encoder

We can verify that the central wavelengths of all the FBGs placed in encoder are designated as available code matrix vectors $(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8)$ and one of the user is assigned a signature code (1,0,1,0,0,1,0,1), from Hadamard code set .The FBGs are then placed with central wavelengths of $\lambda_2, \lambda_3, \lambda_4$ *and* λ_5 while no FBG is placed at central wavelengths of $\lambda_1, \lambda_3, \lambda_6$ *and* λ_8. Now all the encoded data/chips arrive at the differential detectors at the same time. At the receiving decoder, we have placed the matched FBGs corresponding to those used in the transmitting encoder to accomplish the balanced detection as shown below in fig 6.3.

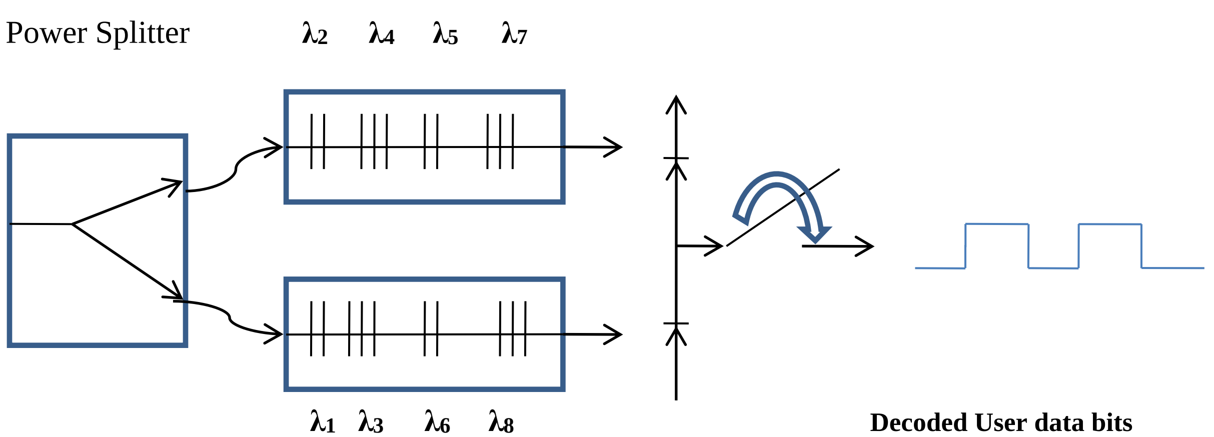


Fig. 6.3: Proposed FBG based decoder

A power splitter is used in the decoder to split the received optical signal into two half's. According to the particular signature sequence assigned to a particular user, two matched series of FBG's are placed at the encoder followed by a balanced photo detector and an information decision device. The receiver containing a decoder per user is illustrated by above shown Fig. 6.3, where the received composite optical signal is divided in to two branches viz. upper and lower, containing identical FBGs placed to that of their encoders and decoders respectively. The signal after getting reflected by FBGs at these two branches is photo detected and the complementary spectra, that contains the original data transmitted is obtained. The arrangements of FBG decoders must match to that of FBG encoders for each user. The Bit-Error-Rate and Eye-Diagram is constructed and analyzed.

6.3 Code Generation (Proposed OCDMA system)

As mentioned, there is code requirement for optical CDMA systems and optical orthogonal codes (OOC) are well suited to meet this requirement. An OOC structure is widely used to achieve prerequisite values of auto and cross correlation properties, which is a set of binary $(0, 1)$ sequences. Moreover using OOC code, it is possible to transmit data asynchronously and efficiently for large number of users. We have chosen Hadamard codes for our optical CDMA system based on FBG. Here codes are generated by selecting the rows of Hadamard code matrix of size $N \times N$ with binary values (0's and 1's), has this unique property that adjust rows differ from each other from exactly $\frac{N}{2}$ positions. All rows contain $\frac{N}{2}$ zeros and $\frac{N}{2}$ ones except first one. This is done in the same way as discussed in Chapter 3. In this way codes can be constructed using iterative procedure. [40]

$$H_1 = [1] \qquad H_2 = \begin{bmatrix} H_1 & H_1 \\ H_1 & \overline{H_1} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \qquad H_2^{n+1} = \begin{bmatrix} H_2^n & H_2^n \\ H_2^n & \overline{H_2^n} \end{bmatrix} \ldots \quad (6.1)$$

Here $\overline{H_n}$ is derived from H_n by replacing all entries with their compliments

For example $H_1 = [1]$ $\qquad H_2 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$

$$H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \qquad \overline{H}_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

Here, except first row containing all the 1's, other rows may be utilized to compose a code per user at the encoder. The first row is an exception because the wavelength corresponding to first row i.e. (1, 1, 1, 1) corresponds to AM keying, in which light has to be propagated all the time which is not at all acceptable. Similar is the case with higher order matrix.

$$H_8 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix}$$

Considering X to be row i and Y as row j and i ≠ j, it is verified that

$$R_{xy}\,(k) \; - \; R_{xy'}(k) \; = 0 \text{ ------------------------ (6.2)}$$

With above equation 2, we can apply this result to design our proposed receiving decoder for balanced detection in Optical CDMA network. Finally, in an N×N Hadamard matrix, codeword containing all ones has been rejected.So it is possible to accommodate codes for N- 1 number of subscribers. Other rows of Hadamard matrix constitute the codes for number of users.

6.4 Results and discussions

After the signal is reflected by FBGs at these two branches at the receiver, it is photo detected and the complementary spectra as that of obtained at transmitter side is obtained. The bit-error-rate and Eye-diagram is constructed and analyzed.

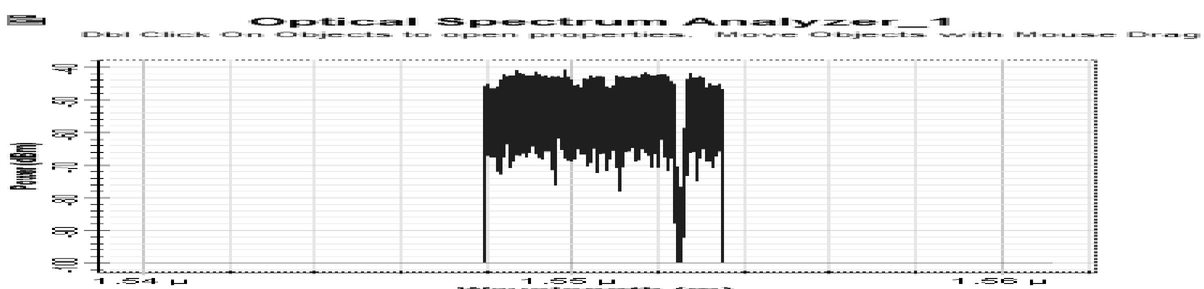


Fig. 6.4: Electrical spectrums at the transmitter

Unnecessary spectral parts of the data as shown in above figure 6.4 above are removed by the properly designed signature codes for the Optical CDMA system. We have reported the system performance for various data rates for two asynchronous users under the application of various modulations formats [67], [68], [71]. Results obtained in terms of BER and eye closure are shown in Fig. 6.5 and 6.6 respectively.

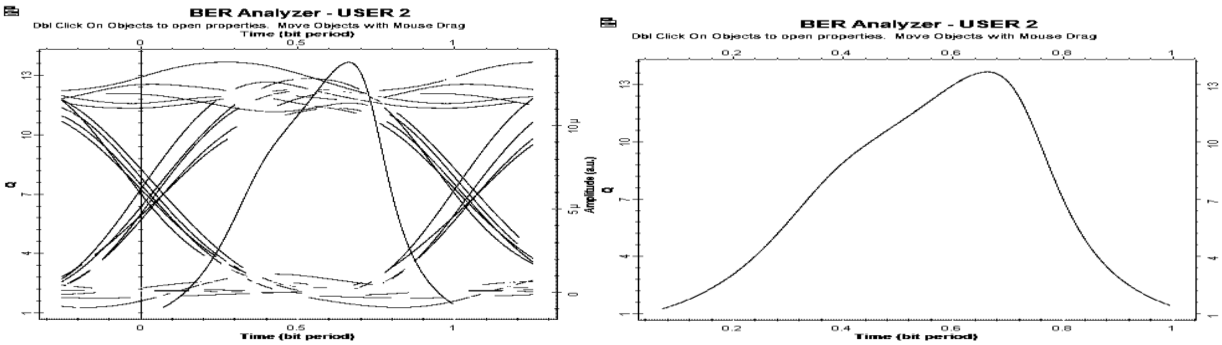


Fig. 6.5: Eye-Diagram and Q-Factor for User 2 (140 Kms Fiber Span)

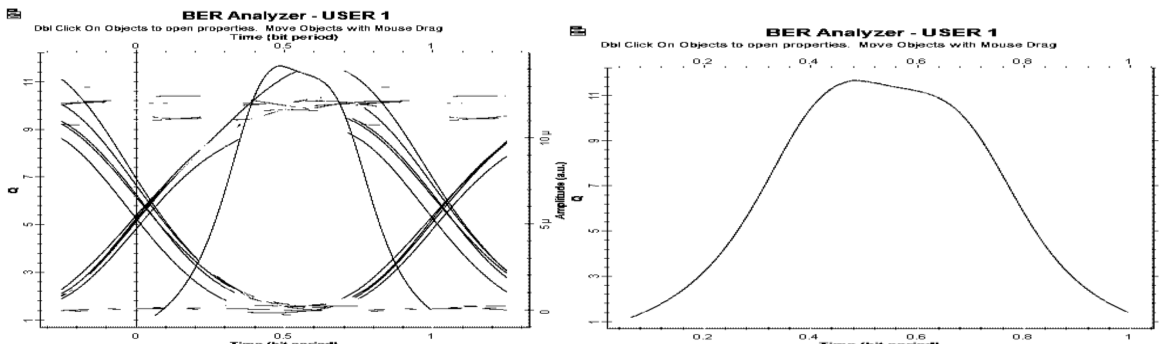


Fig. 6.6: Eye-Diagram and Q-Factor for User 1 (140 Kms Fiber Span)

The NRZ modulation format is reported to be the best among other modulation formats. In the figures 6.7, 6.8, 6.9 and 6.10 given below, it is compared to other modulation formats and is reported that NRZ modulation format outperforms RZ modulation format. Here its comparison in terms of BER and Q-factor is reported to its closest counterpart RZ raised cosine and it is evident that it outperforms it by some margin.

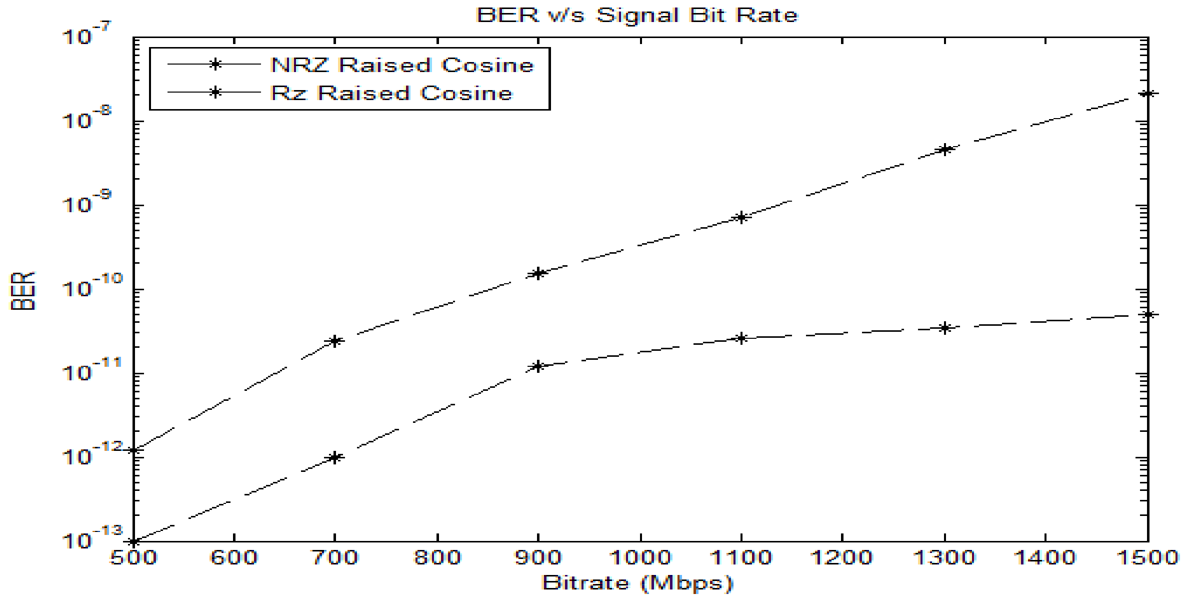


Fig. 6.7: BER Vs Data Rate for User 1(proposed OCDMA System) for different modulation formats

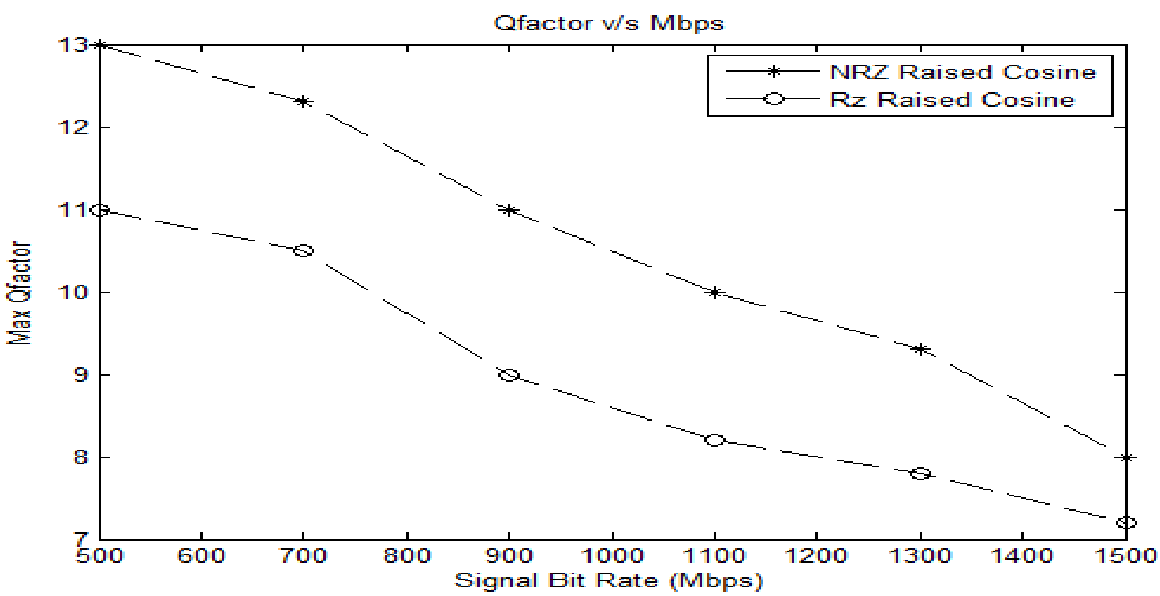


Fig. 6.8: Q-factor Vs Data Rate for User 1(proposed OCDMA System) for different modulation formats

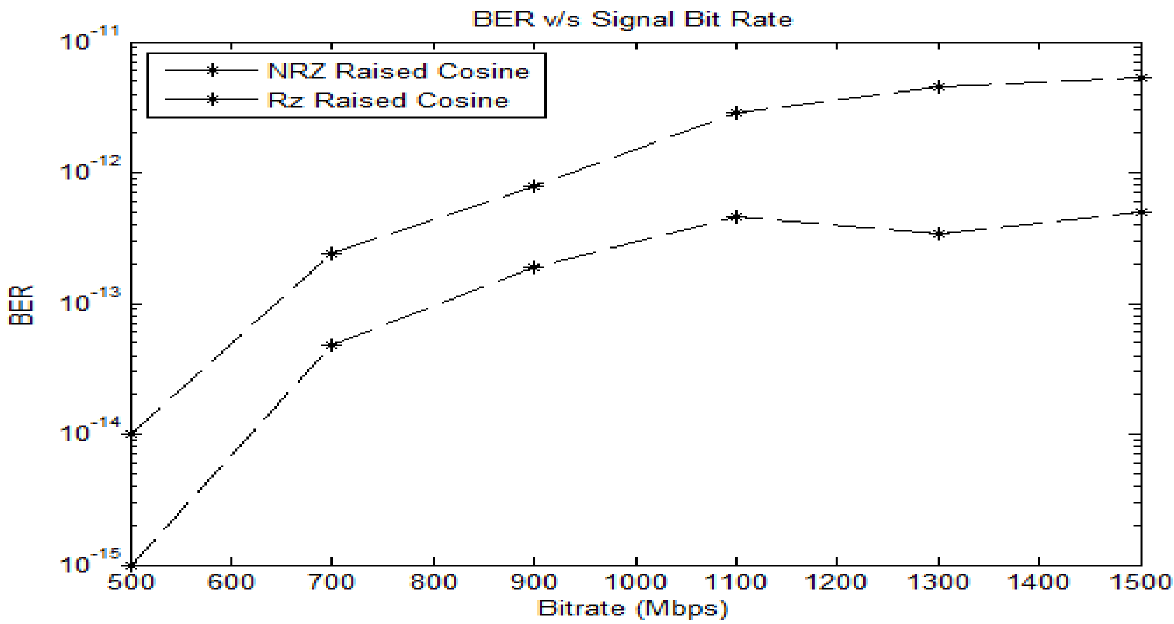


Fig. 6.9: BER Vs Data Rate for User 2(proposed OCDMA System) for different modulation formats

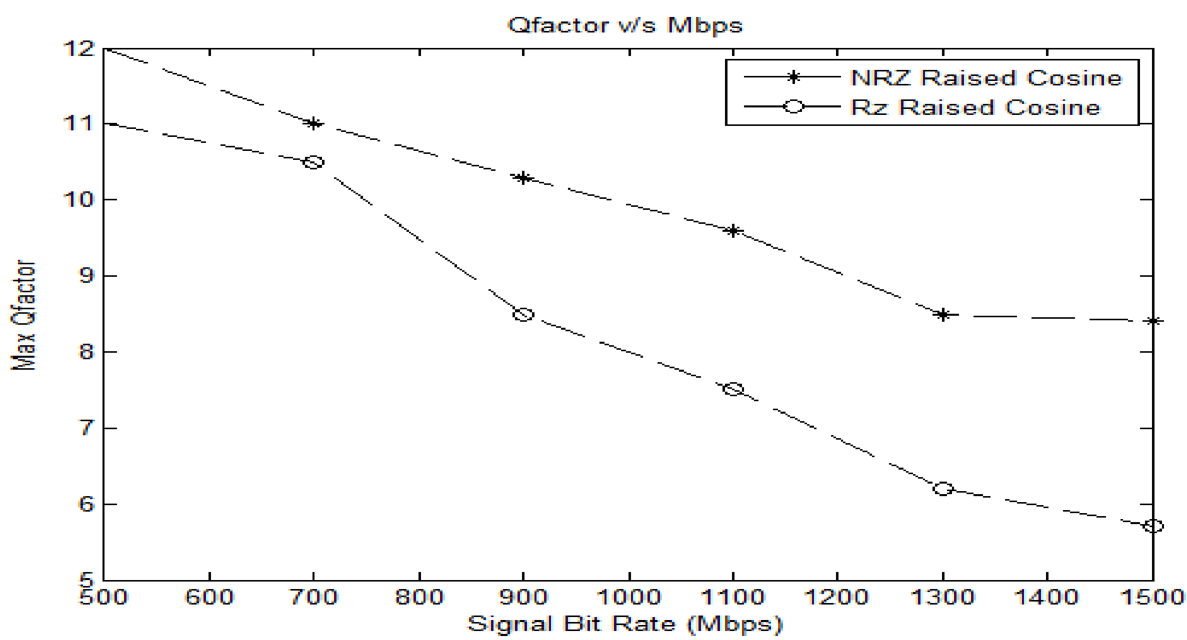


Fig. 6.10: Q-factor Vs Data Rate for User 2 (proposed OCDMA System) for different modulation formats

6.5 Performance analysis

Table 6.1 below gives the obtained values of BER and Q factor for three asynchronous subscribers (proposed OCDMA system)

Table 6.1: BER and Q factor values for proposed three users OCDMA system (Two active at a time)

Number of users	Obtained BER	Q Factor
User 1	1.2746e-012	13.123
User 2	6.5483e-011	12.453

6.6 Conclusions

In this chapter, we have demonstrated a three-user OCDMA spectral coding with FBG based codecs, operating at 1500 Mb/s, with a low-power requirement per user. We have introduced the transmissive spectral characteristics of FBGs to construct encoder/decoder. We have reduced the spectral leakage problem due to non-ideal characteristics of FBGs on coded chips. By designing the optical codes, we have filtered out those chips we don't require. Stability issue with optical source is also resolved to a great extent with the introduction of isolators, when the code length is large. This way we can prevent the chips reflected from the decoders from going in to transmitter end. In contrast to earlier proposed optical systems, we have avoided the use of star-coupler, which is a bi-directional device and can affect the stability of optical source used. In addition we expect the series of multiple FBGs to be fabricated in a single fiber thereby avoiding the use of fiber connectors that may cause power loss. Our system allows every user in OCDMA network to retrieve data bits successfully from multiple accumulated information signals. Erbium Doped Fiber Amplifier (EDFA) can be applied as in-line amplifiers for increasing the signal strength, or it can be used as the preamplifier to compensate for the transmission loss to improve the receiver sensitivity [72]. NRZ modulation is reported to be the best among other modulation formats.

Chapter 7

Conclusions, Recommendations and Future scope

7.1 Conclusions

This thesis presents the Performance Analysis of Optical Code Division Multiple Access System. The motivation and objective of this thesis is to perform an in-depth analysis of the performance of optical network against the impairments like MAI and FWM. The proposed optical network with designed codes has been carried out and the outcomes presented have been validated using extensive simulations. The outcomes obtained from this study are summarized below:

1. The Optical CDMA system employing 3-D spectral-amplitude codes are utilized with phase encoding/decoding technique for both polar and bipolar coded configurations. We have implemented Walsh Hadamard codes for the realization of our proposed set-up and later its performance is compared for other similar available codes. These are the code sequences having fixed in-phase cross-correlation. Here it is ensured that coded signals are fully synchronized (maintains orthogonality) leads to lower MAI and for this purpose Walsh-Hadamard codes for both unipolar and bipolar schemes has been used that act as signature codes. The simulation results have been obtained and compared for both the schemes. It is reported that for bipolar coding, system response in terms of BER and MAI is superior compared to polar scheme. So it is concluded that whenever Optical CDMA system is designed for good performance to transmit multimedia data, we can use bipolar scheme in the network. If the users only transmit voice data, the unipolar method can be employed. In addition, other existing encoding techniques are also taken into consideration and compared with our proposed coding technique for the same simulation set-up. Differential Detection technique have been discussed and adopted for the proposed simulation system which further limits the MAI.
2. A new optimized class of optical codes known as Message Priority and Fast Routing (MPFR) is presented. MPFR code is essential in the priority based communication of OCDMA for multiple user environments since these codes control the multiple access

interface delay cancellation effectively. In this work, receiver senses the interference and provides detection for interference by using an algorithm to achieve better packet delivery ratio (PDR) at the receiver, lower/acceptable BER and MAI. This work explains two dimensional code constructions based on message priority and routing at faster rate. Tridiagonal matrix is used for code construction and message priority is used which enables the priority of messages while communication by simply assigning the priority value in packet header. Proposed work provides better performance than the FCC, ZCC and basic PHC codes by providing less inference in between codes and this enables more number of users in the network.

3. Spectrally encoded/decoded scheme for optical CDMA system has been studied and analyzed for different lengths of fiber. For analyzing the performance of OCDMA system, Q-factor and bit error rate are considered. The simulation results show improved performance of designed OCDMA system.
4. The 2-D Wavelength-Time code utilizing WDM like components are used to design OCDMA system.The proposed system has been designed for optimum results in favour of optical received power, Q-factor and BER for multiple users operating at 2.5Gbps data rate. For asynchronous concurrent communication of high speed OCDMA system analysis has been done for multiple users on eye diagram and BER. Simulation results indicate that at high data rates for acceptable BER, the received optical power should not be less than -15 dBm in all cases.It is further shown that the best option to achieve best results like acceptable BER, Q-factor is to utilize the NRZ raised cosine modulation format.

5. Obtained results for 2D-W/T coded OCDMA system specify that for large number of users at high data rate i.e. 2.5 Gbps received optical power decreases and simultaneously there is increase in BER value at the receiver. So this tradeoff between the two is identified and reported.
6. It is observed that due to non-linearity present in optical fibers, four-wave mixing components happen to overlap with a signal channel; the interference causes a distortion of the signal amplitude. To mitigate this effect we have reduced the spectral leakage problem due to use of non-ideal characteristics of FBGs on coded chips. Our proposed

system filters out those chips which we don't take, thereby reducing the effect of FWM. Further our proposed system gives better performance for NRZ type of modulation format, which is then compared with the simulation results obtained from other modulation formats. This way best suited modulation format for proposed optical CDMA system is reported.

7.2 Recommendations

The recommendations on the basis of results obtained in previous chapters are given below.

1. The proposed technique of 3-D code designing aims to increase the OCDMA network ability against MAI and facilitate users with higher data rates. Hence, the OCDMA system with 3-D S/P/T encoding/decoding technique is recommended for the optical system where different service classes (Audio, Video, Mail, file transfer) for multimedia traffic can be defined and served accordingly.
2. It is recommended that the NRZ raised cosine line code modulation format is the best option available that can be endorsed for Optical CDMA networks.
3. The bipolar phase encoding technique is further recommended for multimedia data transmission whereas unipolar phase encoding technique can be used to transmit voice data.
4. The newly proposed technique MPFR codes provide better routing performance by incorporating the priority bit in header. The suggested structure is implemented and analyzed with transmitter and multiple recipients for various other existing coding techniques for improved performance. Hence is recommended for long haul fiber communications.
5. The proposed MPFR code development is based on minimizing code length. Variation in weight due to priority provides fixed data rates but could support various different quality of service processes and in other case length variation could provide data variation according to user's need. So whenever a flexible optical system based on user desired QoS is needed, MPFR code development structure is recommended.

6. The 3-D optical CDMA systems have better performance as compared to 2-D but increases the complexity. Hence, more number of users can be added.

7. The FBG based encoder/decoder is recommended for reducing FWM effect present in optical systems.

7.3 Future Scope

1. With the advancement in technology, there is continuous need of OCDMA systems with more number of users at higher bit rates. In continuation to the work, we can improve number of users at encoding/decoding sides at higher bit rates using higher dimension of codes.
2. The packet routing and delivery performance in optical system can be improved by introducing header bit in the proposed MPFR technique. This can further be extended to achieve variable data rate by incorporating certain amendments to header bit structure of MPFR scheme.
3. The Optical CDMA system performance against other fiber impairment and PMD (Polarization Mode Dispersion) effect may be considered as future scope of work at still higher bit rates.
4. In the proposed 3-D S/P/T codes, we have highlighted the importance and applications of unipolar and bipolar coding methods. We may extend the work by designing a network capable of using dual unipolar/bipolar coding method at the same time without any need of changing the decoding structures on the receiver end.
5. Furthermore, it is worth to study on the optical network security and privacy of Optical CDMA systems.

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