Design and Performance Analysis of Coherent-OOFDM Techniques in Wavelength Division Multiplexing Optical Network for Long-Haul Communication

Eyasu Kefale

A Thesis Submitted to

Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electronics and Communication engineering (Communication)

Office of Graduate Studies

Adama Science and Technology University

June,2022

Adama,Ethiopia

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APPROVAL PAGE OF M.SC. THESIS

We, the advisors of the thesis entitled "**Design and Performance Analysis of Coherent-OOFDM Techniques in Wavelength Division Multiplexing Optical Network for Long-Haul Communication**" and developed by Eyasu Kefale, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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Co-advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Eyasu Kefale have read and evaluated the thesis entitled "**Design and Performance Analysis of Coherent-OOFDM Techniques in Wavelength Division Multiplexing Optical Network for Long-Haul Communication**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electronics and Communication engineering (Communication)

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC)

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DECLARATION

I hereby declare that this Master Thesis entitle "**Design and Performance Analysis of Coherent-OOFDM Techniques in Wavelength Division Multiplexing Optical Network for Long-Haul Communication**" my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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Name of the student	Signature	Date

RECOMMENDATION

We, the advisor(s) of this thesis, hereby certify that we have read the revised version of the thesis entitled "**Design and Performance Analysis of Coherent-OOFDM Techniques in Wavelength Division Multiplexing Optical Network for Long-Haul Communication**" prepared under our guidance by Eyasu Kefale submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Electronics and Communication engineering (Communication). Therefore, we recommend the submission of revised version of the thesis to the department following the applicable procedures.

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Co-Advisor	Signature	Date

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LIST OF ABBREVIATION AND ACRONYMS

AO-OFDM	All Optical Orthogonal Frequency Division Multiplexing
ADC	Analog to Digital Converters
ASE	Amplifier Spontaneous Emission
AWG	Arrayed Waveguide Grating
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CD	Chromatic Dispersion
DAB	Digital Audio Broadcasting
DCF	Dispersion Compensating Fiber
DFT	Discrete Fourier Transform
DEMUX	De-multiplexer
DVB	Digital Video Broadcasting
DPSK	Differential Phase-Shift Keying
ER	Extinction Ratio
EDFA	Erbium Doped Fiber Amplifier
FBG	Fiber Bragg grating
FFT	Fast Fourier Transform
ISI	Inter Symbol Interference
LED	Light Emitting Diodes
LD	Laser Diodes
LO	Local Oscillator
MCM	Multicarrier Modulation
MZM	Mach-zander Modulator
OOFDM	Optical Orthogonal Frequency Division Multiplexing
OSNR	Optical Signal to Noise Ratio
PD	Photo Detector
PMD	Polarization Mode Dispersion
PRBS	Pseudo Random Binary Sequence
QAM	Quadrate Amplitude Modulator
RF	Radio Frequency

ROF	Radio over Fiber
RSOA	Reflecting Semiconductor Optical Amplifier
SCM	Subcarrier-Multiplexed
SMF	Single Mode Fiber
SOP	State of Polarization
WDM-PON	Wavelength-Division Multiplexing Passive Optical Network

ABSTRACT

Today, communication is a crucial factor and requires a high data rate for transmission with in an error-free environment, so optical communication has emerged as a best solution to high-speed transmission systems due to its higher bandwidth and higher data rates. Fiber optic transmission integrating with some modern processing and modulator techniques are applied in different areas that need transfer of data from one point to another through reducing an optical affect. Coherent OOFDM is a popular technique in optical communication today because of the excessive spectral efficiency, immune to interference, and tolerance of the fiber dispersion. Additionally, it could be a good choice for long-haul optical fiber transmission structures. Coherent-OOFDM employs the OFDM modulation method, which is a type of multicarrier modulation (MCM) in which data statistics are distributed over a large number of low-cost subcarriers and is a solution to inter-symbol interference. The main advantage of coherent OOFDM is that it can deal with a truly unlimited amount of ISI. ISI is generated by chromatic dispersion in high-speed optical communication systems, and it is a severe issue in long-haul systems in the case of higher data rates transmission. The use of standard dispersion compensating devices, such as dispersion compensating fibers, does not completely compensate for high order dispersion, which includes third-order and high dispersion effects and also increase the loses of the system because it is a fiber in it self.so, the purpose of this study deign and performance analysis of the concept of coherent-OOFDM techniques in to the WDM optical network in the case of multiple users, high data rate transmition and long-haul optical link to reduce the optical transmition related issues (ISI, BER etc.) and to improve the performance of optical network. The performance of the proposed network can be evaluated using by different parameters such as SNR, BER, OSNR, Quality factor and eye-diagram at different fiber length transmission by using Optisystem software and in terms of OSNR, SNR, and BER values, the results suggest that coherent-OOFDM-WDM well performance compare to the existing WDM system.

***Keyword**: Dispersion Compensating Fiber, Optical Orthogonal Frequency Division multiplexing, Wavelength Division multiplexing.*

CHAPTER ONE

INTRODUCTION

In recently, lot of researches has going on in the era of optical communication in relation with wavelength-division multiplexing, coherent–optical system, orthogonal frequency division multiplexing, space division multiplexing etc., these is due to the growth of internet traffic that includes voice and video in addition to data services, has directed to increased demand in high data rates and bandwidth with in optimum cost of network devices and services (Rashed et al., 2018). The rapid growth of Internet traffic and new applications are driving the demand for high-capacity, cost-effective optical fiber transmission technology this led to replacement of RF and Microwave (MW) technology in telecommunication world today. Fiber-optic communication is a method of delivering data from one location to another by passing light over an optical fiber. Fiber-optic communication systems have mostly been employed in long-distance applications, where their full transmission capacity can be used to offset the higher cost. For short to medium range wireless communications, optical transmission methods are preferred since they use less power. However, significant power is necessary for other applications with long transmission distances. In an optical fiber, various nonlinear effects begin to appear as the optical power level increases so the introducing of OFDM with optical concept is importance in these days to compensate these effects because it provides large capacity and low cost with efficient power in deployment of long-haul optical communication.

OFDM is a frequency-division multiplexing technique in which data is carried on a large number of closely spaced orthogonal subcarriers. Each sub-carrier in OFDM is modulated using a typical modulation scheme (such as quadrature amplitude modulation or phase-shift keying). The advancement of digital receivers for optical fiber communication networks allows for the use of more powerful modulation and processing schemes such as optical orthogonal frequency division multiplexing OOFDM and the coherent system in the optical network. OOFDM proposed as a modulation technique for the long-haul transmission in both direct and coherent detection it is because of decline the need for high power optical transmitter devices. The integration between OFDM modulation and coherent processing brings two main benefits to optical communication systems (A. H. Ali et al., 2019). In both RF to optical up conversion and optical to RF down conversion, the coherent system brings linearity to the OFDM. The OOFDM provides a coherent system with high spectral efficiency and simple channel and phase estimation, as well as high bandwidth and high spectral efficiency, with the ability to overcome many optical fiber restrictions such as chromatic dispersion (CD) and polarization mode dispersion (PMD), which cause receiving optical pulse distortion (A. H. Ali & Rhaif, 2020).

1.1 Background of the Study

In the development of optical fiber communication enhancement wavelength-division multiplexing is play a significant role. Wavelength-division multiplexing has the ability to give the system additional flexibility and to make network design simple. By delivering many wavelengths across a single fiber, it helps to increase the system's capacity (Sujecki, 2020). WDM systems enhance the data rate transported over a single optical link by employing several wavelengths, each carrying a separate channel and divides the optical spectrum into smaller channels that can concurrently transmit and receive data. Each wavelength can be kept as a discrete channel in a WDM system, and different data can be conveyed and it consists of optical multiplexer (MUX) to combine signals of different wavelengths, while an optical de-multiplexer (DEMUX) is used at the receiver to split them at the destination. (Singh & Singh, 2018).

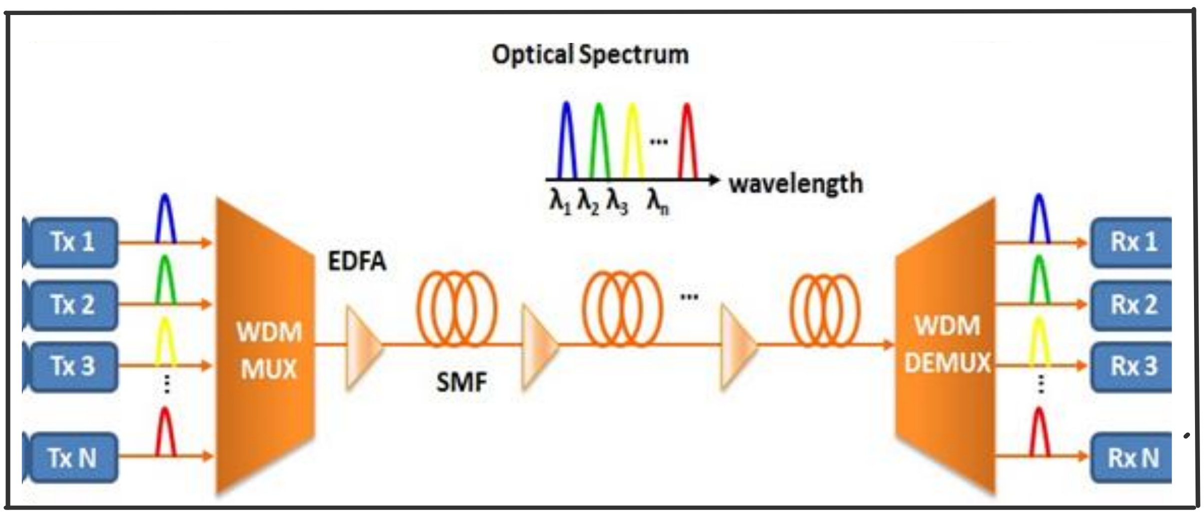


Figure 1.1:Basic Structure of WDM Optical Network (Mounia, 2021)

In general, N optical wavelength numbers can be used as a data carrier in the WDM technique, and these wavelengths are combined with an optical fiber using a WDM multiplexer, while these wavelengths are separated as individual channels at the receiver using a WDM demultiplexes. Each optical wavelength is unique and typical; channel spacing computes the difference between those wavelengths, allowing for minimal overlapping optical carriers. In the link EDFA used to boost the signal in optical domain (A. H. Ali & Farhood, 2019).

1.1.1 The Existence of WDM in Optical Window Generation

The optical network has a large bandwidth and capacity that can be thousand times that of the whole RF spectrum. However, this is not the case because of dispersion, signal attenuation, which is a function of wavelength and other fiber limiting factors like as imperfection and refractive index variation limit the performance of optical communication. As a result, WDM exist in the fourth-generation optical window to reduce this optical effect in fiber transmission and a low attenuation window of 1300nm (0.32dB/km)-1550nm (0.2dB/km) is commonly utilized in the design of WDM optical network.

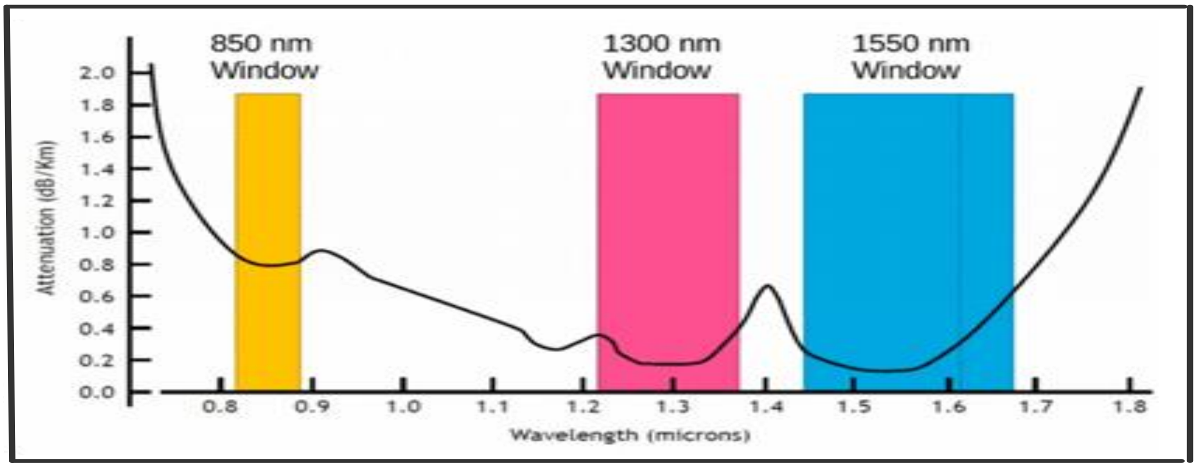


Figure1.2: WDM in Optical Window Generation (Kavitha & Pavani, 2019)

1.1.2 Important of WDM in Optical Fiber Network.

- Reusing Wavelengths and Transparency: Wavelength routing is possible in WDM networks. As a result, the same wavelength can be utilized again in multiple fiber lines. This enables for wavelength reuse, which aids in expanding capacity. It is also allow data to be transferred at various bit rates in variety of protocols. So there aren't many restrictions on how we want to convey the data. As a result, it may be utilized for several very high-speed data transmission applications
- Capacity upgradability and scalability: Optical fiber communication gives a very huge bandwidth. Light serves as the data stream's carrier in this case. As the carries, a single light beam is often employed. WDM, on the other hand, multiplexes photons of different wavelengths into a single optical cable. As a result, more data is now sent across the same cable. This significantly enhances the network's capacity.

- Reliability WDM networks are incredibly reliable and secure. The possibility of data entrapment and crosstalk is quite minimal in this case. It can also recover from network failures in a highly effective manner. A path between a source and destination node pair can be rerouted. As a result, in the event of a link failure, we will not lose any data (Bobrovs et al., 2014).

However, the WDM is the simplest and the best techniques in optical network it required other modification in order to get high speed gigabits or terabit communication in long-haul network. These can be done in two ways: -

1.1.3 Increasing Spectral Efficiency

In optical communications, the most important figure of merit is spectral efficiency, which is the information capacity per unit bandwidth or transmission bits/hertz. To reduce transceiver complexity, optical networks currently use intensity modulation and modern processing, as well as binary modulation. Binary modulation's spectrum efficiency, on the other hand, will not exceed 1 bit/s/Hz. Numerous new modulation forms in signal phase, amplitude and polarization have recently been investigated to increase the system's capacity. The spectrum efficiency of coherent detection combined with sophisticated modulation can easily approach several bits/s/Hz. The OOFDM is one of these sophisticated approaches. (Jaber et al., 2020).

1.1.4 Bandwidth Expansion

Increasing the transmission bandwidth per wavelength, in electronically, is one way to boost the system's capacity. This method uses CMOS technology to increase the electronic bandwidth per wavelength. However, today's digital to analog converters (DAC)/ (ADC) can only handle a bandwidth of 6 GHz. It is difficult to achieve over 100 Gb/s transmissions at a reasonable cost.

1.2 Motivation

The existences of modern modulation and processing techniques in optical communication which has been widely adopted and used the development of wireless communication have a solution of optical transmission effect and efficient utilization of optical spectrum. According to information theory predicts that spectral efficiency will increase as received SNR increases these achieved by increased transmission power which lead to non-linearity, fiber nonlinearity imposes a hard limit on channel capacity improvement. As a result, this thesis focusing on the deployment of coherent–OOFDM in the wave division optical network to improve spectral efficiency with optimal usage of transmitter power. WDM increases capacity by delivering several optical carriers together, while OFDM reduces inter-symbol interference by orthogonal subcarrier alignment and cyclic prefix insertion, and coherent processing improves the received signal's linearity and sensitivity.

1.3 Statement of Problem

In excessive-pace optical transmission structures, inter symbol interference (ISI) is induced through chromatic dispersion and existence of nonlinearities in the fiber that causes for phase and frequency shifts in the transmission, which are a serious problem and significant impact on overall system performance long-haul communication systems whose bit rate is higher. Dispersion compensating fiber is used in the existing WDM network to mitigate the effect of dispersion and another optical impartment in the optical link. DCF is dispersion management approaches for recovering signals over a fiber in long distance. However, dispersion compensation fiber and WDM is very hard to fully compensate especially for very excessive date rate signals, incorporating dispersion-compensating fiber to system also contribute to further lose, and additionally in recent times the internet site visitors growing from day today. For this reason, it necessary to increases the capacity of communication system to handle traffic or to full fill the willingness of the user. Therefore, to minimize the ISI effect, nonlinearity and to increase the capacities this work focus on incorporating coherent-OOFDM techniques to the existing WDM network of optical communication.

1.3 Objective

1.3.1 General objective

The main objective of this study is Design and Performance Analysis of Coherent-OOFDM Techniques in to the WDM based Optical Network for Long-Haul Transmission.

1.3.2 Specific objectives

1). Understand and design basic wavelength-division optical network

2). Study and model Coherent -OOFDM network based on QAM modulation format.

3). Develop the QAM based coherent-OOFDM in to the wavelength division multiplexing long-haul optical network

4). Analyze the performance of the system in terms of ISI, BER, OSNR, and the relationship between BER, SNR, and OSNR with transmission distance.

5). Investigating the effect of introducing Coherent-OOFDM on the performance of the existing network

1.4 Significance of the Study

The importance of optical communication has grown recently for applications of ours daily life of leaving. This communication technology is expected to play a prominent role to modernize the human ways of life with these a great interest in scientific community, military, industry ,climate changes, prediction of natural disasters and discovery of natural resources, due to these different researches open in the area of optical communication because it provides higher data rates than the copper wire communication systems with significantly lower power consumption and simpler computational complexities for long-range communication links. So, introducing of the optical OFDM concept in the wavelength division multiplexing optical communication further goes to performance improvement of optical link through providing high data rate, minimize bit error rat and inter-symbol interference, reduce dispersion of signal and the cost of communication, Spectral efficacy, Security when compare with the wireless communication. The OFDM and Coherent-OOFDM approaches, respectively, can provide great spectral efficiency and increased receiver sensitivity.as result, this work contributes to decrease optical effect and increasing capacity of system.

1.5 Scope of Thesis

The scope of this work based on design and analysis system performance of Coherent-OOFDM techniques in to four channel WDM long-haul optical communication network use Optisystem software tool implementation for the simulation and the model can be evaluated through BER, eye-diagram, Q-factor and OSNR using numerical analysis or semi-analytical approaches Again analyzing the performance of the system at different transmission distances by using different modulation techniques through design the WDM network, coherent-OOFDM system, and integrated network (Coherent -OOFDM-WDM) over a long-haul network (> 100km) with high-speed transmission in giga or terabit communication.

1.6 Limitation of the study

- The investigation of thesis work based on conceptual interpretation and integration which relies on software simulation analysis.

1.7 Thesis outline

The outline of the thesis summarized into five main chapters, which are described in order:

The first chapter examines the introduction sections, which include the background, problem statement, objectives, specific objectives, significance of the research, scope of the study, and limitations of the study. The second chapter includes a survey of the literature and related works that explain the notion of optical fiber, optical fiber issues and OFDM method and describes its transceiver section. The third chapter outlines methodology and the proposed coherent-OOFDM approach in WDM long-haul and ultra-long-haul system in block diagram form with conceptual explanation and designing. The fourth Chapter demonstrated and described simulation design, results and system performance investigation. Finally presents conclusions the extended future work for other achievement.

CHAPTER TWO
LITERATURE REVIEW

2.1 Related Work of Studies

‘Design and Implementation DWDM toward Terabit for Long-Haul Transmission System (Mousa et al., 2020). These studies present the design and implementation of a Terabit/sec high-speed transmission system based on the Denise Wavelength Division Duplexing (DWDM) system. The presented system considers a new solution for long-haul optical transmission systems delivering increased data rates. The system looked at different numbers of input channels. The collected findings demonstrate that the proposed system is immune to nonlinear limitations. The performance analysis of various numbers of optical channels with various data formatting techniques such as Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ) is also discussed, but the performance metric evaluation based on eye-diagram measurement with a 100km optical link and only limited to minimizing of non-linear impairments.

‘’An enhanced WDM optical communication system using a cascaded fiber Bragg grating” (Sayed et al., 2020) **.** This study proposes the use of a cascaded fiber Bragg grating (FBG) device to reduce dispersion in single mode optical fibers and optical pulse delay in optical communication receiver. As a result, as measured by the bit error rate (BER) and quality factor, the system's performance improves. Over a 200km fiber link and in the case of single user, it is evident that the influence of the distance parameter on fiber dispersion is being explored but when the fiber length increasing the attenuation and dispersion more affect the system and limit the application of FBG in long-haul communication. The inter carrier interference of WDM multiplexing signals, which caused light to spread in the fiber over long range communication, was not investigated.

“Comprehensive investigation of coherent optical OFDM-RoF employing 16QAM external modulation for long-haul optical communication system” (Hussien & Ali, 2020) . The purpose of this research is to investigate the performance of external modulation in RoF links while examining the flaws created by the various aspects of the optical system. The Mach–Zehnder modulator (MZM) can be used for external modulation and has a more reliable performance when paired with the OFDM modulation technique. It employs external modulation techniques to focus on a single user in a 10Gbit/sec radio over fiber link for long-distance optical communication. The inquiry is limited to a 100km fiber length spectrum and constellation-based examination of the received signal not emphasis in term of BER and OSNR of the received optical signal.

"Design and Comprehensive Investigation of High Capacity Communication System Based on All Optical Orthogonal Frequency Division Multiplexing Processing(Kareem, 2020)"**.** This paper explains how to improve data rates in all optical orthogonal frequency division multiplexing (AO-OFDM) approaches to increase optical network transmission range. The arrayed waveguide grating (AWG) was used as an optical fast Fourier transform (OFFT) circuit in all optical orthogonal frequency division multiplexing systems is proposed. Arrayed Waveguide Grating (AWG) with dense wave division multiplexing (DWDM) and 20 GHz channel spacing over a 1300km fiber with bitrate of 240Gps per channel. The suggested techniques are less complicated than others in that they can achieve better spectrum efficiency. However, implementing OFFT in an arrayed waveguide grating requires more input power to launch optical signals over a longer distance, resulting in the appearance of non-linearity in fiber link transmission. To investigate the system's performance, BER and launch power analyses were used.

Optical OFDM for ultra-high capacity long-haul transmission applications (Jansen et al., 2011). For next-generation fiber-optic transmission systems, optical OFDM is a promising modulation format. The main challenges for optical OFDM are its sensitivity to laser phase noise and high PAPR. The phase noise tolerance is discussed in this study. The two main phase noise compensations were explored. Carrier phase estimation (CPE) and RF-pilot algorithms (RFP)compensation. Furthermore, OFDM's nonlinear tolerance is addressed for SSMF and LEAF, and it is demonstrated that a nonlinear improvement is RFP-based phase noise compensation.it is possible to achieve a gain of up to 1 dB. The study focused on phase noise reduction rather than fiber concerns like as dispersion and attenuation and the link performance metric evaluation based on OSNR analyses

"Next Generation of High-Speed Optical Communications Networks Using OFDM Technology" (Jaber et al., 2020). This work focuses on the impact of OFDM technology's high-speed optical network transmission on the short hall effect of long-distance transmission. One of the most trusted solutions for meeting the increased demand for bandwidth in broadband services is orthogonal frequency division multiplexing (OFDM). Orthogonal Frequency Division Multiplexing (OFDM) has been applied on-demand in optical communication. In the long-haul transmission format, it is used for direct and coherent detection. OFDM has a variety of features and capabilities that can aid in improving optical fiber performance by removing some of the limitations that come with standard optical fiber communication. the investigation of the work based on 120km of fiber length and 25Gps over a single scenario with BER and Q-factor analysis does not interpret the result other performance parameter like eye-diagram, OSNR, and SNR to measure the quality of received signal.

Design of Long-haul Coherent DWDM Optical Systems (Ibragimov & Fokin, 2018).This study considers issues related to the design of high-speed long-haul coherent DWDM systems. Nonlinear noise reduces value of OSNR significantly. A method for calculating a coherent communication system is represented by a traditional OSNR estimation. The purpose of the work is to estimate the value of OSNR of a coherent communication system using the modern method of noise accounting. The proposed model for estimating the range of operation of a coherent optical system allows us to estimate the maximum distance when transmitting signals in the DP-QPSK format at a rate of 100 Gbit. the performance metric evaluation of deign network only based on OSNR up to 100km fiber length and estimation it does not consider BER, Q-factor and ISI optical receiver performance measurement techniques.

2.2 Optical Communication Impairments

Optical fiber communication is similar to any other mode of communication, a transmitter, a receiver, and a communication channel are the three primary components. The communication channel in a fiber-optic communication system differs from that of other communication systems in that it is an optical fiber (uses light as a transmission media) and the transmitter and the receiver are designed to meet the requirements of this communication channel. The communication system can be divided into two categories: long-haul >= 100 km and short-haul less than 50 km. Long-haul applications, on the other hand, are driving fiber-optic communication technology because of its high data rates. The primary goal of an optical communication channel is to convey data with minimal distortion and loss (Sujecki, 2020). The optical fiber has a loss (attenuation) consider as 0.2dB/km in modern optical window when transmitting light waves. In long-haul applications, however, fiber loss (attenuation) increases by 1% per 100 kilometers. As a result, while designing an optical fiber, the fiber loss (attenuation) must be taken into account when determining the distance between repeaters or amplifiers. Fiber dispersion is another optical fiber disadvantage that must be taken into account while designing the system. As a result, the light pulse broadens and overlaps with the closer pulses as it travels up the fiber. This will eventually make it difficult to precisely reconstruct the original signal. Fiber dispersion can be severe in multimode fibers, but it is less severe in single mode fibers, making single mode fibers more ideal for communication system design, especially for long-haul applications (Rindhe et al., 2015).

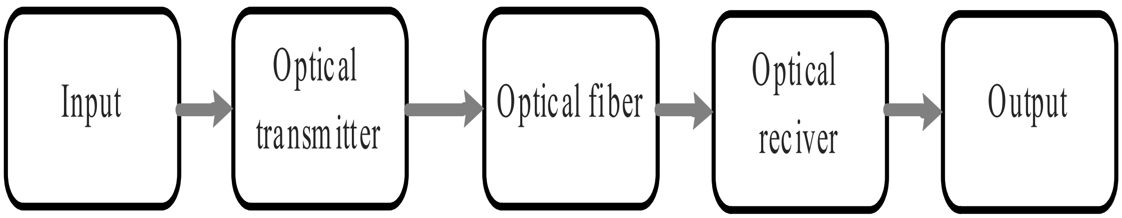


Figure 2.1:General Block Diagram of Optical Communication (et al., 2018)

2.2.1 Optical Transmitter

The optical transmitters used to convert an electrical signal into an optical signal and then feed that signal into an optical fiber. An optical source and optical modulator make up the optical transmitter. The optical sours consist of light emitting diodes (LEDs) and laser diodes (LD).

2.2.2 Optical Fiber Cable

An optical fiber cable consists of a core, cladding, and buffer (a protective outer layer), with the cladding using total internal reflection to guide light along the core. Both the core and the cladding (which has a lower refractive index) are typically composed of high-quality silica glass, but they can also be manufactured of plastic. The next layer is a protective covering that prevents harm to the core and coating. It also incorporates color coding for identification and prevents light from escaping the assembly. A "strand" is the combination of the core, coating, and covering. Fiber strand sizes are always expressed as a fraction of the core diameter.

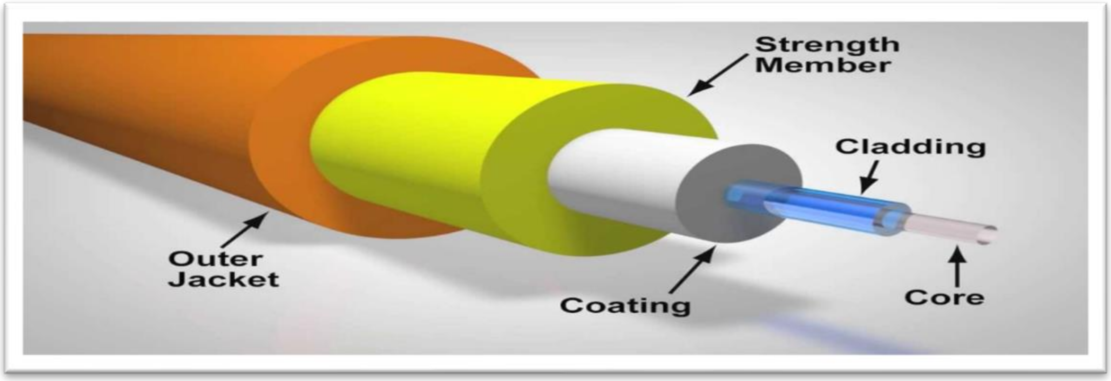


Figure 2.2:Optical Fiber Cable (Gangwar & Sharma, 2012)

2.2.3 Optical Receiver

The optical receiver's is used to detect the signal and transform it from optical to electrical form. A photodiode converts the optical signal to an electrical signal, and an electrical demodulator retrieves the original electrical signal provided.

2.3 Linear Impairments in Optical fiber Communication system

The propagation of a optical field in an optical fiber cable described by nonlinear Schrodinger equations with linear and nonlinear parameter (Njikue, 2018).

$$\frac{\partial}{\partial z}V(z,t)+\frac{j\beta_2}{2}\frac{\partial^2}{\partial z^2}V(z,t)-\frac{\beta_3}{2}\frac{\partial^3}{\partial z^3}V(z,t)=j\gamma(z)|V(z,t)|^2V(z,t)+\frac{1}{2}(g(z)-\alpha(z))v(z,t)+w_n(z,t) \quad (2.1)$$

The optical field as a function of transmission distance and time (z and t, respectively) is represented as V(z,t),β_2 is the group velocity dispersion,β_3 third order dispersion, $\gamma(z)$ is the nonlinear coefficient, g(z) is the optical amplifier's gain coefficient, α(z) is the optical fiber's attenuation coefficient, and Wn is the spontaneous emission fluctuations that cause the amplifier's noise.

2.3.1 Attenuation of fiber

Attenuation is a linear effect occurred in the fiber due to the degradation of power light or signal intensity throughout the length of a fiber cable and is measured in decibels per kilometer (dB/km). In fiber communications, the expressions fiber loss, fiber attenuation or power attenuation are used equally. In most cases, power loss within the fiber is due to scattering and absorption. Photons are lost due to absorption, and their energy is transformed into heat. Scattering happens when minor flaws in the optical fiber deflect portions of light into rays that the optical fiber can no longer carry. The ratio of input optical power to output optical power after L length of optical fiber is known as attenuation (Behera et al., 2017).

$$\alpha = \frac{10}{L}\log\left(\frac{p_{out}}{p_{\text{int}}}\right) \quad (2.2)$$

The power attenuation of optical fiber given by

$$P(l) = p(0)10^{\frac{-\alpha L}{10}} \quad (2.3)$$

The attenuation at a modern wavelength window is reduced to 0.2dB/km because of the attenuation issues less concerned in this day. Because of the low attenuation, the optical signal can travel 100 kilometres through the optical fibre without the usage of amplifiers or regenerators. Optical fibre has recently been the favored medium due to its low attenuation and enormous bandwidth. Fiber optics can improve signal reliability and save system costs by reducing the number of amplifiers and regenerators required. Splices, connectors, and light leakage are all potential sources of attenuation. The typical form of the graph of attenuation is implied by light scattering caused by imperfections in the core structure at the molecular level. Remaining photon-absorbing elements, such as water ions or metals, inside the cladding and core of the fiber, are another cause of attenuation.

2.3.2ASE Noise

Long-haul transmissions typically span thousands of kilometers, with Erbium-doped fiber amplifiers compensating for fiber attenuation over 100kilometer intervals. During the amplification process, spontaneous emission emits photons with unpredictable phase, direction, and polarization state, which perturbs the signal's amplitude and phase. Because of flat frequency power spectrum and additive in nature spontaneous emission noise may be described as an additive white Gaussian noise (AWGN). The term Wn (z, t) in NLSE refers to spontaneous emission, and its power spectral density is expressed as (Bobei, 2020).

$$p_{se} = f_n h f_o \left(\frac{G-1}{2}\right) \quad (2.4)$$

where f_n is the noise figure of an Erbium-doped fiber amplifier (EDFA), h is Planck's constant, f_o is the optical carrier frequency, and G is the amplifier gain. Summing the noise throughout the whole amplifier bandwidth yields the total noise power. The total power of the amplified spontaneous emission noise can be formulated as

$$P_{Tse} = np_{se}B_{amp} \tag{2.5}$$

where, *Bamp* is the effective bandwidth of an amplifier, and the factor of n represents the orthogonal polarized modes supported by a single-mode fiber.

2.3.3 Fiber Dispersion

The spreading of the light pulse as it passes along the fiber is known as fiber dispersion. Fiber dispersion is the spreading of the light pulse as it passes through the fiber and starts to overlap with consecutive pulses as the transmission length extends. This causes the pulse to overlap with neighboring pulses, making obtaining the original signal more difficult at the receiver. Different types of signal dispersion can occur during signal propagation and these are, intermodal, chromatic, and polarization-mode dispersion.

2.3.4 Intermodal Dispersion

Because each mode of the optical signal travels a different transmission distance over the same duration of time, intermodal dispersion or modal delay arises. This means that each mode moves along the fiber at a distinct group velocity. The broadening of optical pulses happens as a result of modes of light entering the optical fiber at the same moment and leaving at separate times. The optical signal is distorted when the optical pulses are broadened. The intermodal delay increases as the length of the optical cable increases and MMFs have multiple modes, intermodal delay is the most significant dispersion in MMFs.

2.3.4 Intramodal Dispersion

It also known as chromatic dispersion cause for broadening pulse and that happens in a single mode fiber. Intramodal dispersion it is generated because of the broadening optical signal pulses. The finite width of an optical source's spectrum emission causes this broadening or spreading of pulses. During passage through the optical fiber length, the pulses expand with each kilometer and as the length of the optical cable increases, the pulses become wider, causing overlap between adjacent pulses. Because of these data will be corrupted and unrecoverable. As a result, the optical signal to noise ratio (OSNR) would drop, while the bit error rate (BER) will rise. Intramodal dispersion in the fiber can be formulated as (Sanchez et al., 2013).

$$D_w = -\frac{\lambda}{c} n_1 \Delta \frac{d^2k}{d\lambda^2} \tag{2.6}$$

$\beta 2$ is the Group Velocity Dispersion parameter and expressed as

$$\beta_2 = \frac{d^2\beta}{d\omega^2} \tag{2.7}$$

where ώ is the angular frequency and β is the wave propagation constant. Material dispersion and waveguide dispersion are the two types of chromatic dispersion. The changing of the refractive index of the core material of a fiber with the change of the optical wavelength causes material dispersion. The fact that the index of refraction variation as a function of wavelength is the primary reason of material dispersion. The optical fiber refractive index decreases when the wavelength increases. Material dispersion coefficient described as

$$D_M = \frac{\lambda}{c}\left|\frac{d^2 n}{d\lambda^2}\right| \tag{2.8}$$

waveguide dispersion another type of intramodal dispersion generates due to pulse broadening because only one portion of the optical power that transports along the optical fiber is enclosed in the core. The chemical composition of the optical fiber core determines waveguide dispersion. The wavelength is determined by the mode-field diameter (MFD), which is measured the width of the beam of light transmitting in a single mode fiber. Because of this, only 80% of light in a conventional single mode fiber is restricted to the core, resulting in waveguide dispersion and as refractive index of the cladding is lower than the refractive index of the core, the remaining 20% propagates quicker through the internal layer of the cladding. Therefore, different frequencies and wavelengths of signals are becoming dispersed and because of this the pulse cannot be differentiated.

$$D_w = -\frac{\lambda}{c} n_1 \Delta \frac{d^2 k}{d\lambda^2} \tag{2.9}$$

where λ is the wavelength, c is the speed of light in vacuum, represents the refractive index of the core, Δ denotes to the difference of the relative refractive index, and k stands for the propagation constant.

2.3.5 Polarization Mode Dispersion

Fiber birefringence changes the polarization state of the optical signal and generates pulse broadening, resulting in polarization mode dispersion. There are two separate SOPs moving at different speeds. The difference in timing between them is known as the differential group delay

(DGD). The elliptical rather than circular shape of the core, as well as fiber torsion, bending, and thermal stress, all induce local fiber birefringence, causes PMD. Concatenation of many elementary PMDs results in the total PMD throughout the fiber. Because PMD is randomly distributed and fluctuates over time due to temperature and physical movement, the total DGD is a stochastic variable. Single mode fibers contain an inherent property termed polarization mode dispersion due to in the presence of birefringence (PMD) and direction and magnitude of this change in fiber birefringence across the fiber's length are random. (Udayakumar et al., 2013). The polarization-mode dispersion in the fiber given as

$$D_{Md} \approx \frac{\Delta\tau}{\sqrt{L}} \tag{2.10}$$

$\Delta\tau$ is the difference of propagation time between the two polarization modes and mathematically given as:

$$\Delta\tau = L\left|\frac{1}{v_1} - \frac{1}{v_2}\right|, \tag{2.11}$$

where L is the pulse's travel distance, and v_1 and v_2 are the group velocities of the two polarization modes.

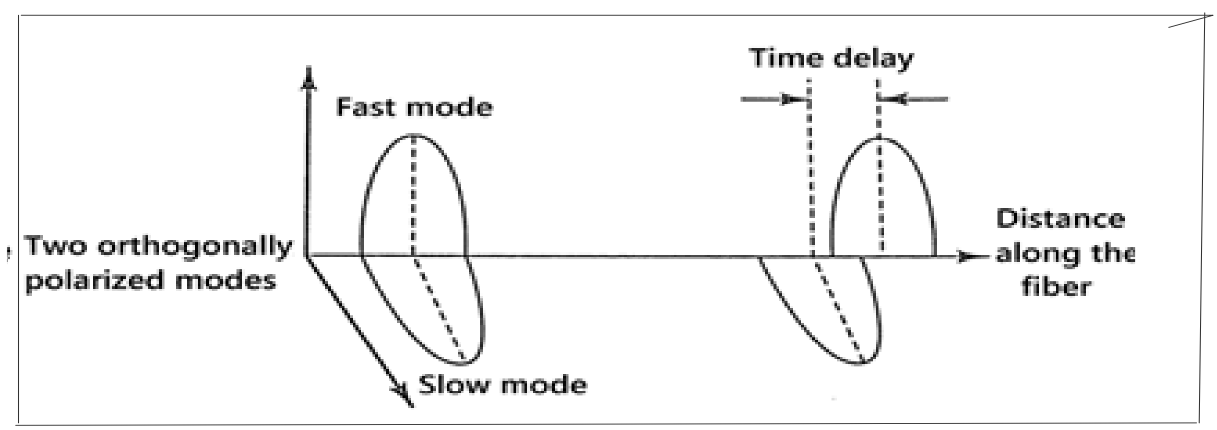


Figure 2.3:The Effect of PMD Along the Fiber Transmission (Sanchez et al., 2013)

2.4 Non-Linear effect in Optical Fiber Transmission

The existence of a nonlinear effect in an optical communication system might cause communication between two receiving locations to be disrupted. A primary factor that can deteriorate the optical signal and impair transmission is fiber dispersion and attenuation. It is, however, not the only factor. Fiber nonlinearity can cause the optical signal to be distorted, affecting optical transmission. The Kerr nonlinearity and the stimulated elastic scattering process are two types of fiber nonlinear impairments. The Kerr nonlinearity is caused by the fiber refractive index, which is affected by the signal intensity. and expressed as (Pamukti & Perdana, 2016).

$$n\left(\omega,|E|^2\right)=n(w)+n_2|E|^2 \tag{2.12}$$

Where the nonlinear index coefficient is $n2$, and ω is the angular frequency. Self-phase modulation, cross-phase modulation, and four-wave mixing are three major nonlinear processes that make up the Kerr nonlinearity. The impact of self-phase modulation (SPM) is depends on the refractive index and occurs during the propagation of an ultra-short pulse through a single mode fiber, resulting in a fluctuating medium refractive index. A phase shift in the pulse will occur as a result of this variation. (Rasheed et al., 2012). The frequency spectrum of the pulse will vary as a result of this. The optical intensity is proportional to the nonlinear phase shift, which is given by

$$\phi=n_2kL\left|E(l,T)\right|^2 \tag{2.13}$$

Where $\emptyset$ is the nonlinear phase shift, n is the Kerr coefficient, l is the length of the fiber, E(l, t) is the electrical field at l distance=$2\pi/\lambda$, where λ is the wavelength of the signal. The action of SPM extends the optical pulse spectrum without changing the pulse shape. The optical pulse will generate more frequency components, resulting in a frequency chirp. Cross-phase modulation, on the other hand, occurs when two or more optical pulses alter each other's intensity and phase of pulse cause broadening. When two optical fields, E1 at frequency $\omega 1$ and E2 at frequency $\omega 2$, propagate through the fiber at the same time, the nonlinear phase shift is given by

$$\phi=n_2kL\left(|E_1|^2+|E_2|^2\right) \tag{2.14}$$

where E1 and E2 represent the optical fields. Because of chromatic dispersion, XPM causes the signal to broaden as it travels across the optical fibre. Another type of Kerr nonlinearity is occurring three wavelengths interfere with each other, causing refractive index gratings result four wave mixing occurs. The gratings will interact with the signals and produce new frequencies, giving rise to the fourth wavelength. The second type Non-linear effect are the stimulated elastic scattering, helps the energy transfer from the optical field to the medium (Nain et al., 2017). It includes two types: Stimulated Raman Scattering, and Stimulated Brillouin Scattering.

2.4.1 Stimulated Raman and Brillouin Scattering

SRS occurs when light particles traveling through a single mode fiber cause molecule to vibrate and become stimulated. As a result, light particles are scattered, which is referred to as SRS. (Asvial & Paramitha, 2016). This can occur in both forward and reverse directions. When the optical input power in the optical fiber is high, Stimulated Brillouin Scattering occurs. It produces a backward-propagating beam of light. When the input power is low, the SBS impact is small, but when the input power is high, it becomes considerable.

2.5 Overview of Orthogonal Frequency Division Multiplexing and it is Basic

Despite the many advantages of OFDM, and its big use in wi-fi communications, OFDM has only these days been applied to optical communications. This is partly because of the recent demand for increased information quotes across dispersive optical media and in part due to the fact tendencies in virtual signal processing (DSP) era make system optical data rates feasible. One of the fundamental strengths of OFDM modulation format is its rich variant and simplicity of adaption to a extensive range of packages. In wireless systems, OFDM has been incorporated in wireless LAN (IEEE 802. 11a/g, or better known as Wi-Fi), wireless WAN (IEEE 802.16e, or better known as (WiMAX), and digital radio/video systems (DAB/DVB) adopted in most parts of the world. In RF cable structures, OFDM has been incorporated in ADSL and VDSL broadband entry to via phone copper wiring or power line (Kenshil, 2018). This rich diversity is due to OFDM modulation's inherent advantages, such as dispersion robustness, simplicity of dynamic channel prediction and mitigation, high spectral efficiency, and dynamic bit and power loading capacity. Optical OFDM has made significant progress recently. Many unique suggestions and demonstrations of optical OFDM systems from many areas of application have been seen, all aiming to benefit from the above-mentioned OFDM advantages. Despite the fact that OFDM has been extensively investigated in the RF domain, the first paper on optical OFDM just emerged in decay, where they reported in-depth performance analysis of hybrid AM/OFDM subcarrier-multiplexed (SCM) fiber optic systems. The lack of interest in optical OFDM in the past comes from the fact that silicon signal processing power had not yet advanced to the point where sophisticated OFDM signal processing could be conducted in a CMOS integrated circuit. According to their underlying techniques and programs, optical OFDM detection is divided into two categories: coherent detection and direct detection. While direct detection has been the basis of optical communications for decades, recent advances in forward-searching research have undeniably pointed to the trend that coherent detection is the future of optical communications. The coherent equivalent has many fewer permutations than DDO-OFDM. This is owing to the fact that direct-detection OFDM has a wider range of applications due to its reduced cost of communication (H. Ali, 2017).

2.5.1 OFDM Basics

OFDM is a multicarrier modulation technique that can support high data rates and provide better performance than single-carrier modulations, such as resistance to frequency-selective fading channels, ease of effective equalization, efficient spectrum usage, subcarrier allocation flexibility, and subcarrier modulation adaptability. OFDM has undergone extensive research and is utilized in both wired and wireless communication. OFDM is a type of multicarrier modulation in which the data signal is divided into multiple narrowband subcarriers and sent over a large number of lower-rate subcarriers. OFDM is also configurable to robust channel dispersion. The OFDM guard intervals utilized to achieve the system's orthogonality provide large bandwidth and high data speeds. The use of guard intervals, on the other hand, will have an impact on the system's spectral efficiency. OFDM is an effective solution to the problem of inter-symbol interference generated by a dispersive channel, which is why it is frequently used in wireless and optical communication systems. (Shieh, 2011). The OFDM technique consists of two parts these are, transmitter and receiver section. The transceiver contains number of blocks and each are explained and discussed as follows.

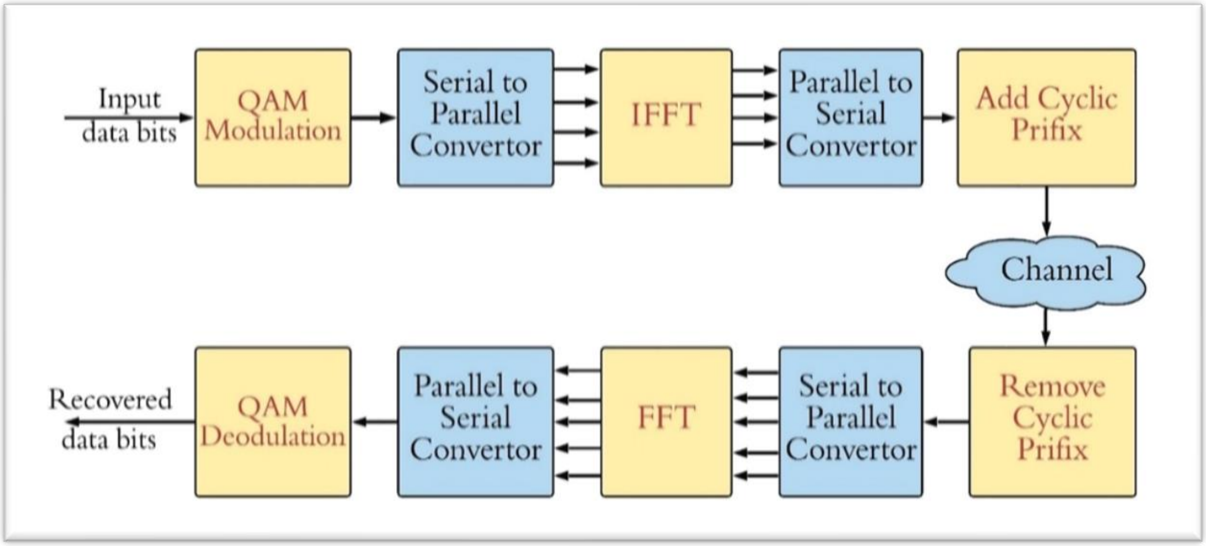


Figure 2.4:Block diagram of OFDM Transmitter and Receiver (Koundal & Dewra, 2019)

2.5.2 Serial to Parallel Conversion

The data is mapped using multilevel modulation techniques or translating data to complex values in an OFDM transmitter, and the data stream's sequence is transformed from serial to parallel. The parallel data symbols that arise are divided into several subsets. The number of subcarriers determines the number of data symbols that are conveyed by each subset. Let's pretend we have eight data symbols to send over four subcarriers to demonstrate this process. By dividing the number of data symbols by the number of subcarriers, the number of data symbols for each subset simply computed.

2.5.3 Inverse Fast Fourier Transform

Modern OFDM has the advantage of using the Inverse Fast Fourier Transform (IFFT). IFFT has the capacity to efficiently and accurately perform frequency up conversion and multiplexing of complicated subcarriers. The FFT is also used to conduct demodulation and de-multiplexing at the receiver. The IFFT/FFT digital process is thus at the heart of the OFDM transceiver. The FFT algorithms will ensure that the subcarriers in OFDM transceivers are orthogonal and will help to avoid interference. The basic goal of maintaining subcarrier orthogonality is to avoid having the subcarrier center frequency overlap with other subcarriers while the subcarrier spectrum overlaps. By supporting the system's orthogonality, the FFT method can ensure that no interference arises between adjacent signals. (Almasoudi, 2013). The IFFT mathematically described by

$$x(n) = \frac{1}{\sqrt{N}} x(k) e^{j2\pi k/N}$$
$$x(k) = Ae^{j2\theta} \tag{2.15}$$

The user's data bit x(k) is encoded using the N-th symbol and the k-th subcarrier. The phase and amplitude of the signal constellation's points are denoted by A and, Ɵ respectively. The time domain of the k-th subcarrier within the n-th symbol duration can be defined as (Dhingra et al., 2018).

$$x_{n,k}(t) = X_{n,k} \Upsilon(t - nT_s) e^{j2\pi f_k(t)}$$
$$\Upsilon(t) = \begin{cases} 1, t \in [0, T_s] \\ 0, t \notin [0, T_s] \end{cases} \qquad k=0,1..N_s \tag{2.16}$$

where N_s denotes to the number of subcarriers, f_k represents the k-th subcarrier frequency, T_s is the symbol period of OFDM, and Ґ(t) has a unity magnitude over the duration time of with a shape of rectangular pulse. In the n-th symbol period, the relationship between any two subcarriers is described by

$$\frac{1}{T_s} \int_{(n-1)T_s}^{nT_s} x_{k,n}(t) x^*_n(t) dt = e^{j2\pi(f_k - f_l)\frac{\sin(\pi(f_k - f_l)T_s)}{\pi(f_k - f)}} \tag{2.17}$$

where fk and fl are the subcarriers frequencies, and Ts is the symbol period

$$f_k - f_l = m\frac{1}{T_s} \tag{2.18}$$

When the above equation is meet, the two subcarriers are orthogonal to each other. This orthogonality condition will help to recover the signal without Inter carrier Interference (ICI), regardless of the strong overlapping of the signal spectral and frequency spacing of the subcarrier given by;

$$\Delta f = f_k - f_{k-1} \tag{2.19}$$

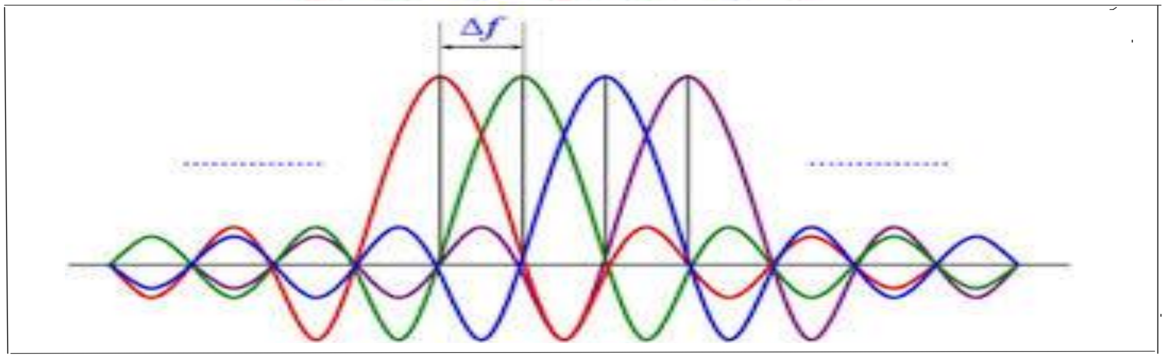


Figure 2.5:The Orthogonal Subcarrier Spectrum of the OFDM (Sharma & Kr. Singh, 2016)

2.5.4 Cyclic Prefix for OFDM

One of the most essential strategies for avoiding dispersion medium effects such as chromatic dispersions (CP) and polarization dispersions mode is to use a cyclic prefix. CP is one of the approaches that can be used to remove ISI. An extension from the symbol's last part is added to the symbol's beginning of the new symbol. The subcarrier time plus the guard time equals the OFDM symbol time.

$$T_{OFDM,s} = T_{sub} + T_G \tag{2.20}$$

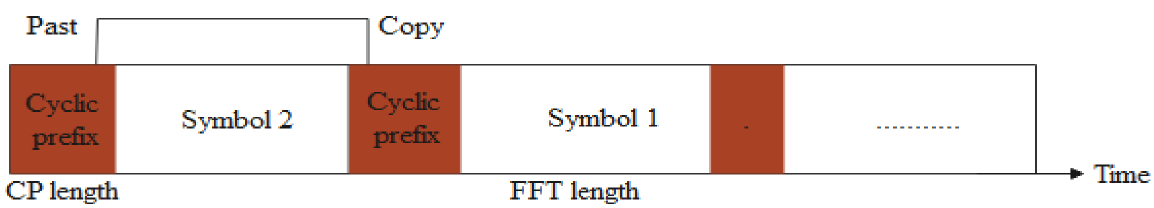


Figure 2.6: Cyclic Prefix insertion in OFDM symbol

To retain the lowest effect of ISI, the CP length should be greater than the length of the multipath channel delay. If the multipath channel delay is greater than the CP length, ISI will occur between the adjacent symbols.

2.5.5 Fast Fourier Transform

This operation done at the receiver part of OFDM system. After removing the cyclic prefix, the OFDM symbols are used the FFT technique to convert the right values to the frequency domain. Without the usage of a large number of oscillator’s and filters, FFT can recover the subcarriers in a single step. The down covert digital signal represents by (Sanchez et al., 2013).

$$z(k) = e^{\frac{j2\pi kv}{N}} \sum_{p=0}^{k-1} l_p s(k-\eta) + n(k) \tag{2.21}$$

The OFDM transmitter and receiver subcarriers will be revealed to be orthogonal using FFT techniques, which will aid in noise cancellation. While the subcarrier signal overlaps, the main purpose of subcarrier orthogonality is to keep the subcarrier center frequency from overlapping with that of other subcarriers.

2.5.6 Advantages of OFDM

Orthogonal frequency division multiplexing offers a number of benefits that make it a viable option for future optical technologies such as:

- Multipath delay spread tolerance: Inter symbol interference is reduced by using guard time in orthogonal frequency division multiplexing because it is immune to multipath delay spread, which causes inter symbol interference in different mobile networks.
- Immunity to frequency selective fading Channels: if the channel enforces frequency selective fading, advanced equalization techniques are necessary for single carrier modulation schemes.
- High spectral efficiency: In the frequency domain, OFDM permits subcarriers to overlap while remaining orthogonal to one another.
- Efficient modulation and demodulation: The subcarrier is modulated and demodulated using the IFFT and FFT techniques, which are crucial in OFDM.

2.5.7 Disadvantages of OFDM

OFDM, more complicated than single carrier modulation, has some drawbacks due to its complexity. OFDM requires a more linear power amplifier and enables multicarrier modulation techniques, which are more sophisticated than single carrier modulation techniques. Furthermore, OFDM has a variety of disadvantages, including:

- High peak to Average power ratio (PAPR).
- Sensitive to Doppler shift.
- Sensitive to frequency synchronization problems.

CHAPTER THREE
MATERIALS AND SYSTEM MODEL

3.1 Introduction

In this chapter approach for design and development of coherent-OOFDM communication systems over WDM network has been designed and simulated using Optisystem software with different modulation schemes such as QAM-OOFDM, PSK-OOFDM. It's used to develop, design, and test the Coherent-OOFDM technology in optical network. In the Optisystem, global and system parameters for WDM, coherent-OOFDM, and coherent-OOFDM in wave division optical networks were studied and analyzed.

3.2 Methods

The successful conducted of this work follow the following steps: -

Phase-I: In this section, you will look over several literature reviews that are linked to the thesis subjects, as well as identifying the gap in technology in the literature and understanding the theoretical concept. In includes the basics of optical communication, coherent processing, OOFDM techniques, and WDM systems, as well as the impact of these systems on development of optical communication.

Phase-II In this part concentrates on designing the system using simulation tools while adhering to the theoretical principle. It entails system analysis, parameter identification, system modeling based on specified parameters, simulation and analysis of findings, testing the proposed work, and a conclusion about the efficiency or improvement of the proposed work in relation to the existing system.

3.3 Materials

When a new system model or proposed it should be test and check by using simulation software, before real implementation. In this thesis, all system models and simulations are carried out using the simulation software called Optisystem. Optisystem is a software platform that allows users to plan, test, and simulate optical links in modern optical networks at the transmission layer. This application includes a variety of optical and wireless components for developing and building a comprehensive optical network, which is a low-cost and time-saving system that allows the researcher to work more efficiently. This program provides a wide variety of wireless and optical characteristics to assist researchers in designing a full optical fiber network.

Optisystem support the following internal tools to analysis the effect of each parameter on design network, Spectrum and BER analyzer, Eye diagrams, Q-Factor measurement; Constellation diagrams, Power meter, WDM analyzer, SNR, OSNR and Optical spectrum analyzer. As a result, it is utilized by a variety of telecommunications businesses, today.

3.4 The Model of Coherent-OOFDM Techniques in Wave Division Network

The integration of coherent-OOFDM in wave division optical network is presented below as a block diagram form**.** In this arrangement, that transmitter includes QAM modulation Coherent-OOFDM baseband transmission, RF up conversion, and optical modulation, whereas the receiver includes Coherent-OOFDM baseband reception, RF down conversion, and optical detection. The PRBS used to generate at random data characteristic and input for M-array PSK or QAM modulation schemes are used to encode or map the input signal in the OFDM modulator. Before being transported through an optical carrier and onto a single mode fiber, the baseband signal from OFDM modulator converted in to analog signal through analog to digital converter it is input for an RF up converter then modulate through an optical modulator using light as a carrier from laser sources. Optical data is translated to electrical impulses by photo detectors at coherent-OOFDM receiver, which are subsequently converted to digital signals by analog to digital converters and further processing in OFDM demodulator and QAM decoder.

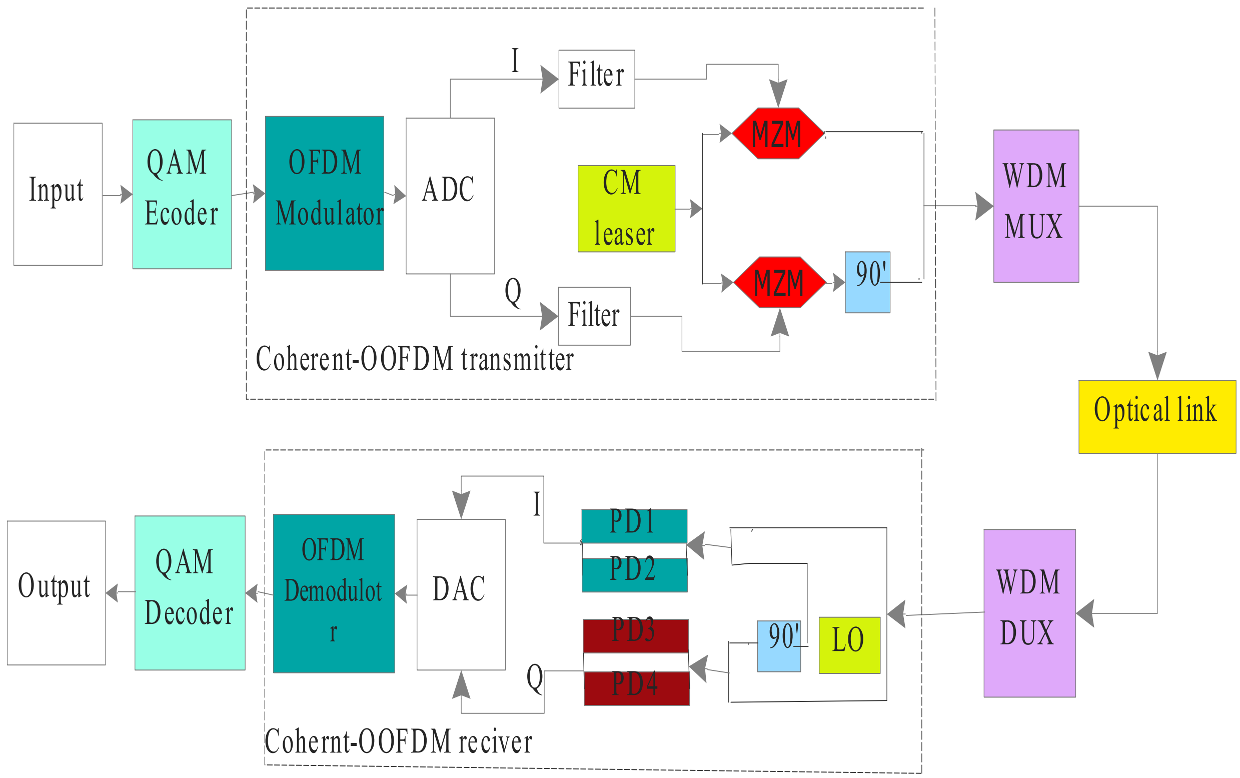


Figure 3.1: The Proposed System Model

3.4.1 Coherent- OOFDM Transmitter

The coherent- OOFDM transmitter system consists of; the QPSK/QAM sequence generator, analog digital converter, baseband OFDM modulator and optical modulator. The I and Q components of an OFDM generator output are mapped to an optical signal via an external optical modulator and continuous signal laser source, then multiplexed and driven into an optical transmission channel in an optical up conversion (Galmecha et al., 2021).

3.4.2 Quadrature Amplitude modulation

The M-level modulation format modifies data by modulating both the amplitude and phase of the original signal to increase the number of bits per symbol. QAM (Quadrature Amplitude Modulation) is an amplitude modulation technique that combines Amplitude Shift Keying and Phase Shift Keying, respectively. The modulation of two signal amplitudes that are out of phase with each other is known as quadrature amplitude modulation (QAM). In coherent-OOFDM transmission system the basic function expressed as a sinusoidal signal in the form of:

$$s_n(t) = A(t)e^{2\pi f_n t} \tag{3.1}$$

The quadrature amplitude modulation form of $S_n(t)$

$$s_n(t)=A(t)\cos(2\pi f_n t)+jA(t)\sin(2\pi f_n t) \tag{3.2}$$

Where A(t) and jA(t) phase (I) and quadrature (Q) correspondingly, and by utilizing a Quadrature Amplitude Modulation (QAM) modulator, the data bit stream is divided into Phase (I) and Quadrature (Q) and then mixed and translated to a complex symbol. The complex symbol was broadcast and divided at the receiver using a Quadrature Amplitude demodulator to achieve the output result. Multi-level optical modulation systems offer high spectral efficiency at the cost of reduced tolerance, according to Shannon's rule, which defines the theoretical maximum bit rate that can be transmitted over a bandwidth limited channel in the presence of noise (Singya et al., 2021).

3.4.3 Mathematical Formulation of Multicarrier Modulation of Coherent-OOFDM Signal

Orthogonal frequency-division multiplexing (OFDM) is a special class of multicarrier modulation. An OFDM signal is made up of a continuous stream of OFDM symbols with a regular period Ts in the time domain (Arthur et al., 2018). The baseband multicarrier modulation transmitted signal s (t) is represented as

$$s(t)=\sum_{i=-\infty}^{\infty}\sum_{m=-\frac{N_{sc}}{2}+1}^{m=\frac{N_{sc}}{2}} q_{mi}e^{\left(j2\pi f_m\left(t-iT_s\right)\right)}f(t-iT) \tag{3.3}$$

Where q_{mi} is the i-th information symbol at the m-th subcarrier, f (t) the symbol waveform and the frequency of sub-carrier given by

$$f_m=\frac{m-1}{t_s} \tag{3.4}$$

The pluses waveform of the symbol f(t) in multicarrier modulation transmitted signal s (t) is expressed as

$$f(t)=\begin{cases}1,\left(t_c<t\le t_s\right)\\ 0,\left(t_c\le -t_{c,}t\ge t_s\right)\end{cases} \tag{3.5}$$

Where t_c cyclic prefix length, T_s OFDM symbol period and t_s observation time.

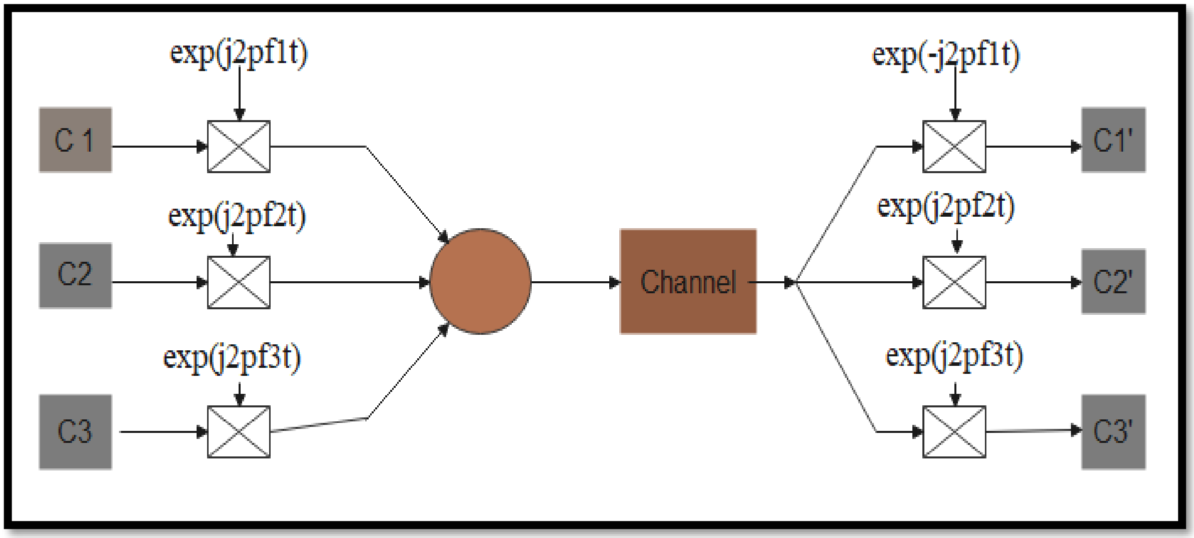


Figure 3.2: Generic of Multicarrier Modulation System

The detection information symbol at the output of multicarrier modulation represented by

$$q_{mi} = \frac{1}{T_s} \int_0^{T_s} r(t - iT_s) e^{(-j2\pi f_m t)dt} \tag{3.6}$$

r(t) represents the received time domain signal. The sub-carriers in an OFDM multicarrier system can be overlapped to save bandwidth, and the orthogonal sets give non-interfering carriers and better spectral efficiency than traditional multicarrier transmission. The insertion of a cyclic prefix is one of the enabling strategies for OFDM to transmit overlapped subcarrier and to reduce channel dispersion-induced inter-symbol interference (ISI) and ICI. Because the maximum delay spread of multi-path fading in OFDM principles is smaller than the guard time Δ_t, the cyclic prefix can completely eliminate ISI. In coherent–OOFDM optical transmission the delay spread due to dispersion among the subcarriers should not exceed the guard time for complete inter symbol interference elimination in optical medium and it is depending on this formulated condition.

$$\frac{c}{f_o^{\,2}} |D_c| N_{sc} \Delta f \leq \Delta_t \tag{3.6}$$

where, f_o is the optical carrier's frequency, D_c is the total accumulated chromatic dispersion in ps/km, and Nsc is the number of subcarriers. Nsc subcarriers are transmitted in coherent-OOFDM systems every OFDM symbol period of Ts (Bi et al., 2017). As a result, for coherent-OOFDM systems, the total symbol rate R is described as

$$R = \frac{N_{sc}}{T_s} \tag{3.7}$$

In the development of Coherent–OOFDM in wave division optical network, the bandwidth of OFDM in each wavelength channel given by

$$B = \frac{2}{T_s} + \frac{N_{sc} - 1}{t_s} \tag{3.8}$$

Where ts is the observation period. Assuming that a large number of subcarriers are used, the bandwidth efficiency of OFDM η is found to be

$$\eta = \frac{nR}{B} \tag{3.9}$$

The index n, describe the polarization transmitted electric filed in fiber. optical OFDM in wave division optical network the spectral efficient further improved by using high order QAM modulation.

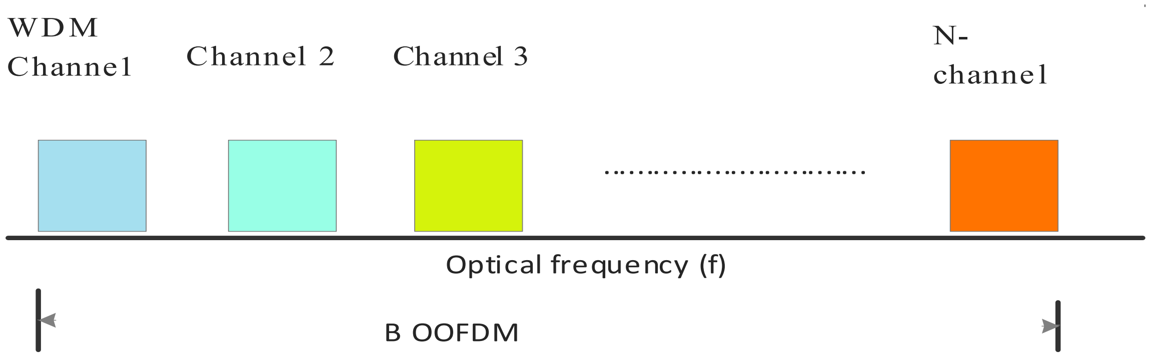


Figure 3.3: The Bandwidth of OOFDM in WDM Channel.

3.4.4 Digital to Analog Converter

After OFDM modulator convert the data bits into each OFDM symbol and construct the time domain signal using the IFFT with the cyclic prefix insertion. The digital signal is then transformed to analogue using a digital-to-analogue converter, and the alias signal is removed using a low-pass filter (LPF). The digital signal is often stored in media or a communication line, and then a digital to analog converter converts it to an analog signal for data display or additional analog signal processing. For example, in a digital communication system, when the receiver receives a digital modulation signal, we can extract the digital signal using a demodulator and decoder, and then convert the digital signal to an analog signal using a digital analog converter. A digital to analog converter is essentially a digital code that represents a digital value transformed to an analog voltage or current (Pickering, 2018).

3.4.5 Coherent Optical I/Q Modulator and detector

Optical I/Q modulator convert real/imaginary components of the resultant base band time domain from the RF domain to the optical domain it consists of a pair of Mach-Zehnder modulators (MZM) with a 90° phase offset. In high-data-rate transmission systems, dual-drive MZMs are critical for extending reach without dispersion compensation. Two independent RF electrodes are used in the dual-drive design. Both electrodes must be synchronized by the design in order to modulate the optical field at the same time and with the same group delays. Furthermore, to suppress harmonics in the modulated optical spectrum, a suitable phase-delay between inputs signals can be introduced. The received optical signal is split into two equal arms (in-phase arm and quadrature arm). Field amplitude modulation is achieved in both arms by operating MZM in a push-pull mode, with an extra phase shift of π /2 introduced in one of the arms. Two DD- MZMs are used in the I/Q modulator to modulate the I/Q components of the RF drive signal individually, and their outputs are mixed in a 90° hybrid. The optical modulation of base band signal expressed as

$$E(t) = e^{\left(jw_{Lt}t + \phi_{Lt} \right)} \cdot s(t) \tag{3.10}$$

The angular frequency and phase of the transmitter laser are W_{Lt} and φ_{Lt}, respectively. A local laser is used in conjunction with two Mach-Zehnder modulators, one of which has a 90-degree phase shift and combining the two signals yields the modulated signal. The important of of the In-phase quadrature modulator to reduces symbol rotation or the addition of a dimension to the signal is its principal advantage.

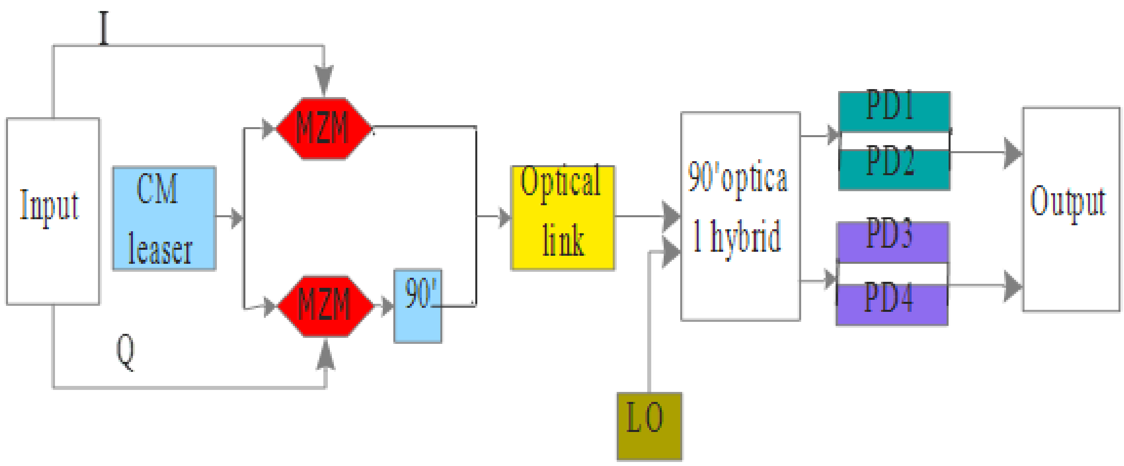


Figure 3.4: Coherent Optical I/Q Modulator and Detector System

Two sets of balanced receivers' detector and an optical 90° hybrid are employed on the receiver side to provide optical I/Q detection. The incoming optical single at the receive can be expressed as:

$$E(t) = e^{(jw_{TI} + \phi_{TI})} s(t) \otimes h(t) \tag{3.11}$$

and fed in to optical to RF down converter or detection. The transmitter and receiver leaser have equal frequency the process is homodyne detection. The transmitter and receiver leaser have different frequency the process is heterodyne detection. The coherent -OOFDM receiver recovered the received information signal after detection and OFDM baseband processing.

3.4.6 The Detection Approach in Coherent-OOFDM Processing

Coherent-OOFDM is for linear detection and excellent spectrum efficiency. Through the use of a cyclic prefix code, the coherent-OOFDM system may be able to overcome several optical fiber limitations such as chromatic dispersion (CD), polarization mode dispersion (PMD), and immunity to inter-symbol interference. Coherent OFDM offers the best receiver sensitivity, spectrum efficiency, this allow long distance communication with a smaller number of optical amplifier requirement this reduce cost of communication and complexity in transmitter and receiver design. The number of subcarriers generated at the OFDM transmitter has a direct effect on the performance of coherent–OOFDM. When the number of subcarriers is relatively great, interference between the sub-carrier channels occurs and the use of spectrum will be increased. As a result, keeping track of the number of subcarriers in a coherent optical OFDM system is critical. To generate optical signal, we used the optical local oscillator or a leaser sources at a certain wavelength. Optical coherent detection is divided into two categories based on the magnitude of frequency generated by the local oscillator: heterodyne detection and homodyne detection. The local oscillator frequency in heterodyne detection is not equal to the incoming signal frequency. When two signals are combined in a photodetector, a new frequency is formed called the intermediate frequency (IF), which is the difference between the two frequency. Thermal and shot noise are reduced as a result, and the signal to noise ratio is enhanced. In optical communication, a coherent –OOFDM system will fully adapt and estimate polarization mode dispersion. The product of the electric fields of the modulated light signal and the continuous-wave of the local oscillator is used to detect the coherent receiver (Kikuchi, 2016). Complex electric field of the transmitted optical signal be given by:

$$E(t) = Ae^{(j\omega_{Tl} + \phi_{Tl})} \cdot y(t) \tag{3.12}$$

Where A, complex amplitude transmitted signal, y(t) represent linear convolution of baseband OFDM signal and channel impulse response. The complete electric field of local oscillator signal E_{Lo} given by:

$$E_L(t) = A_L e^{(j\omega_L + \phi_L)} \tag{3.13}$$

Where A(t) is the complex amplitude and ω is the angular frequency. Depend on the number of photodiodes used the electric filed incident and the photocurrent generated on the photodiode given by

$$E_1 = \frac{1}{\sqrt{2}}(E + E_L) \tag{3.14}$$

$$I_1(t) = \frac{\Re}{\sqrt{2}}\left[\mathrm{Re}\left(Ae^{(j\omega_{Tl} + \phi_{TL})} + A_L e^{(j\omega_L + \phi_L)}\right)\right]^{ms} \tag{3.15}$$

Where *R* is the responsivity of the photodiode given by

$$\Re = \frac{2\pi q\eta}{h\omega_{Lt}} \tag{3.16}$$

3.4.6.1 Heterodyne Detection

Heterodyne detection approach selected when the transmitter and receiver leaser frequency are different or the intermediate frequency different from zero and the symbol rate equal to1/T_w which determine modulation bandwidth of the optical carrier. Through this electric field of received signal is down-converted to an IF signal that includes both amplitude and phase information without spectral folding. The complex amplitude of received photocurrent in this case given by

$$I(t) = 2\Re\sqrt{P(t)P_L(t)} * e^{(j(\theta+\theta_n))} \tag{3.17}$$

where p(t) and p_L(t) signal power and local oscillator power and Θ and $Θ_n$ are signal phase and total phase noise phase modulated signal respectively. The phase-locked loop (PLL) circuit must be used at the IF stage to synchronously demodulate the heterodyne detected IF signal. Despite the fact that total phase noise may change over time, the electrical PLL circuit may estimate phase noise and decode the symbol of the phase current.

3.4.6.2 Homodyne Detection

When the local oscillator frequency and the transmitted optical signal frequency are equal the output signal recovered from the modulated signal using homodyne detection. In optical coherent detection, homodyne detection is the simplest digital signal processing (DSP) technique, which decreases receiver bandwidth demands. As a result, homodyne detection is a better choice for formats with high spectral efficiency, such as optical orthogonal frequency division multiplexing, which has a flat optical spectrum and is less prone to high-frequency distortion. Again, homodyne detection is the simplest approach for detecting coherence since it takes the least amount of digital signal processing because it does not require any carrier frequency offset or compensation and it does not require direct carrier phase recovery. It is the most sensitive coherent system, but it is difficult to build and the receiver photocurrent in this case given by

$$I(t) = 2\Re\sqrt{p(t)p_L(t)}\cos(\theta(t) - \theta_l(l) \tag{3.18}$$

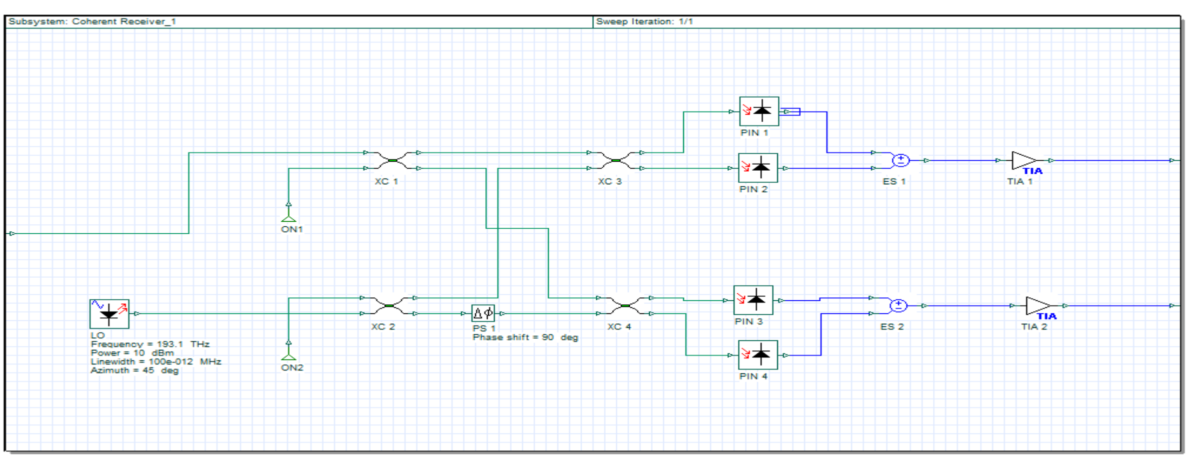


Figure 3.5: Schematic Diagram of Homodyne Detection

The homodyne receiver measures the inner product of the signal phasor and the LO phasor, as shown in the equation above. In order to successfully decode the symbol, the local oscillator phase, must track the transmitter phase noise to eliminate the total phase noise. Optical phase local loops must be used to realize this function. The incident electric field on each photodiode is given by (Dahiya & Garg, 2020).

$$E_{1,2} = \frac{1}{2}\left[Ae^{(j\omega_{LT}+\phi_{LT})} * y(t) \pm A_L e^{(j\omega_L+\phi_L)} \right] \tag{3.19}$$

$$E_{3,4} = \frac{1}{2}\left[Ae^{(j\omega_{LT}+\phi_{LT})} * y(t) \pm jA_L e^{(j\omega_L+\phi_L)} \right] \tag{3.20}$$

The electric filed incident on photodiodes one and two are $E_{1,2}$ and photodiodes three and four $E_{3,4}$ respectively. The output photocurrent from the balanced photodiode has in phase and quadrature and proportional to the square of the electric filed incident on the photodiode and expressed as:

$$I(t) = \frac{1}{2}\left[|E(t)|^2 \right] + \left[|E_L(t)|^2 \right] + 2\,\mathrm{Re}\left(E(t)E_L(t) \right)^* \tag{3.21}$$

The two-photo diode PD1 and PD2 are used for recovering of the In-phase component and expressed as:

$$I_I(t) = I_1 - I_2 = 2\,\mathrm{Re}(E(t)E_L(t))^* \tag{3.22}$$

The remaining two photodiodes, PD3 and PD4, are utilized to recover the Quadrature (Q) component, which is written as:

$$I_Q = I_3 - I_4 = 2\,\mathrm{Im}(E(t)E_L(t) \tag{3.23}$$

The real component of photocurrent is represented by Re, and imaginary component by Im the total complex signal I(t) is given as follows.

$$I(t) = I_I + jI_Q \tag{3.24}$$

After completing the optical detection, the signal is transmitted to the OFDM demodulator and QAM decoder to extract the original signal at the coherent-OOFDM receiver. The received signal at the OFDM demodulator represent by

$$r(t) = I(t) = e^{(j\omega_{If}t+\phi_{If})}\left(s(t) \otimes h(t) \right) \tag{3.25}$$

Where s(t) is baseband OFDM signal and h(t) optical channel impulse response. The intermediate frequency and phase formulated as:

$$\omega_{If} = \omega_{Tl} - \omega_{Rl}$$
$$\phi_{If} = \phi_{Tl} - \phi_{Rl} \tag{3.26}$$

ω_{If} , ϕ_{If} angular frequency and phase offset between transmit and receive lasers respectively

3.4.7 Coherent-OOFDM Receiver

In the RF OFDM receiver, the down-converted OFDM signal is first sampled with an analogue-to-digital converter (ADC). Analog to digital converters convert analog signals to digital signals in one way. Before a symbol decision can be made, the signal must go through several stages of operation. FFT window synchronization, in which the OFDM symbol is properly delineated to avoid inter symbol interference, frequency synchronization, in which the frequency offset must be estimated and compensated, and subcarrier recovery, in which each subcarrier channel must be estimated and compensated, are the three methods. The received information symbol represents after successful FFT, frequency synchronization, and subcarrier recovery (S.Swaminathan and N.R.Raajan2, 2017).

$$r_{mi} = e^{\phi} H_{mi} u_{mi} + n_{mi} \tag{3.27}$$

The received information symbol is r_{mi},u_{mi} transmitted information symbol φ, the OFDM symbol phase, the frequency domain channel transfer function is H, and the noise is n_{mi}. Estimated value for channel transfer function

$$H_{mi} = e^{-j\phi} \frac{r_{mi}}{u_{mi}} \tag{3.28}$$

r_{mi} which is then mapped back to the original digital bits through QAM decoder in order to deliver information to the receiver.

3.5 Coherent-OOFDM with EDFA and Single Mode Fiber

The Coherent-OOFDM system design consists of a Coherent-OOFDM transmitter, a fiber link and a Coherent-OOFDM. A pseudo random binary sequence (PRBS) is used to generate a bit sequence in the Coherent-OOFDM transmitter, encode through a QAM encoder. An OFDM modulator with subcarrier and FFT points is coupled to the QAM encoder. The I/Q optical modulator (RF to optical converter) receives the in-phase (I) and quadrature (Q) signals from the OFDM modulator and which composed of two lithium Niobate (LiNbO3) Mach-Zehnder modulators (MZM). The MZM will modulate the electrical signal from the OFDM modulator to the optical carrier with a laser source of 193 THz to 193.4 each four user with spacing of 100 GHz. The global and component parameters for the design of the coherent-OOFDM transmitter are presented below.

Table 3.1: Global and Component Parameters Coherent-OOFDM Transmitter

Parameter	Value
OFDM FFT point	1024
Number of sub-carriers	512
Cyclic prefix	Symbolic extension
Sequence length	32768
Sample per bit	4
Number of samples	131072

The number of samples, sequence length and sample per bit are the global parameters and related to each other. The number of samples for the input data is the product of sequence length and number of bits in the sample.

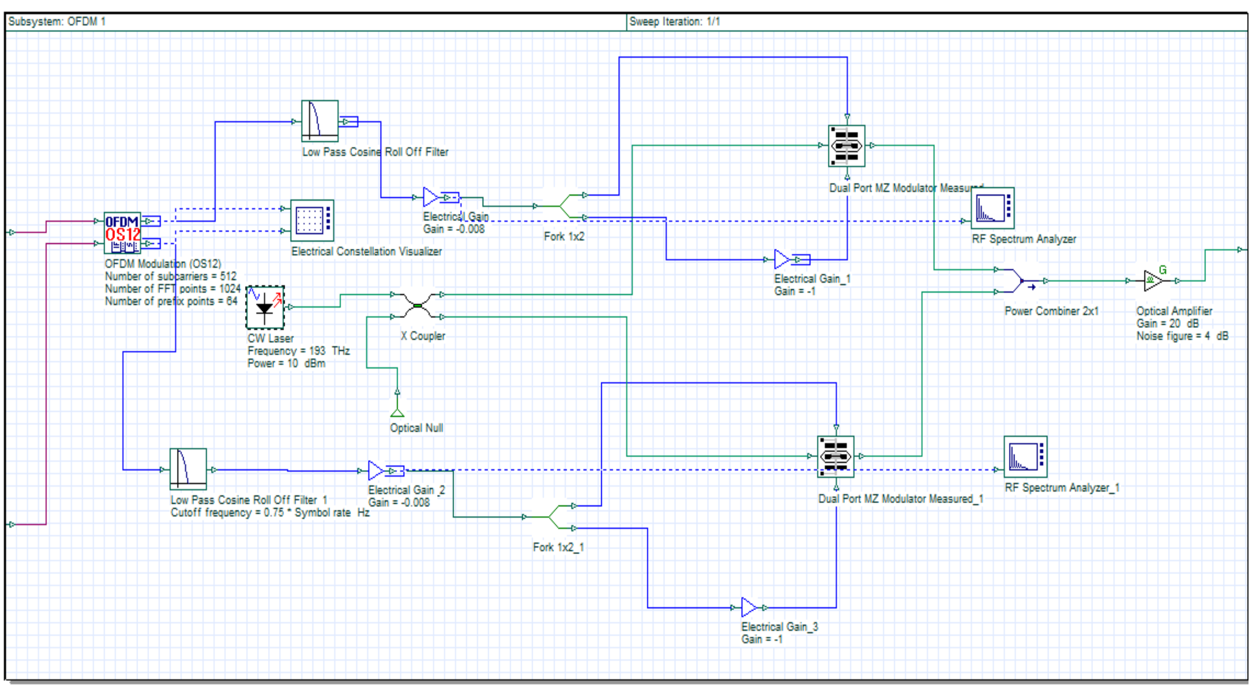


Figure 3.6: Design of Coherent-OOFDM Transmitter

The optical IQ modulated formed from two MZ modulator and used to up convert the OFDM signal in to optical domain.it used to reject the need of image rejection filter and reduce bandwidth requirement. Each MZ modulator consists of real or imaginary part of OFDM signal and one output of MZ modulator drive by 90-degree phase shift and then combines and launch to the optical fiber. in the receiver optical detection perform the conversion of optical signal in to electrical signal which consists of optical 90 hybrid and two pair of balanced photo detector. Mathematically the phase shift given by(Nehra & Kedia, 2016)

$$\Phi = \frac{V_B}{V_{SH}}\pi \tag{3.29}$$

Where V_B biase voltage and V_{SH} half switching voltage and filed transfer function of IQ modulator formulated through.

$$\frac{E_{out}}{E_{inp}} = \frac{1}{2}\left(\frac{\cos\Phi_1(t)}{2} + j\frac{\cos\Phi_2(t)}{2}\right) \tag{3.30}$$

where E_{out} denotes the outgoing phase modulated optical field, E_{inp} denotes the incoming phase modulated optical field and and Φ_1 and Φ_2 denote the phase shifts associated with the in phase and quadrature OFDM driving signals, respectively.

Table 3.2: The Parameter of MZ Optical Modulator.

Parameter	Value
Extinction ratio	30dB
Insertion lose	1dB
Bias voltage	4v
Switching voltage	8v

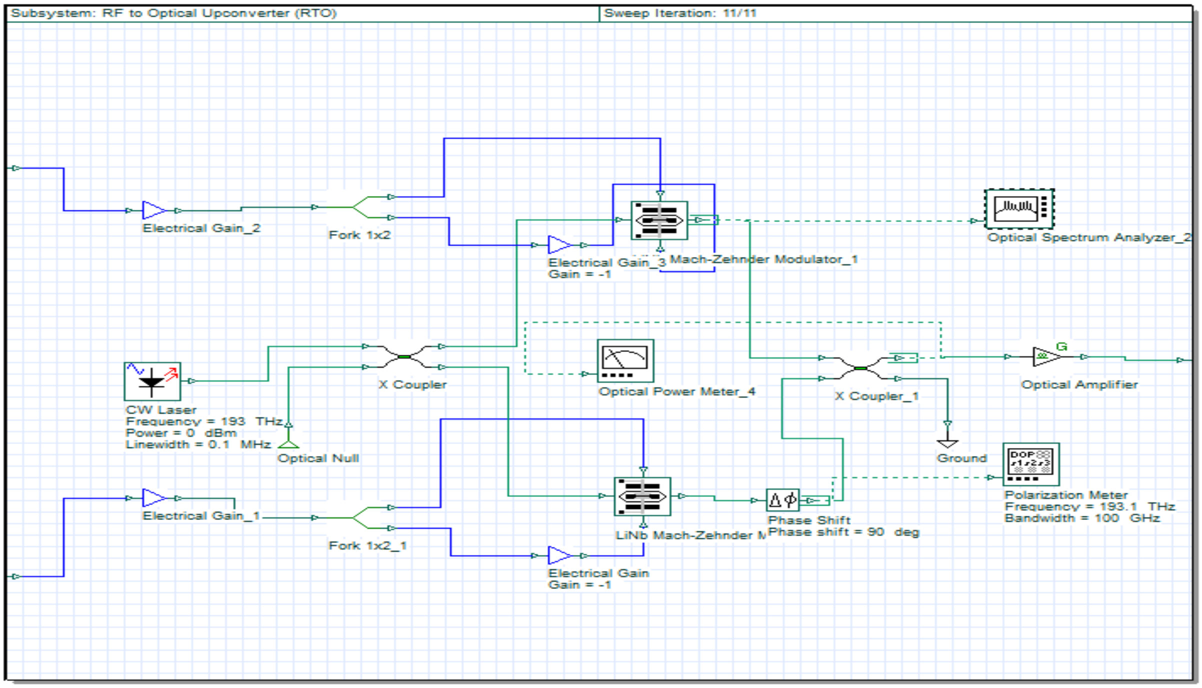


Figure 3.7: RTO in Coherent-OOFDM Transmitter

In the receiver of Coherent-OOFDM system network the incoming optical single convert to electrical signal through homodyne coherent detection and RF down converter which consists of two identical pair of balance detector with the local oscillator that have the same frequency with input leaser sources and balanced pairs of optical hybrids with optical 90° phase to complete in phase (I) and Quadrature (Q) detection the fed in to OFDM demodulator.

Table 3.3: The Parameter of Coherent-OOFDM Receiver

Parameter	Value
Responsivity	1A/W
Dark current	15nA
Sensitivity	10dBm

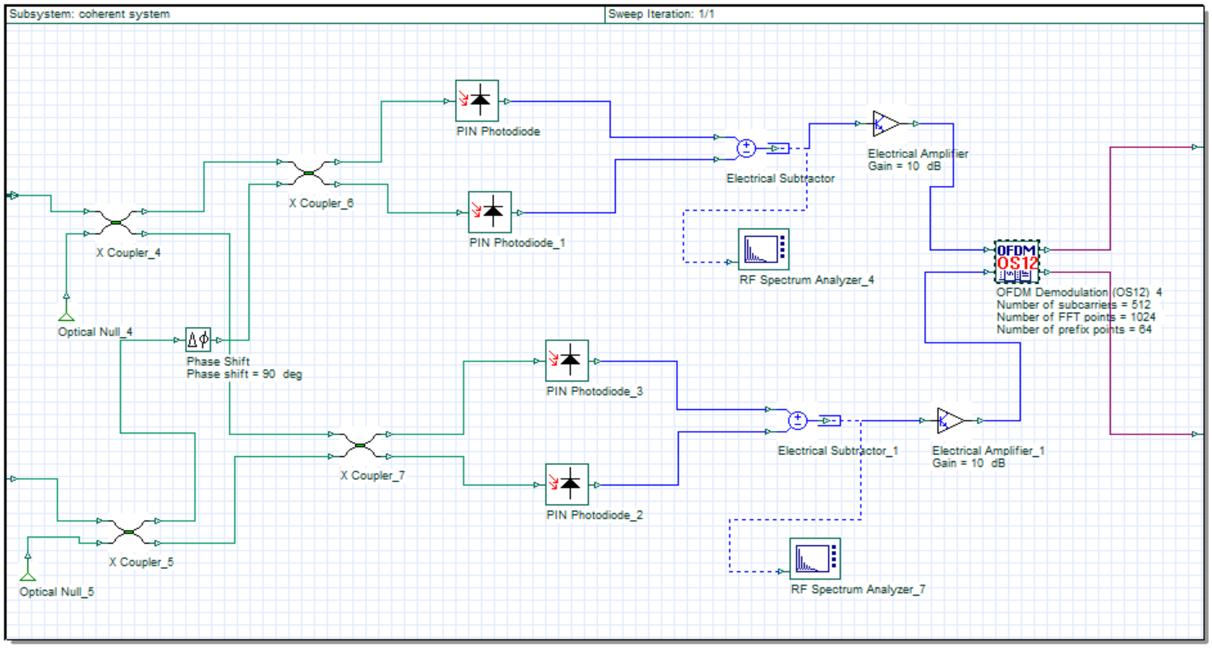


Figure 3.8: Coherent detection and OFDM Demodulator in Coherent –OOFDM Receiver

3.6 Wave-division network with EDFA using Single mode fiber

The design of wave-division network consists of three-part transmitter section, optical link and receiver section. In transmitter section optical modulated i.e machad zender modulator is used to modulate input signal through light signal from input leaser sources. To generate digital data, a pseudo random bit generator is utilized, and a pulse generator is used to convert it to electrical signal modulator, which combines electrical signal with light source to produce an optical signal that is supplied to a wave-division multiplexer. In wave-division transmission, the implementation of EDFA and dispersion compensating fibre is required for signal attenuation and dispersion reduction, respectively.

Table3.4: WDM Design Parameter

Parameter	Value
Number of channels	Four
Leaser power	-5dBm to 5dBm
Bit rate for each channel	250Gbps
Spacing frequency	100Ghz
Sequence coding	NRZ

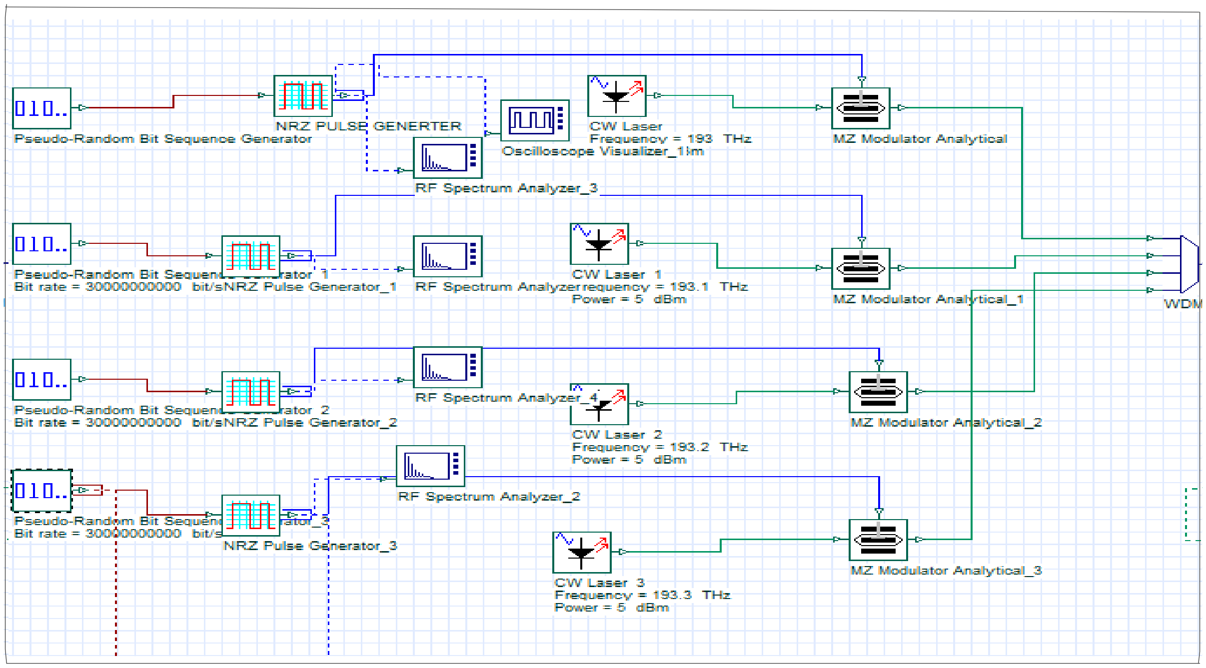


Figure 3.9: Design of WDM Transmitter Network

The design of wave division transmission link consists of optical amplifier that boosts the signal in optical domain, dispersion compensation fiber to reduce the effect of dispersion in the link and different parametric measurement. In this design single mode fiber are used with the following criteria Dispersion 16.75ps/nm/km, Attenuation 0.2dB/km, Core area 30 mm^2, Dispersion slope 0.085 ps/nm2/km, non-linear effect is on, refractive index profile $26e^{-021}m^2/w$ and the reference wavelength of 1550nm and EDFA amplifier with the gain 0f 15dB and noise figure 4dB.

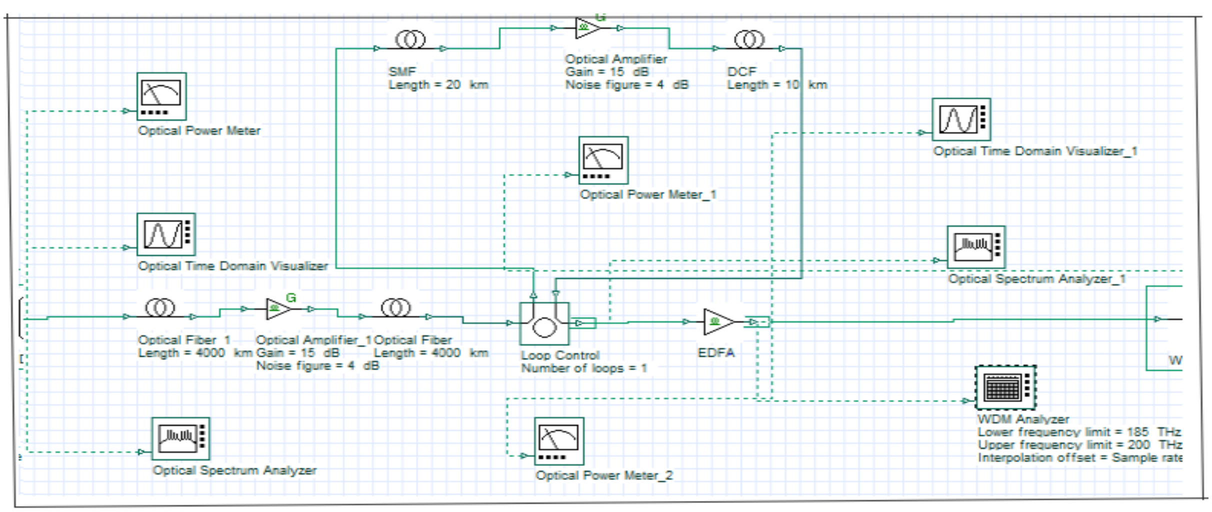


Figure 3.10: Design of WDM Optical Link

The receiver section the incoming optical signal from the wavelength-division demultiplexer convert to electrical signal through PIN photo detector and finally low pass Bessel filter is which 0.75 of symbol rate pass the lower frequency signal.

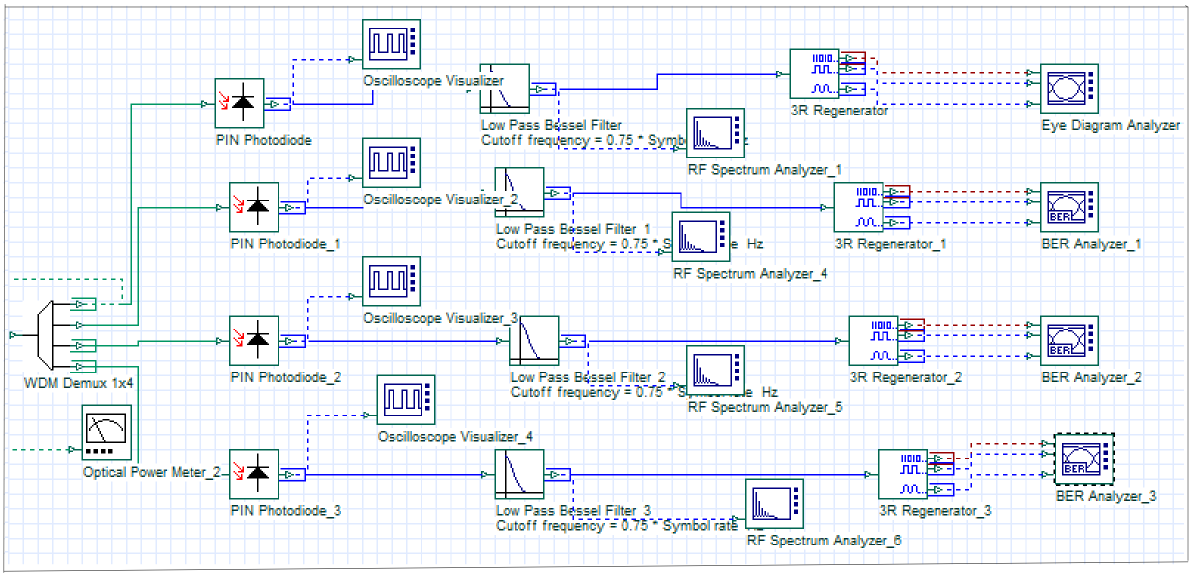


Figure3.11: Design of WDM Receiver

3.7 The Deployment of Coherent–OOFDM in Wave-Division Optical Network

Coherent-OOFDM provides ultimate performance in receiver sensitivity, spectral efficiency, and robustness against polarization and chromatic dispersion. WDM systems help to increase the system's capacity by delivering various wavelengths across a single fiber. Due to this integration of Coherent-OOFDM techniques in wave-division network retain efficiency for the system and reduced the optical effect. The Coherent-OOFDM transmitter is built with a Pseudo Random Binary Sequence (PRBS) to generate a bit sequence, and QAM encoder. The QAM encoder maps the input data in to symbol to generate the sinusoidal wave form for an OFDM modulator with subcarrier 512 and 1024 FFT points. The OFDM-based band signal is translated into the optical domain via an optical modulator, which uses light as a Carrie from a leaser source and launch to optical fiber though a WDM multiplexer.

Table 3.5: Design Parameter for Coherent-OOFDM-WDM

Parameter	Value
Data rate	1Tbps
Bit encoder	QAM
Bessel filter cut off frequency	0.75*symbol rate
Laser frequency	193 to 193.3THZ
EDFA gain(dB)	20
responsivity	Constant type
Dark current	15nA
Reference wavelength	1550nm

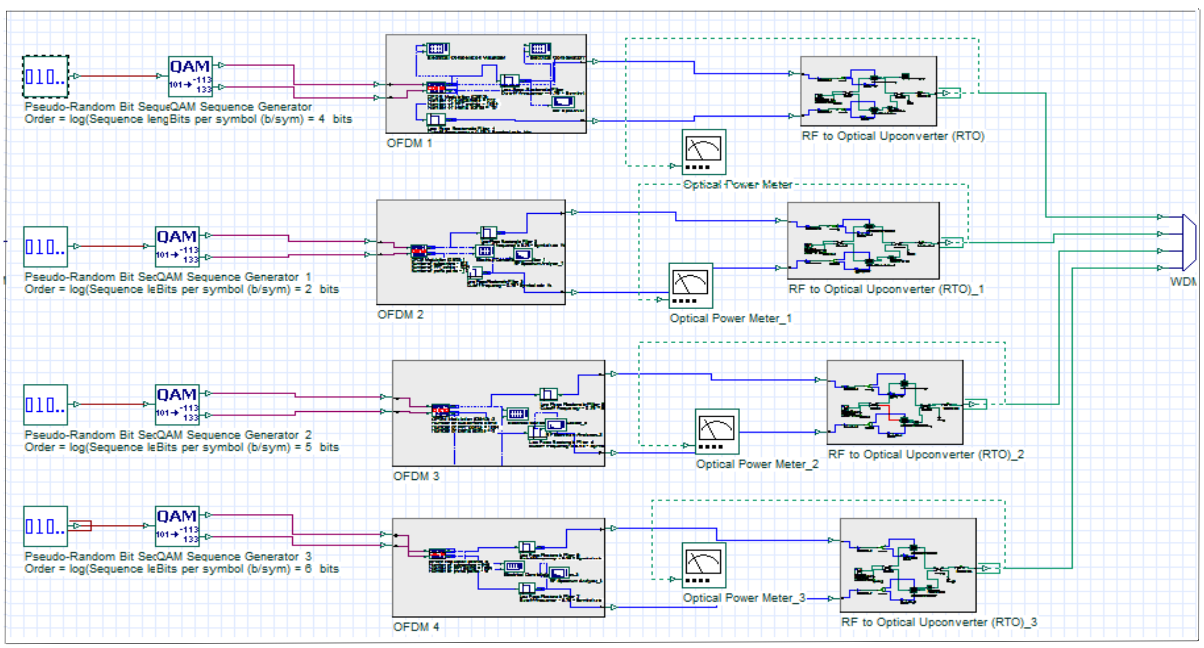


Figure3.12: Schematic Diagram of Coherent-OOFDM in Wave-Division Network

The design of long-haul optical link depends on optical sources, optical fiber cable and optical detector variables and characteristics. In the optical fiber selection, the type mode used in the design must be specified. In this design, single-mode fibers are used with the following criteria: Dispersion 16.75ps/nm/km, Attenuation 0.2dB/km, Core area 30 mm^2, Dispersion slope 0.085 ps/nm2/km, the non-linear effects are activated, with a refractive index profile of 26e-021m2/w and a reference wavelength of 1550nm. The design and analysis of optical link transmission distance or fiber length, transmission data rate is also considered in this part. The transmission length of 8000km and data rate of 1Tbit/sec are considered. Erbium-doped fiber amplifiers (EDFAs) are used before and after the optical fiber to compensate for the loss in the fiber. EDFAs allow information to be transmitted over longer distances without the need for conventional repeaters and they amplify light at around the 1500 nm to 1600 nm range. In general, the power budget of the link depends on optical power emerging from the end of the fiber attached to the light source, and P_R is the receiver sensitivity. Mathematically given by(Ahmed, 2014).

$$p_t = p_s - p_r \tag{3.31}$$

$$=2\, l_c + \alpha_f L + S_M$$

Where l_c is the insertions loss, α_f is the fiber attenuation in (dB/km) and L is the transmission length. System margin is normally taken depend on the type of leaser used and the attenuation limited fiber length decided from power budget equation and expressed as:

$$L_f = \frac{p_t - s_R - \alpha_{cs} - s_m}{\alpha_f} \tag{3.32}$$

Where α_{cs} connecter and splice lose.

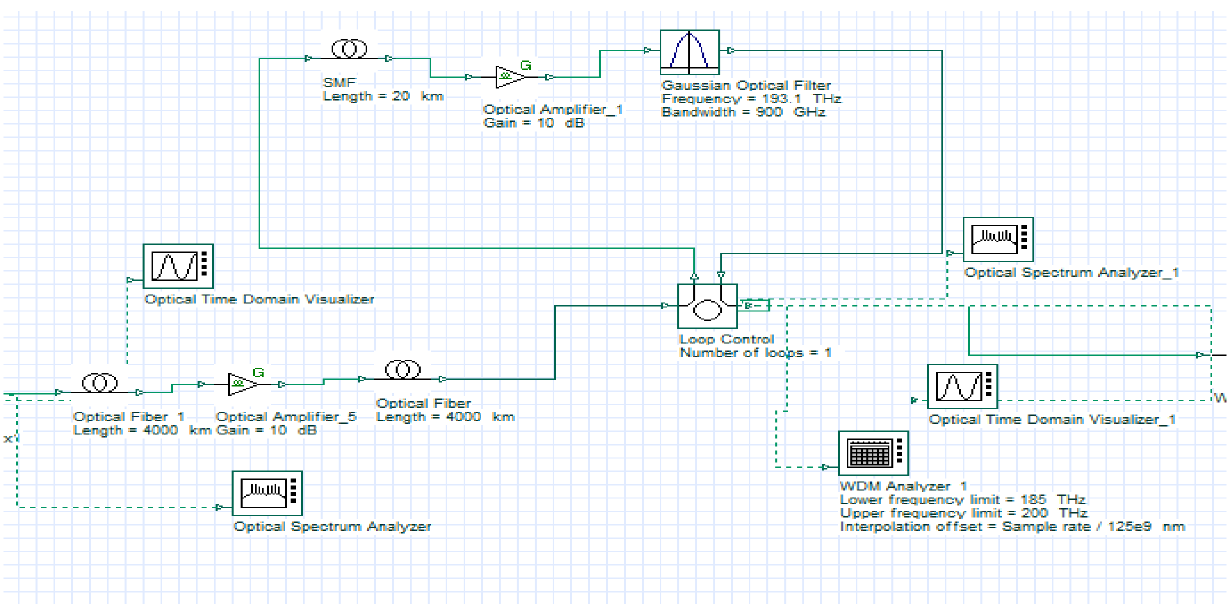


Figure 3.13: The Coherent-OOFDM in WDM link Design.

In the coherent –OOFDM –WDM receiver, the WDM DEMUX divides the incoming optical signal from the optical fiber link in to four different wavelengths, each of which is recognized by its own wavelength in the homodyne coherent detector. Each receiver is made up of two pairs of balanced coherent detectors and a local oscillator (LO) that performs the I/Q optical to electrical conversion and noise cancellation. Then the signal is delivered to the OFDM demodulator, which has comparable parameters to the OFDM modulator, after being detected by the balanced detectors. After that, the cyclic prefix removes with FFT operation. Finally, to form a binary signal, the output signal is fed into a QAM decoder and delivered to the destination.

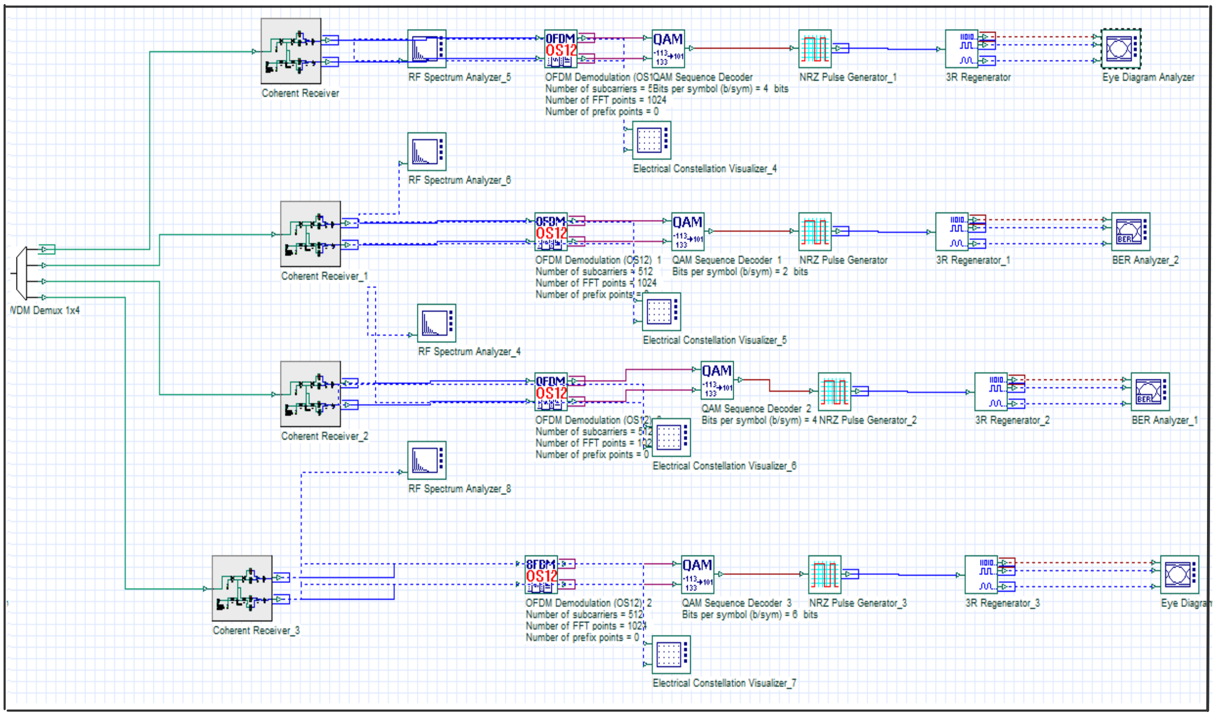


Figure3.14: Design of Coherent-OOFDM Receiver in Wave Division Network

3.8 System Design Performance Evaluation Parameter

Different evaluation Parameter can be used, such as signal to noise ratio, optical SNR (OSNR), Q-factor, eye opening penalty, and BER, to measure transmission quality. The signal-to-noise ratio (SNR) at the decision point is defined as the ratio of signal to noise power. The optical amplifier spontaneous emission noise builds along the transmission line during the amplification process lowering the OSNR. As a result, the OSNR is defined as the ratio of optical power received and noise power accumulated. General OSNR of each stage of amplify in the optical link can be expressed as (Ibragimov & Fokin, 2018).

$$OSNR = \frac{P_{in}}{NF_{stage} h f_o \nabla f} \tag{3.33}$$

Where NF_{stage} noise figure of the stage, f_o is optical frequency and ∇f noise figure bandwidth. OSNR value optical link affected by spontaneous emission noise caused by the operation of optical amplifiers and noise caused by the nonlinearity of optical fiber. the noise model of coherent optical system can be presented as follows

$$\frac{1}{OSNR_{BER}} = \frac{1}{OSNR_{ASE}} + \frac{1}{OSNR_{NL}} \tag{3.34}$$

The Q-factor in optical receiver can be expressed as follow.

$$Q = \frac{I_1 - I_0}{\delta_{1-}\delta_0} \tag{3.35}$$

Where I1 and I0 are the average photocurrents for one- and zero-symbol levels, respectively, and δ 1 and δ_0 are the standard deviations. The overall variance in photocurrents associated with symbol 1/0 is

$$\delta_{1,0}^2 = i_{sh,1,0}^2 + i_{them,1,0}^2 \tag{3.36}$$

$i_{sh,1,0}^2$ the variance corresponding to short noise and $i_{them,1,0}^2$ corresponding to thermal noise. The BER is an important measure in determining the quality of digital transmission. It expresses the probability that the decision circuit will misinterpret the bit being received. PDFs can be used to describe the fluctuating signal levels corresponding to 0 and 1 bits. Matmatically the BER defend as (MobarokHossainRubel & Golam Mahmud, 2012).

$$BER = p(0/1)p(1) + p(1/0)p(0) \tag{3.33}$$

Pr(0) and Pr(1) are the a priori probabilities of symbols 0 and 1, respectively, and Pr(0/1) is the conditional probability that symbol 1 was transmitted by the decision circuit decided in favor of 1. Pr(1/0) is the conditional probability that symbol 0 was transmitted by the decision circuit decided in favour of 1.we can express also BER interim of error function

$$BER = \frac{1}{4} ercf\left(\frac{I_1 - I_{tsh}}{\delta_1\sqrt{2}}\right) + \frac{1}{4} ercf\left(\frac{I_{tsh} - I_0}{\delta_0\sqrt{2}}\right) \tag{3.34}$$

CHAPTER FOUR

SIMULATION RESULT AND DISCUSSION

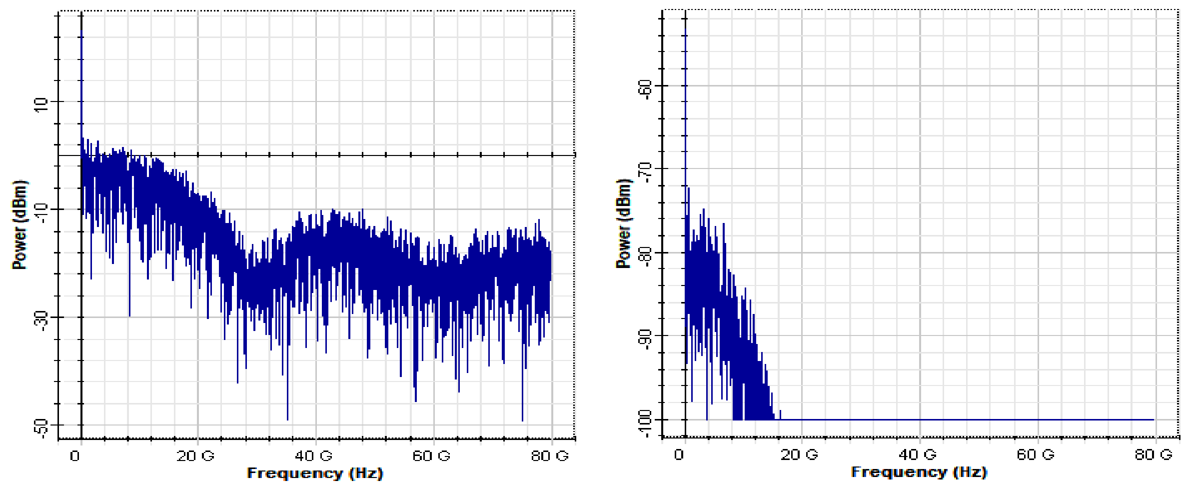
In recent years, the need for high-speed and large-bandwidth optical communications has exploded. The enhanced modulation QAM, along with the coherent-optical orthogonal frequency division multiplexing (OOFDM) method, has recently been recognized as a promising solution to meet the growing demand for high data rates and huge capacity. Coherent -OOFDM is integrated with a WDM optical network study and examined in this thesis using Optisystem software version 19. The system performance is investigated by measuring the signal to noise ratio (SNR), Q- factor, ISI effect, RF and Optical spectrum, the optical signal to noise ratio (OSNR), and by studying the constellation of diagram OOFDM modulator.

Table 4.1 Summarization of basic simulation parameter

Parameter	Value
Number of channels	Four
Fibre attenuation	0.2dB/km
Fibre length	Long-haul(8000Km)
OFDM FFT point	1024
Number of sub-carriers	512
Sequence length	32768
Sample per bit	4
Number of samples	131072
Spacing frequency	100Ghz
Input leaser power	-5 t0 5dBm
Responsivity	1A/W
Dark current	15nA
Sensitivity	10dBm
Laser frequency	193 to 193.3THZ
EDFA gain(dB)	20
Reference wavelength	1550nm
Dispersion	16.75ps/nm/km

4.1 Result of Wavelength-Division Optical Network Design with EDFA

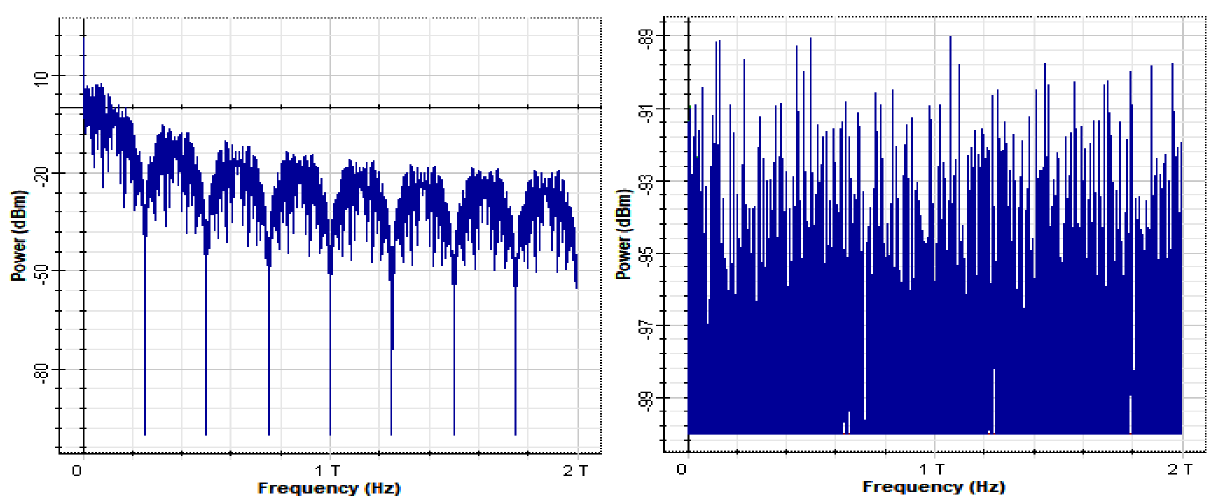
The simulation results of WDM for different data rate and fiber length up to 8000km are in the case of four channel presented and discussed in this section.



(a) (b)

Figure 4.1: RF Spectrums of channel one in WDM Network at the Transmitter and Receiver

Figure (a) describes the RF spectrum of input signal before optical modulator with the RF power of 26. 79301dBm.Figure. (b) spectrum of received signal after the photodetector in the receiver one with RF power of -50.9985dBm it is deviated from the input RF value due to transmission impairments like dispersion and attenuation of signal when the input bitrate of each channel 250Gbps at PRBS.



(a) (b)

Figure 4.2: RF Spectrums channel two in WDM Network at the Transmitter and Receiver

Figure (a) describes the spectrum of input signal before optical modulator with the RF power of 27. 265101dBm.Figure. (b) spectrum of received signal after detection in the receiver two with RF power of -88.482669dBm at the bit rate of 250Gbps for each channel.

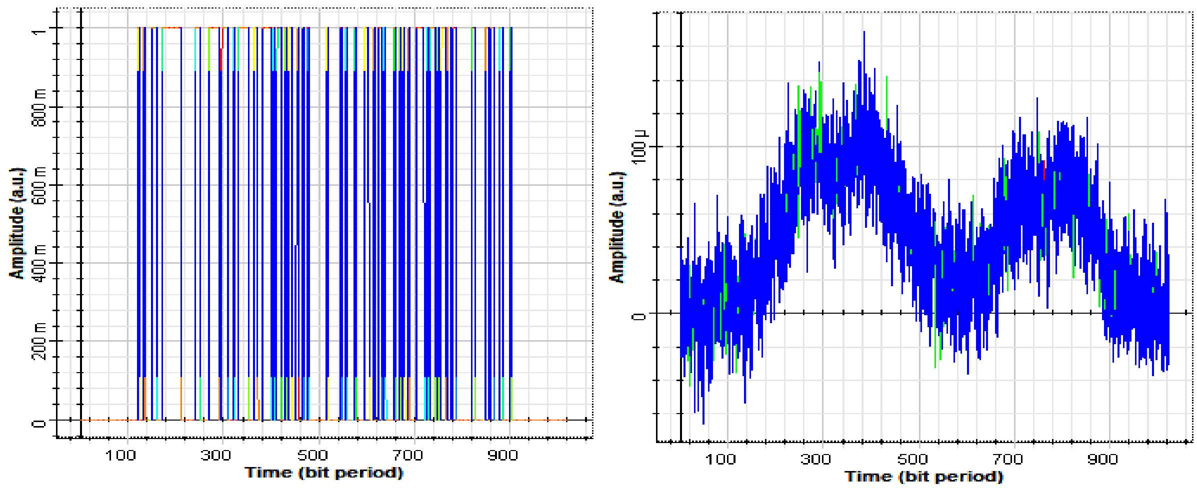


Figure 4.3: Channel four input and output electrical signal in WDM Network at the Transmitter and Receiver

Figure (a) shows input electrical signal generated by PRBS before modulate by laser sources with amplitude of 1.05 and figure (b) received modulated electrical signal after optical transmission and its amplitude reduced to 0.05 due to optical pulse distortion.

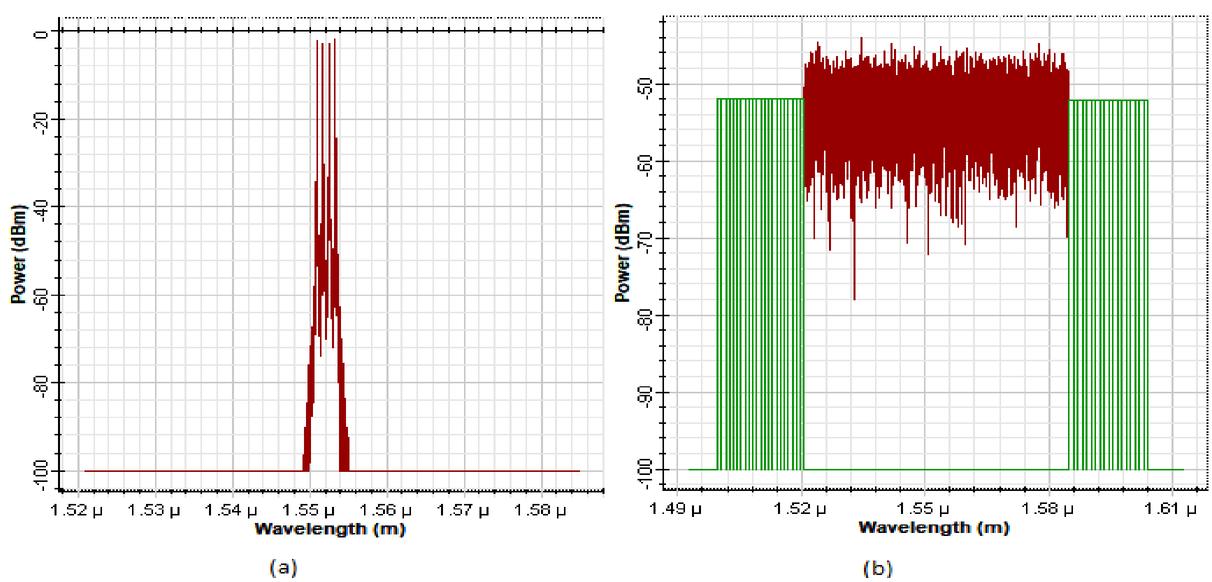
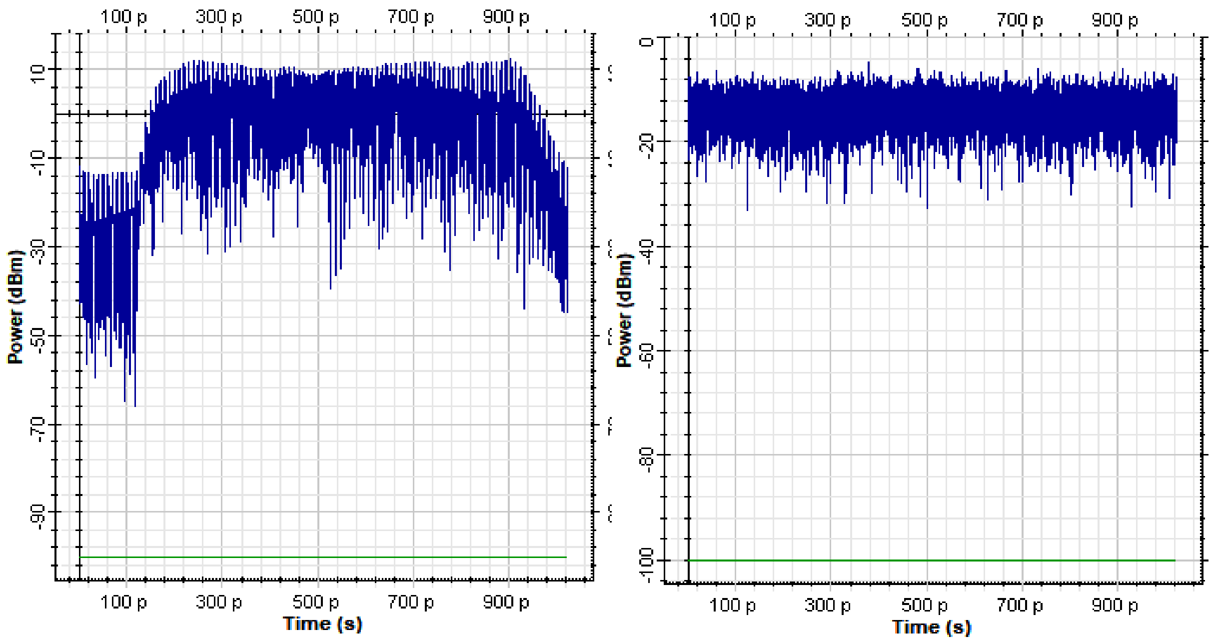


Figure 4.4: Optical Spectrums in WDM optical link after optical modulator and after 8000 fiber length

The energy distribution of optical filed in the frequency domain is given in relative units by the Optical Spectrum Analyzer and it is employed in the development of systems. Figure (a) spectrum of four WDM signal (193-193.3Thz) in optical domain at spectrum power of 2. 67866dBm.Figure. b shown the spectrum after 8000 km fiber length as it includes noise component these due to as the fiber length increase the attenuation of the fiber increase spectrum power reduced to -41.30dBm.



(a) (b)

Figure 4.5: Optical filed in time domain in WDM optical link after optical modulator and after 8000 fiber length.

Figure (a) it shows the optical filed at time domain with optical power of 17. 9070dBm.Figure. b shown the optical filed after 8000 km fiber length as it includes noise component these due to as the fiber length increase the attenuation of the fiber increase optical power reduced to -0.09619dBm.

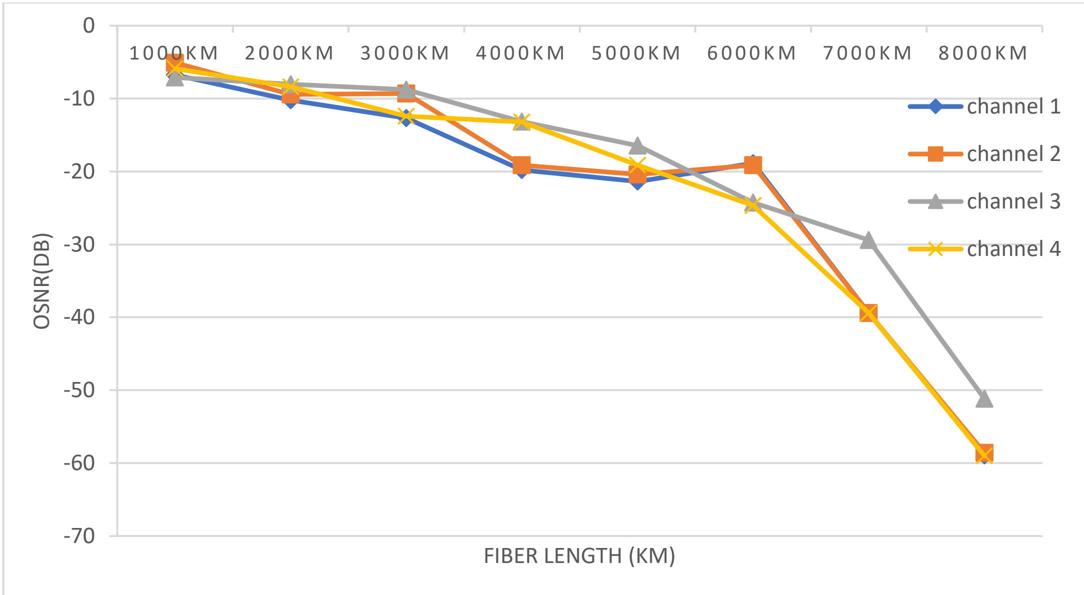


Figure 4.6: The Relation between OSNR and Transmission Fiber distance in WDM

Figure 4.6 Illustrated the effect fiber length in optical signal ration of receive signal in the optical link in the case of four different channel and a fiber length up to 8000km.as the fiber length increase the optical signal to noise ratio reduced this due to imperfection and impairments in the optical fiber.

Table 4.2: SNR and OSNR four channel over 8000km and 250 Gb/sec for each channel

User wavelength (nm)	SNR (dB)	OSNR (dB)
1553.32	-61.573834	-59.532635
1552.52	-61.429374	-59.388117
1551.72	-57.062710	-55.021510
1550.91	-61.180234	-59.139035

The table 4.2 describe signal to noise ratio of four channel each have distinct wavelength to share single link in the fiber in electrical and optical domain after the fiber length of 8000.

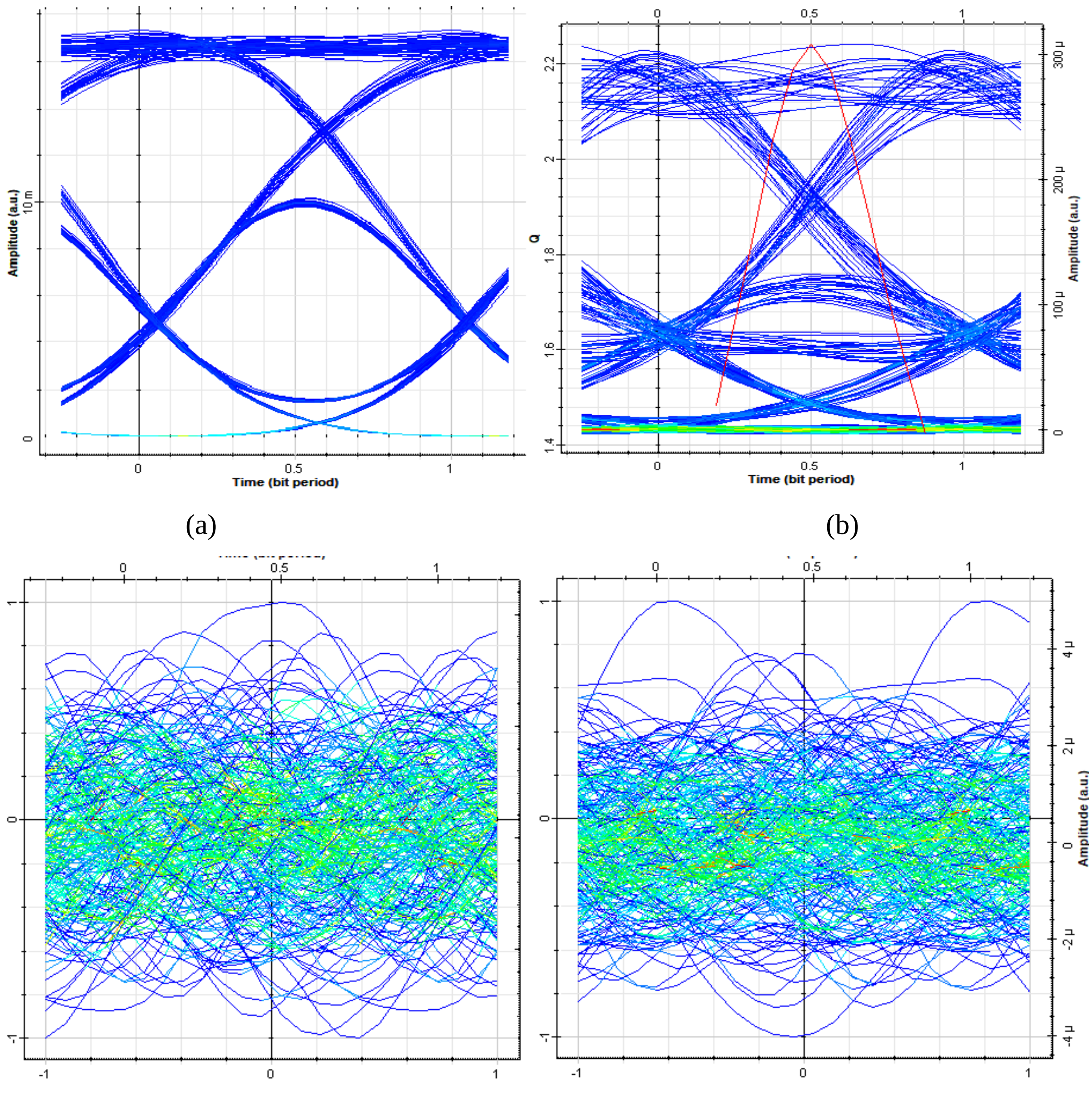
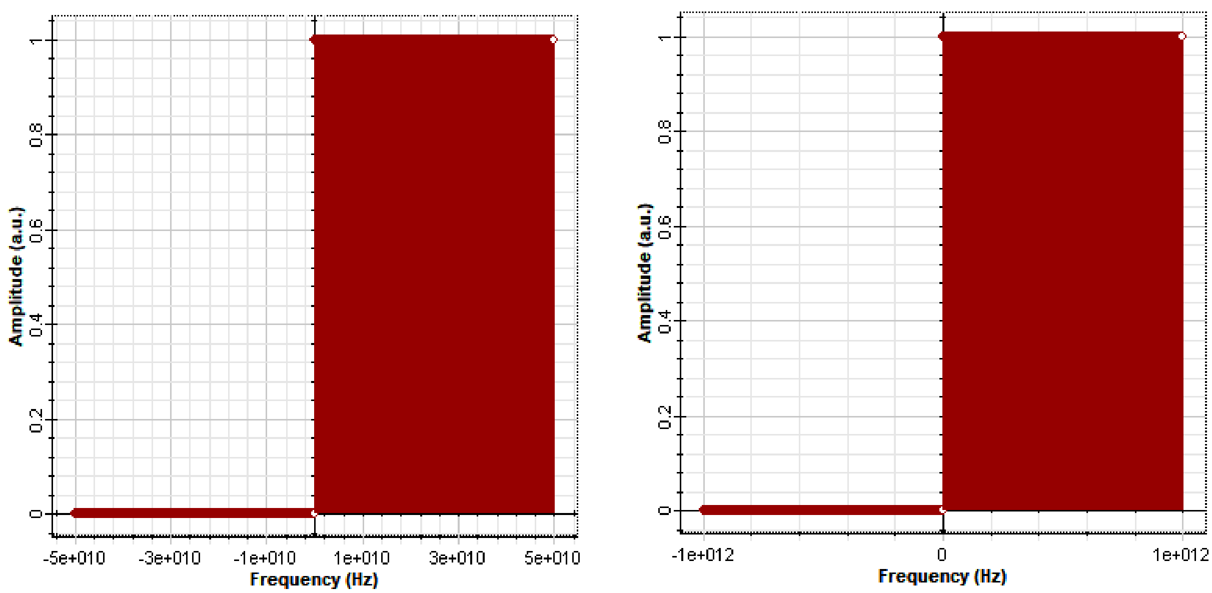


Figure 4.7: Eye-diagram result at WDM receiver (a) channel one (b) channel two (c) channel three (d) channel four

Figure 4.7 illustrates the eye-diagram of the received signal in a WDM optical network with an optical amplifier and a DCF with different fibre lengths. (a) The eye diagram of receiver one at a fibre length of 10km with a q-factor of 4.39015 and a minimum BER rate of 4.05295e-006. Figure (b) shows receiver two at a fibre length of 100km with a q-factor of 0.9898 and a minimum BER of 0.0146-13. figure (c) the eye-diagram of receiver three at a fibre length of 1000km with a q-facto value of 0 and a minimum BER of 1. figure (d) the eye-diagram of receiver four at a fibre length of 8000km with a q-facto value of 0 and a minimum BER of 1 These indicate the signal not detected by the receiver. The results show that as fibre length increases, the optical pulse becomes distorted and the ISI effect becomes more visible, indicating the WDM optical network's limitation in long-haul transmission. These works proposed the use of coherent-OOFDM in the wave division optical network to overcome the limitations of the WDM optical network in long-distance transmission.

4.2 Result and Discussion of Coherent-OOFDM-WDM Optical network Design.

Implementation of coherent-OOFDM in wave-division optical network with modern modulation format and EDFA amplifier simulate using Optisystem software result discus in this section. the deployment of coherent -OOFDM in WDM is require to improve range of communication and reducing optical impairments. To analysis the design different tools are used these are constellation visualizer, RF spectrum measurement, optical power meter, WDM analyzer, eye-diagram analyzer, optical spectrum analyzer all tools are built in the software.



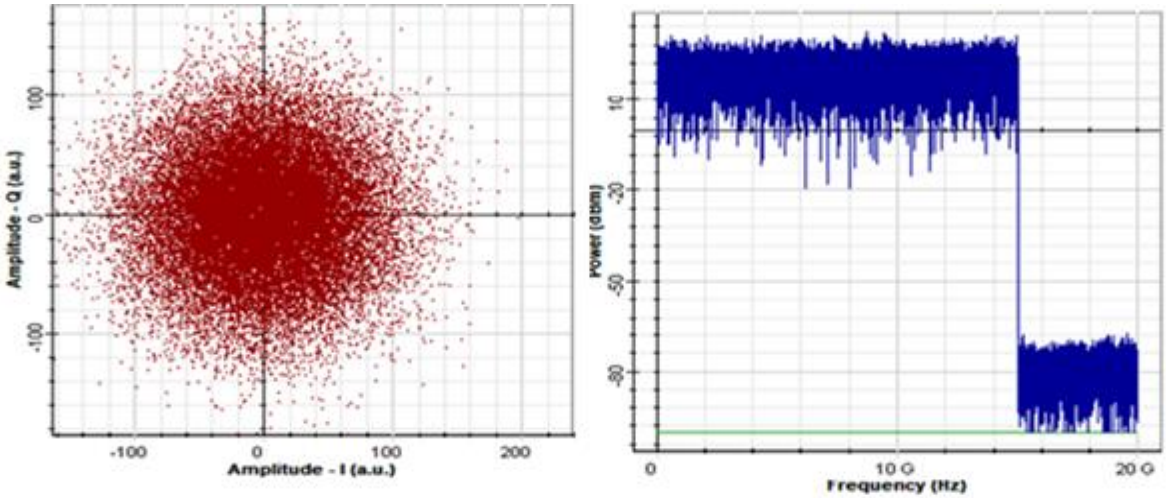
(a) (b)

Figure 4.8: Sub-Carrier Configuration of OFDM signal at the Modulator and Demodulator

Figure 4.8 indicates the sub-carrier configuration of OFDM signal at the transmitter and receiver of the wave division network that introduce for multicarrier transmission in the design.

4.2.1 Result of Coherent-OOFDM-WDM transmitter and Long-haul link

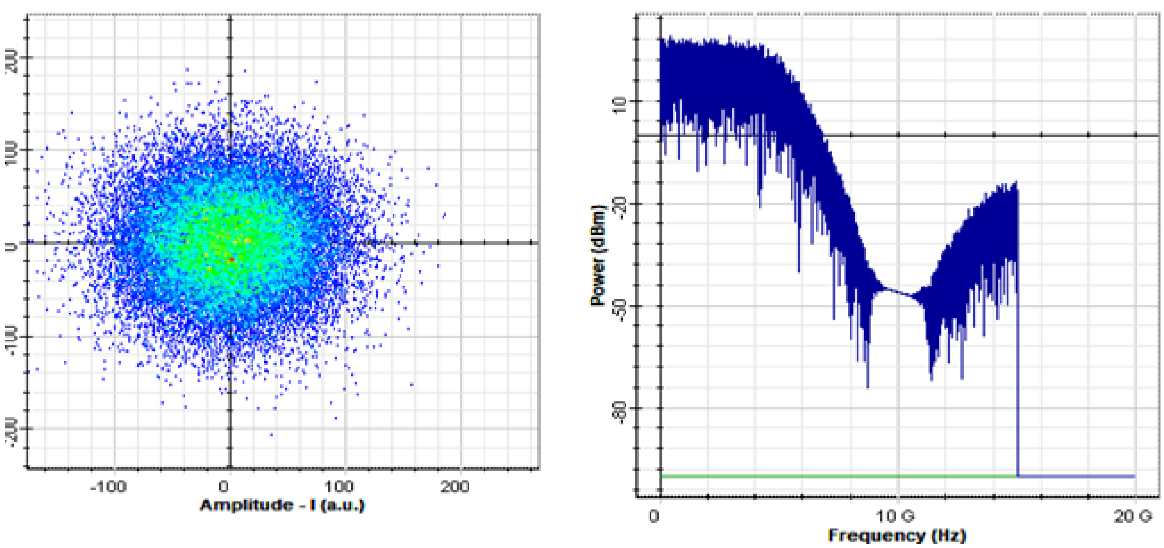
In this section implementation of optical modulator and OOFDM in wave division optical transmitter discuss and analyzed through constellation visualizer, WDM analyzer spectrum and OSA spectrum measurement.



(a) (b)

Figure 4.9: Constellation signal after OFDM modulator and RF spectrum of channel one.

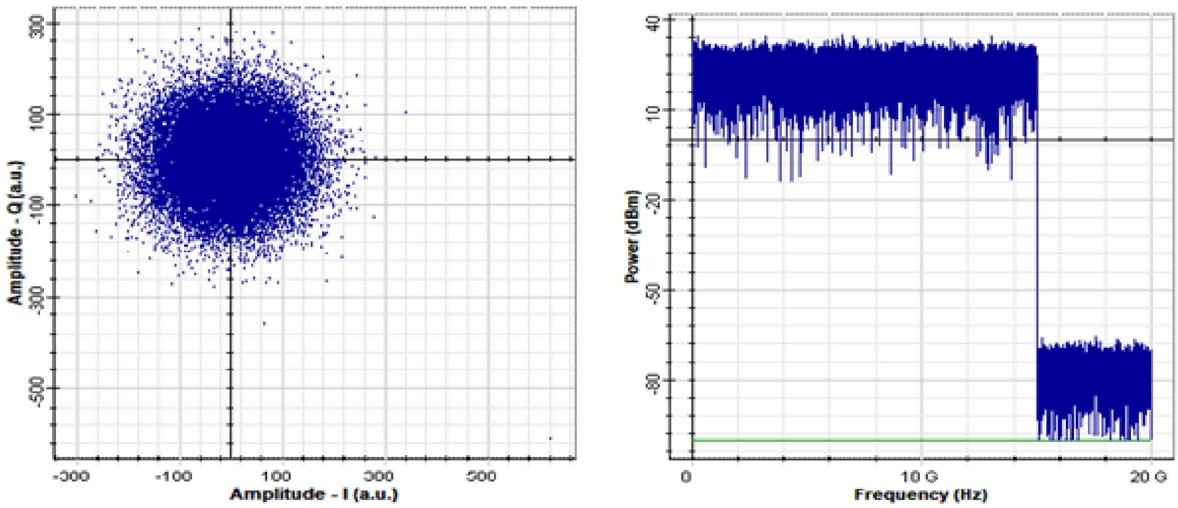
The constellation diagram describes the interference and the distortion level of the transmitted signal and RF spectrum measure power of OFDM signal in frequency domain. The result above describe user one in the case of 4-bit QAM mapping and 250Gbit/sec and RF power of 42.1989 dBm.



(a) (b)

Figure 4.10: Constellation diagram of channel two and RF spectrum

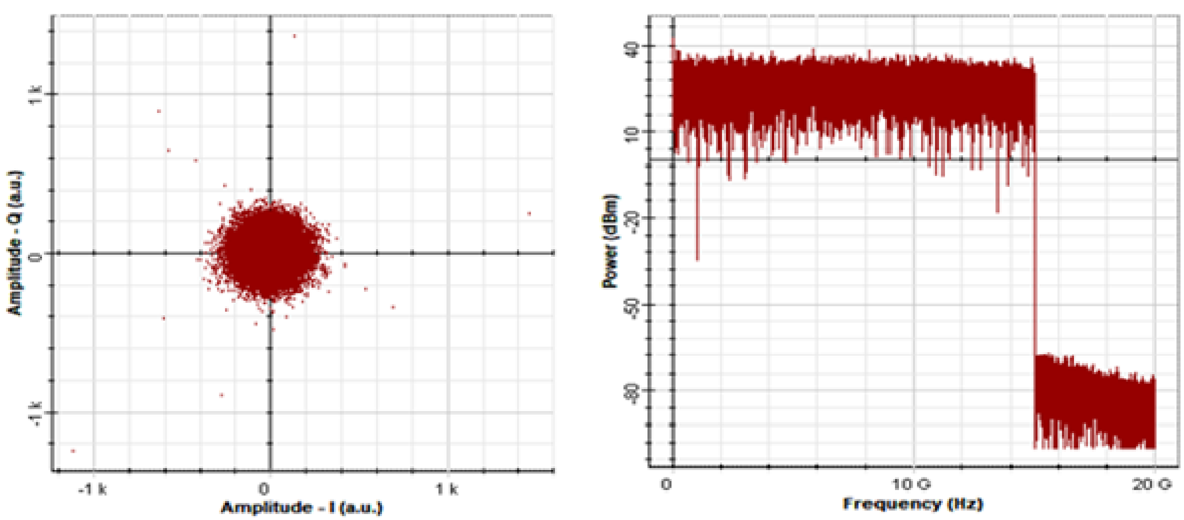
The result show constellation and the RF spectrum of user two when two-bite per symbol mapping and RF power of 35.2928dBm after OFDM modulator.



(a) (b)

Figure 4.11: Constellation diagram of channel three and RF spectrum

Figure 4.11 describe when the user transmits a bit rate of 250Gbit/sec and 5-bit per symbol mapping and RF power 41.6510 dBm.



(a) (b)

Figure 4.12: Constellation diagram of channel four and RF Spectrum

Figure 4.12 the constellation and RF spectrum of user four at the transmitter part before optical modulator and spectrum power measured 49. 8081dBm.Form figure 4.9-12 indicate increase the bit per symbol increasing spectral efficiency that increase RF spectrum power.

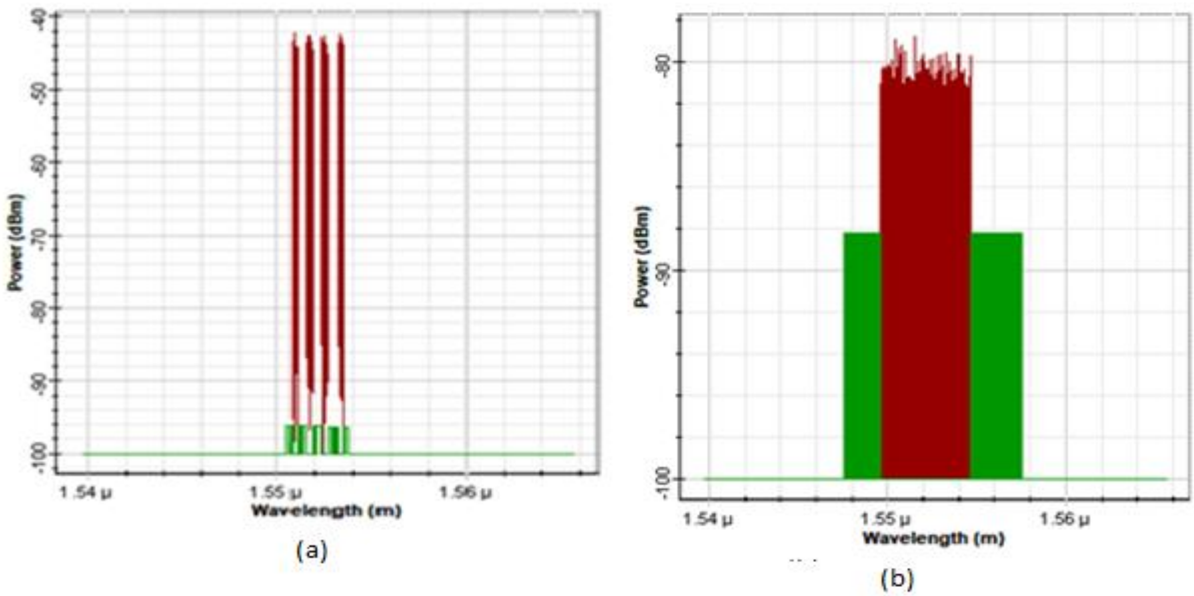


Figure 4.13: Optical spectrum after optical modulator and after fiber length of 8000km

Figure (a) demonstrate the optical modulated signal after WDM in coherent–OOFDM wave division link with data rate of 1Tbit/sec and reference wavelength of 1550 nm and spectrum of four channel with spectrum power of -45.689 dBm. Figure(b) spectrum of four signal after the fiber length of 8000 km and spectrum power reduced to-55.6789 dBm.

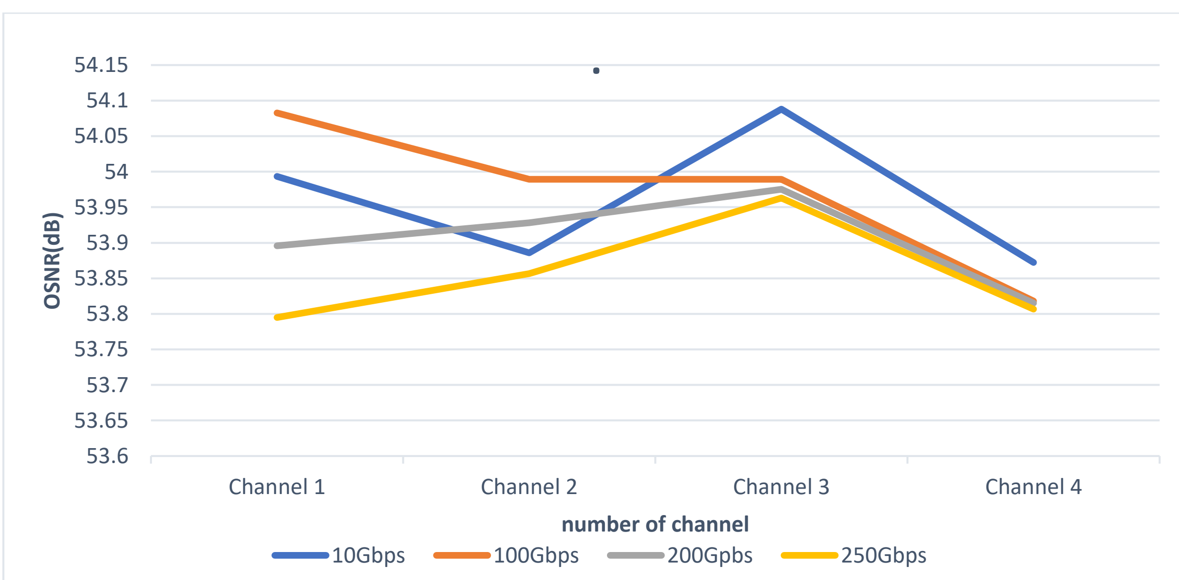
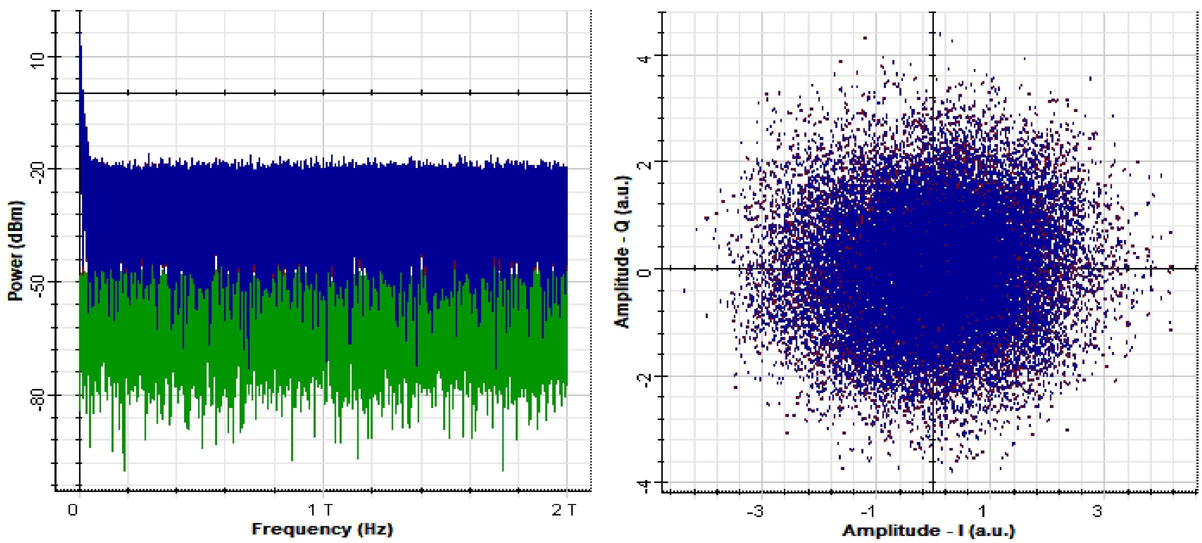


Figure 4.14: The Relation between OSNR and Bit rate

Figure 4.14 describe the relation between optical to signal ration with bit rate of user and the result indicates when the value of the bit rate increases the OSNR slowly decrease this due to the enhancement of optical effect in high data rate transmission.

4.2.2 Result of coherent–OOFDM in wave division receiver

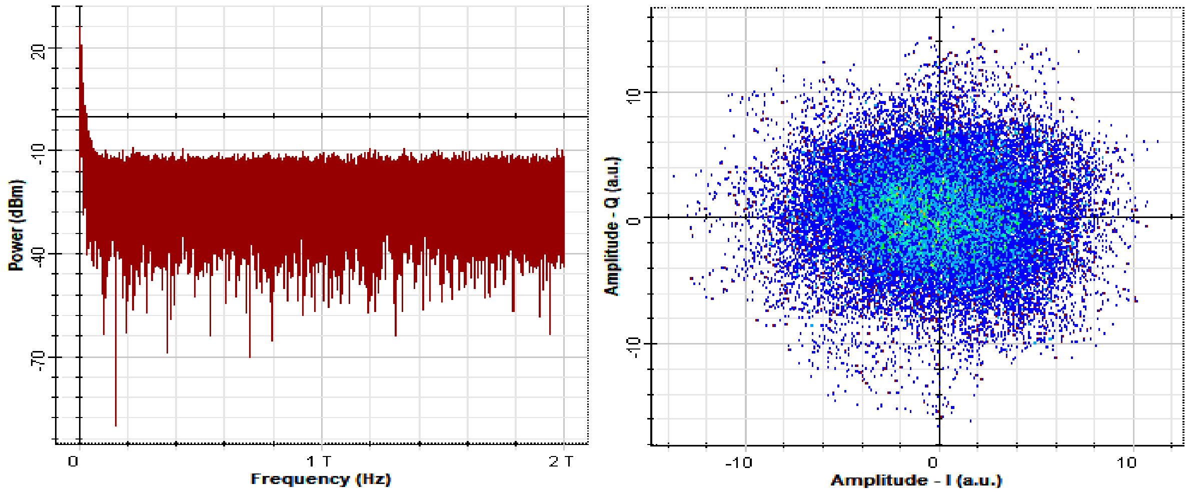
In this section implementation of coherent processing and OOFDM demodulator in wave division optical receiver after the fiber length of 8000km has been discussed.in the receiver of coherent –OOFDM wave division network the result of four different user interim of, received spectrum power and receiver bit error and q-factor through eye-diagram can be analyzed after demultiplexed each user.



(a) (b)

Figure 4.15: Channel one RF spectrum and constellation after OFDM demodulator.

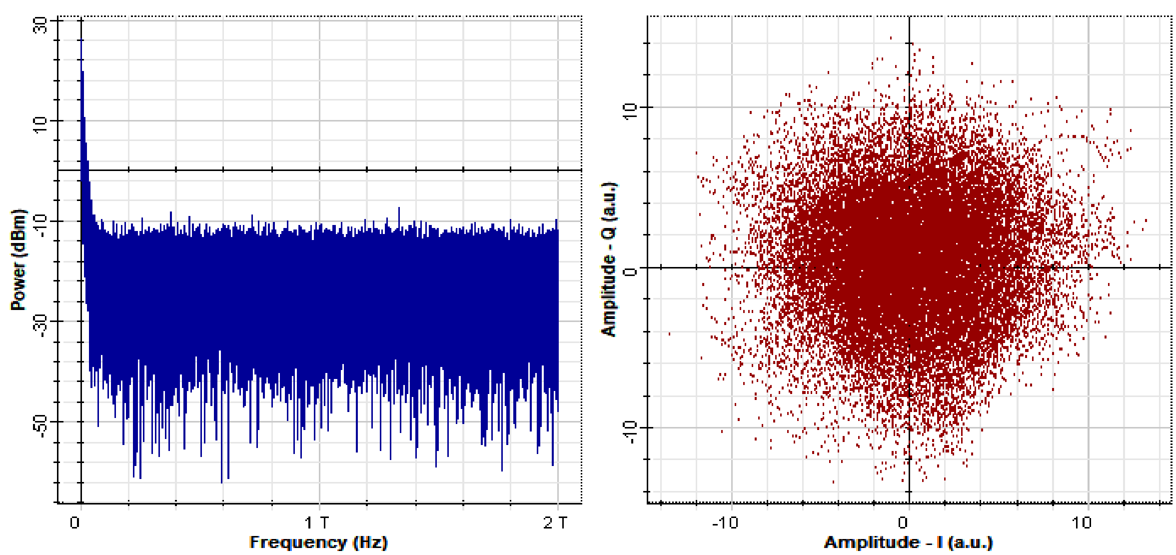
Figure 4:15 show the RF spectrum power after coherent detection of channel one with the received spectrum power of 19.61dBm and the constellation of received signal after optical signal detection and demodulation of OFDM based band signal.



(a) (b)

Figure 4.16: Channel two RF spectrum and constellation after OFDM demodulator

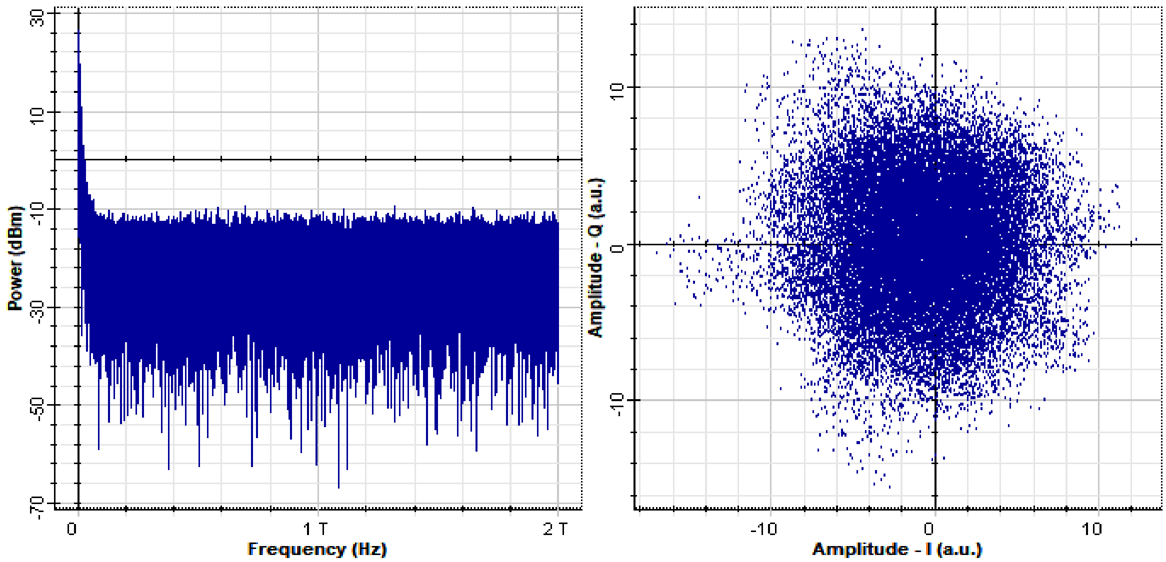
Figure 4.16 show spectrum of channel two after detection that encodes by 2-bit QAM at the transmitter and generated by 250 Gb/sec and due to different transmission effect at the receiver spectrum power reduced to 31.68dBm and Figure b indicate the constellation of the OFDM demodulator signal at these RF spectrum power.



(a) (b)

Figure 4.17: Channel three RF spectrum and signal constellation at the Receiver

The Figure 4.17: demonstrates the receive signal of channel three a coherent–OOFDM wave division receiver interim of received spectrum power at 30.602dBm and constellation of demodulated based band signal generated OFDM demodulator.



(a) (b)

Figure 4.18: Channel four RF spectrum and signal constellation at the receiver

The Figure 4.18 illustrated received signal of channel four after encoded and random generated bit of 6 bit per symbol and 250 Gb/sec at the transmitter. RF Spectrum power received component measured 30.071 dBm and the constellation of signal at this power showed in Figure.b

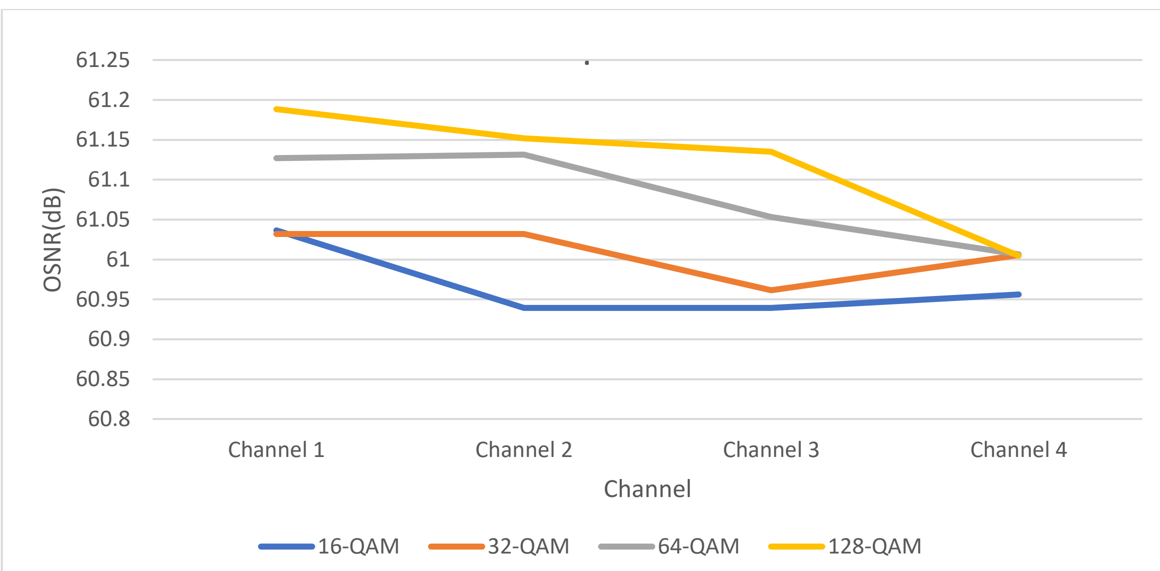


Figure 4.19: OSNR of coherent-OOFDM-WDM system with different QAM level

The Figures 4.19 compare 16-QAM, 32-QAM, 64-QAM, and 128-QAM of coherent-OOFDM in wave division optical networks in terms of their value of OSNR in the case of four channel.

From the figure, when the order of modulation increases spectral efficiency, this leads to an increase the OSNR of each user, but complexity also increases the cause for error bit detection at the receiver.

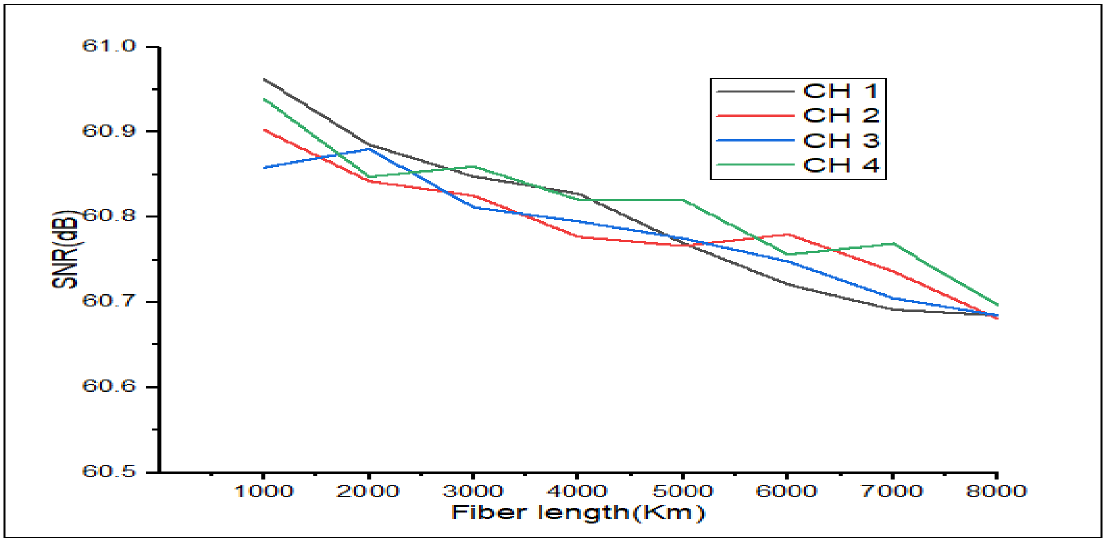
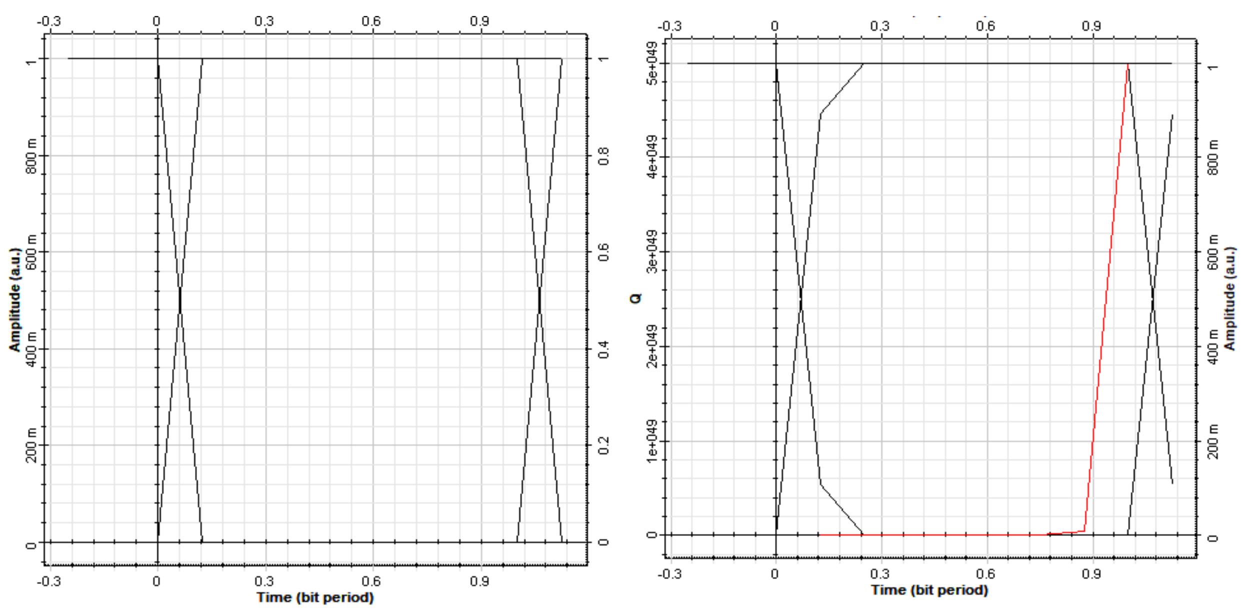


Figure 4.20: The Relation Between SNR and Fiber Length

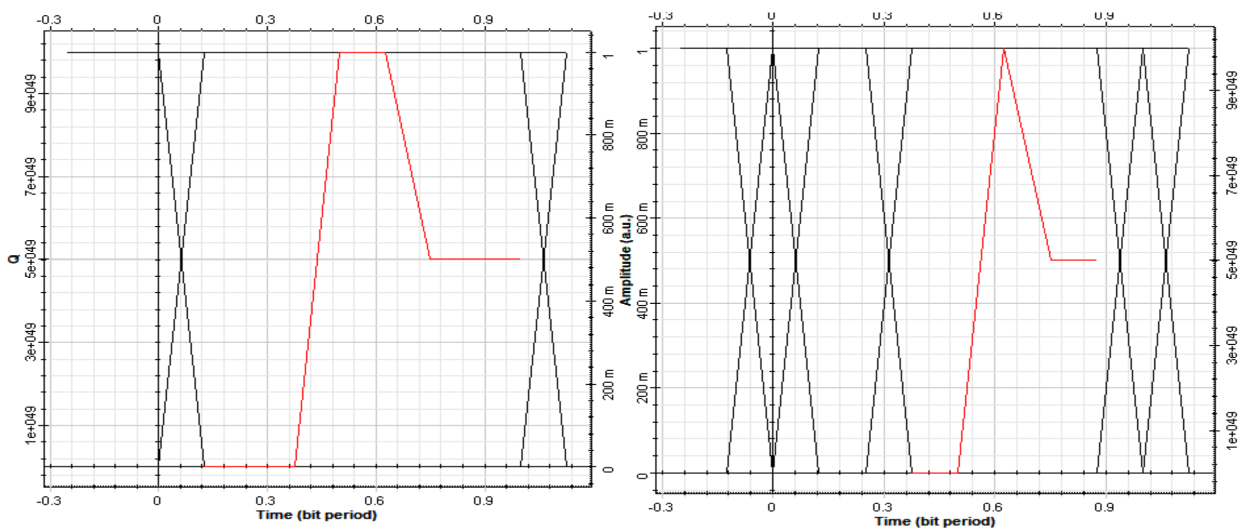
Figure 4.20 describe signal to noise ration of received signal at different fibre length in four different users at the coherent-OOFDM-WDM receiver.



(a) (b)

Figure 4.20: Eye-diagram result for channel one and two at the receiver

Figure 4.20 describe result of eye-diagram at the receiver QAM based Coherent –OOFDM in wave division optical network. In Figure a. indicate the eye diagram of user one with q-factor of 1e+050 and minimum BER is zero. Figure b shows the eye pattern and the q-line of user two with Q-value of 5e+049 and eye-height of one. An important parametric performance measurement of the optical receiver is eye-diagram measurement. The eye diagram is a frequent signal quality indication in high-speed digital communications. The width of the eye opening defines the time interval during which the received signal can be sampled without error due to interference from subsequent pulses in an eye-diagram configuration, which is referred to as ISI. The vertical distance between the top of the eye opening and the highest signal intensity determines the degree of distortion. The more one's eye closes, the harder it becomes to distinguish between them. An eye pattern approach is used to review and validate signals to ensure that they are of sufficient quality to maintain communications. As a result, the eye diagram, which illustrates the noise in the signal and how to identify logic 0 from logic 1, is one of the basic metrics used to study the system. The vertical and horizontal apertures of the eye provide crucial information about the receiver's ability to detect 1 and 0 bits accurately.



(c) (d)

Figure 4.21: Eye-diagram result channel three and four at the receiver

In Figure c. demonstrate the eye diagram of channel three with q-factor of 9e+050 and minimum BER is zero. Figure d show the eye pattern and the q-line of channel two with Q-value of 9e+049 and eye-height of one. The eye patter of coherent-OOFDM in wave division network are more open at the receiver these indicate less ISI effect and distortion of received signal. The table below show signal noise ratio of the proposed method for each channel.

Table:4.3: SNR and OSNR four channels over 8000km and 250 Gb/sec for each channel in coherent-OOFDM-WDM receiver.

User wavelength (nm)	SNR (dB)	OSNR (dB)
1553.32	54.087794	61.074046
1552.52	53.971557	61.013371
1551.72	54.094508	61.188233
1550.91	53.962855	60.863619

The table shows the signal to noise ratio and the optical signal to noise ratio of four channel at a fiber length of 8000km in the coherent-OOFDM wave division optical network, and it achieves more reliable and enhanced results compared to the existing WDM system. In general, the investigation of the proposed work over the existing system interim of different performance measurement parameters is presented below in table form.

Table 4.4 comparison of WDM and Coherent-OOFDM-WDM Optical network design

Model	Channel	Modulation type	RF Spectrum power (dBm)	BER	Q-factor	SNR (dB)	ISI effect From eye-diagram
WDM Optical Network	1	NRZ	-50.99	4.05295e-006	4.39	-61.5	High
	2	NRZ	-88.48	0.0146	0.9898	-61.4	
	3	NRZ	-86.98	1	0	-57.0	
	4	NRZ	-86.41	1	0	-61.1	
Coherent-OOFDM-WDM Optical Network	1	QAM	19.61	0	1e+050	54.08	low
	2	QAM	31.68	0	5e+049	53.97	
	3	QAM	30.602	0	9e+049	54.09	
	4	QAM	30.071	0	9e+049	53.96	

Table 4.4 shows the investigation of the proposed work over the conventional network based on different performance measuring parameters. In the design of the WDM network, NRZ is used to generate the pulse according to the input data from the user, and QAM coding is applied in

the case of coherent-OOFDM-WDM transmitter. The performance metric shows that the coherent-OOFDM-WDM network has better quality of received signal in terms of ISI, BER, and Q-factor than the existing WDM optical network at the receiver.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study cover solution to the rising demand for bandwidth and high data rates in modern communication by minimizing optical transmission effect like dispersion and non-linear effect that cause for the distortion of optical pulse at the receiver. The deployment coherent OOFDM is with Wavelength Division Multiplexing (WDM) systems, provide to the system high bandwidth, considerable data speeds, and great spectral efficiency without increasing the system's cost or complexity. The performance of integrating a coherent-OOFDM system in a WDM with QAM mapping for 8000 km long-haul transmission at 1Tbps was proposed, simulated, and examined. The usage of WDM aided in increasing the system's capacity and combined and transmit the bit rate of each user using single optical link. The systems were built with four channels to enable coherent OOFDM signals; each with 250 Gbps will be used to obtain a data rate of 1Tbs. The proposed system produces reliable results, and the findings show that the method is effective. The results demonstrated the Coherent-OOFDM-WDM system's effectiveness, demonstrating that it can deliver a great amount of data. An Eye-diagram and OSNR visualizer was utilized to evaluate the system's performance. A RF spectrum analyzer and an optical spectrum analyzer were also utilized to analyses the RF and optical signals, respectively. Electrical Constellation visualizer was used to assess the OFDM modulated and detected signal. In terms of OSNR, SNR, and BER values, the results suggest that the system performs well compare to the existing system. The resultant data confirmed the Coherent-OOFDM-WDM system's not only adaptable and cost-effective but it also efficiency in providing significantly higher data rates signal.

5.2 Recommendation

To reduce linear and non-linear impairment and enhance capacity in optical communication the focus has been on the deployment of coherent OOFDM with QAM in wave division optical network. For further work recommended the following points: -

- In coherent-OOFDM deployment we use QAM coding but QAM order increase the system become complex and the probability of error bit occurring also increase to handle this effect the future work incorporates MIMO processing.

- II. IFFT/FFT is utilized to electronically implement OFDM modulation and demodulation. This modulation and demodulation, on the other hand, can be done in the same way as FFT OFDM by using WTs, where the wavelets, rather than the sinusoids, form the main function. Because the signal expands in the Wavelet, which is an orthogonal set, the orthogonality of the subcarriers can be preserved in WTs of finite length, eliminating the need for the cyclic prefix, recommend future work to use WT instead of IFFT/FFT.
- Furthermore, in future work the system's quality can be increased by using a coded OFDM approach, which employs a sequence of error-correcting codes.

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Adama,Ethiopia

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