

Modeling and Performance Analysis of High Speed Optical Fiber Communication with Orthogonal Frequency Division Multiplexing



Bekele Tesema Hora

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Bekele Tesema Hora

Advisor Dr. Demissie Jobir Galmecha

Co-Advisor Dr. Ram Sewak Singh

A Thesis Submitted to the Department of Electronics

And Communication Engineering

School Of Electrical Engineering and Computing

Office of Graduate Studies

Adama Science and Technology University

August, 2021

Adama

Approval Sheet

We, the advisors of the thesis entitled “Modeling and Performance Analysis of High Speed Optical Fiber Communication with Orthogonal Frequency Division Multiplexing” and developed by Bekele Tesema Hora, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Major Advisor

Signature

Date

Co-advisor

Signature

Date

We, the undersigned, members of the Board of Examiners of the thesis by Bekele Tesema Hora have read and evaluated the thesis entitled “Modeling and Performance Analysis of High Speed Optical Fiber Communication with Orthogonal Frequency Division Multiplexing” 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.

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I hereby declare that this Thesis entitled” Modeling and Performance Analysis of High Speed Optical Fiber Communication with Orthogonal Frequency Division Multiplexing” is 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 used for this thesis have been duly acknowledged through appropriate citations.

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Mojar Advisor

Signature

Date

Co-Advisor

Signature

Date

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Table of Contents

Approval Sheet	i
Declaration.....	ii
Recommendation	iii
Acknowledgement	iv
Table of Contents.....	v
List of Tables	ix
List of Figures.....	x
List of Abbreviation	xiii
Abstract	xv
CHAPTER ONE	1
1. Introduction	1
1.1. Background of the Study.....	1
1.2. Fiber Optic Communication System.....	3
1.2.1. Linear Effects in Optical fiber Communication system.....	4
1.2.2. Fiber Loss	4
1.2.3. Fiber Dispersion.....	5
1.2.4. Intermodal Dispersion.....	5
1.2.5. Chromatic Dispersion	5
1.2.6. Polarization Mode Dispersion	6
1.3. Nonlinear Effects	6
1.4. Statement of the Problem	8
1.5. Objective	8
1.5.1. General Objective	8
1.5.2. Specific Objective.....	8

1.6.	Significance of the Study	8
1.7.	Scope of the Study	9
1.8.	Limitation of the Study	9
1.9.	Organization of the Study.....	9
CHAPTER TWO		10
2.	Literature Review.....	10
2.1.	Introduction	10
2.2.	Related Works	10
2.3.	Orthogonal Frequency Division Multiplexing	12
2.3.1.	OFDM Basics	13
2.3.2.	Mathematical Formulation of OFDM Signal	14
2.4.	Orthogonality.....	15
2.5.	OFDM Modulation System	16
2.5.1.	Serial to Parallel Conversion	16
2.5.2.	M-ary Quadrature Amplitude Modulation	16
2.5.3.	Quadrature Amplitude modulation (QAM).....	17
2.5.4.	Inverse Fast Fourier Transform	17
2.5.5.	Cyclic Prefix for OFDM	17
2.5.6.	Fast Fourier Transform	18
2.5.7.	Analog to Digital Converter	18
2.5.8.	Digital to Analog Converter	18
2.6.	Advantages of OFDM	19
2.7.	Disadvantages of OFDM.....	19
2.7.1.	Peak to Average Power Ratio.....	19
2.8.	Dispersion Compensating Techniques	20

2.8.1.	Dispersion Compensating Fiber (DCF)	20
2.8.2.	Fiber Bragg Grating (FBG)	20
2.9.	Wave Division Multiplexing	20
CHAPTER 3		22
3.	Materials and Methods	22
3.1.	Introduction	22
3.2.	Materials	22
3.3.	Methods	22
3.4.	Proposed Block Diagram of Optical OFDM	23
3.4.1.	Optical OFDM Transmitter	24
3.4.2.	RF to Optical Up Converter	24
3.4.3.	Mach-Zehnder Modulator	24
3.4.4.	Optical to RF Down Conversion	25
3.4.5.	Intensity Modulation	25
3.4.6.	Optical I/Q Modulator	25
3.4.7.	Optical OFDM Receiver	27
3.5.	Coherent Detection OFDM	27
3.5.1.	Coherent Detection OFDM system with single mode fiber	28
3.5.2.	Homodyne Detection	32
3.6.	Direct Detection OFDM	32
3.6.1.	Direct Detection OFDM with single Mode Fiber	33
CHAPTER FOUR		37
4.	Results and Discussions	37
4.1.	The Result for 4-QAM of CO-OFDM	37
4.2.	The Result for 16-QAM of CO-OFDM	42

4.3.	The Result for 32-QAM of CO-OFDM	45
4.4.	The Result for 64-QAM of CO-OFDM	48
4.5.	The Result for 4-QAM of DD-OFDM	51
4.6.	The Result for 16-QAM of DD-OFDM	55
4.7.	The Result for 32-QAM of DD-OFDM	57
4.8.	The Result for 64-QAM of DD-OFDM	59
5.	Conclusion and Recommendation	68
5.1.	Conclusion.....	68
5.2.	Recommendation	68
6.	REFERENCE	69

List of Tables

Table 3.1: The parameters for Coherent Detection OFDM.....	29
Table 3.2: Single mode fiber parameters for CO-OFDM	30
Table 3.3: Single mode fiber global parameters for CO-OFDM.....	31
Table 3. 4: Single mode fiber parameters for DD-OFDM	34
Table 3.5: Single mode fiber global parameters for DD-OFDM.....	36
Table 4.1: Signal details at 4-QAM OFDM at receiver part	61

List of Figures

Figure 1.1: Generation of Fiber Transmission capacity [5]	2
Figure 1.2: General diagram of Optical Communication System [7]	3
Figure 2.1: FDM spectra [30]	14
Figure 2.2: Multicarrier Modulation systems [34].....	15
Figure 2.3: Wavelength division multiplexing [41].....	21
Figure 3.1: Block diagram of Optical OFDM	23
Figure 3.2: RF to optical up converter	24
Figure 3.3: Schematic diagram of Coherent optical OFDM	29
Figure 3.4: Optical transmission link	30
Figure 3.5: Coherent detection of receiver part.	31
Figure 3.6: Homodyne detection in coherent OFDM	32
Figure 3.7: Direct detection OFDM Transmitter	33
Figure 3.8: Optical fiber transmission link for Direct Detection OFDM.....	34
Figure 3.9: Direct Detection OFDM Receiver	35
Figure 4.1: Constellation diagram of 4-QAM at transmitter side CO-OFDM.	38
Figure 4.2: Electrical Constellation diagram after OFDM modulator at transmitter side.....	38
Figure 4.3: RF spectrum of in phase and quadrature and quadrature components after OFDM...39	
Figure 4.4: Optical OFDM spectrum after the two Mach-Zehnder modulator and optical link. ..39	
Figure 4.5: RF spectrum of OFDM at receiver side	40
Figure 4.6: Constellation diagram of coherent optical OFDM at the Receiver part.....	40
Figure 4.7: Constellation diagram of the OFDM signal after OFDM demodulation.	41
Figure 4.8: The constellation Diagram of 16-QAM at the transmitter side of OFDM	42
Figure 4.9: The electrical constellation diagram after OFDM modulator.....	43
Figure 4.10: RF spectrum of in phase quadrature signal after OFDM modulator.....	43
Figure 4.11: RF spectrum and electrical constellation diagram	44
Figure 4.12: Electrical constellation diagram OFD signal after OFDM demodulator	44
Figure 4.13: The constellation diagram of 32-QAM at transmitter part of CO-OFDM	45
Figure 4.14: Electrical constellation diagram of OFDM signal	46
Figure 4.15: RF spectrum of I/Q component after OFDM modulator of LP filter	46
Figure 4.16: The Electrical constellation diagram of OFDM signal after Coherent detection.	47

Figure 4.17: The electrical constellation diagram of OFDM signal after OFDM demodulator....	47
Figure 4.18: Electrical Constellation diagram of 64-QAM at transmitter side of CO-OFDM	48
Figure 4.19: RF spectrum of In-phase and Quadrature component of the OFDM signal.....	49
Figure 4.20: The Constellation diagram after coherent detection	49
Figure 4.21: The constellation diagram of OFDM signal after demodulator.....	50
Figure 4.22: Constellation diagram of 4-QAM at transmitter part of DD-OFDM.....	51
Figure 4.23: RF spectrum of OFDM signal after LP filter.....	52
Figure 4.24: OFDM signal after quadrature modulator in frequency domain	52
Figure 4.25: Modulated optical signal after Mach-Zehnder modulator.....	53
Figure 4.26: Optical spectrum after fiber optic link.....	53
Figure 4.27: The constellation of OFDM signal after Quadrature demodulation.	54
Figure 4.28: The constellation diagram of 16-QAM at transmitter part of OFDM.....	55
Figure 4.29: RF spectrum of OFDM signal after Quadrature Modulator	55
Figure 4.30: The optical spectrum of OFDM signal after MZM of 16-QAM	56
Figure 4.31: RF spectrum after optical link and constellation of OFDM signal of 16-QAM.....	56
Figure 4.32: The constellation diagram of 32-QAM of DD-OFDM at transmitter side.....	57
Figure 4.33: The RF spectrum of OFDM signal after Quadrature demodulator	57
Figure 4.34: The optical spectrum of OFDM signal after of 32-QAM.....	58
Figure 4.35: RF spectrum optical link and constellation diagram of OFDM signal of 32-QAM .	58
Figure 4.36: Constellation diagram of 64-QAM at transmitter side of DD-OFDM.....	59
Figure 4.37: The RF spectrum of 64-QAM OFDM signal after Quadrature demodulator	59
Figure 4.38: The optical spectrum of OFDM signal after MZM of 64-QAM	60
Figure 4.39: RF spectrum of optical link and constellation of OFDM signal of 64-QAM.....	60
Figure 4.40: The diagram of Quality factor.....	61
Figure 4.41: The diagram of threshold frequency	62
Figure 4.42: The Diagram of Min. BER	62
Figure 4.43: The Diagram of Amplitude of the signal.....	63
Figure 4.44: Eye diagram in terms Quality factor	64
Figure 4.45: Eye diagram in terms of Min. BER.....	64
Figure 4.46: Eye diagram in terms of BER pattern	65
Figure 4.47: The Relationship between BER and transmission distance.....	65

Figure 4.48: The Relationship between BER and OSNR as the transmission length increases....	66
Figure 4.49: The BER of CO-OFDM system with different launched power	66
Figure 4.50: The relation between BER and OSNR for M-Modulation formats at 4500 Km.	67

List of Abbreviation

AO-OFDM.....	All Optical Orthogonal Frequency Division Multiplexing
AWG.....	Arrayed wave guide Grating
CD.....	Chromatic dispersion
CNR.....	Carrier Noise Ratio
CO-OFDM.....	Coherent Orthogonal frequency Division Multiplexing
DAB.....	Digital Audio Broadcasting
DCF.....	Dispersion Compensating Fiber
DD-OFDM.....	Direct Detection Orthogonal Frequency Division Multiplexing
DGD.....	Differential Group Delay
DPSK.....	Differential Phase Shift Keying
DVB.....	Digital Video Broadcasting
DWDM.....	Dense Wave length Division Multiplexing
EDFA.....	Erbium Doped Fiber Amplifier
FBG.....	Fiber Brag Grating
FDM.....	Frequency Division Multiplexing
FFT.....	Fast Fourier Transform
IFFT.....	Inverse Fast Fourier Transform
ISI.....	Inter symbol Interference
LAN.....	Local Area Network
MCM.....	Multi carrier Modulation
MZM.....	Mach-Zehnder Modulator
OFDM.....	Orthogonal Frequency Division Multiplexing
OSNR.....	Optical Signal to Noise Ratio
PAPR.....	Peak Average to Power Ratio
PMD.....	Polarization Mode dispersion
PSK.....	Phase Shift Key
QAM.....	Quadrature Amplitude Modulation
QPSK.....	Quadrature Phase Shift Key
RF.....	Radio Frequency
ROF.....	Radio Over Fiber

SCM.....Subcarrier Modulation
SMF.....Single Mode fiber
SNR.....Signal to Noise Ratio
WDM.....Wave Division Multiplexing
WLAN.....Wireless Local Area Network

Abstract

The 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 is applied in various areas that need transfer of data from one point to another. The higher data rates with simple transmitter and receiver modeling is one of the best solutions to design the spectrally efficient high speed optical transmission system using different modulation techniques. Therefore, the current telecommunications infrastructure is depend on optical fibers for transmission of data from one place to another, because of their higher bandwidth and low attenuation. In the recent past, optical communication networks have been specifically designed and optimized to support different communication standards increasing the capabilities of optic fiber, integrated waveguides and related optical fiber hardware, and signal conditioning circuits. So this thesis presents study, modeling, simulation and analysis of optical performance under different transmission system which is considered in a practical high speed design using Orthogonal Frequency Division Multiplexing (OFDM). This can be done by using both Coherent Detection OFDM and Direct Detection OFDM to minimize dispersion effects in optical communication because OFDM is basic for modern technology to increase the data rate and increase the requirement of bandwidth in broadband services. Many optical fiber problems, such as chromatic dispersion (CD) and polarization mode dispersion (PMD) are solved using OFDM. The performance analyses made in this work by using different parameters such as BER, OSNR, Quality factor at different distance transmission by using different quadrature modulations. These are 4-QAM, 16-QAM, 32-QAM, 64-QAM to maintain the OSNR value, spectral efficiency and the required data rates. Different results for these all M-QAM modulation at different distances and at different Quadrature modulation at different stage. It observed RF spectrum values, different constellation diagram and the result of the relationship between BER and OSNR values at different distances were observed. Comparison among different Quadrature modulators in terms of their BER and OSNR were analyzed.

KEY WORD: Orthogonal Frequency Division Multiplexing, Chromatic Dispersion. Quadrature Amplitude Modulation, Bit Error Rate, Optical Signal to Noise Ratio,

CHAPTER ONE

1. Introduction

1.1. Background of the Study

The fiber optic communication system transfers data from one point to another that could be separated by large kilometers or by under oceanic distances. An electromagnetic signal wave with a frequency ranging from a few megahertz to several hundred terahertz is frequently used to transport data from one location to another [1]. Communication via fiber optics it was once thought of as light signal systems to identify them from microwave systems, which have a carrier frequency of around five orders of magnitude lower (1 GHz). Optical fiber communication systems are uses a light signal systems that use optical fibers for data transmission. So this system have been emerged in the world since 1980 that used as the basic technology in telecommunications [2]. Optical communication is a system that uses light signal to transmit in transmission channel to propagate data from one place to another. Optical communication is used replace to RF and Microwave (MW) technology because of its advantage of higher bandwidth and lower cost. In Optical fiber communication the information are from one point to another by transferring the light pulse in optical fiber made of silica. The light pulses form an electromagnetic signal that is modulated to carry information [3]. It was first proposed in the 1970s with a revolution in the telecommunication industry and played an important role in the development of telecommunication system. Optical fiber systems have used in terms of the radio transmitter systems for long-haul data transmission. They are widely used for internet traffic telephone and cable TV networks and high-speed local area networks (LANs) etc. However, if we just concentrate on the light wave communication then the same can be traced back to the middle of the 20th century, with multiple independent researchers working on the ways to harness the wide bandwidth capacity of the light wave in the data transmission. Developments in fiber optic communication can be divided into various generations based on their operating wavelength and data transmission capacity. Starting with the first generation in 1975 worked at a wavelength of $0.8\mu\text{m}$ based on GaAs semiconductor lasers, and was able to provide around 45Mbps data rate with a repeater spacing of 10km. To further increase the data rate in the year 1980's second generation comes into picture which it transmits at wavelength of $1.3\mu\text{m}$ and uses InGaAsP semiconductor laser as a source. Second generation systems were capable of providing

a data rate of around 1.7Gbps with the repeater spacing of 50km. Repeater spacing is mainly decided by the losses provided by the fibers, and further reduction in the losses up to $\sim 0.2\text{dB/km}$ increases the repeater spacing $\sim 100\text{km}$ leading to the third generation of light wave systems, which comes into existence in the 1990 [4]. The third generation of light wave systems works at the wavelength of $1.55\text{ }\mu\text{m}$ was actually developed by Nippon Telegraph and Telephony (NTT) and was able to provide 2.5Gbps data rate when operating with silica-based single mode fibers. The fourth generation uses WDM technique and it provides data rate of 10 Tb/s with the distance between repeater is greater than 10,000 km and working on the wavelength of: 1.45 to $1.62\text{ }\mu\text{m}$. And 5th generation depends on Raman amplification methods and optical solitons. Which provides data rate 40 - 160 Gb/s with the distance between repeater is 24000 km - 35000 km and that works on wavelength were 1.53 to $1.57\text{ }\mu\text{m}$.

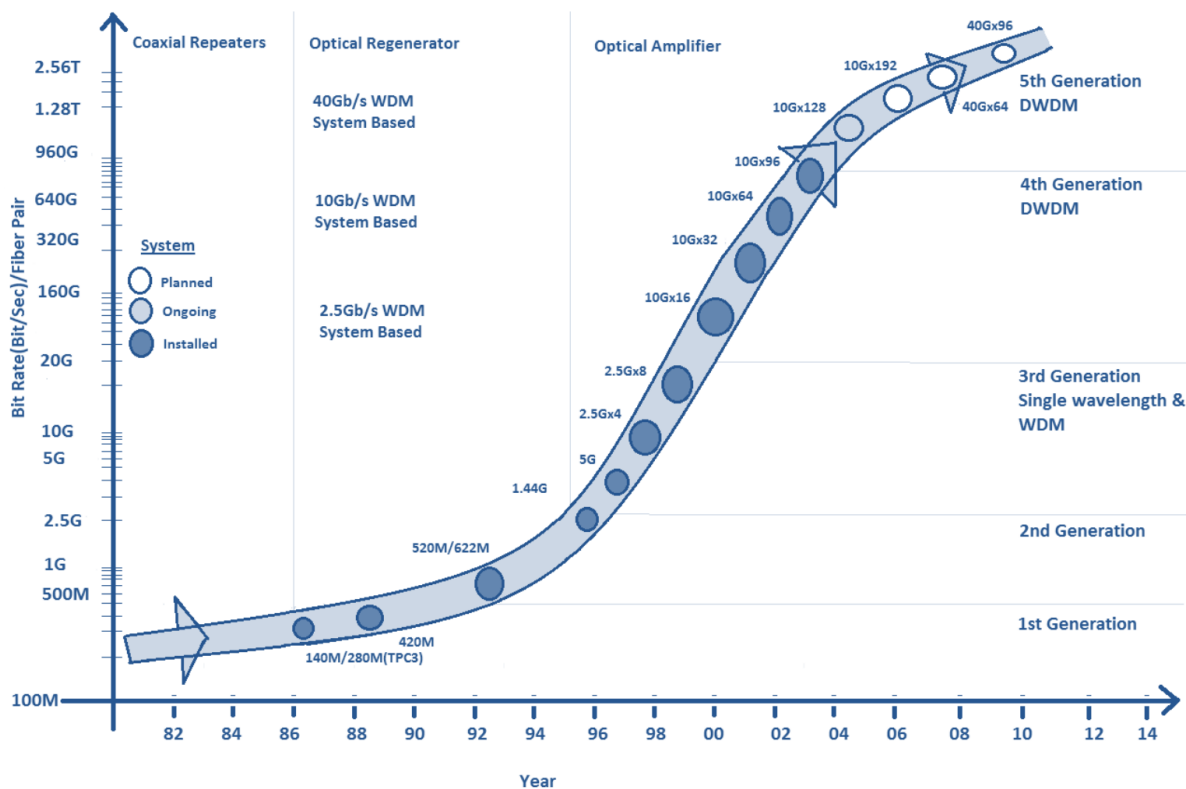


Figure 1.1: Generation of Fiber Transmission capacity [5]

From these discussions, it is observed that optical communication field is quite an established field but at the same time has a huge potential to explore the new capabilities. In the present generation of optical transmission systems, 10Gbps and 40Gbps is quite attractive in WDM or

DWDM configuration with channel spacing of 200 GHz to 50GHz or even smaller [6]. The technology of fiber optics is very much based on the use of light to transmit the data. The youngest mode of communication is optical fiber technology. Over the past five years the growth of optic fiber industry has been explosive. For the transmission of data from one point location to another we use optical fiber technology. The major importance of optical technology is to lower the production cost and to point to point communication and for the security of transmission. An optical fiber is a flexible, transparent fiber made of extruded glass (silica) or plastic that is smaller than a human hair. It can be used as a waveguide to carry optical signal from one point other. The advantage of optical fiber communications are most often supports transmission for longer distances communication and at higher bandwidths or data rates than wire connections. Because optical fibers transfer messages more effectively and it has the ability over come to electromagnetic interference, they are used to replace metal cables. Optical fibers are again utilized for illumination and are coiled in bundles so that they may carry images and be viewed in limited locations. Sensors and fiber lasers are among the various applications for which specially developed fibers are employed. A communication system based on optical fiber is made up of three major parts: a transmitter, a receiver, and a communication channel. The communication channel in a fiber-optic communication system is an optical fiber, and the optical transmitter and receiver are constructed to satisfy the requirements as shown in Figure below [7].

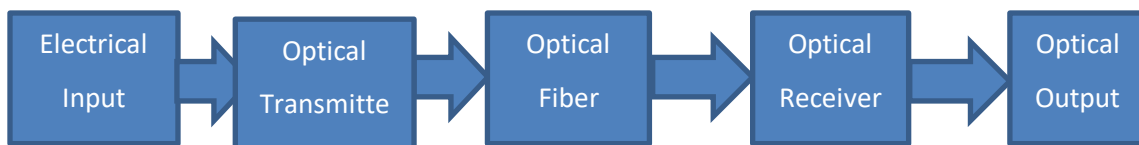


Figure 1.2: General diagram of Optical Communication System [7]

1.2. Fiber Optic Communication System

The fiber optical communication is also another type optical telecommunication that uses light signal to carry information at a distance from one place to another and this can be take place by using electronic devices. The earliest basic electrical device is evolved in1880 which are date back several years and this earliest electrical equipment is invented to do was photo phone. Optical communication is a modern telecommunications technology that sends data between two sites using light signals traveling through a transmission medium. When compared to RF and microwave (MW), optical communication has a higher bandwidth and lower cost; hence it is a

superior option for replacing them. In optical fiber communication, information is sent from one location to another using a light signal sent through an optical fiber [8]. Optical communication was first created in the 1970s as part of the telecommunications industry's evolution, and it played a key role in the development of the telecommunication system [5]. And optical fibers are emerged an alternative solution to replace copper wire communication in the core networks due to advantages over the electrical and RF waveguides and optical fiber again used to replace the radio transmitter systems for long haul data transmission [5]. The optical fibers are mostly used in fiber optical communication where allow to propagate over longer distances large bandwidth or higher data rate than wire cables. And again optical fiber is used to replace metal wires due to less signal loss and also immune to electromagnetic interference.

1.2.1. Linear Effects in Optical fiber Communication system

Most of the losses of optical fiber transmission of the signal in optical fibers resulted due to different linear effects. Dispersion and various optical signal losses, such as attenuation, are linear effects. The diminishing amount of signal pulses or signal power as the length of the signal increases might be termed a transmission loss. In optical fiber there are two different types dispersion exists these are modal and chromatic. Modal dispersion is only exists in multimode fibers and different propagating speeds in fiber for different wavelengths cause chromatic dispersion, which is dependent on the pulse's spectral breadth. So due to chromatic dispersion the broadening of the pulse and phase shifting is occur [9].

1.2.2. Fiber Loss

The impurities are the main factor for the loss in optical fiber for silica based material. The loss is increases at shorter wavelengths because of infrared photon absorption. And the loss may be resulted different sources of material absorption, scattering, mode coupling, leak modes, bending and design of the fiber, radiation induced attenuation, defective construction losses, inversion square law losses, transmission losses, core and cladding losses. The most basic advantage of fiber optic laser based communication is in long haul distance telecommunication. The wavelength, core refractive index, relative refractive index difference, core radius and a number of propagation mode or normalized frequency can decide the number of mode. Optical fibers have a core in the middle that is surrounded by a cladding layer with a refractive index somewhat lower than the core radius. Step index fibers are distinguished from graded index fibers by the

fact that the refractive index of the core changes step by step from center to core boundary. Even though fiber attenuation is very low which is 0.2dB/km in modern fiber optics but still it is an important factors for linear effect gradually minimizes the signal power and signal needs to be amplified after some specific distances to replace these losses. Fiber loss is depends on wavelength and mostly occur because of material absorption and Rayleigh scattering [9]. This can expressed as follows:

$$P_o = P_i \exp(-\alpha L) \quad (1.1)$$

Where, P_i is input power of fiber length L , and P_o is an output power from receiver part of fiber, α is an attenuation coefficient. So the relation between attenuation and input power, output power and length of the fiber can be expressed as:

$$\alpha(\text{dB/km}) = -\frac{10}{L} \log_{10} \left(\frac{P_o}{P_i} \right) \quad (1.2)$$

1.2.3. Fiber Dispersion

As the transmission of length increases spreading of the light pulse as it travels through the fiber is starts to overlap with adjacent pulse is known as fiber dispersion. This will cause the pulse to overlap with neighboring pulses, making it increasingly difficult to get the original signal [10]. During the propagation of a signal, many types of signal dispersion can occur. Intermodal dispersion, chromatic dispersion, and polarization-mode dispersion are the three types [11].

1.2.4. Intermodal Dispersion

Each mode of the signal at a particular frequency has a separate group velocity value as it travels through the fiber, resulting in modal delay [12]. The signal will broaden as a result of the fluctuation in group velocities, and the signal's regular shape will progressively shift. Intermodal dispersion rises with fiber length, and it only happens in multimode fibers because single-mode fibers have only one mode.

1.2.5. Chromatic Dispersion

Chromatic dispersion is basically due to the dependency of the refractive index on the frequency. Thus, different frequency component of the pulse travels with different velocity and causes pulse broadening at the receiving end [13]. This pulse broadening effect is more significant at higher data rate transmissions. Transmitted signal power gets attenuated due to this broadening of the

propagating pulse. This pulse broadening effect is more significant at higher data rate transmissions. Transmitted signal power gets attenuated due to this broadening of the propagating pulse. The key parameter that causes pulse broadening in fibers is the group velocity dispersion parameter. The pulse broadening that happens in single mode fibers is known as chromatic dispersion. The optical source's spectral width is limited, which causes this broadening. Because chromatic dispersion is proportional to wavelength, it increases as the spectral width of the optical source grows [14]. The occurrence of chromatic dispersion is caused by two factors: material dispersion and waveguide dispersion. So the result of dispersion is in the design and modeling of the optical links is accounted with the use of dispersion parameter $D(\text{ps/km-nm})$. In optical fiber, dispersion parameter and the group velocity parameter $\beta(\text{ps}^2/\text{km})$ at a given operating wavelength (λ) are related as:

$$D = -\frac{2\pi c}{\lambda^2} \beta_2 \quad (1.3)$$

1.2.6. Polarization Mode Dispersion

Polarization-mode dispersion (PMD) describes how a signal's group delays are affected by its state of polarization (SOP); there are two distinct SOPs that move at different speeds. The differential group delay (DGD) is the difference in timing between them [15]. PMD is caused by the elliptical rather than circular form of the core, as well as fiber torsion, bending, and thermal stress, all of which cause local fiber birefringence. The total PMD in the complete fiber is the result of the concatenation of several elementary PMDs. The total DGD is a stochastic quantity because PMD is randomly distributed and fluctuates over time owing to temperature and manual movement. In the presence of birefringence, single mode fibers have an inherent feature called polarization mode dispersion (PMD). This variation in fiber birefringence over the fiber's length varies in both direction and magnitude at random [16].

1.3. Nonlinear Effects

The performance of an optical communication system can be harmed by fiber nonlinearities. As a result, in an optical communication system, the presence of this nonlinear effect can disrupt communication between two receiving locations. It is caused by the intensity dependence of the refractive index, commonly known as the Kerr effect and stimulated scattering [17]. As the

power level of the laser and the length the fiber is increase the nonlinear effect is also increases. Optical fiber nonlinear effects can be divided into two categories:

- Kerr nonlinearity
- Stimulated elastic scattering

The Kerr nonlinearity is a result of the refractive index in fiber optics being affected by the transmitted signal intensity [18]. And the Kerr nonlinearity effect contains three basic nonlinear impairments these are;

- Self-phase modulation (SPM)
- Cross phase modulation (XPM)
- Four wave mixing (FWM)

The other type of optical fiber nonlinear effect is the stimulated elastic scattering which supports the transfer of energy to the medium from the optical field. Again it has two types these are;

- Stimulated Raman scattering (SRS)
- Stimulated Brillouin scattering (SBS)

Self-phase modulation (SPM), four wave mixing (FWM), and cross phase modulation (XPM) are nonlinear impairments in glass fiber that might influence signal transmission quality to the desired location. The modulation bandwidth is reduced by using higher level modulation techniques, which provides a solution to this difficulty. When nonlinearity and dispersion are evaluated combined the situation changes. Nonlinearity is sometimes mistaken for dispersion. When many channels are examined, optical fiber nonlinearity effects result in channel interaction. Through good system design, these nonlinear impairments can be mitigated. Improve the channel bit rate to increase the information spectrum efficiency, and decrease the channel spacing to increase the information spectral efficiency, or a combination of the two, to make fiber nonlinearity impairments even more prominent.

1.4. Statement of the Problem

In optical communication system with increase in the length of fiber the dispersion of the optical signal also increases. Data traffic incorporating video and image transmission has become considerably more widespread on the Internet, and such traffic currently consumes more bandwidth than traditional telephone traffic. In high speed optical communication links interaction of fiber dispersion with the spectral components of the propagating pulse makes the evolving pulse at the receiver end more complex especially in the case of realistic fibers with nonlinearities. For a long haul transmission, presence of nonlinearities induces phase and frequency shift influences the overall system performance severely. Due to dispersion it becomes very difficult to implement a long distance transmission system. As a result, we'll try to solve the issues caused by chromatic dispersion, polarization mode dispersion (PMD), and other nonlinear phenomena. OFDM is recognized as the modulation method for long distance transmission systems in both direct detection as well as coherent detection because it can overcome several optical fiber barriers such as chromatic dispersion (CD) and polarization mode dispersion (PMD).

1.5. Objective

1.5.1. General Objective

- Modeling and Performance Analysis of High-Speed Optical Fiber Communications by using OFDM.

1.5.2. Specific Objective

1. To evaluate the performance of direct detection OFDM and coherent detection OFDM systems for different M-QAM modulation formats.
2. To make comparison between DD-OFDM and CO-OFDM systems by M-QAM modulation techniques.
3. To analysis the performance of long-haul fiber optic with OFDM and CO-OFDM using Signal to Noise ratio (SNR), Bit error rate (BER) , Q-factor and Eye diagram

1.6. Significance of the Study

Coherent optical OFDM (CO-OFDM) is a next-generation optical communications technology that combines the benefits of both coherent and OFDM systems in a single optical fiber. CO-

OFDM has a wide bandwidth as well as a high spectral efficiency. Many optical fiber barriers, such as chromatic dispersion (CD) and polarization mode dispersion (PMD), can be overcome by the CO-OFDM system, as well as inter-symbol interference (ISI). The OFDM and CO-OFDM approaches, respectively, can provide great spectral efficiency and increased receiver sensitivity. Because of its capacity to overcome chromatic (CD) and polarization mode dispersion (PMD) difficulties, coherent optical OFDM is a significant option for long-haul optical transmission. As a result, this work contributes to decrease dispersion.

1.7. Scope of the Study

In order to achieve system performance for systems limited by inter symbol interference and noise, optisystem software evaluates metrics such as BER and Quality factor using numerical analysis or semi-analytical approaches and we have been modeling direct detection OFDM and Coherent detection OFDM technique in optisystem software. Again analyzing the performance of the system at different transmission distances by using different modulation techniques this can be in terms different variables such as SNR (signal-to-noise ratio), BER (bit error rate), Q-factor, and Eye diagram.

1.8. Limitation of the Study

There are many types of modulations that can enhance the capacity and performance of high data rate. But in this thesis, we only considered 4-QAM, 16-QAM, 32-QAM and 64-QAM. But higher order modulation techniques may be important to enhance the capacity of the system and the performance of data rate by using 256-QAM and 1024-QAM.

1.9. Organization of the Study

This thesis is divided into five chapters, each of which is discussed in turn:

Chapter 1 discusses the introduction parts which consists background, statement of problem, objectives, specific objectives, significance of the study, scope of the study and limitation of the study. Chapter 2 presents the literature review and related works which explain the concept of optical fiber and OFDM techniques. Chapter 3 presents the methodology of the study in terms of modeling and simulation of optical OFDM using coherent detection OFDM and direct detection OFDM by using optisystem software. Chapter 4 discusses the simulation result and analysis of optical OFDM. And finally conclusion and recommendation of the thesis is discussed.

CHAPTER TWO

2. Literature Review

2.1. Introduction

The basic purpose of a long-distance optical fiber communication system is to provide the highest data rate throughput across the shortest distance possible without signal regeneration. Given the bandwidth constraints imposed by optical amplifiers and, eventually, the fiber itself, increased spectral efficiency (measured in bits/s/Hz) is critical. Given the signal power constraints imposed by fiber nonlinearity, increasing power or signal to noise ratio efficiency is critical for lowering the needed average transmitted energy per bit or achieving an acceptable signal to noise ratio per bit. Because of its higher spectral efficiency, resilience to multipath fading, and interference resistance, Orthogonal Frequency Division Multiplexing (OFDM) is becoming more common in long-haul optical communication networks. OOFDM (Optical Orthogonal Frequency Division Multiplexing) could help meet the increased demand for bandwidth in broadband services.

2.2. Related Works

Yoon-Khang Wong, S. M. Idrus, and I. A. Ghani [19] Performance Analysis of Wireless over Fiber Communication Links with a Suggested OFDM Scheme Radio over Frequency is concerned with future technical systems that can combine the enormous capacity of optical networks with the mobility of wireless networks. He investigates the performance and attributes of Orthogonal Frequency Division Multiplexing as a modulation technology (OFDM).

Mary Anjaley Josy John, Gokul P G [20] The Performance Evaluation and Simulation of OFDM in Optical Communication Systems is a proposal that investigates the structure and architecture of single-channel, four-channel, direct-detection, and coherent-detection optical OFDM systems, as well as performance analysis using bit error rate and Q-factor. Single-channel systems can transmit data at 10 Gbps, while four-channel systems can transmit data at 40 Gbps. As a result, he proposed CO-OFDM (Coherent Optical OFDM) as the next-generation optical fiber communications technology, because it incorporates the advantages of both coherent and OFDM systems.

Shitize trehan [21] The researchers researched and provided a comparative analysis of single-span long-haul optical fiber links using various modulation techniques. Differential phase shift key (DPSK) modulation techniques in high-speed Dense Wavelength Division Multiplexing systems are the subject of this research. Eight 40 GB/s channels are multiplexed with a two-channel gap in this experiment.

Ali Hayder Abdul Kareem [22] examines the design and analysis of a All Optical Orthogonal Frequency Division Multiplexing Processing is used to create a high-capacity communications system. This paper examines how to extend transmission range by improving data rates in all optical orthogonal frequency division multiplexing (AO-OFDM) techniques. In this study, the arrayed waveguide grating (AWG) was presented as an inverse fast Fourier transform (IFFT/FFT) circuit in all optical orthogonal frequency division multiplexing systems Arrayed Waveguide Grating (AWG) with dense wave division multiplexing (DWDM) and channel spacing of 20 GHz. The suggested method is less complicated than others in that it can achieve All Optical Orthogonal Frequency Division Multiplexing and spectrum efficiency.

Bobby barua [23] Over a turbulent atmospheric channel, a performance analysis of STBC and LDPC coded OFDM free space optical communication systems was proposed. Several analytical approaches for an RF subcarrier modulated Free Space Optical communication system are developed in this paper for both non-orthogonal and orthogonal modulation, taking into account the influence of atmospheric turbulence, which is modeled by lognormal and gamma-gamma distributions for weak and strong turbulent, respectively. Primarily, investigations are made to develop an analytical approach to evaluate the carrier to noise ratio (CNR) and bit error rate (BER) of a FSO link with RF non orthogonal subcarrier modulation (SCM) followed by optical intensity modulation taking into considerations the effect of atmospheric turbulence with coherent and direct detection followed by RF synchronous demodulation.

Faris Mohammed Ali [24] is explained about RoF system which is a viable approach for future microcell and Pico cell wireless data network deployments, and Orthogonal Frequency Division Multiplexing (OFDM) is again proposed as a standard for broadband wireless networks for deployment with RoF systems to increase overall system performance.

Juan Miguel Pérez Rosas [25] This article investigates the use of Direct Detection among the various O-OFDM designs, with a focus on the downlink of Passive Optical Networks, where cost-effective Optical Network Units are required and this article examines Direct Detection

Optical OFDM (DD-OFDM) communications systems in general, with an emphasis on optical access network applications.

2.3. Orthogonal Frequency Division Multiplexing

The data information is conveyed over numerous lower rate subcarriers in orthogonal frequency-division multiplexing (OFDM), which is categorized as multicarrier modulation (MCM). The resistance to channel dispersion and the ease with which it can estimate phase and channel in a time-varying environment are the two main advantages of OFDM. Silicon digital signal processing (DSP) technology is also employed. OFDM has a high peak-to-average power ratio (PAPR), phase noise, and frequency sensitivity, among other disadvantages. As a result, a thorough understanding of OFDM fundamentals and applications is required for our research. OFDM is a modern and appealing modulation technique that uses less bandwidth and is resistant to multipath fading. The use of OFDM to alleviate ICI induced by a dispersive channel is a realistic approach. It also boasts a higher spectral efficiency and lower power consumption. Most contemporary and developing broadband wireless and wired communication technologies use OFDM nowadays. Several academics have recently demonstrated that OFDM is a potential solution for optical communications [26]. OFDM has been extensively investigated during the last two decades in response to the growing requirement for high data rates in modern communication systems. OFDM is a modulation scheme that enables a high data rate while also being resistant to multipath fading [26]. OFDM (Orthogonal Frequency Division Multiplexing) is a Multi Carrier Modulation (MCM) method that transports data using a high number of subcarriers. The capacity of OFDM to overcome channel dispersion is its key advantage. OFDM is also popular because of its capacity to transport information at high data rates. OFDM has been used in a number of applications in the RF domain, including digital audio broadcasting (DAB), digital video broadcasting (DVB), and Wireless Local Area Networking (WLAN). Since its introduction to the optical domain in 2005, OFDM has been examined and investigated in two primary ways classified by detection scheme. Direct detection optical OFDM (DD-OFDM) is the first technique, while coherent optical OFDM is the second (CO-OFDM) because it incorporates the advantages of both coherent and OFDM systems, CO-OFDM (Coherent Optical OFDM) is the next generation of optical communications technology. CO-OFDM has high spectrum efficiency and can detect linearly. The CO-OFDM system can overcome many optical fiber

restrictions, such as Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) (PMD). The system is also immune to inter-symbol interference because to the cyclic prefix code (ISI). Due to its flexible spectrum efficiency and improved resistance against both fiber chromatic dispersion (CD) and polarization-mode dispersion (PMD), optical orthogonal frequency-division multiplexing (OFDM) has recently gained a lot of interest [27].

2.3.1. OFDM Basics

Frequency Division Multiplexing (FDM) is a modified variant of OFDM (FDM). Different information for distinct users is delivered at the same time via different frequency carriers in the FDM technology as shown in Figure below. After being modulated by the user's data, each subcarrier in the transmitter is equipped with a wide guard band to prevent it from overlapping with subsequent subcarriers. This guard band, however, will lower the system's spectral efficiency. The received signals are then demodulated by oscillator banks at the receiver. Orthogonal frequency-division multiplexing (OFDM) is a type of multicarrier modulation in which the data signal is split into several narrowband subcarriers. In 1966, the OFDM concept was initially presented [28], due to frequency-selective channels, the goal is to maximize data rate while minimizing inter-channel and inter-symbol interference. OFDM has a number of advantages over single-carrier modulations, including resistance to frequency-selective fading channels, ease of effective equalization, efficient spectrum usage, subcarrier allocation flexibility, and subcarrier modulation adaptability [29]. OFDM has been included into various wireless protocols, including Digital Audio Broadcasting (DAB), Digital Video Broadcasting-Terrestrial (DVB-T), wireless local area networks (IEEE 802.11a/g), and 3GPP-Long-Term Evolution, because to these characteristics (3GPP-LTE).

FDM is special example of, OFDM employs a large number of carriers per spectrum that are very close to one another but at an exact distance from one another, ensuring that they remain orthogonal to one another. OFDM is an effective solution to inter-symbol interference problem caused through a dispersive channel, thus, it is utilized widely in communication systems [30]. Furthermore, OFDM is distinguished by the fact that it transfers the complexity of transmitters and receivers from the analog to the digital domain. However, the basic concept of OFDM is a method of divide a stream of high data rate into multiple less data rate streams and then transmitted in the same time through a number of orthogonal subcarriers.

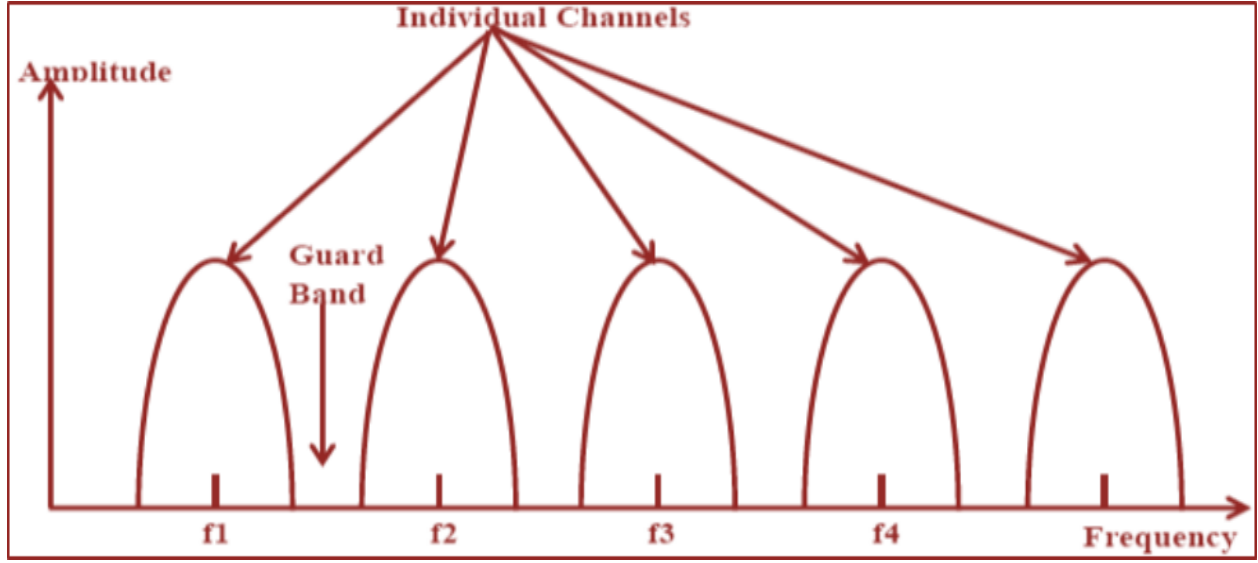


Figure 2.1: FDM spectra [30]

As a result, reduce the relative amount of dispersion in time caused through dispersive channels like optical fibers. OFDM based design has an inherent ability to include an extended guard time periodically in each OFDM symbol [31].

2.3.2. Mathematical Formulation of OFDM Signal

Orthogonal frequency division multiplexing is a type of multicarrier modulation in which data is transmitted using a series of carriers modulated on QAM and PSK with varying frequencies [32]. The signal conveyed by multicarrier modulation is denoted by $s(t)$.

$$s(t) = \sum_{k=0}^n \sum_{i=0}^n (c_{ki}) s_{ki}(t - iT_s) \quad (2.1)$$

$$s_k(t) = \Pi(t) e^{j2\pi f_k t} \quad (2.2)$$

Where: c_{ki} , is the i^{th} information symbol, k^{th} , is the subcarrier

s_k , is the waveform for the k^{th} subcarrier

N_{sc} , is the number of subcarriers

f_k , is the frequency of the subcarrier

T_s , is the symbol period and

$\Pi(t)$ is the pulse shaping function

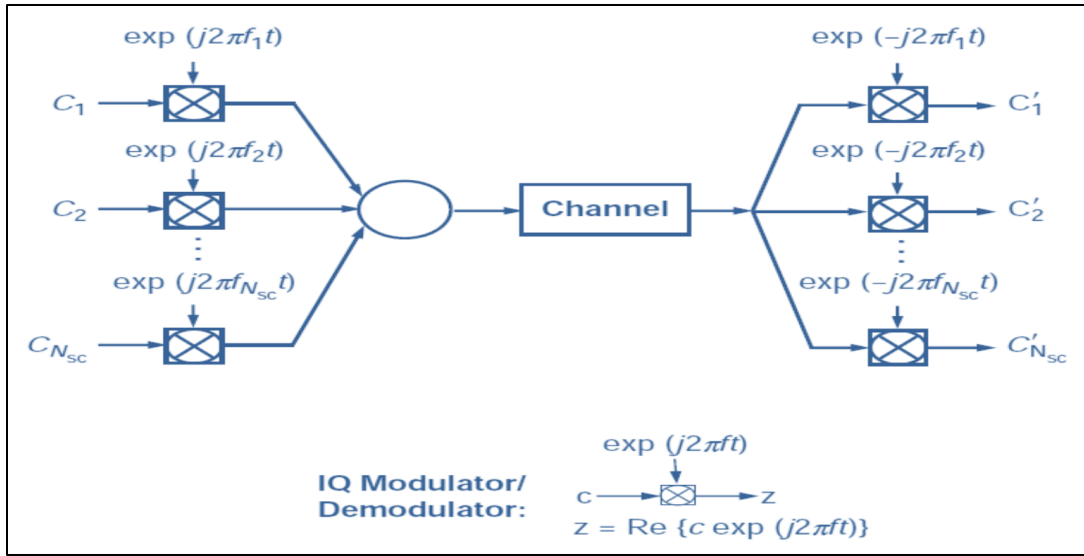


Figure 2.2: Multicarrier Modulation systems [34].

2.4. Orthogonality

Different multiple information signals are transmitted correctly over the same channel and detected without any interference is due to orthogonality. In order to achieve orthogonality in the frequency domain, OFDM divides each information symbol into orthogonal subcarriers. Then the signal of OFDM is generated from summation of sinusoids with each the sinusoids are corresponding to the subcarriers [33]. The orthogonality characteristics of OFDM signal which look like its spectrum. The OFDM subcarrier has a sink, which is $(\sin(x)/x)$ and this spectrum is shown in figure below.

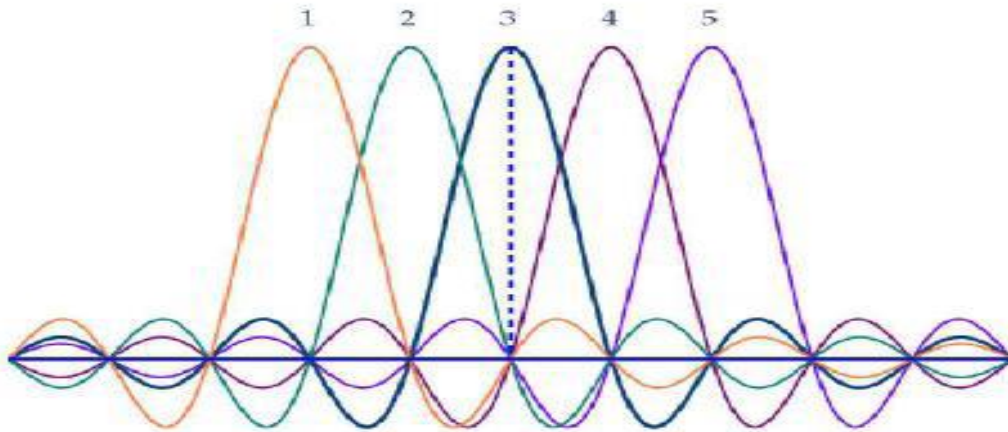


Figure 2.3: The spectrum of the orthogonal OFDM [33]

2.5. OFDM Modulation System

The OFDM modulation contains two parts these are, transmitter and receiver as shown in figure below. The transceiver contains number of blocks and each are explained and discussed as follows.

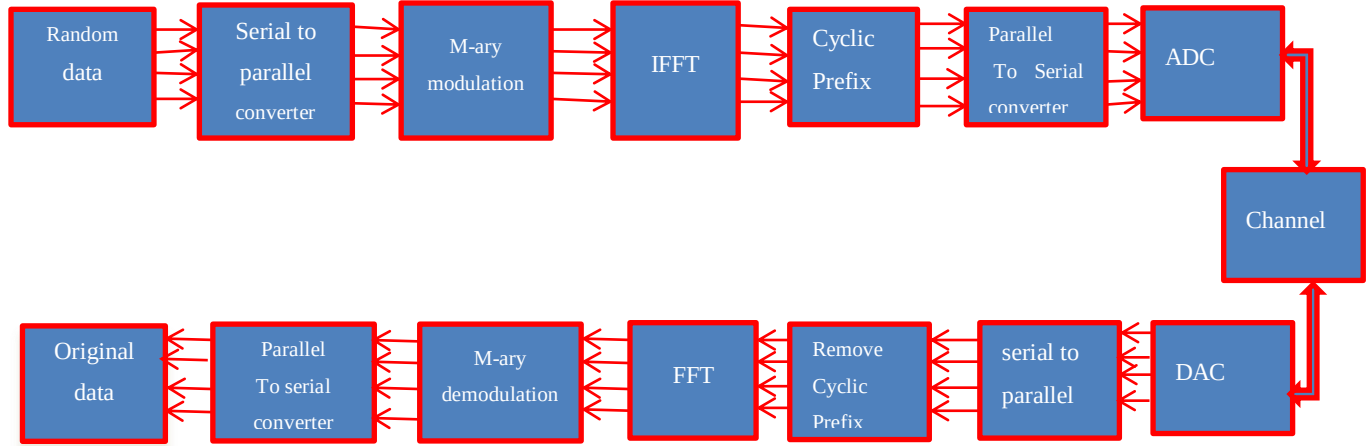


Figure 2.4: Block diagram of OFDM Transmitter and Receiver

The transmitter converts the serial input data to parallel data before modulating it with an M-ary modulator, which can be QAM, BPSK, or PSK. After that, the data is sent through IFFT, with a cyclic prefix added to prevent Subcarrier overlap. The signal is subsequently transferred over the channel after a parallel to serial conversion [34].

2.5.1. Serial to Parallel Conversion

The message signals must be transformed to parallel data using a serial to parallel converter once the binary values have been converted to complex symbols. These data must be divided into subsets, each of which transfers a specified number of symbols determined by the number of subcarriers. As a result, each OFDM symbol converts the incoming data signal into the symbol required for transmission. For example, each subcarrier in an 8-QAM subcarrier modulation contains 3 bits of data, while 4-QAM has 2 bits, 16-QAM has 4 bits, and 64-QAM has 6 bits.

2.5.2. M-ary Quadrature Amplitude Modulation

M-ary Quadrature Amplitude Modulation is a single carrier modulation technique that allows multiple symbols to be delivered at the same time by combining them into a single symbol [35]. The advantages of using single carrier M-ary Quadrature Amplitude modulation include ease of wavelength allocation, reduced power dissipation, increased compactness, and the ability to

implement in real time [36]. Single or multiple in phase quadrature modulators can be used to map a single narrow line width cavity laser into an optical M-ary quadrature signal.

2.5.3. Quadrature Amplitude modulation (QAM)

To enhance the amount of bits per symbol, the M-level modulation format modifies data by modulating both the amplitude and phase of the original signal. Quadrature Amplitude Modulation (QAM) is a type of amplitude modulation that combines ASK and PSK (Amplitude Shift Keying and Phase Shift Keying and Quadrature Amplitude Modulation (QAM) consists of two signal amplitudes that are out of phase with each other and are referred to as quadrature. 4-QAM, 16-QAM, 8-QAM, 16-QAM, 64-QAM, 256-QAM, and 1024-QAM are two, three, four, six, eight, and ten bits per symbol, respectively. As a result, quadrature amplitude modulation can be written as follows:

$$S(t) = A_I \cos(2\pi f_c t) + A_Q \sin(2\pi f_c t) \quad (2.3)$$

Where A_I and A_Q phase (I) and quadrature (Q) correspondingly, and the data bit stream is separated into Phase (I) and Quadrature (Q) are merged together and translated to complex symbol by using Quadrature Amplitude Modulation (QAM) modulator. In order to obtain the output result, the complex symbol was broadcast and divided at the receiver using a Quadrature Amplitude Modulation (QAM) demodulator. According to Shannon's law, which determines the theoretical maximum bit rate that can be sent over a bandwidth limited channel in the presence of noise, multi-level optical modulation systems offer great spectral efficiency at the cost of reduced tolerance.

2.5.4. Inverse Fast Fourier Transform

The usage of contemporary OFDM is an advantage of Inverse Fast Fourier Transform (IFFT). IFFT has demonstrated its ability to efficiently and correctly perform frequency up conversion and multiplexing of complicated subcarriers. In addition, the FFT is required for demodulation and DE multiplexing at the receiver. The IFFT/FFT is the fundamental component of the OFDM transmitter and receiver.

2.5.5. Cyclic Prefix for OFDM

The cyclic prefix is one of the most important strategies to avoid dispersion medium effects like chromatic dispersions (CP) and polarization dispersions mode [37]. Two further OFDM

approaches are modulation and demodulation of independent orthogonal subcarriers using FFT and IFFT, which were intended for good signal performance [37]. Following the two consecutive OFDM symbols results in a dispersive medium with a τ_d delay spread. That is, each OFDM symbol only contains two subcarriers, each with a fast and slow delay spread at τ_d , as denoted by the terms "fast subcarrier" and "slow subcarrier," respectively.

2.5.6. Fast Fourier Transform

After removing the cyclic prefix, the OFDM symbols are used to the FFT technique to convert the right values to the frequency domain. Without the usage of a large number of oscillators and filters, FFT can recover the subcarriers in a single step. The FFT techniques will reveal that the OFDM transmitter and receiver subcarriers are orthogonal, which will aid in noise cancellation. Subcarrier orthogonality's major goal is to keep the subcarrier center frequency from overlapping with those of other subcarriers while the subcarrier signal overlaps.

2.5.7. Analog to Digital Converter

Analog to digital converters are a type of data converter that converts an analog signal to a digital signal in one direction [38]. Analog to digital converters can be implemented in a variety of ways, including serial and parallel converters. A sample and hold circuit converts an analog signal to discrete form before converting it to a digital signal [38]. It is called a parallel converter if the sample is compared to different quantization levels simultaneously and converted to digital signal in the first step; otherwise, it is considered a serial converter if the output is compared to different quantization levels serially.

2.5.8. Digital to Analog Converter

A device that converts a digital signal to an analog signal is known as a digital to analog converter. The digital signal is normally stored in media or transmission line then a digital to analog converter changes the digital signal to analog signal in order to control data display or further analog signal processing. For example, from digital communication system, when receiver receives the digital modulation signal, then after through demodulator and decoder, we can get the digital signal, and follow by using digital analog converter to convert this digital signal to the analog signal. Basically, digital to analog converter is a digital code that represents digital value converted to analog voltage or current.

2.6. Advantages of OFDM

Orthogonal frequency division multiplexing has different advantages that will make it's an alternative for future 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:** For single carrier modulation schemes, sophisticated equalization techniques are required if the channel enforces frequency selective fading.
- **High spectral efficiency:** OFDM allows subcarriers to overlap in the frequency domain while remaining orthogonal to one another at the same time.
- **Efficient modulation and demodulation:** The IFFT and FFT techniques are used to modulate and demodulate the subcarrier, and these two techniques are fundamental in OFDM.

2.7. Disadvantages of OFDM

Again OFDM has some disadvantages these are due to complexity, these are due to OFDM uses a more linear power amplifier and offers multicarrier modulation techniques, which are more complicated than single carrier modulation techniques. And OFDM has a number of drawbacks, including:

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

2.7.1. Peak to Average Power Ratio

The high peak to average power ratio (PAPR) of OFDM modulation is considered a drawback. Since the OFDM signal is formed by combining multiple data streams that are modulated by separate subcarriers If all of the subcarriers are brought together coherently, this can result in a significant peak to average power ratio. A peak power equal to N times the average power is created when N separate signals are combined in a coherent way with the same phase. To

overcome a peaky OFDM signal, the power amplifier must be set to a lower signal power than the saturation power.

2.8. Dispersion Compensating Techniques

Dispersion is the change in the shape of pulse accumulation over fiber optical transmission. When we use EDFA in transmission medium as amplifier, there is no need of use regenerators. Even though EDFA provides large gain but could not clean up the incoming signal. Due to this dispersion and nonlinear effects are occurred as a result. So this all problem puts into design of dispersion compensation techniques.

2.8.1. Dispersion Compensating Fiber (DCF)

Dispersion compensating fiber a better fiber optic designed to have opposite dispersion parameters to that transmission optical fibers and it's a single mode fiber that have high negative dispersion coefficient and used reduce the dispersion of single mode fiber. Dispersion compensating fiber is the ability to completely compensating the chromatic dispersion in transmission optical fibers in large wave length ranges.

2.8.2. Fiber Bragg Grating (FBG)

The Fiber Bragg grating (FBG) is one of the most fundamental dispersion correction techniques. At the end, it produces multiple frequencies with different lengths, and the frequency component of the signal changes, resulting in variable phase delays. As a result, FBGs are utilized in fiber optics as a reflecting device in which core refractive index modulation occurs at a specific wave length. Reflection occurs when the wave length of the signal going through the optical fiber matches the modulation periodicity of the FBG.

2.9. Wave Division Multiplexing

Wavelength division multiplexing (WDM) is a technique for multiplexing different optical carrier signals into a single optical fiber carrier signal by employing different wavelengths of laser light. As a result, this multiplexing approach allows for bidirectional communication via a single fiber stand, as well as multiplication capacity [39], Each wavelength, once again, has its own channel. The optical spectrum channel is divided into smaller channels by wavelength division multiplexing, which are utilized to broadcast and receive data at the same time [40].

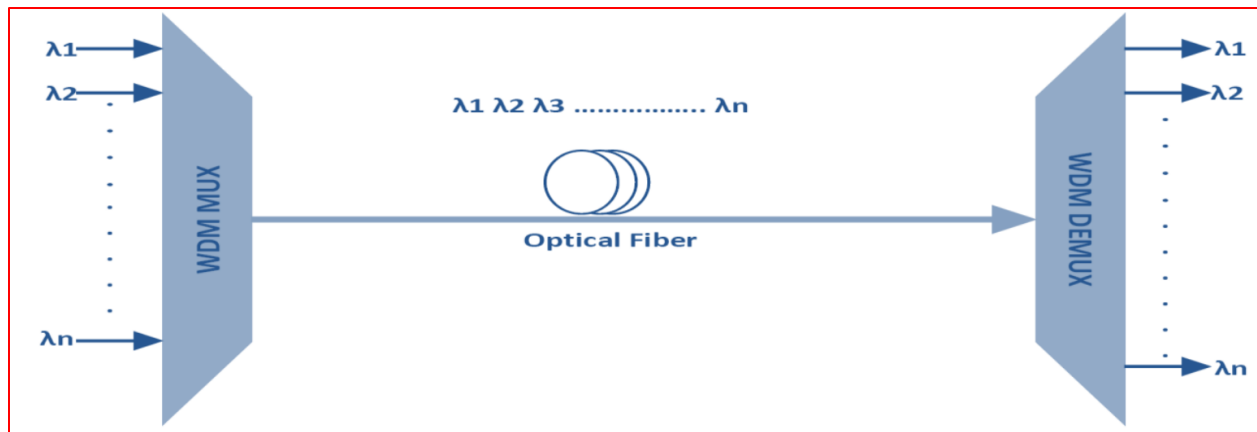


Figure 2.3: Wavelength division multiplexing [41]

The optical fiber wavelength division multiplexing networks seen above are those in which wavelength replaces frequency and each transmitter broadcasts a different wavelength, where $i=1, 2, 3, \dots, N$. The two types of wavelength division multiplexing systems are as follows: Dense wavelength division multiplexing and coarse wavelength division multiplexing are two types of wavelength division multiplexing.

CHAPTER 3

3. Materials and Methods

3.1. Introduction

The approach for modeling and performance analysis of high-speed optical communication systems employing OFDM has been designed and simulated using OptiSystem software with several modulation schemes such as 4-QAM-OFDM, 16-QAM-OFDM, 32-QAM, and 64-QAM-OFDM. It is used to design, construct and simulate the optical OFDM technology. To do this thesis general and specific objectives of the study area, the following procedural methods will be followed to complete the project is described under:- The first step will be literature survey, collecting data and analyzing, simulation and designing of the High speed long haul optical fiber.

3.2. Materials

In this work we used Optisystem software. Optisystem is a software platform that enables users to plan, test, and simulate optical links at the transmission layer of modern optical networks. This program contains a wide range of optical and wireless components for designing and constructing a complete optical network, which is a low-cost and time-saving method that allows the researcher to work more efficiently. Finally we used matlab to analyze performance of the system at different modulation scheme and at different distance transmission.

3.3. Methods

- ❖ This research has been conducted according to the following steps:
 - Studying the basic theory, architectures and related subjects.
 - Revising the existing work in the literature which is related to the Optical OFDM.
 - Identifying the parameters which required for modeling of our system
 - Modeling our system by using Optisystem software
 - Testing of the proposed system which is simulated.
 - Compare and contrast our result by using different parameters and classify them into main categories depending on their performance.

3.4. Proposed Block Diagram of Optical OFDM

The optical OFDM is based on the same principles as OFDM, but it differs in that the signal is transformed from a wireless signal to an optical signal in the electrical domain. The optical OFDM block diagram is presented below; in this arrangement, that transmitter includes OFDM baseband transmission, RF up conversion, and optical modulation, whereas the receiver includes OFDM baseband reception, RF down conversion, and optical detection. The serial to parallel converter divides the binary serial digital data at the transmitter into N-channel parallel signals. And the M-ary PSK or QAM modulation schemes are used to modulate the entire signal. The data is then modulated to the appropriate symbols using a constellation diagram. N parallel symbols are then translated to serial and added as OFDM carriers before each symbol using IFFT. The cyclic Prefix was then added, and the signal was converted to an OFDM baseband analog signal via the digital to analog converter. Before being transported through an optical carrier and onto a single mode fiber, the baseband signal is converted to an RF carrier frequency. Optical data is translated to electrical impulses by photo detectors, which are subsequently converted to digital signals by analog to digital converters. The cyclic prefix is then eliminated, and the parallel to serial conversion takes place. The signal is then converted to the frequency domain using the Fast Fourier Transform. Finally, the signal is demodulated and converted to a serial signal.

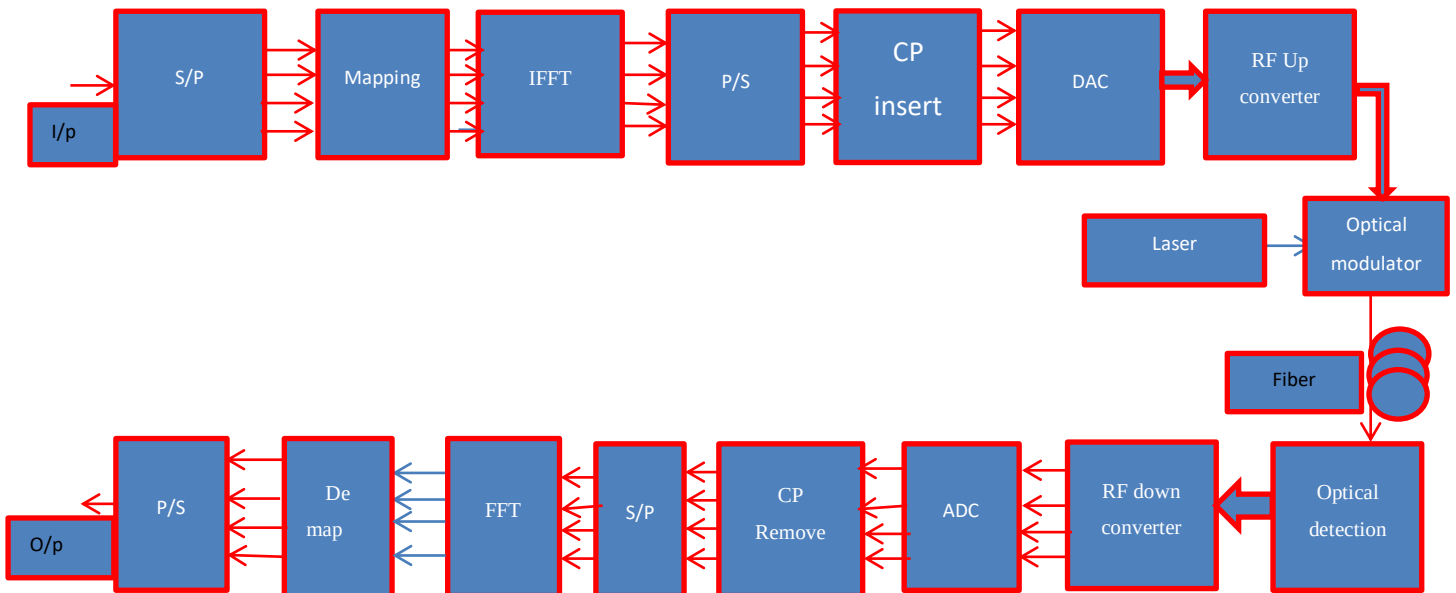


Figure 3.1: Block diagram of Optical OFDM

3.4.1. Optical OFDM Transmitter

The optical OFDM transmitter system has two basic components; these are baseband OFDM generator and an optical up converter. So in an optical up conversion the I and Q components of an OFDM generator output are mapped to an optical signal through an external optical modulator and continuous signal laser source. There are two types of external modulators that are basically used for Optical OFDM systems; these are Optical IQ modulators and Intensity modulators.

3.4.2. RF to Optical Up Converter

The basic function of RF to optical up converter is to change OFDM signal from base band signal to optical domain. To up convert the real/imaginary components of the resultant base band time domain from the RF domain to the optical domain, the RF to optical up converter employs an optical In-phase Quadrature modulator, which comprises of two Mach-Zehnder modulators.

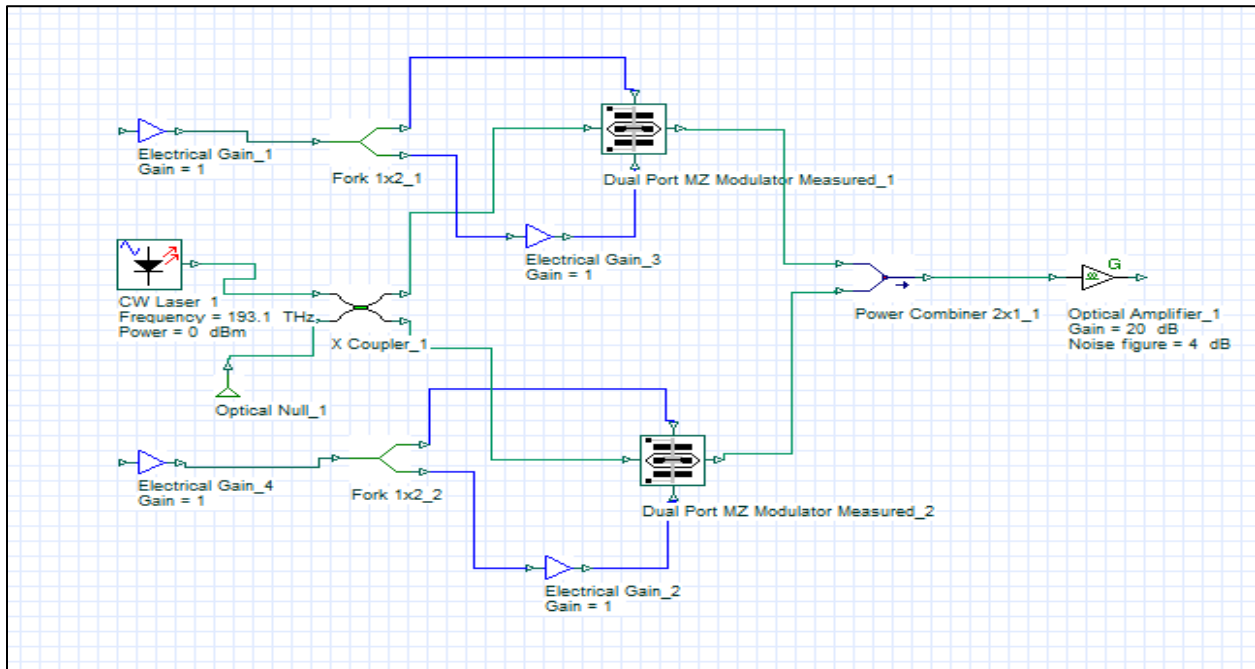


Figure 3.2: RF to optical up converter

3.4.3. Mach-Zehnder Modulator

The Mach-Zehnder modulator is the best device for high-data-rate optical communication systems, and it's typically used for intensity modulation in classic schemes that employ one of two modulation formats: non-return-to-zero (NRZ) or return-to-zero (RTZ) (RZ). In this case, LiNbO3 is generally used to make modulators whose refractive index is modified by the applied

voltage or electric field. Modulating the refractive index of the crystal with electrical data can vary the phase of the incoming light signal. By converting a crystal into a Mach-Zehnder interferometer, phase modulation can be converted to intensity modulation [42].

3.4.4. Optical to RF Down Conversion

The output of optical to RF down conversion is an electrical signal. For the structure of direct up/down conversion, an optical to RF down converter uses two pairs of the balanced receivers and one optical hybrid to perform In-phase Quadrature detection optically. In Intermediate frequency structure, optical to RF down converter which consists of one pair of balanced photo detectors to down convert the optical OFDM signal to an intermediate frequency.

3.4.5. Intensity Modulation

Intensity modulator made up of continuous wave laser and a single Mach-Zehnder-modulator. The result of Mach-Zehnder-modulator is directly proportional to the electrical OFDM signal and the electrical OFDM should be real and positive signal [43]. As a result, the real and imaginary of the baseband OFDM symbol are explained by the I and Q components of the OFDM generators, which are converted to RF orthogonal frequency division multiplexing using an electrical In-phase Quadrature modulator. In Mach-Zehnder-modulator, the input of optical power which results from the CW laser is dividing between two wave guide ends and the electrical OFDM putted to these two arms of wave guide to activate optical phase modulation. And the output of Mach-Zehnder-modulator is the combination of two optical signals passing through two wave guide arms, so the maximum intensity can be achieved if the two arms are in-phase which results in constructive interference [44].

3.4.6. Optical I/Q Modulator

In-phase quadrature used to overcomes the nonlinearities and digital to analog converter amplifier limitation by using multiple In-phase quadrature modulators that are driven by the help of binary electrical signals [45]. The In-phase Quadrature Modulator, on the other hand, takes advantage of sine and cosine's orthogonality. Again, the simplest In-Phase Quadrature modulator configuration is a local laser with two Mach-Zehnder modulators in tandem, one of which has a 90 degree phase shift. The modulated signal is created by combining the two signals. The main advantage of the In-phase quadrature modulator is its resistance to symbol rotation or the addition of a dimension to the signal. An optical IQ modulator, consisting of a CW laser and two

Mach-Zehnder-modulators, converts the in-phase quadrature sections of the complex baseband OFDM wave to an optical signal. So the optical signal of the CW laser connected to both Mach-Zehnder as input optical signal for both of Mach-Zehnder modulators. At the OFDM transmitter, two digital to analog converters were used to convert the digital signal's in-phase (I) and quadrature (Q) components to analog signals. The modulated signal can be written as follows as a result of two Mach-Zehnder modulators:

$$E(t) = X(t) \exp(j\omega_{LD1}t + \phi_{LD1}) \quad (3.1)$$

The signal at the receiver is expressed as follows: $X(t)$ is the transmitted electrical signal,, and are the angular frequency and phase transmitter laser diode, respectively, and the signal at the transmitter is expressed as follows:

$$E_r(t) = E(t) \otimes h(t) + w(t) \quad (3.2)$$

The incoming signal is detected using two identical pairs of balanced coherent detectors and an optical 90° optical hybrid port, where $h(t)$ is the channel impulse response and $w(t)$ is the channel noise.

$$E1 = \frac{1}{\sqrt{2}} [E_r + E_{LD2}] \quad (3.3)$$

$$E2 = \frac{1}{\sqrt{2}} [E_r - E_{LD2}] \quad (3.4)$$

$$E3 = \frac{1}{\sqrt{2}} [E_r - jE_{LD2}] \quad (3.5)$$

$$E4 = \frac{1}{\sqrt{2}} [E_r + jE_{LD2}] \quad (3.6)$$

Where, E_{LD2} is an electrical signal which comes from local oscillator at the receiver part. The two photo diode PD1 and PD2 are used for recovering of the In-phase (I) component which can be expressed as follows:

$$I2 = |E|^2 = \frac{1}{2} [|E_r|^2 + |E_{LD2}|^2 + 2\text{Re}(E_r E_{LD2}^*)] \quad (3.7)$$

Where Re represented the real component and real component of photocurrent is again expressed as follows:

$$I_1(t) = I_1 - I_2 = 2\text{Re}(E_r E_{LD2}^*) \quad (3.8)$$

Again remain of the two photodiode, PD3 and PD4 are used to recover Quadrature (Q) component which can be expressed as follows:

$$I_Q(t) = I_3 - I_4 = 2\text{Im}(E_r E_{LD2})^* \quad (3.9)$$

Where the Im is represented for imaginary component so from above equation the total complex signal I(t) will be expressed as follows:

$$I(t) = I_1 + jI_Q = E_r E_{LD2}^* \quad (3.10)$$

So, the OFDM signal which detected is:

$$Y(t) = I(t) = X(t) \exp(j\Delta\omega t + \Delta\phi) \otimes h(t) + W(t) \quad (3.11)$$

Where $\Delta\omega$ represents change in angular frequency which is the difference between the local oscillator and the laser diode at the transmitter part and $\Delta\phi$ is represents change phase is the difference in phase between this local oscillator and laser diode. This can be expressed as follows:

$$\Delta\omega = \omega_{LD1} - \omega_{LD2} \quad (3.12)$$

$$\Delta\phi = \phi_{LD1} - \phi_{LD2} \quad (3.13)$$

So, to recover the original signal the detected signal must be transmitted the OFDM receiver

3.4.7. Optical OFDM Receiver

Optical OFDM receiver is consists two types optical detector these are; coherent detection and direct detection. Coherent detection will be used when an optical In-phase Quadrature modulator is used at the transmitter side, where as direct detection can be used when an intensity modulator is used at transmitter side.

3.5. Coherent Detection OFDM

CO-OFDM (Coherent Optical OFDM) is the next-generation optical communications technology. CO-OFDM is for linear detection and high spectrum efficiency. The coherent OFDM system may alleviate various optical fiber restrictions such as Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD). The system is additionally immune to inter-symbol interference because to the cyclic prefix code because it combats (ISI) [46]. Although coherent OFDM offers the best receiver sensitivity, spectrum efficiency, and polarization dispersion resistance, it also necessitates the most complexity in transmitter and receiver design.

High receiver sensitivity is possible with coherent optical OFDM, allowing us to send data across long distances. At the same time, the number of subcarriers has a direct effect on the performance of coherent optical OFDM. The diagram below shows a schematic diagram of a coherent optical OFDM system. When the number of subcarriers is relatively great, interference between the channels occurs. The use of spectrum will be decreased if the number of subcarriers is very tiny. As a result, in a coherent optical OFDM system, keeping track of the number of subcarriers is crucial. Different modulation techniques will alter the optical signal to noise ratio (OSNR), nonlinear effect, and optical fiber dispersion tolerance. We should have to give attention to that of variation differential group delay (DGD) which will affect the performance. So the performance of the system can improve by increasing differential group delay (DGD). But after some point the performance of the system will fall by increasing differential group delay (DGD). That is due to the main factor affecting the performance of the system becomes Polarization mode dispersion (PMD). To generate optical signal we used the optical local oscillator at a certain wavelengths. The optical coherent detection can be classified in two parts depending on the amount of frequency that generated by local oscillator and these two are heterodyne detection and homodyne detection. In heterodyne detection, the local oscillator frequency is not equal to the incoming signal frequency. When two signals are merged in a photodiode, a new frequency called the intermediate frequency (IF) is created, which is the difference between the two frequencies. As a result, thermal noise and shot noise are reduced, and the signal to noise ratio is improved. A coherent optical OFDM system in optical communication will perfectly adapt and estimate polarization mode dispersion.

3.5.1. Coherent Detection OFDM system with single mode fiber

A coherent detection OFDM system is made up of five components. An OFDM transmitter, an RF to optical up converter (RTO), an optical fiber transmission connection, an optical to RF down converter (OTR), and a coherent OFDM receiver are all part of this system. The bit sequences generated by PRBS are fed into a 4-QAM (2 bit per symbol), 16-QAM (4 bit per symbol), 32-QAM (5 bit per symbol), or 64-QAM (6 bit per symbol) sequence generator. M-QAM data is delivered to an OFDM modulator with 512 subcarriers and 1024 FFT points. OFDM modulation, transmission, and multiplexing can all be done digitally using inverse fast Fourier transforms (IFFT). The OFDM modulator's output is filtered using a low pass (LP)

cosine roll of filter, and the OFDM modulator's output is given to an RF optical to up converter and Up-conversion is accomplished using a CW laser and two Mach-Zehnder modulators used Convert RF OFDM data into optical domain and modulate the electrical signal that comes from the OFDM modulator to the optical carrier with a CW laser source frequency of 193.1(THz) and a power of 100 watts (-4dBm).

Table 3.1: The parameters for Coherent Detection OFDM

Parameters	Value
Subcarrier	512
CW laser Frequency	193.1 THz
FFT points	1024
Extension Ratio	20dB
Switching RF voltage	4V
Insertion loss	5dB
Thermal power density	1×10^{-21}

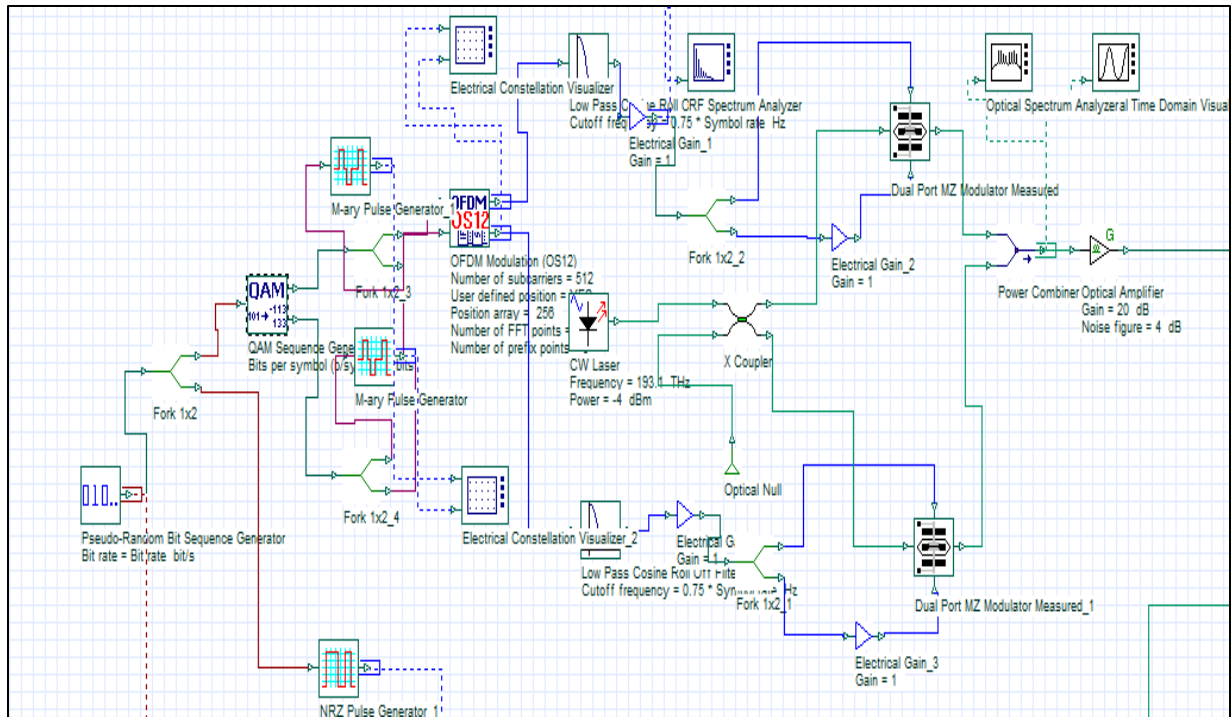


Figure 3.3: Schematic diagram of Coherent optical OFDM

The signal was then broadcast via a single mode fiber transmission connection with 0.2dB/km attenuation, 16ps/nm/km dispersion, 0.08ps/nm²/km dispersion slope, and a nonlinearity coefficient of (2.6x10⁻²⁰). An optical amplifier is used to enhance the optical signal and compensate for fiber loss.

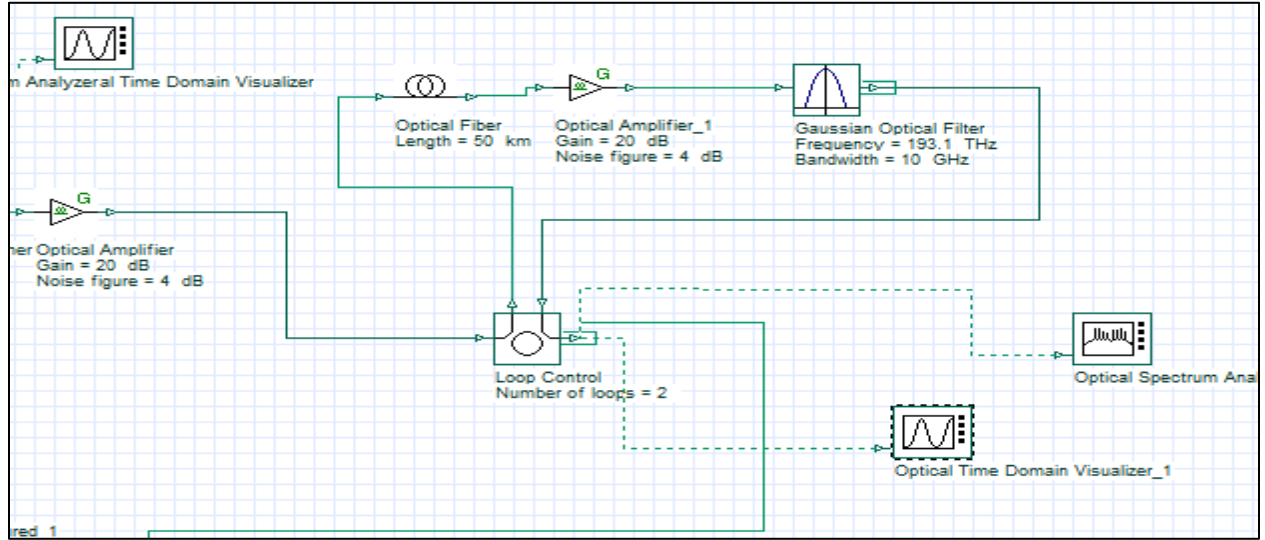


Figure 3.4: Optical transmission link

In the receiver section, two identical pairs of balanced coherent detectors with local oscillator directly detect the optical signal from the optical transmission link, completing the in phase and quadrature optical to electrical conversion and canceling the noise once more.

Table 3.2: Single mode fiber parameters for CO-OFDM

Single mode fiber parameters for CO-OFDM	
Dispersion	16 ps/nm/km
Dispersion slope	0.08 ps/nm ² /km
Non-linearity coefficient	2.6x10 ⁻²⁰
Attenuation	0.2dB/km
Dark current	10nA
Responsivity	1A/W

The RF down conversion structure of the optical OFDM at the receiver part is uses two balanced pairs of optical hybrids with optical 90° phase to complete in phase (I) and Quadrature (Q) detection. And each coherent detector is composed of two PIN detectors and two couplers. Every

PIN photo detectors has 10nA dark current, Responsivity of 1A/W, again thermal power density (1×10^{-21}) W/Hz and with center of frequency 193.1THz. Then the fed into OFDM demodulator which the same and equal parameters of OFDM at the transmitter side of the system and the output of OFDM demodulator is fed into M-QAM sequence decoder and giving output.

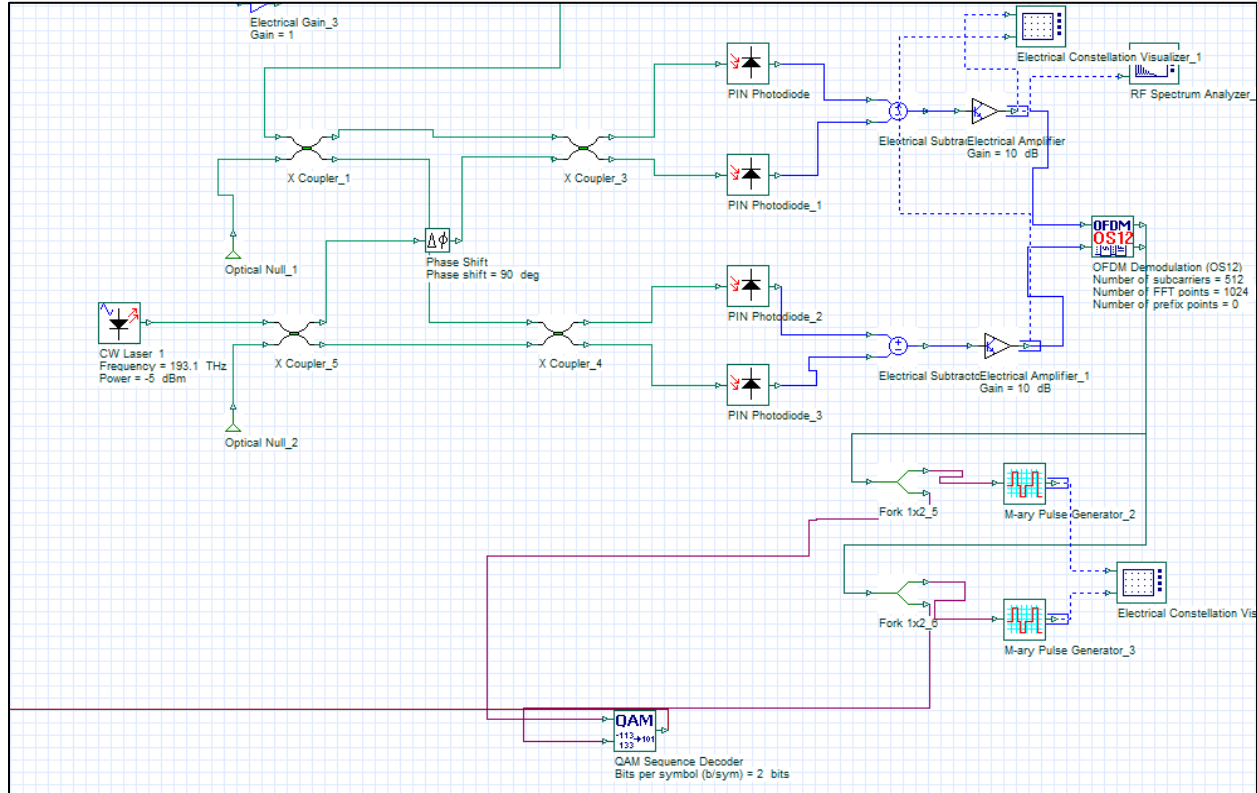


Figure 3.5: Coherent detection of receiver part.

The table 3.3 shows that the global parameters of Coherent Detection OFDM which are used in the system.

Table 3.3: Single mode fiber global parameters for CO-OFDM

Parameters	Value
Time window	$1.6384 \times 10^{-6} \text{ s}$
Sample Rate	$80 \times 10^9 \text{ HZ}$
Sequence Length	16384bits
Sample per bit	8
Symbol Rate	10Gb/s

Number of samples	1310702
Reference Wave length	1550nm

3.5.2. Homodyne Detection

Homodyne detection is the simplest digital signal processing (DSP) approach in optical coherent detection, and it decreases receiver bandwidth demands. As a result, homodyne detection is an excellent option for high-spectral-efficiency formats such as optical orthogonal frequency domain multiplexing, which has a flat optical spectrum and is thus less prone to high-frequency distortion. Again, homodyne detection is the simplest approach for coherence detection since it requires the least amount of digital signal processing, requiring no carrier frequency offset or compensation, as well as direct carrier phase recovery. Once again, it has the smallest optoelectronic and electrical bandwidth requirements [47].

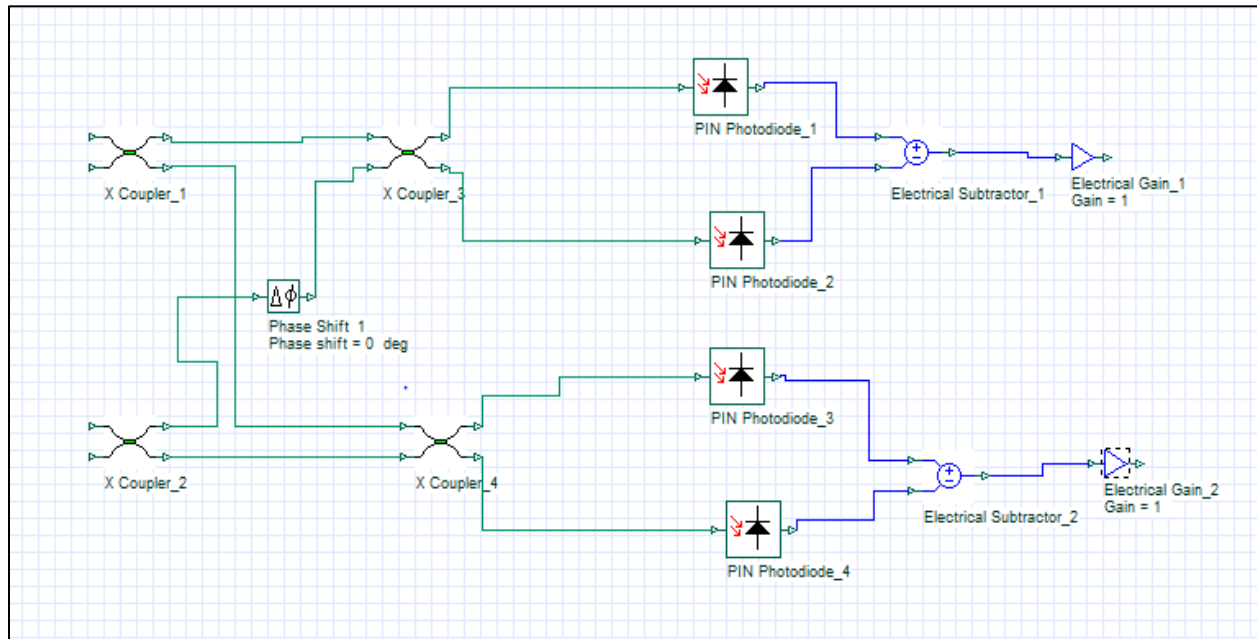


Figure 3.6: Homodyne detection in coherent OFDM

3.6. Direct Detection OFDM

Direct detection optical OFDM is utilized for simpler transmitters and receivers than coherent OFDM and is significant for short-range applications due to its low cost implementation. The advantage of DD-OFDM is that it is less susceptible to impulse clipping noise. The linear and nonlinear mapping kinds of direct detection optical OFDM can be distinguished Optical OFDM

with direct detection. The distinction between these two mapping systems is that the baseband OFDM spectrum may need to be copied directly to the optical OFDM spectrum. The spectrum of optical OFDM in a linear mapping Direct Detection optical OFDM system is the linear transfer of baseband OFDM spectrum, indicating that the replication is direct.

3.6.1. Direct Detection OFDM with single Mode Fiber

The direct detection OFDM system consists of three different blocks which include the transmitter part, Optical fiber transmission link and receiver part. So the direct detection OFDM transmitter system is implemented by feeding the pseudo random bit sequence (PRBS) with 4-QAM (2 bit per symbol), 16-QAM (4 bit per symbol), 32-QAM (5 bit per symbol) and 64-QAM (6 bit per symbol) generator which used as encoder. By feeding the OFDM modulator with (512) subcarriers and a number of FFT points of (1024), as well as in-phase (I) and quadrature (Q) outputs, the 4-QAM symbols were then transmitted utilizing parallel overlapping orthogonal subcarriers. After passing through a low pass cosine roll filter, the electrical inputs of In-phase (I) and Quadrature (Q) were modulated with a quadrature modulator using a 7.5GHz RF carrier frequency.

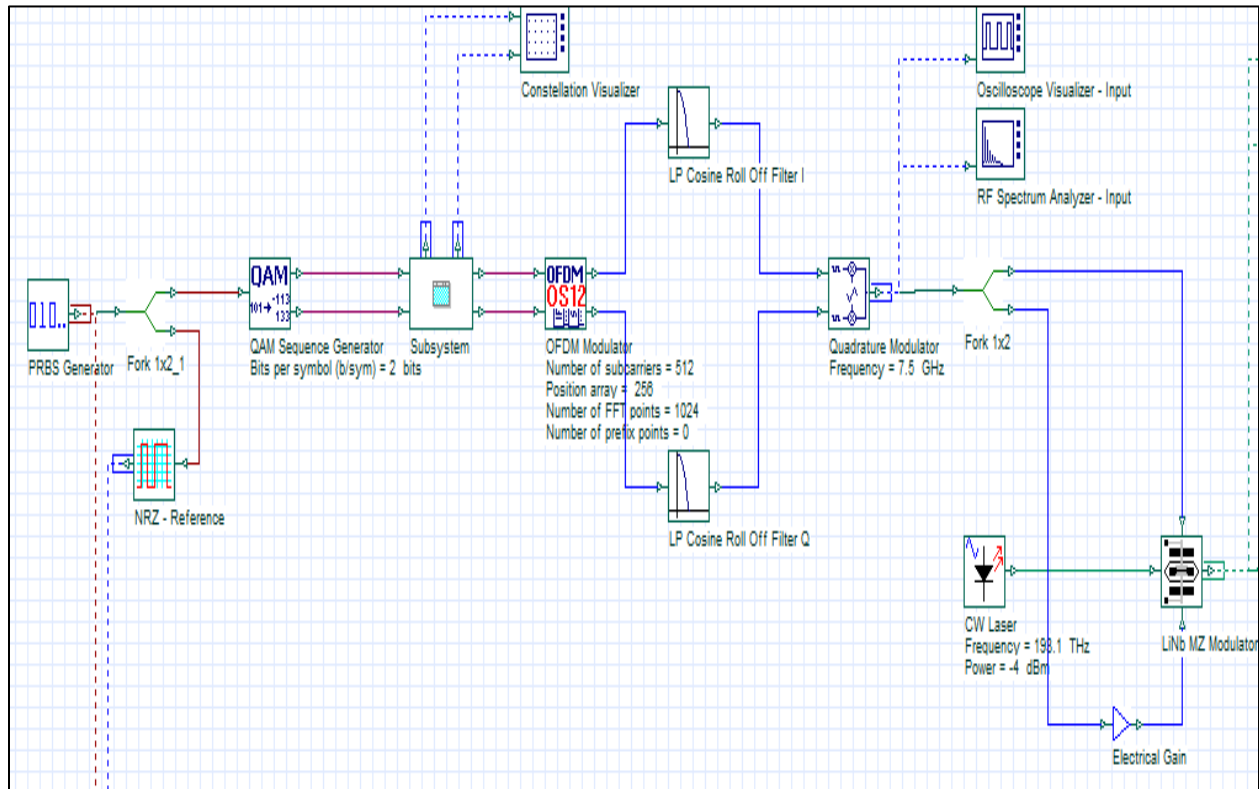


Figure 3.7: Direct detection OFDM Transmitter

Then the signal is enter into RF to optical up converter (RTO) which contains a single Mach-Zehnder modulator (MZM) which used to modulate the electrical signal from OFDM modulator to the optical carrier with the laser frequency of (193.1) THz and power (-4) dBm is feed in to optical fiber transmission link.

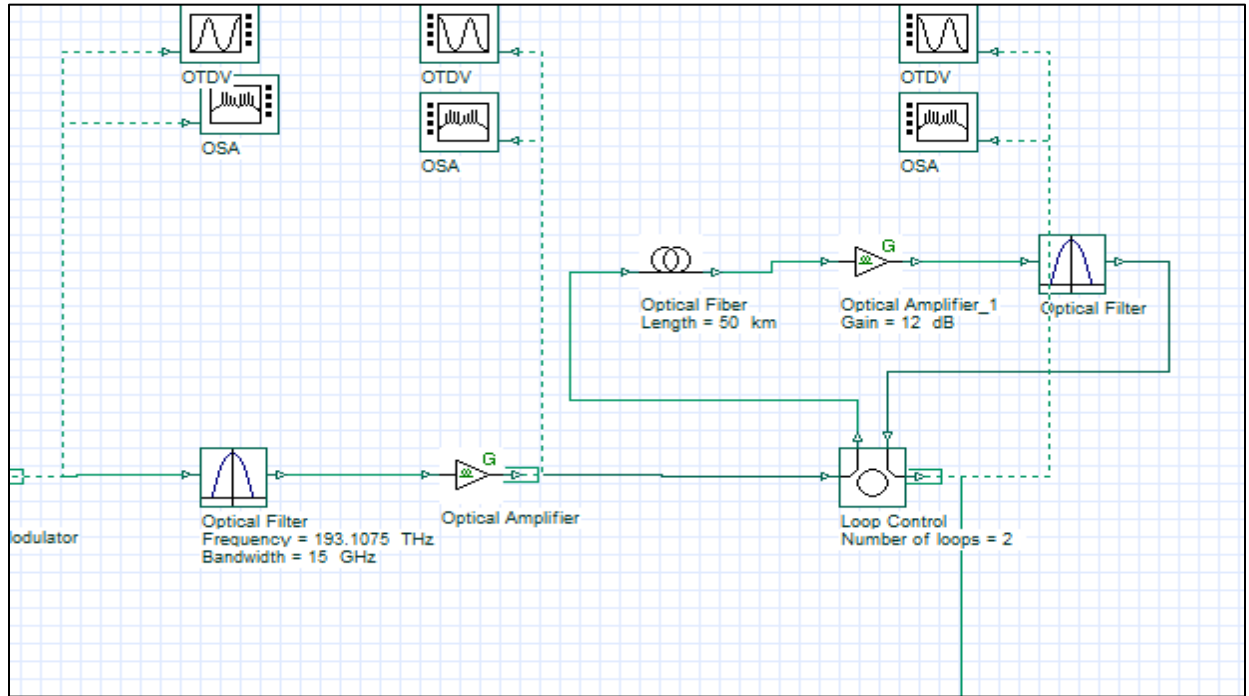


Figure 3.8: Optical fiber transmission link for Direct Detection OFDM

And the resulting optical fiber signal is transmitted over single mode fiber by using different global parameters which are discussed in below tables.

Table 3. 4: Single mode fiber parameters for DD-OFDM

Single mode fiber parameters for DD-OFDM	
Dispersion	16 ps/nm/km
Dispersion slope	0.08 ps/nm ² /km
Non-linearity coefficient	2.6x10 ⁻²⁰
Attenuation	0.2dB/km
Dark current	10nA
Responsivity	1A/W

At receiver side a reverse process is applied for demodulation and recovering signal and the optical signal detected by using PIN photo detectors which has a dark current 10nA, thermal power density (1.5×10^{-22}) and center of frequency of (193.1) THz. The electrical input signal is replicated in the quadrature demodulator, and the signal is then ready to enter the OFDM demodulator, which has the same settings as the OFDM modulator but removes the guard period. The FFT procedure is applied to each OFDM symbol in the OFDM demodulator, and the transmitted spectrum is recreated. Finally, the binary signal is built by decoding our input into binary output using a QAM decoder.

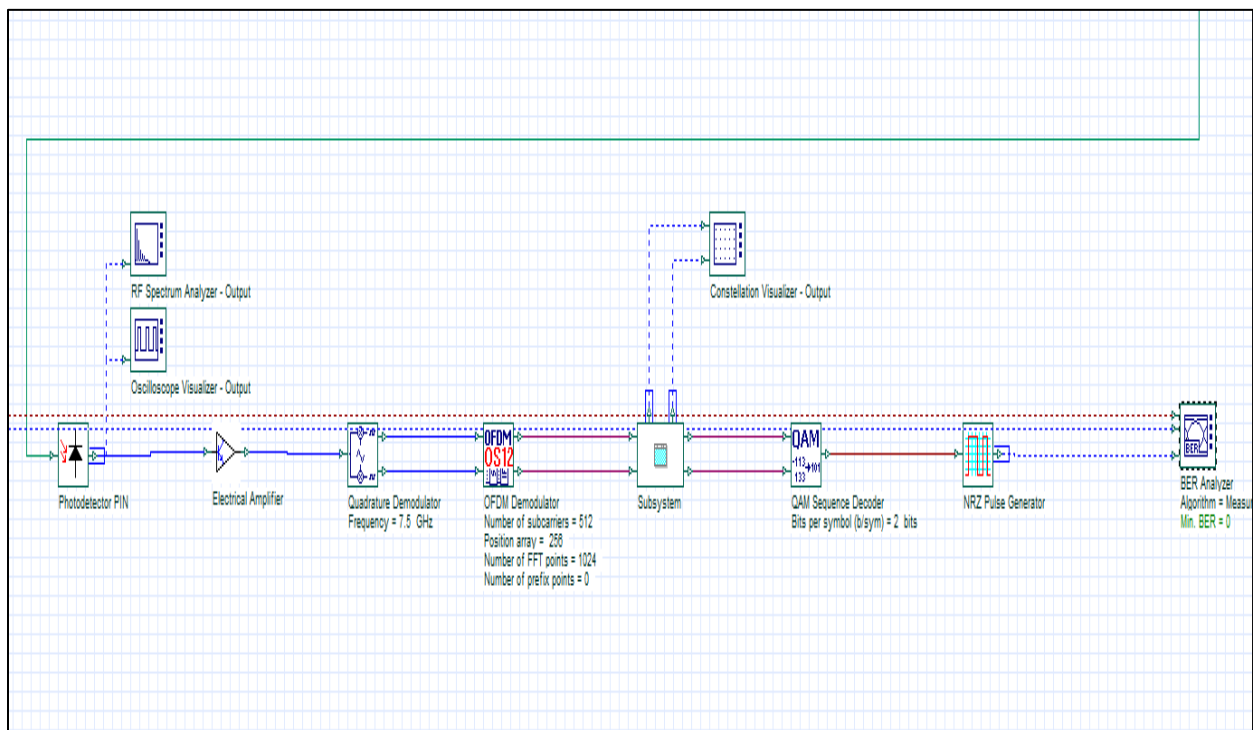


Figure 3.9: Direct Detection OFDM Receiver

The table below shows that the global parameters of DD-OFDM which is similar parameter that we used in Coherent Detection OFDM.

Table 3.5: Single mode fiber global parameters for DD-OFDM

Parameters	Value
Time window	$1.6384 \times 10^{-6} \text{s}$
Sample Rate	$80 \times 10^9 \text{HZ}$
Sequence Length	16384bits
Sample per bit	8
Symbol Rate	10Gb/s
Number of samples	1310702
Reference Wave length	1550nm

CHAPTER FOUR

4. Results and Discussions

Implementing both Direct Detection OFDM and Coherent Detection OFDM with 4-QAM, 16-QAM, 32-QAM, and 64-QAM with Optisystem simulation software v.17 is used to fully develop and simulate both Direct Detection OFDM and Coherent Detection OFDM systems. For designing, modeling, and testing optical fiber communications network connections, Optisystem is useful software design environment. The Optiwave Company's Optisystem system level simulator is used by telecommunication firms all over the world to build optical fiber communication networks. This software models and implements all optical networks using a large number of optical and wireless components, which is a low-cost and time-saving approach that allows the researcher to work more effectively.

4.1. The Result for 4-QAM of CO-OFDM

So, the simulation results of coherent detection OFDM at different stages and different transmission length are explained as such a way. The figure below shows that the electrical constellation diagrams after 4-QAM modulator at transmitter part. The QAM constellation diagram is usually represented as two dimensional representations which are arranged with square and grid that are equally spaced between horizontal and vertical axis. The data in digital telecommunication are often given in binary so the number points of grid are represented as power of two. As a result, the constellation diagram is used to analyze the modulated signal, which is depicted as a two-dimensional scatter diagram that is used to evaluate the signal's interference and distortion.

Figure 4.1 shows that the constellation diagrams of 4-QAM modulator in coherent detection OFDM at receiver part.

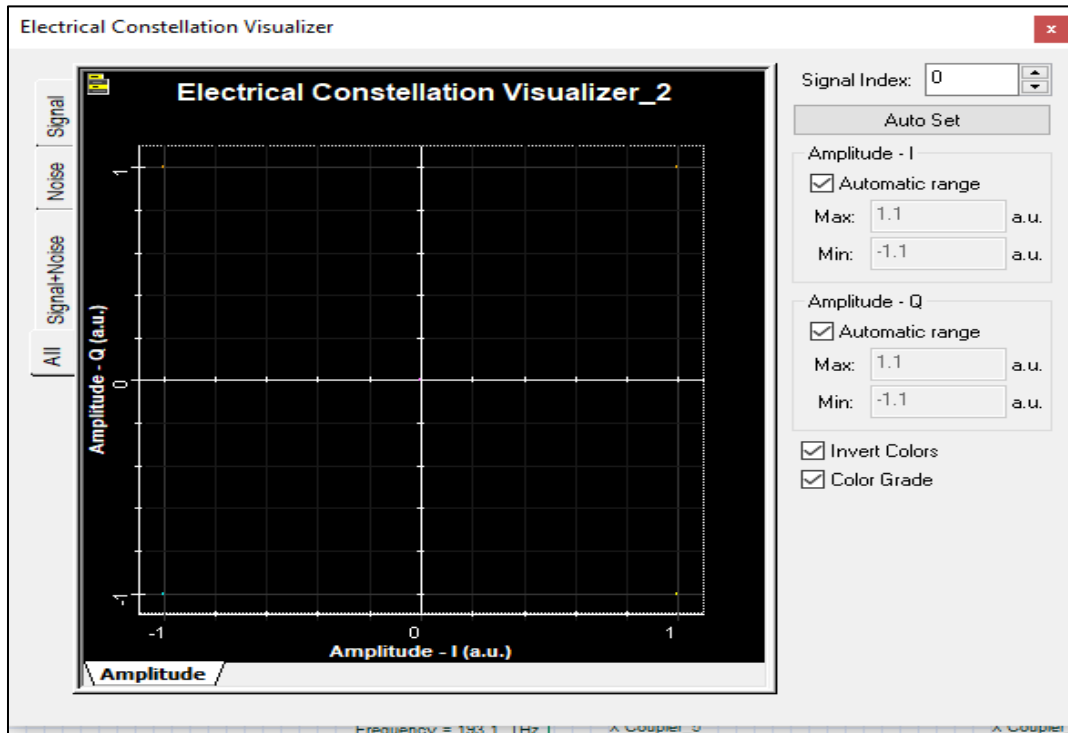


Figure 4.1: Constellation diagram of 4-QAM at transmitter side CO-OFDM.

The figure 4.2 shows that the electrical constellation diagrams after OFDM modulator.

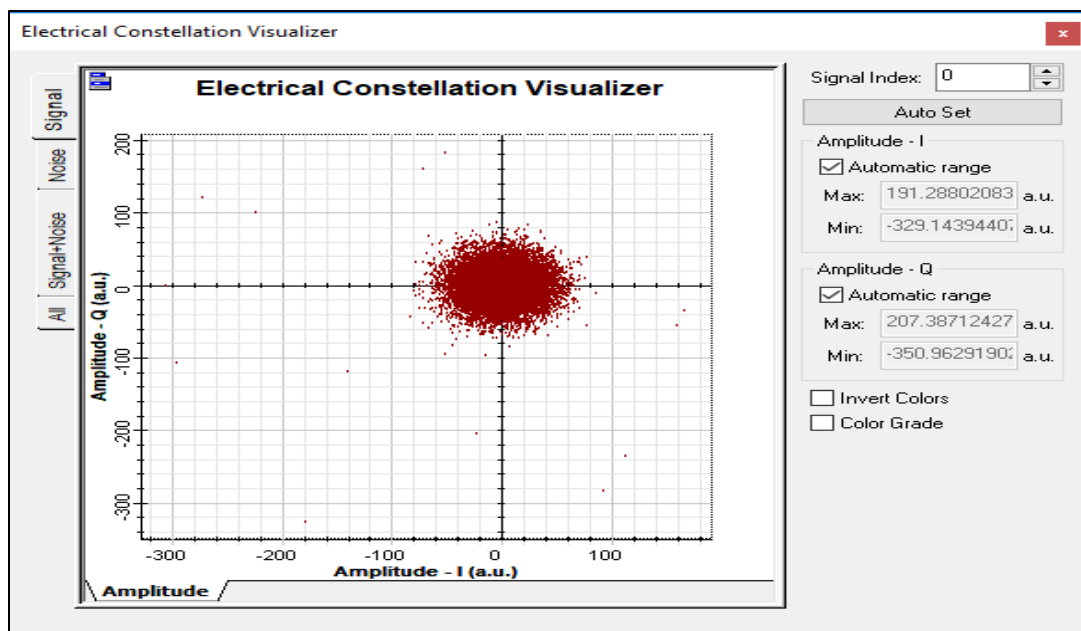


Figure 4.2: Electrical Constellation diagram after OFDM modulator at transmitter side.

And the figure 4.3 shows the RF spectrum for both in phase and Quadrature component of the system for coherent optical OFDM at transmitter side. And RF power is approximately (39.6) dBm.

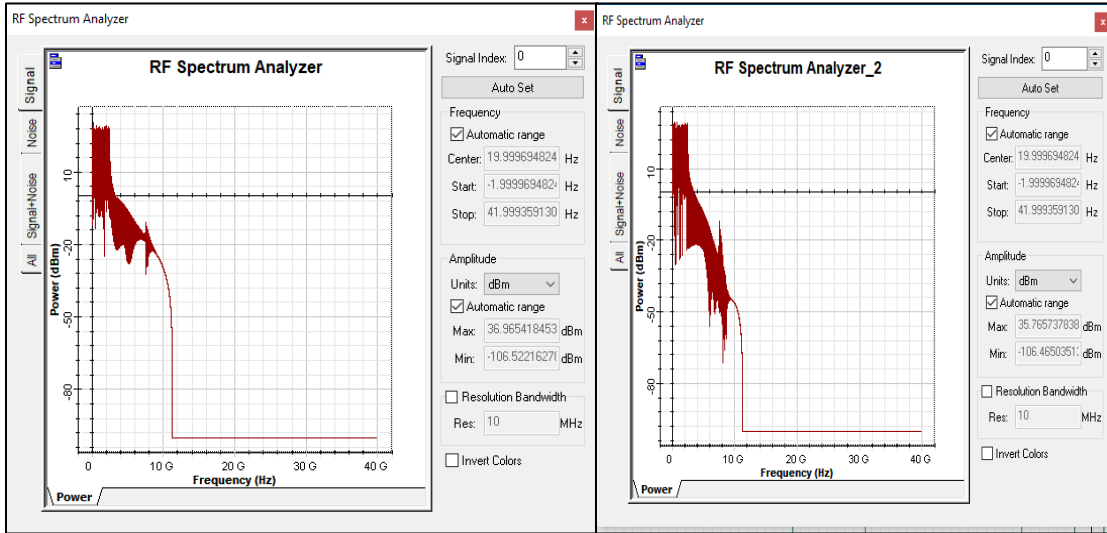


Figure 4.3: RF spectrum of in phase and quadrature and quadrature components after OFDM. And again the figure 4.4 shows that the result of optical spectrum analyzer after modulating the electrical signal with optical by using two of Mach-Zehnder modulator and after optical link respectively.

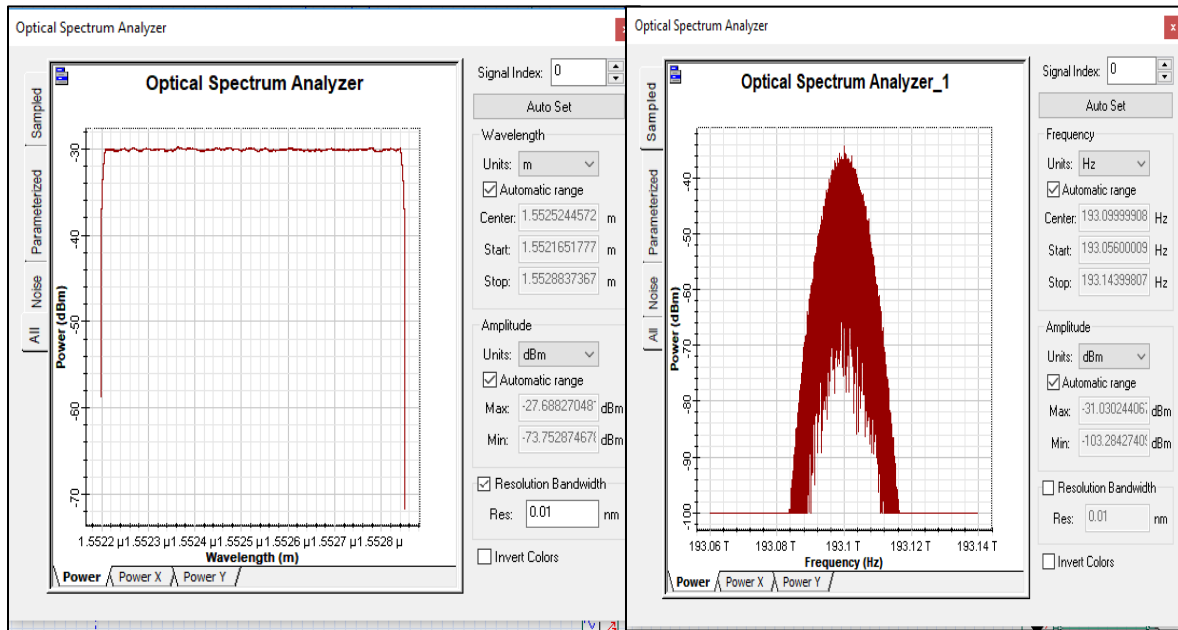


Figure 4.4: Optical OFDM spectrum after the two Mach-Zehnder modulator and optical link.

And again the figure 4.5 shows the RF spectrum of coherent OFDM system at the receiver side after single mode fiber of. So on RF spectrum diagram the blue color signal represents the thermal noise from photo detectors and fiber dispersion. So the signal can be distorted and corrupted.

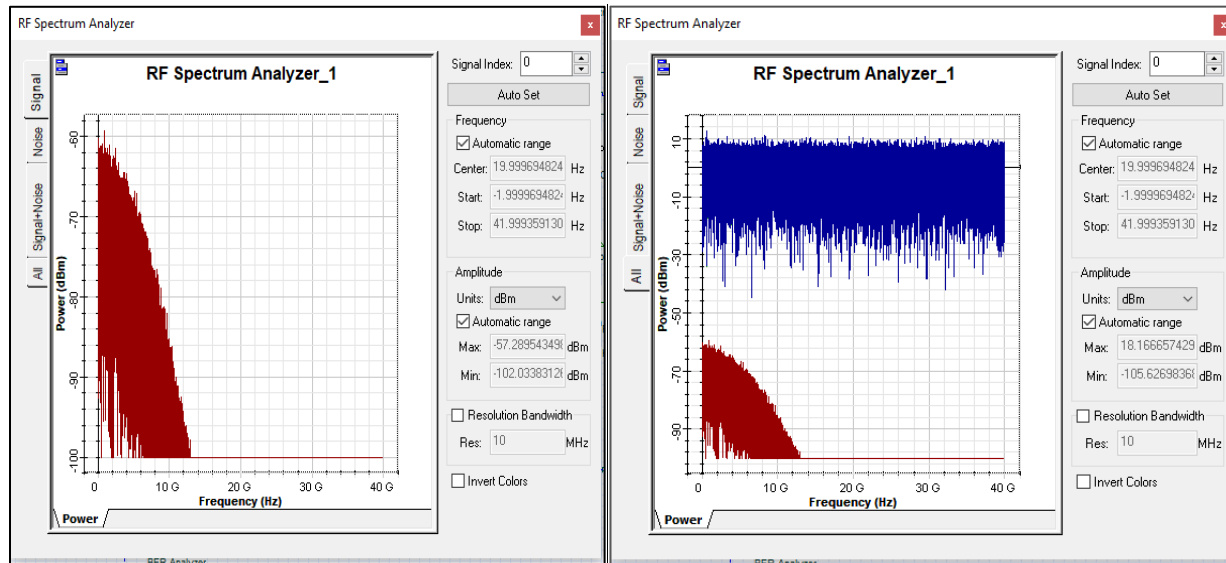


Figure 4.5: RF spectrum of OFDM at receiver side

The figure 4.6 show that the constellation diagram of OFDM signal after coherent receiver.

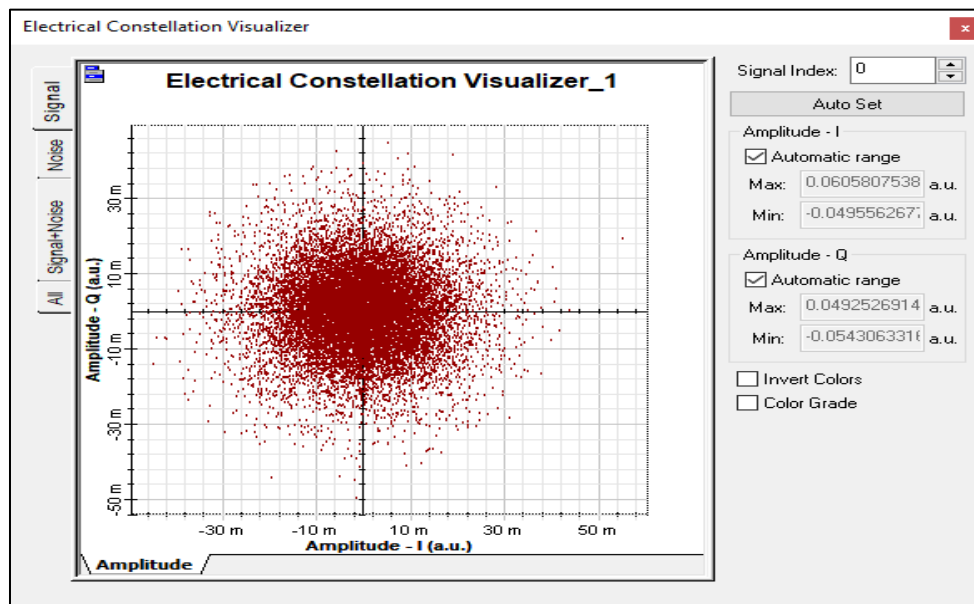


Figure 4.6: Constellation diagram of coherent optical OFDM at the Receiver part

Figure 4.7 shows that the electrical constellation diagram after OFDM demodulator of receiver part which are explained in two colors, from this the blue color is the transmitted signal and the other noise that comes from detectors and due to dispersion.

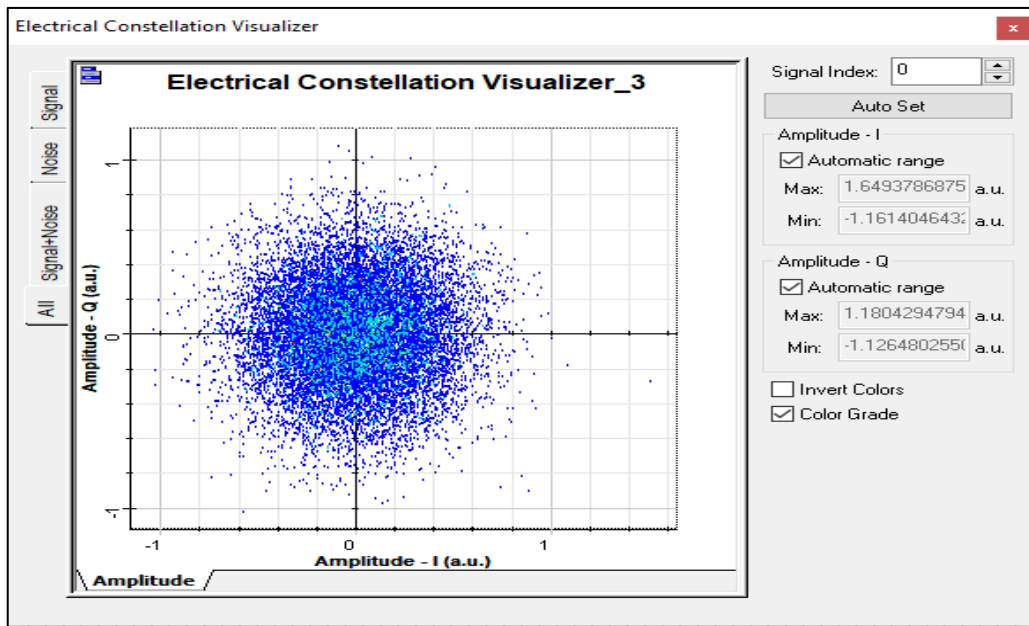


Figure 4.7: Constellation diagram of the OFDM signal after OFDM demodulation.

4.2. The Result for 16-QAM of CO-OFDM

The simulation results of coherent detection OFDM at different stages and different transmission length are explained as such a way. The figure below shows that the electrical constellation diagrams after 16-QAM modulator at transmitter part. The QAM constellation diagram is usually represented as two dimensional representations which are arranged with square and grid that are equally spaced between horizontal and vertical axis. The data in digital telecommunication are often given in binary so the number points of grid are represented as power of two. So the constellation diagram is used analyses the modulated signal is which represented as two dimensional scatter diagram which used to study the interference and distortion that may occur in the signal. Figure 4.8 indicates that the constellation diagrams of 16-QAM modulator in coherent detection OFDM at receiver part.

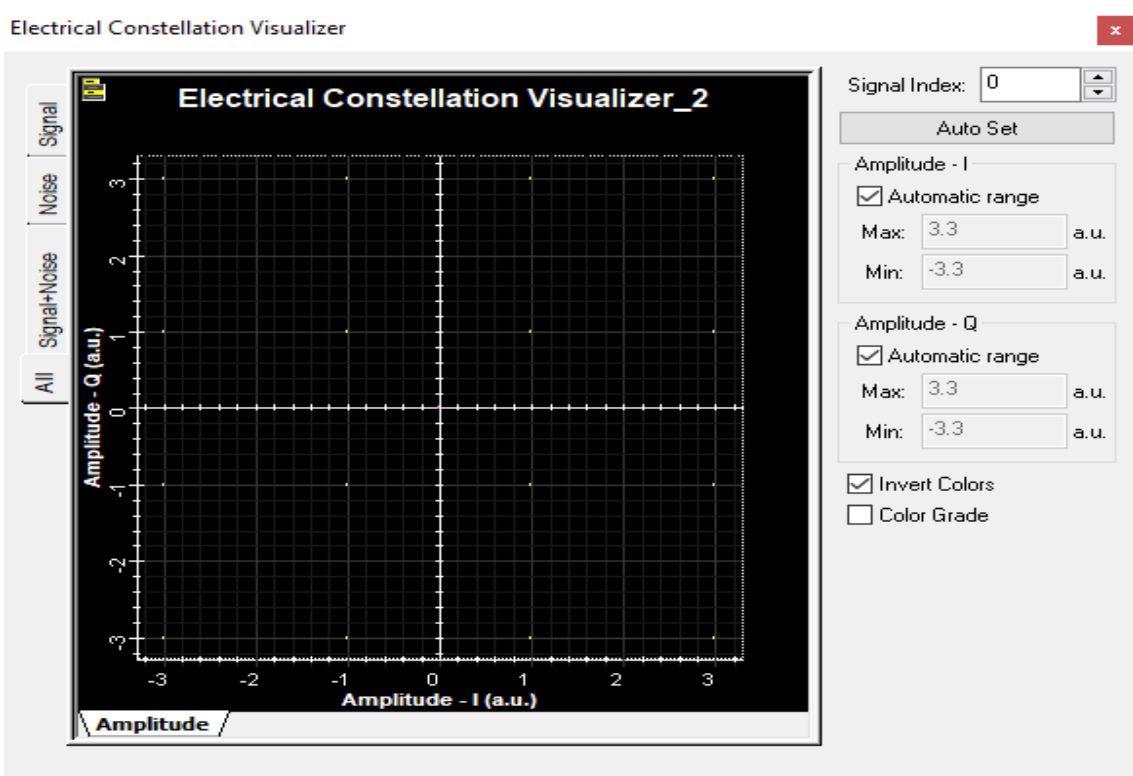


Figure 4.8: The constellation Diagram of 16-QAM at the transmitter side of OFDM

Figure 4.9 shows that the electrical constellation diagrams after OFDM modulator.

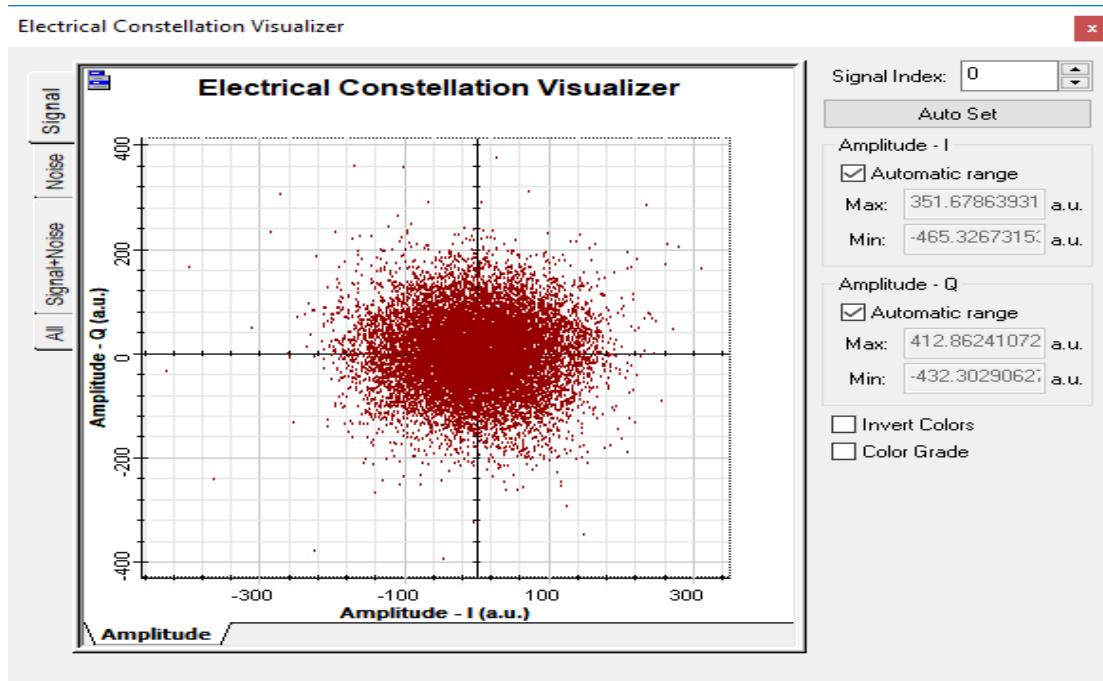


Figure 4.9: The electrical constellation diagram after OFDM modulator

Figure 4.10 indicates RF spectrum of in phase and Quadrature component of signal from OFDM modulator after low pass filter.

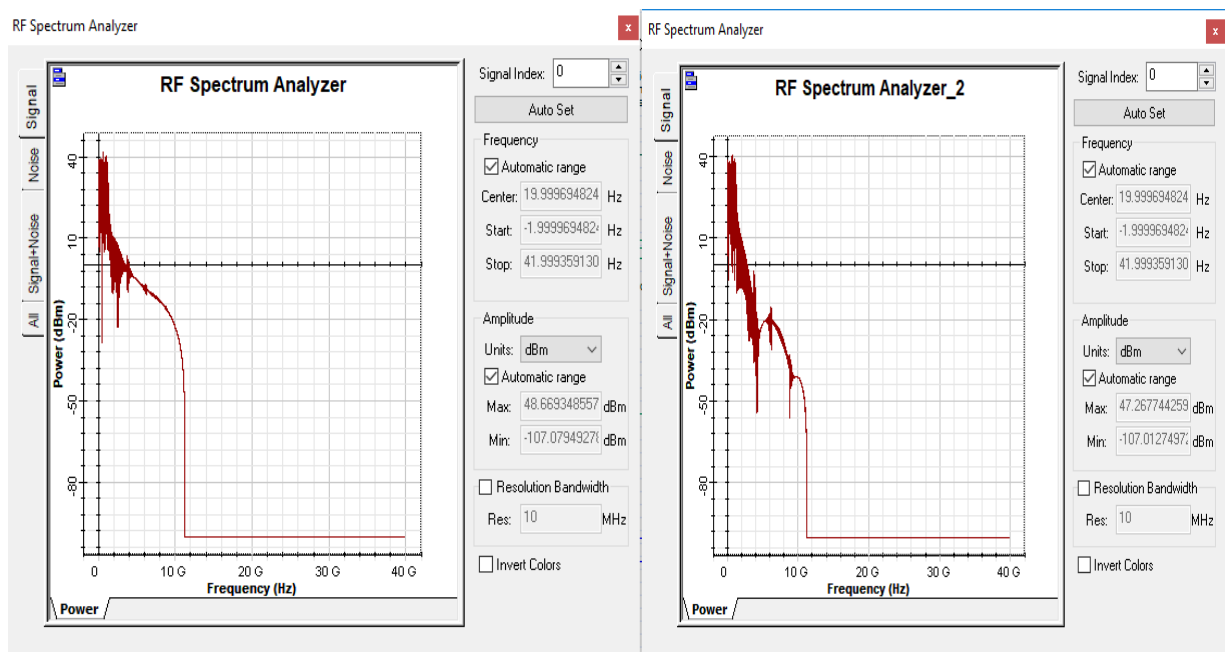


Figure 4.10: RF spectrum of in phase quadrature signal after OFDM modulator

Figure 4.11 shows the RF spectrum and Electrical constellation after coherent detection

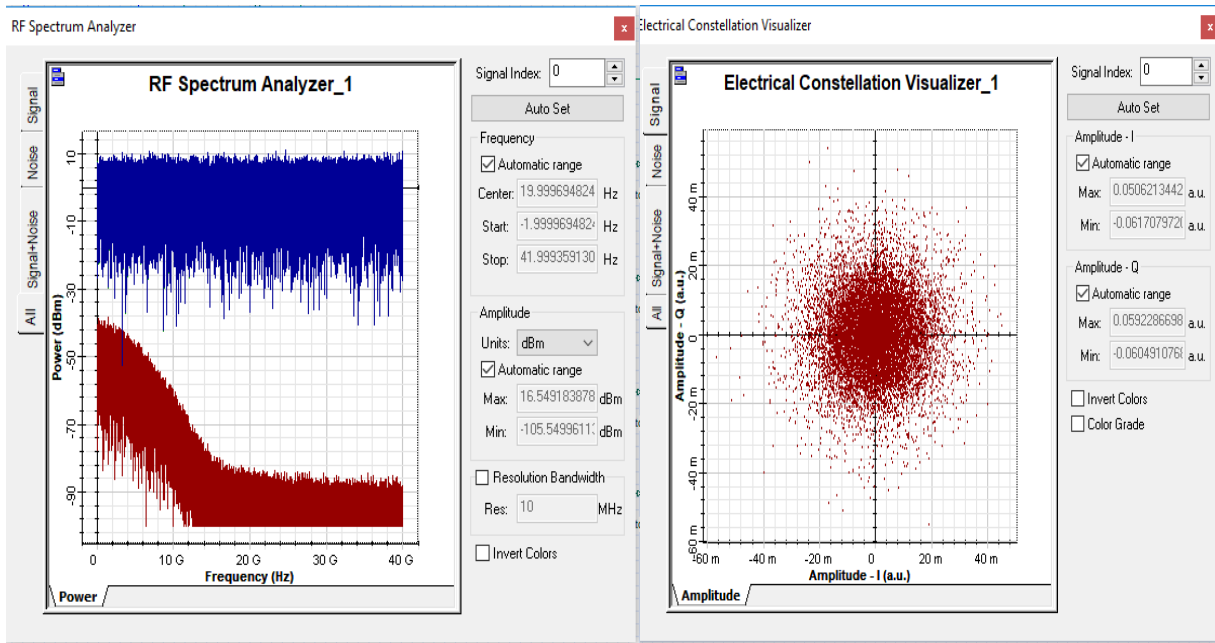


Figure 4.11: RF spectrum and electrical constellation diagram

And the figure 4.12 indicates when the above two signal are mixed together it creates dispersed signal due to different reason such as attenuation and fiber dispersion.

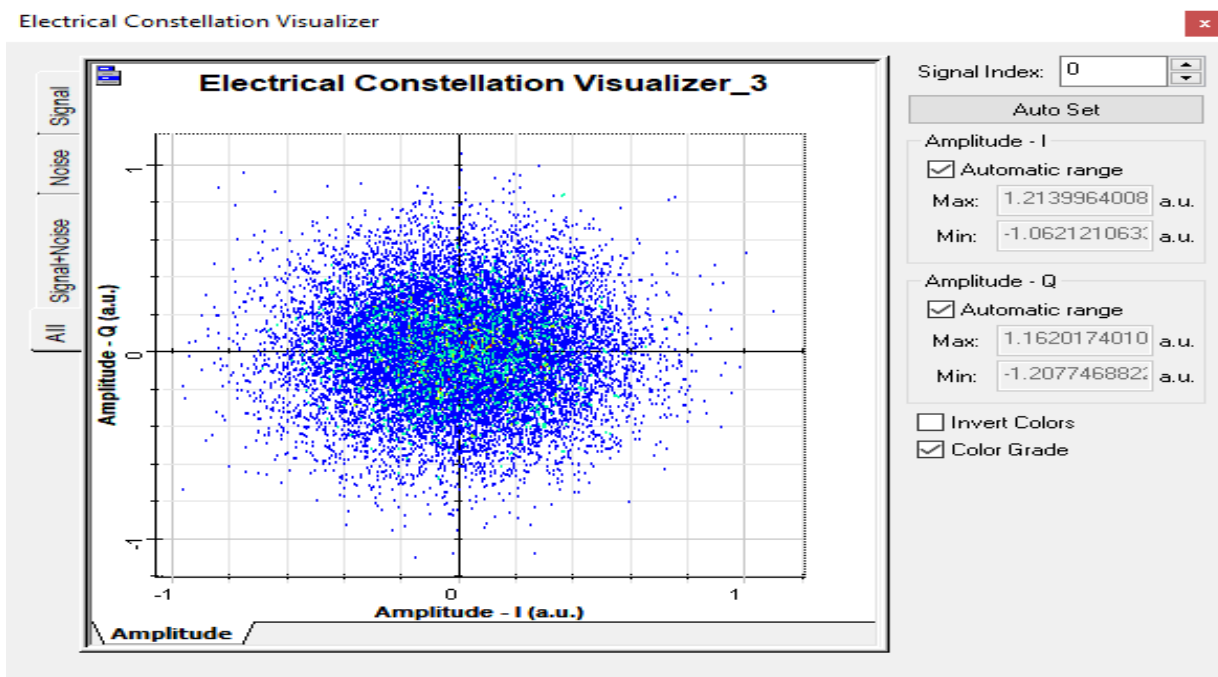


Figure 4.12: Electrical constellation diagram OFD signal after OFDM demodulator

4.3. The Result for 32-QAM of CO-OFDM

The simulation results of coherent detection OFDM by using 32-QAM are explained on the figures below which indicates that the electrical constellation diagram after 32-QAM modulator at transmitter part. The QAM constellation diagram is usually represented as two dimensional representations which are arranged with square and grid that are equally spaced between horizontal and vertical axis. The data in digital telecommunication are often given in binary so the number points of grid are represented as power of two. So the constellation diagram is used to analyses the modulated signal is which represented as two dimensional scatter diagram which used to study the interference and distortion that may occur in the signal.

Figure 4.13 indicates that the constellation diagrams of 32-QAM modulator in coherent detection OFDM at receiver part.

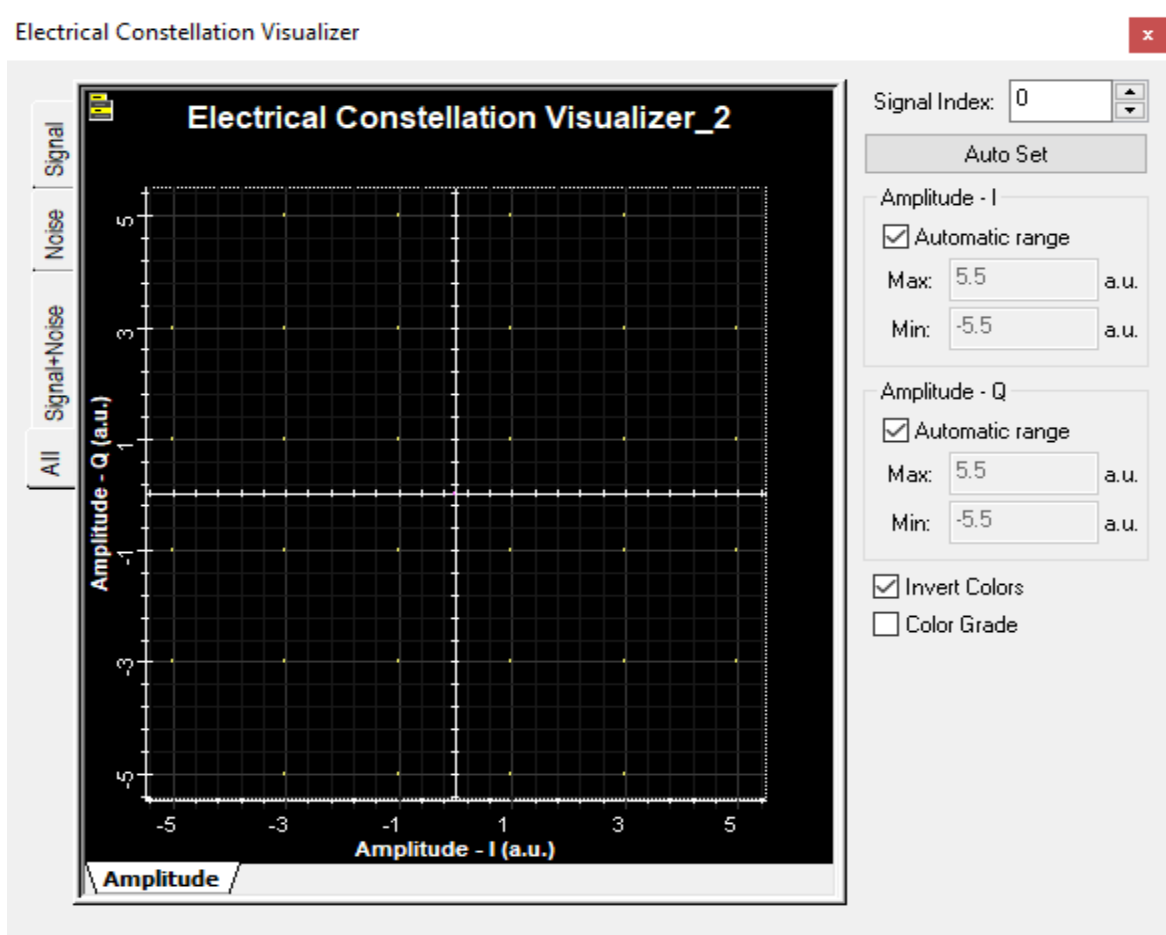


Figure 4.13: The constellation diagram of 32-QAM at transmitter part of CO-OFDM

Figure 4.14 shows that Electrical constellation diagram OFDM signal after OFDM modulator

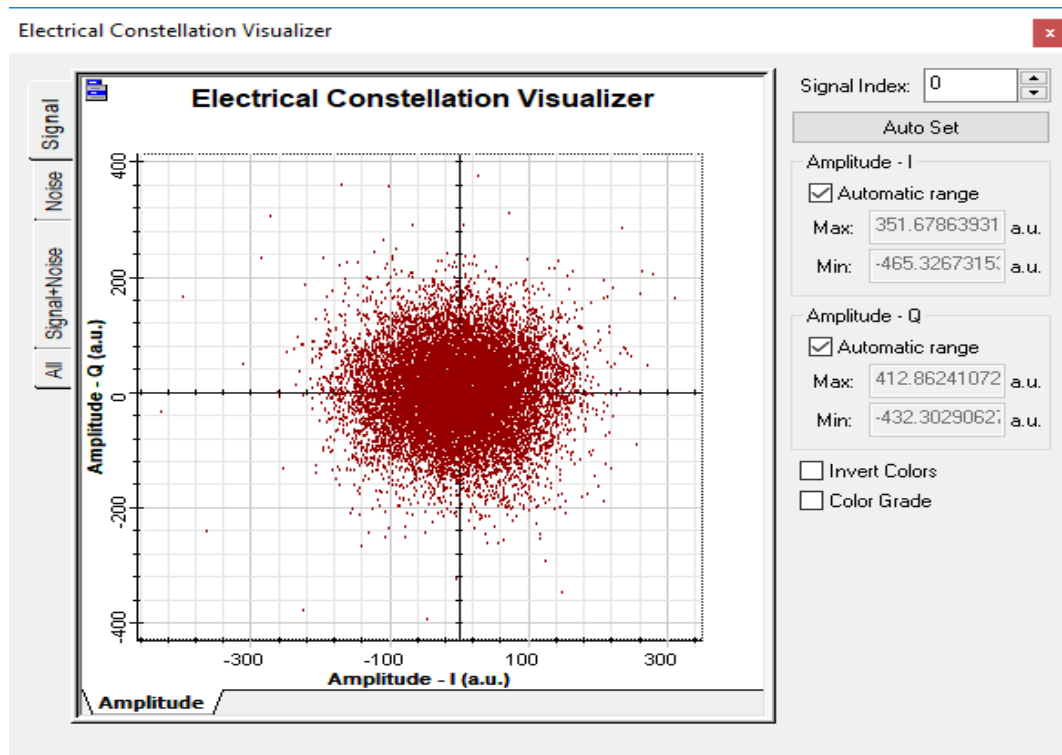


Figure 4.14: Electrical constellation diagram of OFDM signal

The 4.15 figure shows that both in phase and quadrature component of the signal after low filter

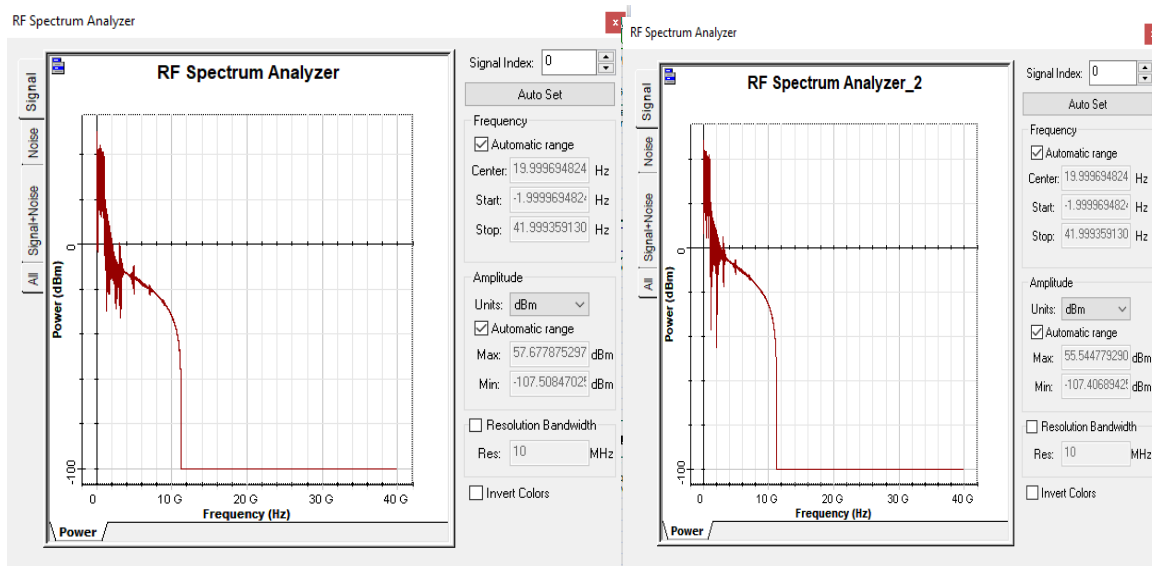


Figure 4.15: RF spectrum of I/Q component after OFDM modulator of LP filter

Figure 4.16 shows that the electrical constellations diagram of OFDM signal after coherent detection.

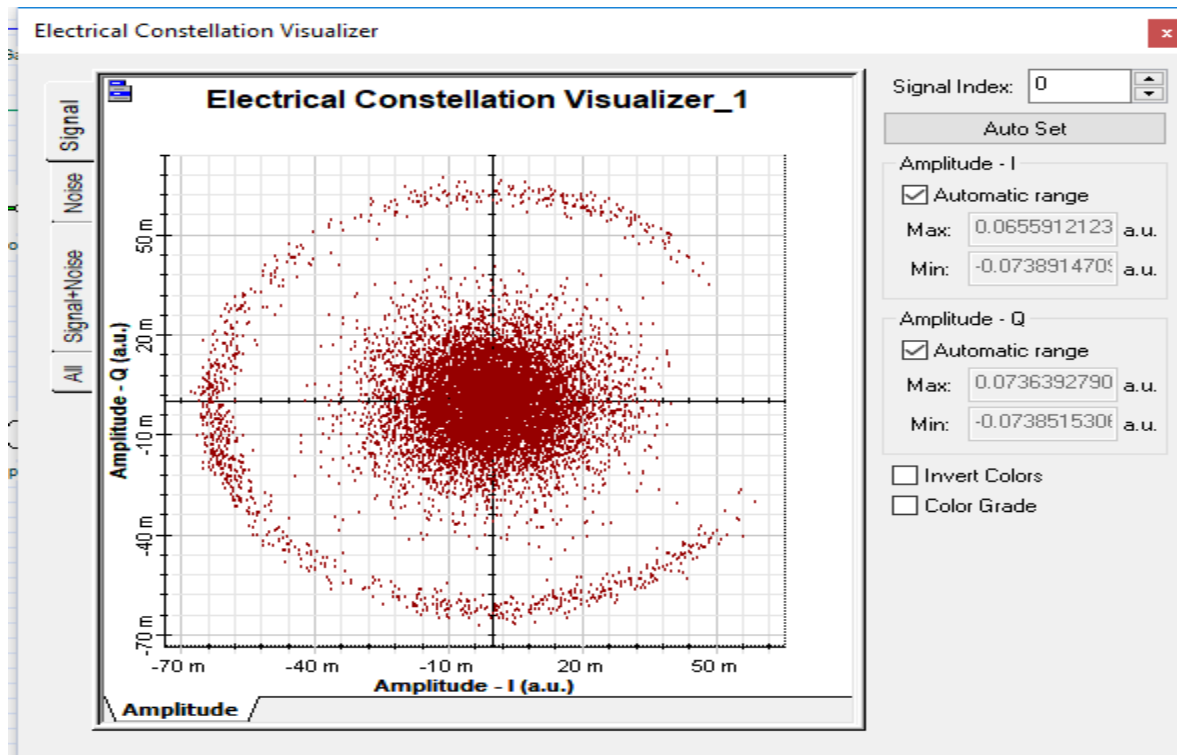


Figure 4.16: The Electrical constellation diagram of OFDM signal after Coherent detection.

Figure 4.17 shows that the electrical constellation diagram of OFDM signal after OFDM demodulator.

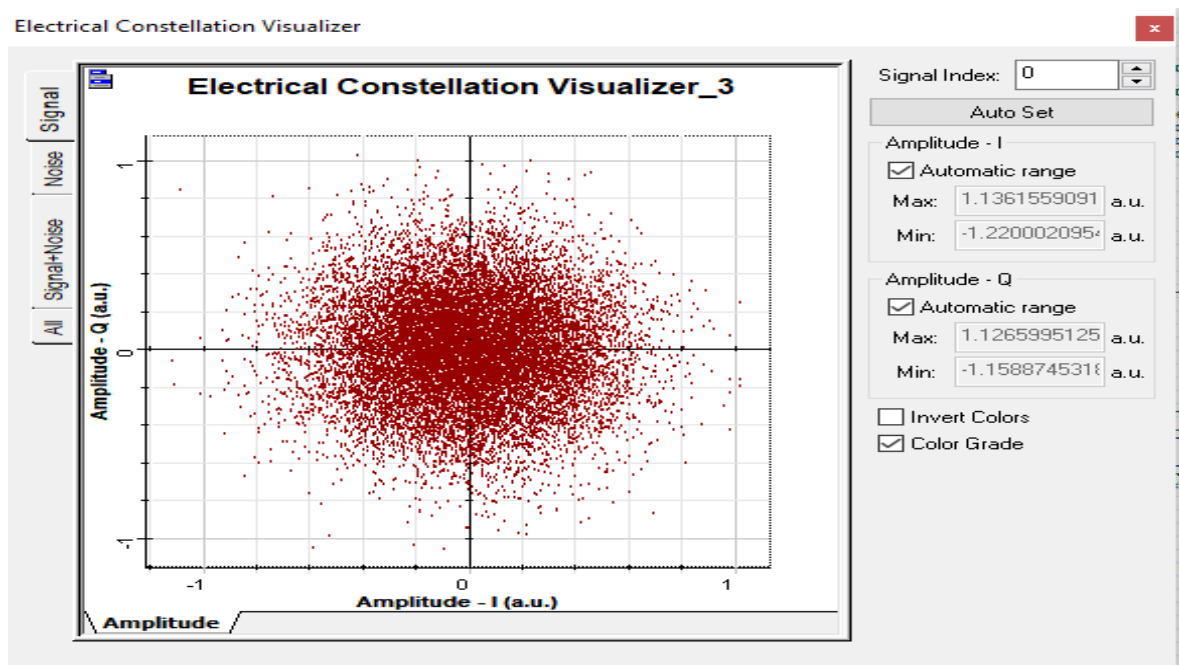


Figure 4.17: The electrical constellation diagram of OFDM signal after OFDM demodulator

4.4. The Result for 64-QAM of CO-OFDM

The coherent detection OFDM by using 64-QAM is described on the figures below which indicate that the electrical constellation diagram after 64-QAM modulator at transmitter part and RF spectrum. The 64-QAM constellation diagram is usually represented as two dimensional representations which are arranged with square and grid that are equally spaced between horizontal and vertical axis, so figure bellow show that the constellation diagram of 64-QAM signal at the transmitter part.

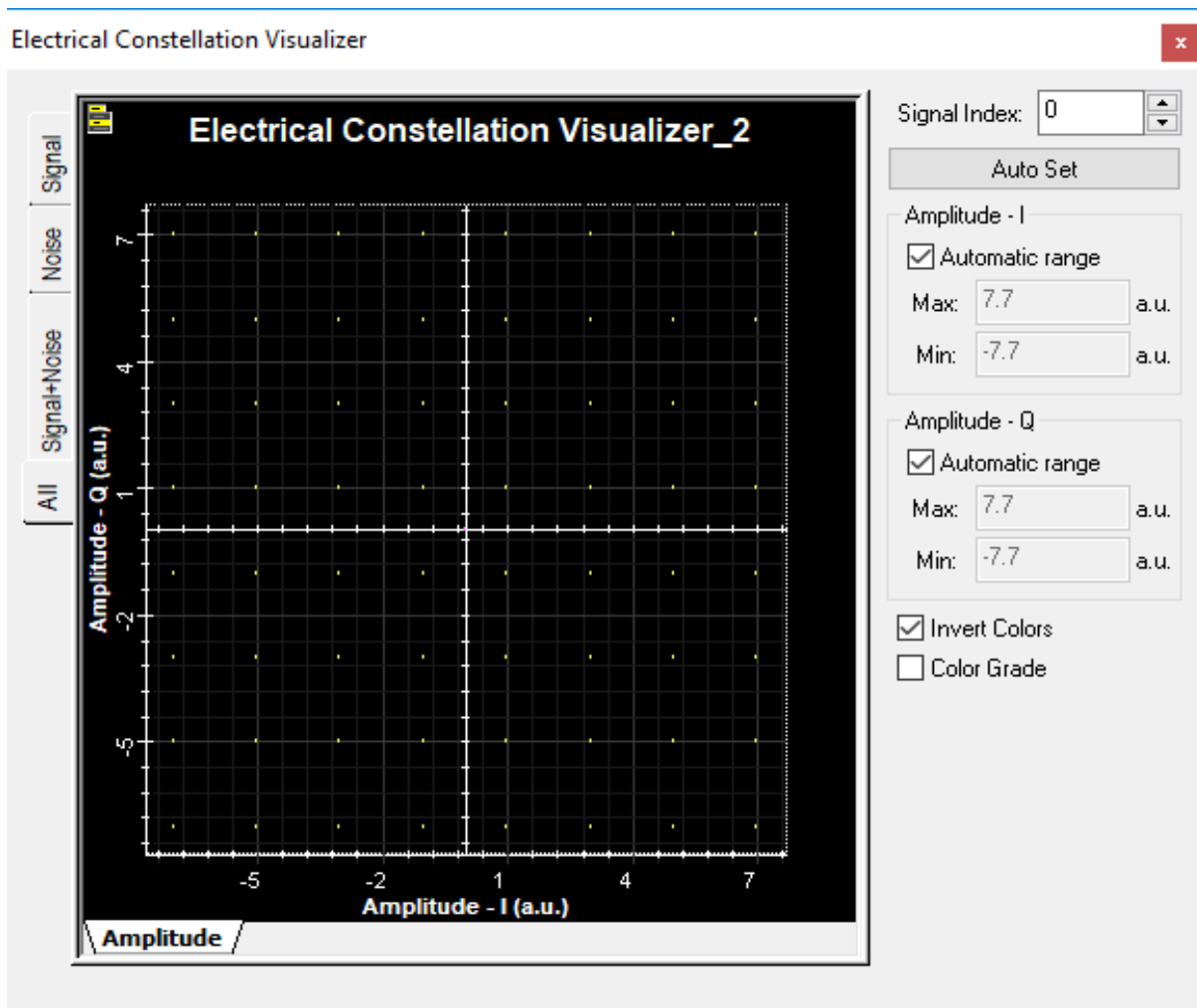


Figure 4.18: Electrical Constellation diagram of 64-QAM at transmitter side of CO-OFDM

The figure bellows show that the RF spectrum of both inphase and Quadrature component of of OFDM signal after OFDM modulator of low pass filter.

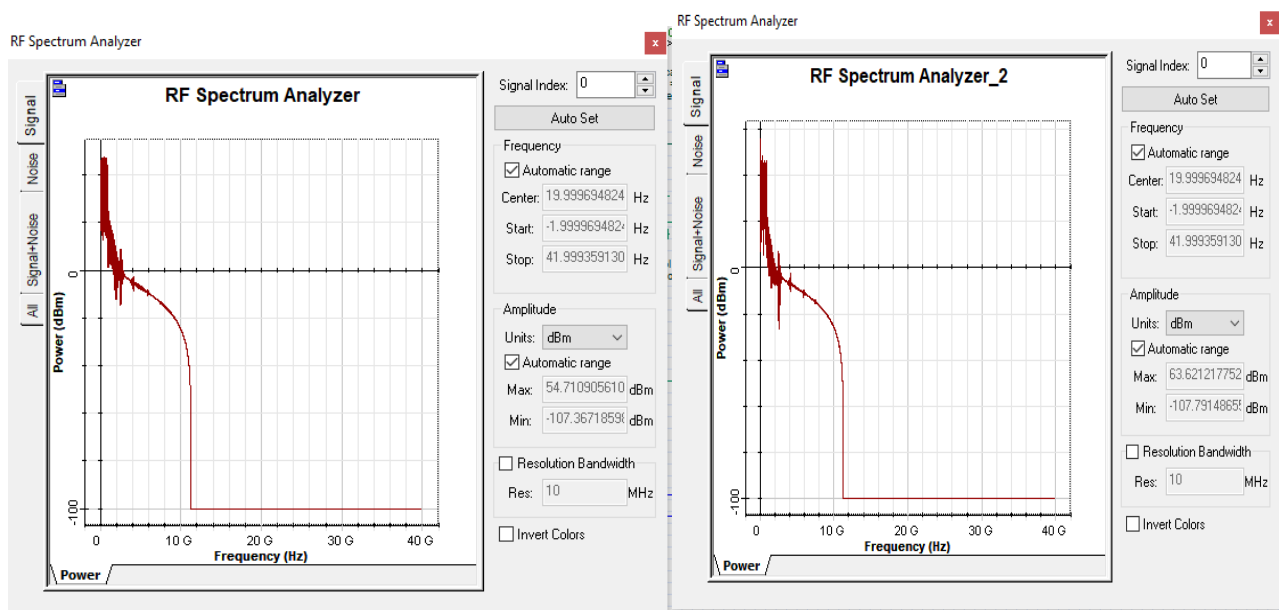


Figure 4.19: RF spectrum of In-phase and Quadrature component of the OFDM signal

The figure 4.20 shows that the constellation diagram of OFDM signal after Coherent detection

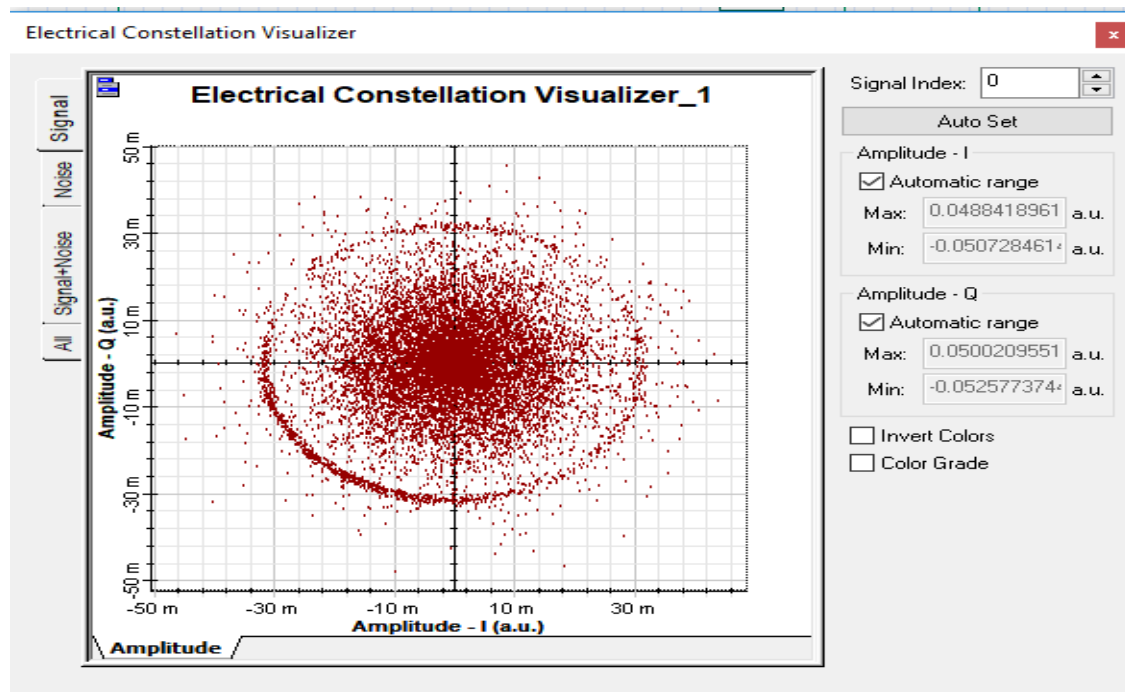


Figure 4.20: The Constellation diagram after coherent detection

The 4.21 show that the constellation diagram of OFDM signal after OFDM demodulator

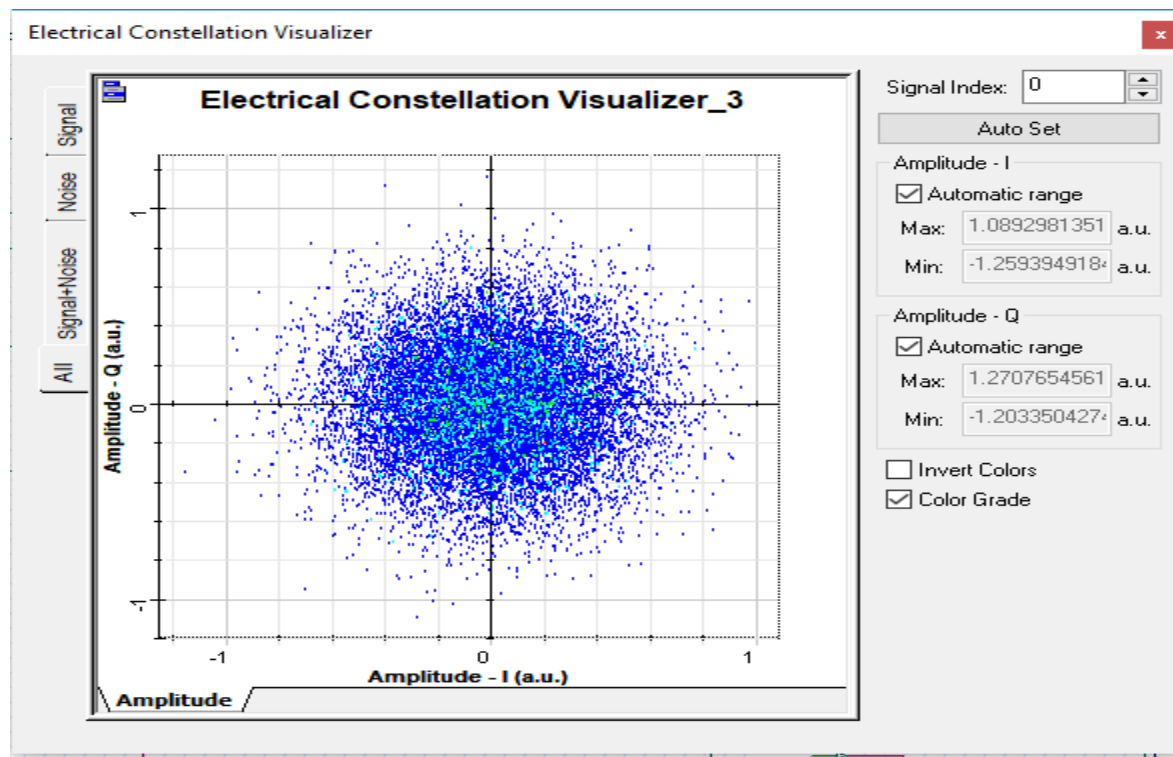


Figure 4.21: The constellation diagram of OFDM signal after demodulator

4.5. The Result for 4-QAM of DD-OFDM

The simulation results of direct detection OFDM at different stages and different transmission lengths are explained as such a way. The figure below shows that the electrical constellation diagrams after 4-QAM modulator at transmitter part. The QAM constellation diagram is usually represented as two dimensional representations which are arranged with square and grid that are equally spaced between horizontal and vertical axis. The data in digital telecommunication are often given in binary so the number points of grid are represented as power of two. So the constellation diagram is used analyses the modulated signal is which represented as two dimensional scatter diagram which used to study the interference and distortion that may occur in the signal.

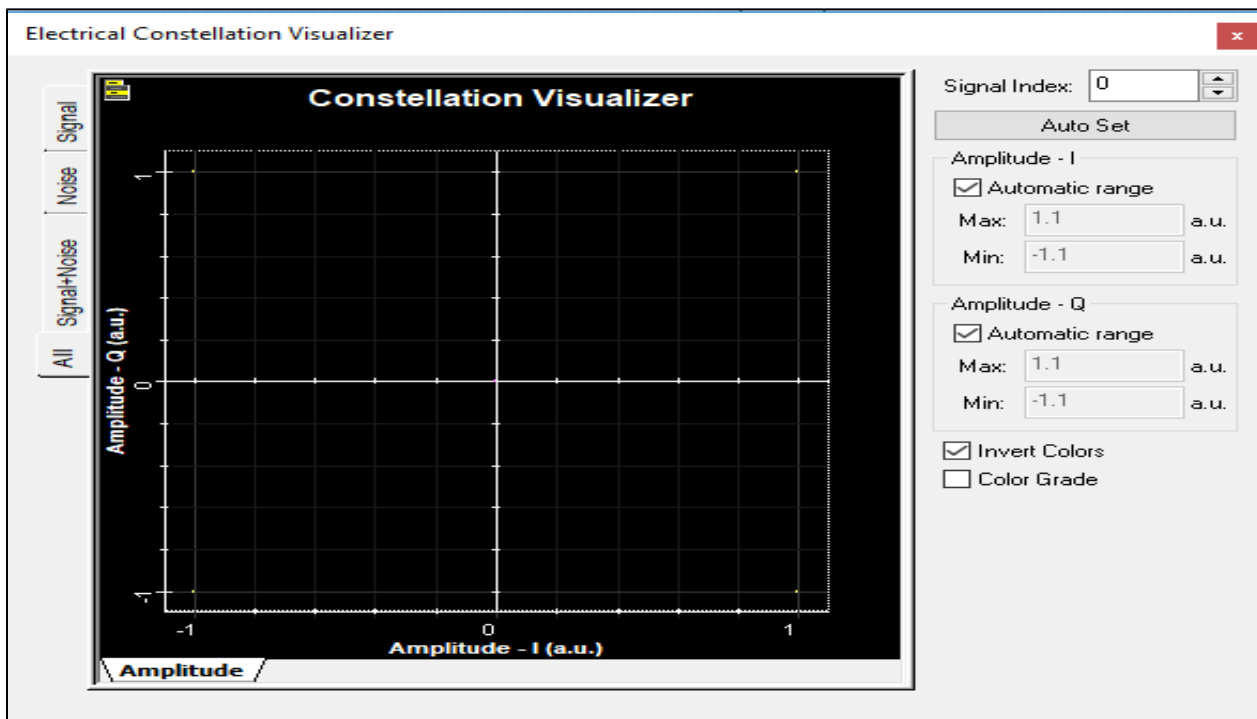


Figure 4.22: Constellation diagram of 4-QAM at transmitter part of DD-OFDM

The below figure 4.23 shows the spectrum analyzer of OFDM signal after low pass filter which measured power approximately (36.58) dBm.

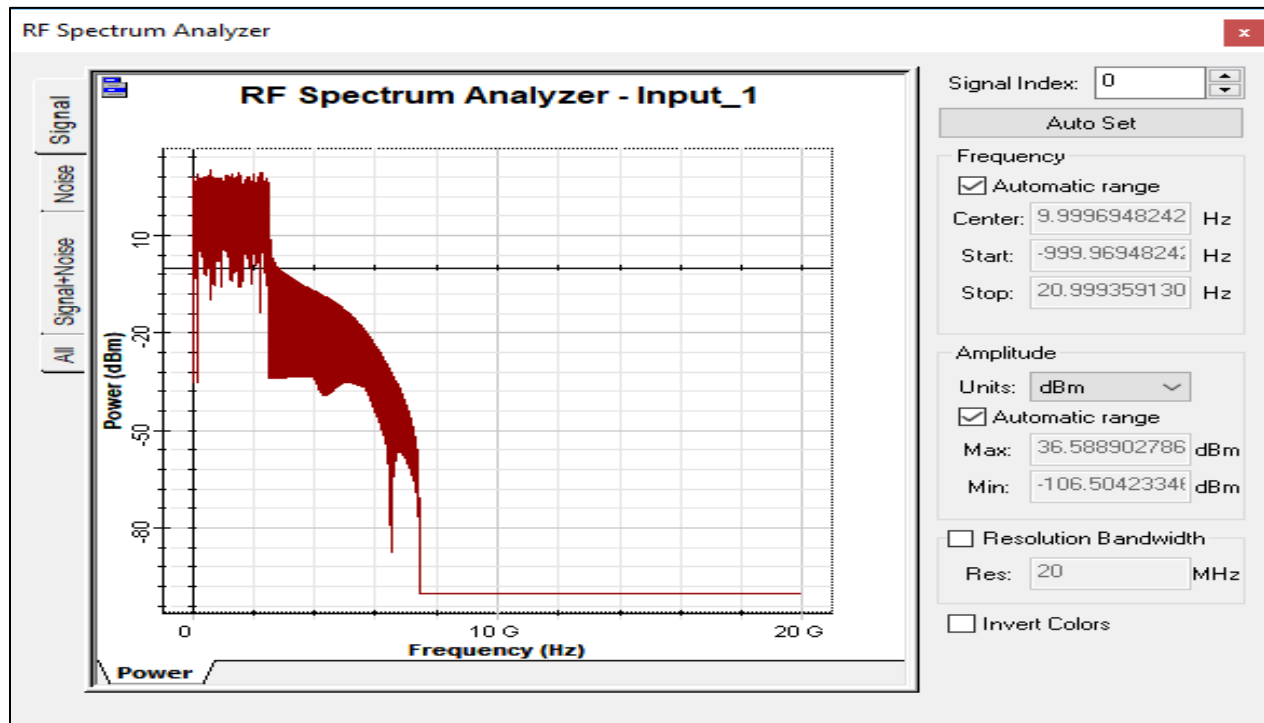


Figure 4.23: RF spectrum of OFDM signal after LP filter.

The below figure 4.24 is shows the RF spectrum analyzer OFDM signal after at Quadrature modulator which the signal is in frequency domain and the measured RF power is approximately (-8.4) dBm.

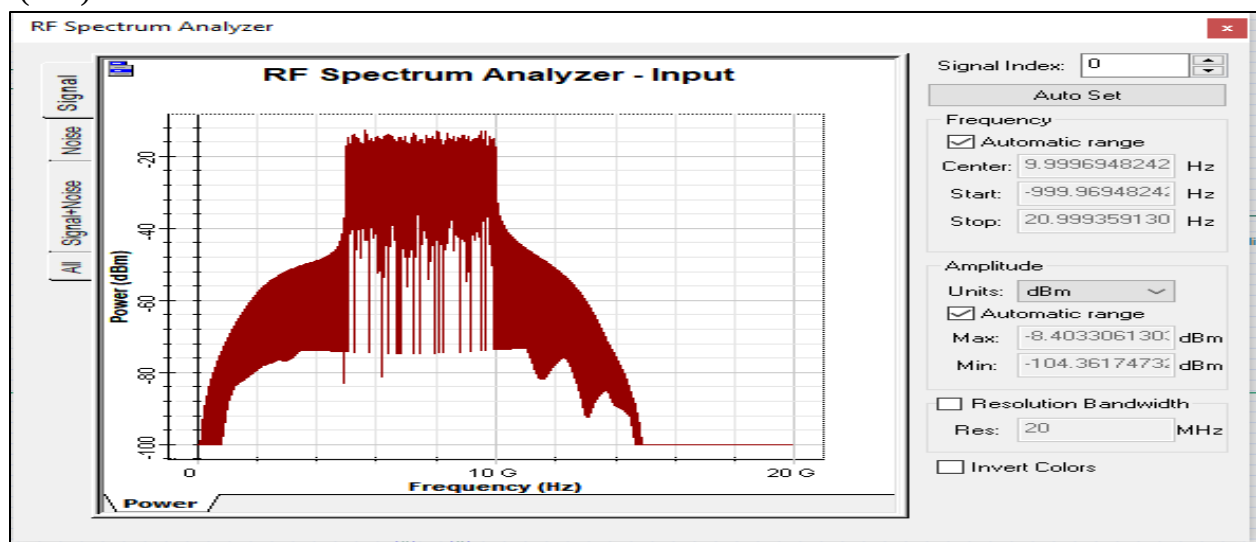


Figure 4.24: OFDM signal after quadrature modulator in frequency domain

Figure 4.25 below shows that the optical spectrum analyzer which used to change the RF OFDM signal optical signal at frequency of (193.1) THz by using Mach-Zehnder modulator with appropriate power that are produced from the laser and the resulted signal is in frequency domain. And the measured RF power is approximately (-13.6) dBm.

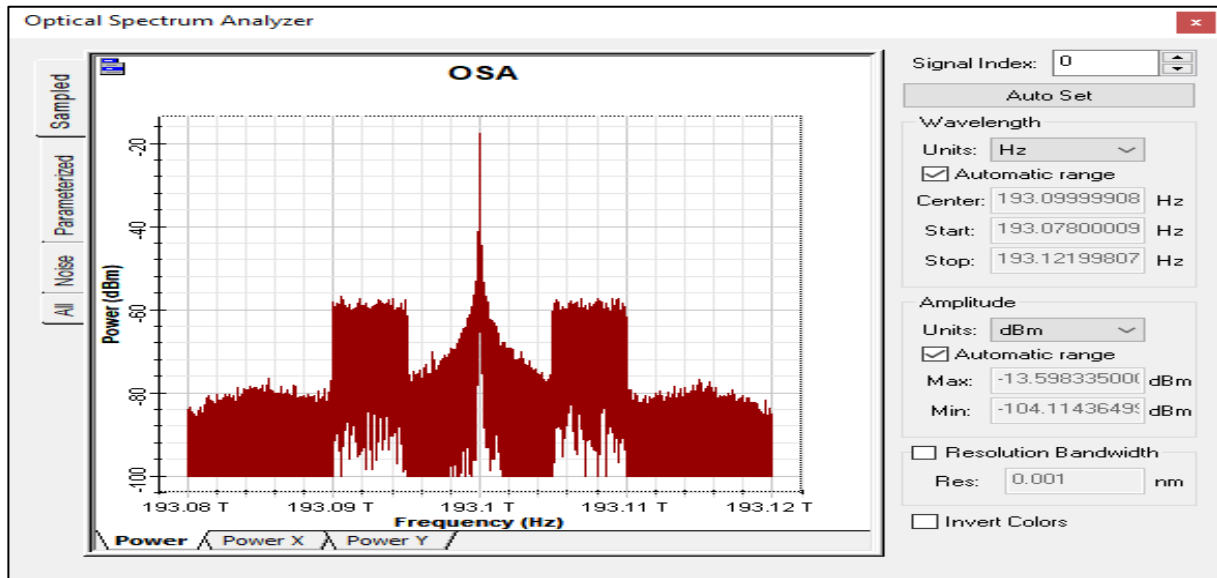


Figure 4.25: Modulated optical signal after Mach-Zehnder modulator

And the figure 4.26 is shows that the optical spectrum analyzer after optical fiber transmission link which has a measured RF power is approximately (-5.2) dBm.

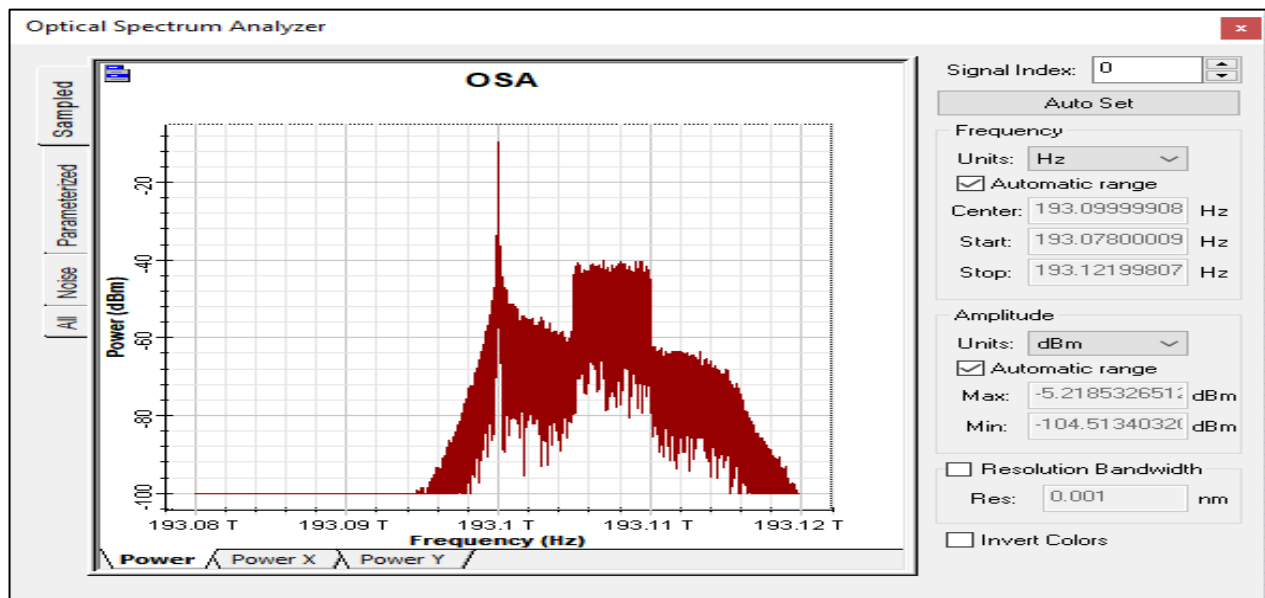


Figure 4.26: Optical spectrum after fiber optic link.

Figure 4.27 shows that the constellation diagram of OFDM signals after quadrature demodulation.

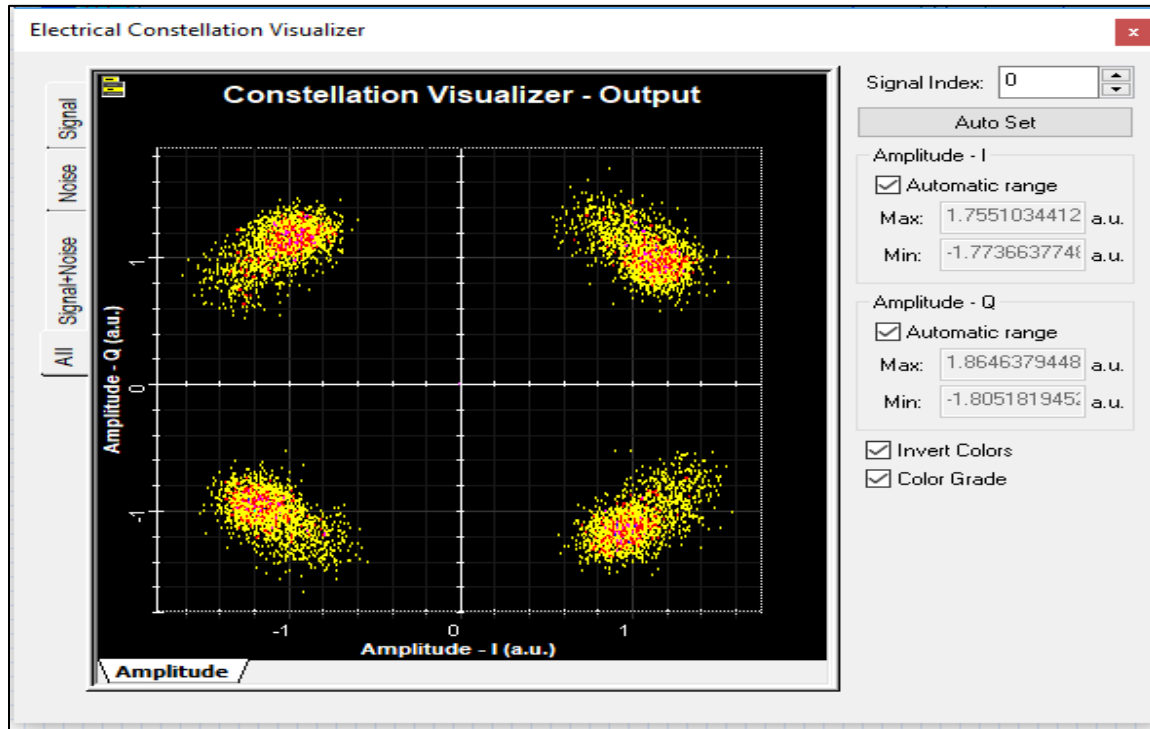


Figure 4.27: The constellation of OFDM signal after Quadrature demodulation.

4.6. The Result for 16-QAM of DD-OFDM

The simulation results of direct detection OFDM at different stages and different transmission lengths are explained as such a way. The figure 4.28 shows that the electrical constellation diagrams after 16-QAM modulator at transmitter part.

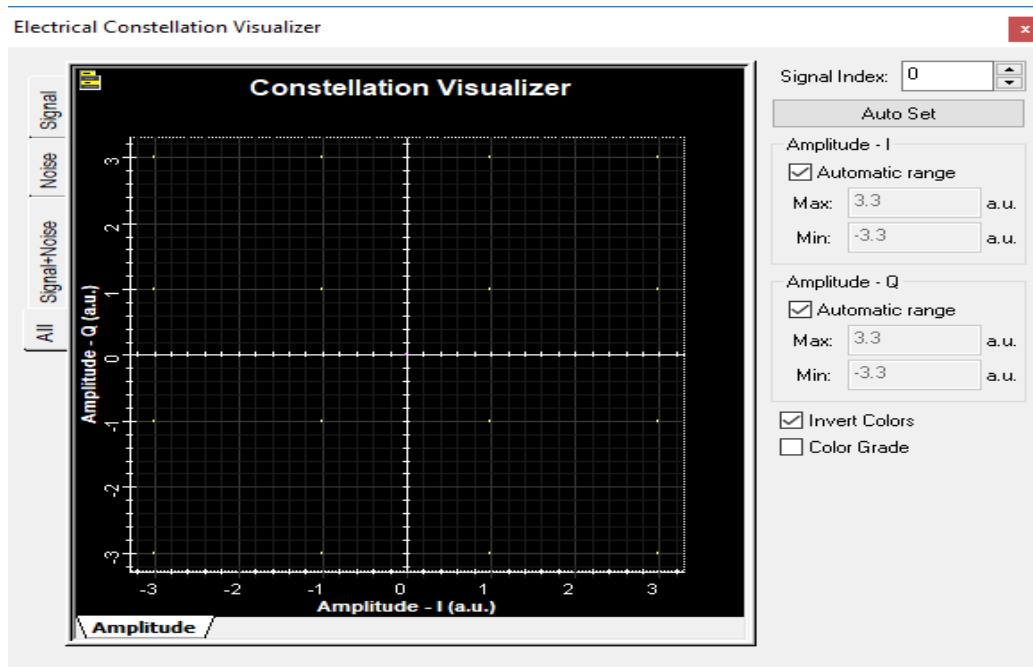


Figure 4.28: The constellation diagram of 16-QAM at transmitter part of OFDM

Again the figure 4.29 show that the RF spectrum of OFDM signal after Quadrature demodulator.

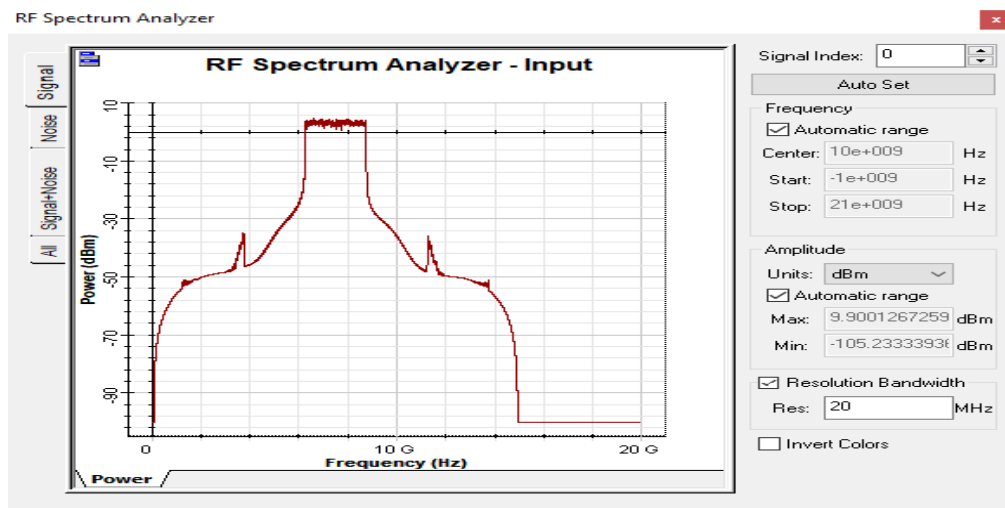


Figure 4.29: RF spectrum of OFDM signal after Quadrature Modulator

Figure 4.30 shows that the optical spectrum of OFDM signal and optical spectrum after optical amplifier which used to change the RF OFDM signal optical signal at frequency of (193.1) THz by using Mach-Zehnder modulator with appropriate power that are produced from the laser and the resulted signal is in frequency domain.

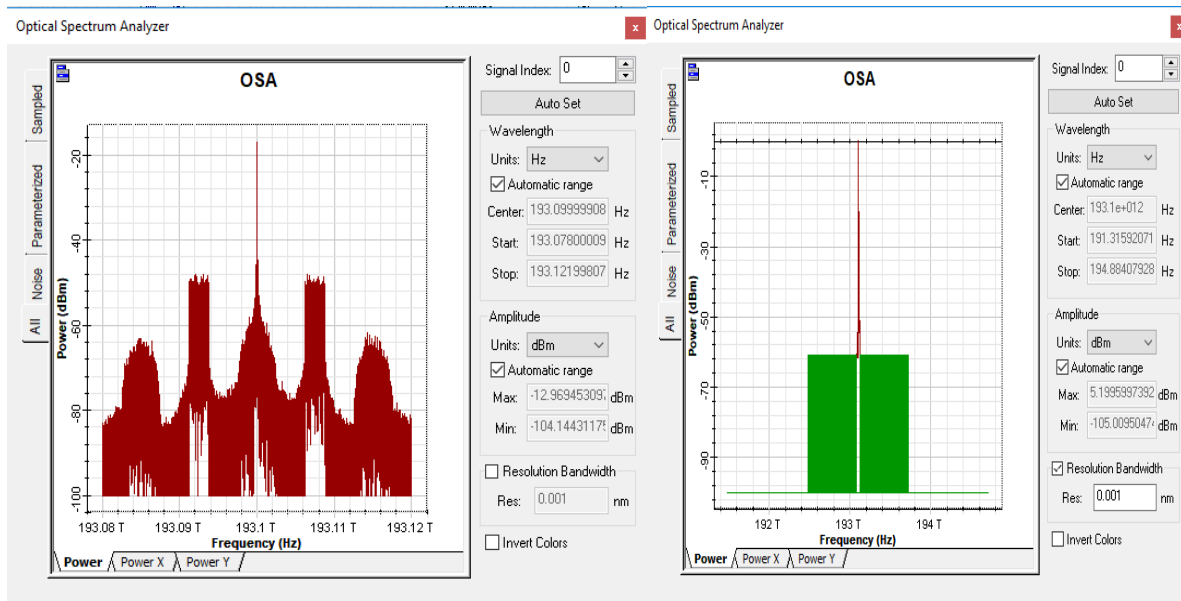


Figure 4.30: The optical spectrum of OFDM signal after MZM of 16-QAM

Figure 4.31 shows the RF spectrum after optical link and constellation diagram of 16-QAM OFDM signal after demodulation.

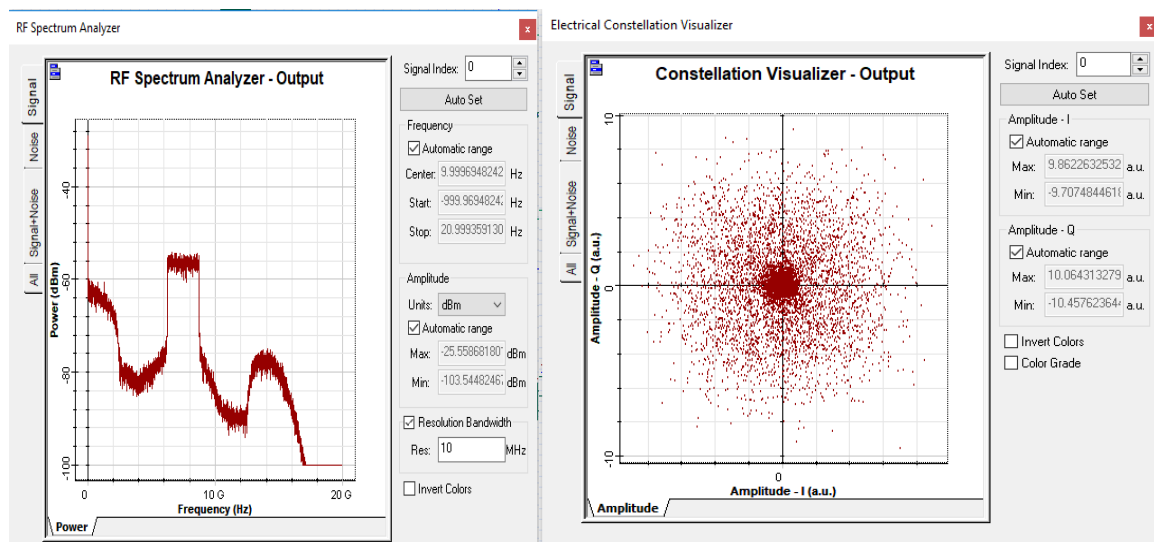


Figure 4.31: RF spectrum after optical link and constellation of OFDM signal of 16-QAM

4.7. The Result for 32-QAM of DD-OFDM

The simulation results of direct detection OFDM by using 32-QAM are explained on the figures 4.32 which indicates that the electrical constellation diagram after 32-QAM modulator at transmitter part.

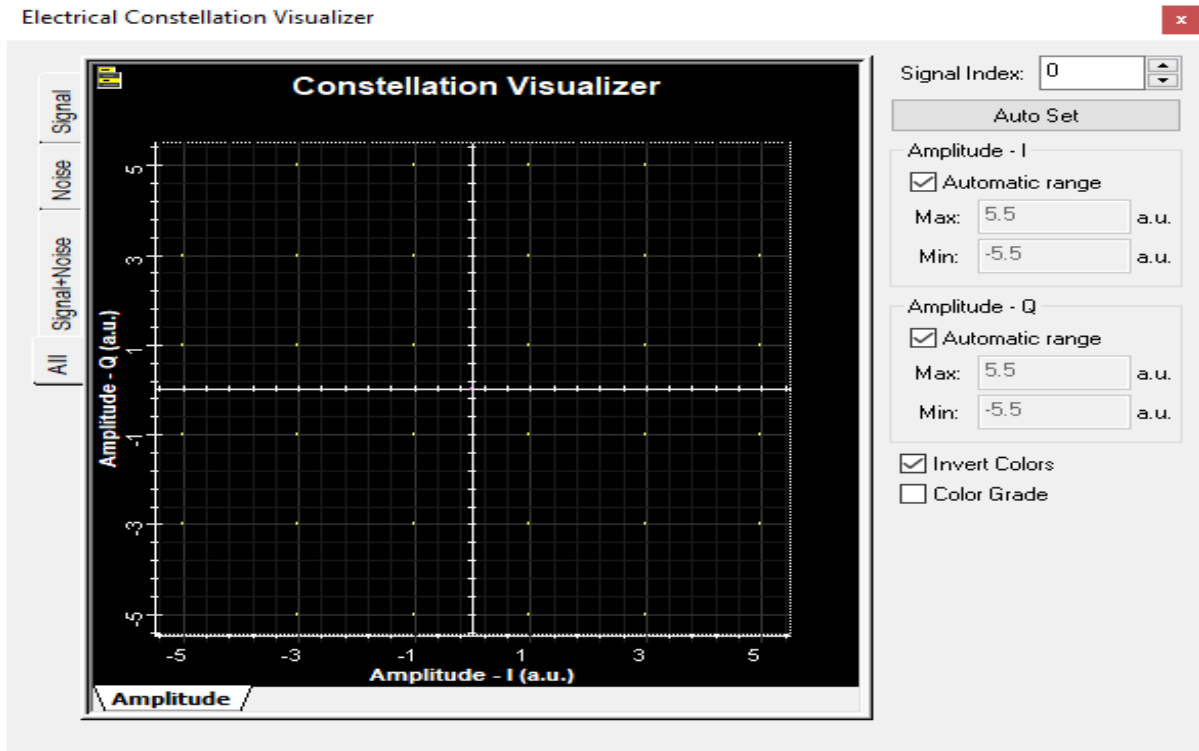


Figure 4.32: The constellation diagram of 32-QAM of DD-OFDM at transmitter side

Again the figure 4.33 show that the RF spectrum of OFDM signal after Quadrature demodulator

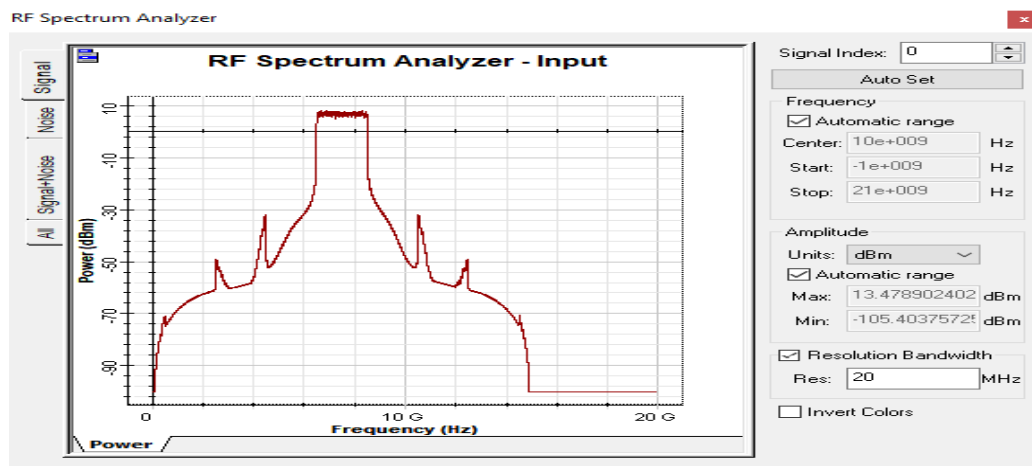


Figure 4.33: The RF spectrum of OFDM signal after Quadrature demodulator

Figure 4.34 shows that the optical spectrum of OFDM signal and optical spectrum after optical amplifier in 32-QAM DD- OFDM which used to change the RF OFDM signal optical signal by using Mach-Zehnder modulator with appropriate power that are produced from the laser and the resulted signal is in frequency domain.

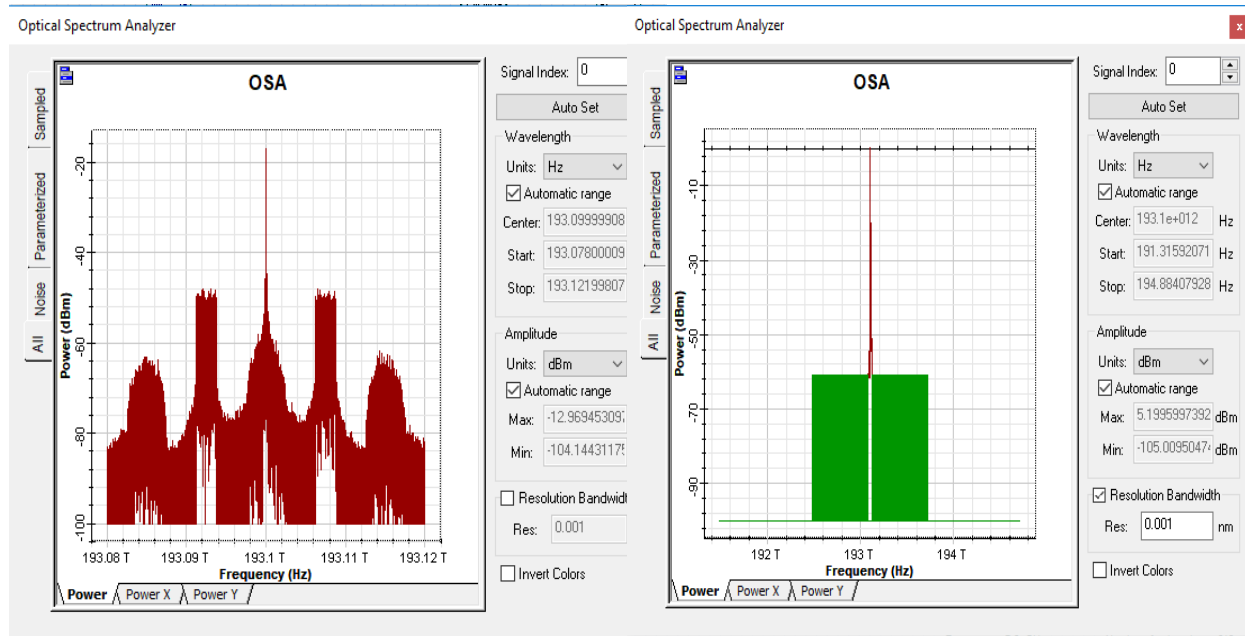


Figure 4.34: The optical spectrum of OFDM signal after of 32-QAM

The figure 4.35 shows the RF spectrum after optical link and constellation diagram of 32-QAM OFDM signal after demodulation.

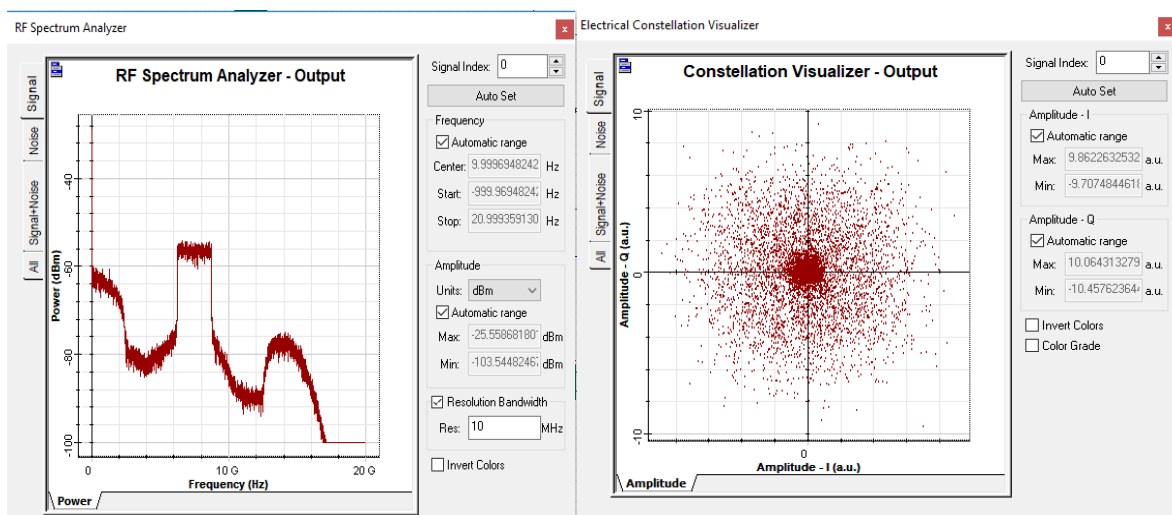


Figure 4.35: RF spectrum optical link and constellation diagram of OFDM signal of 32-QAM

4.8. The Result for 64-QAM of DD-OFDM

The simulation results of direct detection OFDM at different stages and different transmission lengths are explained as such a way. The figure 4.36 shows that the electrical constellation diagrams after 64-QAM for DD-OFDM modulator at transmitter part.

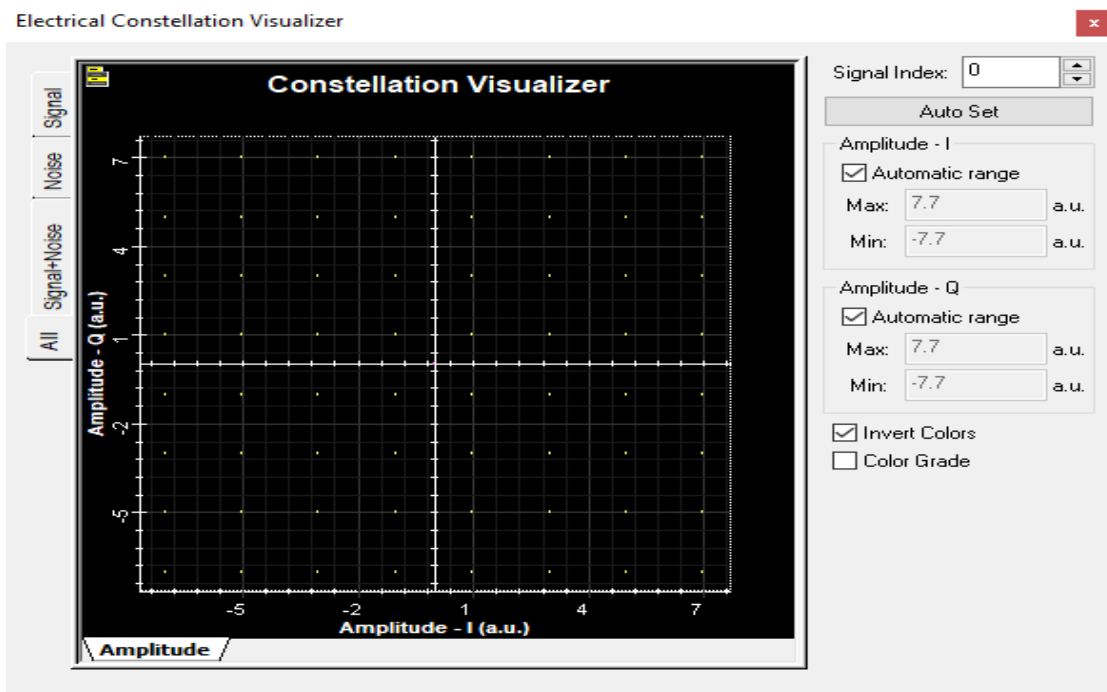


Figure 4.36: Constellation diagram of 64-QAM at transmitter side of DD-OFDM

And figure 4.37 indicates that the RF spectrum of 64-QAM DD-OFDM signal after Quadrature demodulator.

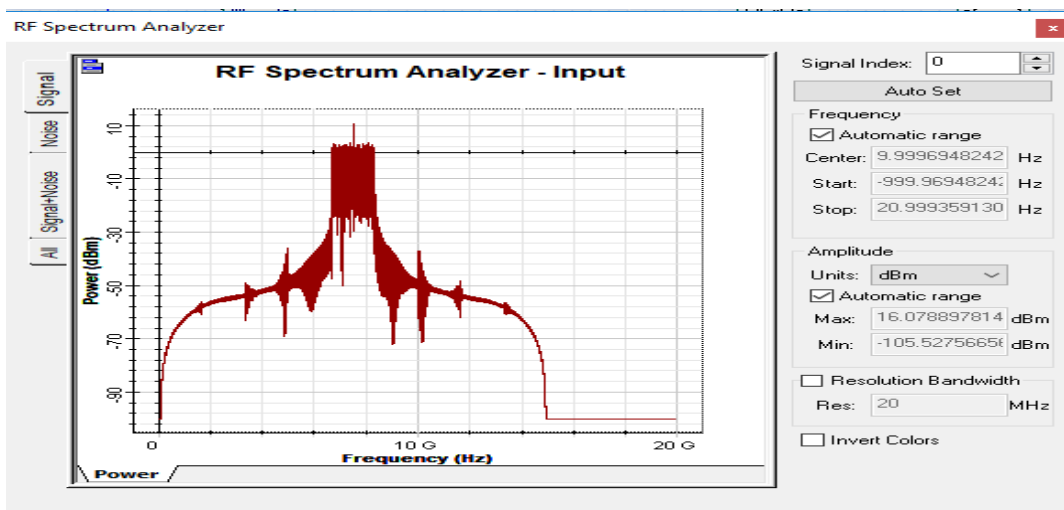


Figure 4.37: The RF spectrum of 64-QAM OFDM signal after Quadrature demodulator

Figure 4.38 indicates that the optical spectrum of OFDM signal and optical spectrum after optical amplifier in 64-QAM DD- OFDM which used to change the RF OFDM signal optical signal by using Mach-Zehnder modulator with appropriate power that are produced from the laser and the resulted signal is in frequency domain.

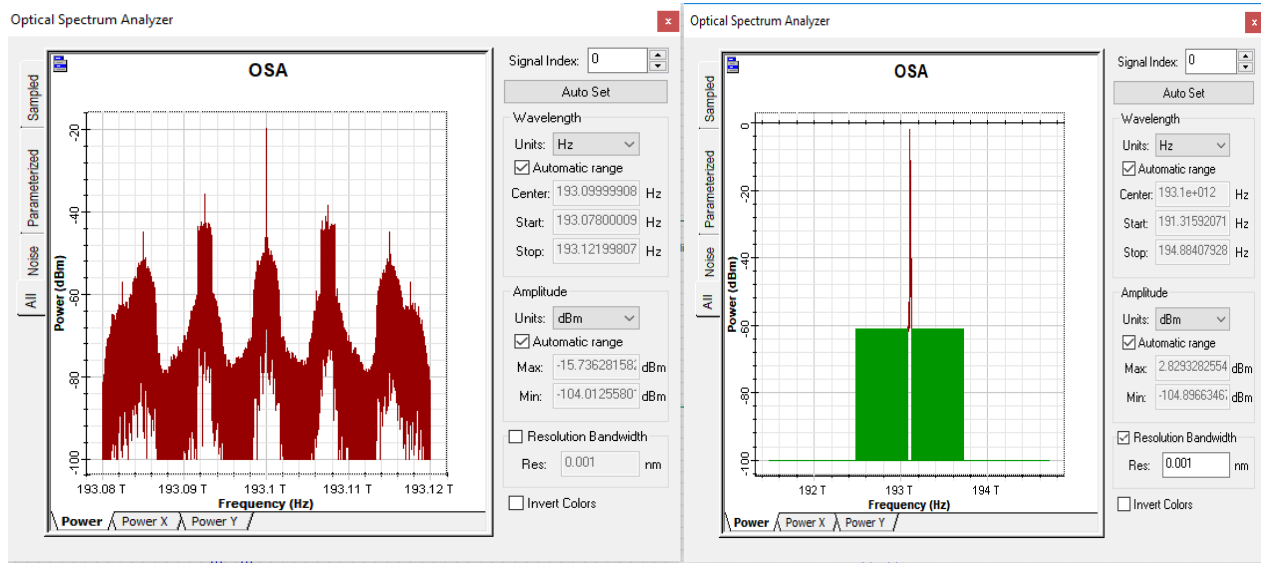


Figure 4.38: The optical spectrum of OFDM signal after MZM of 64-QAM

Figure 4.39 indicates that the RF spectrum after optical link and constellation diagram of 64-QAM DD-OFDM signal after demodulation.

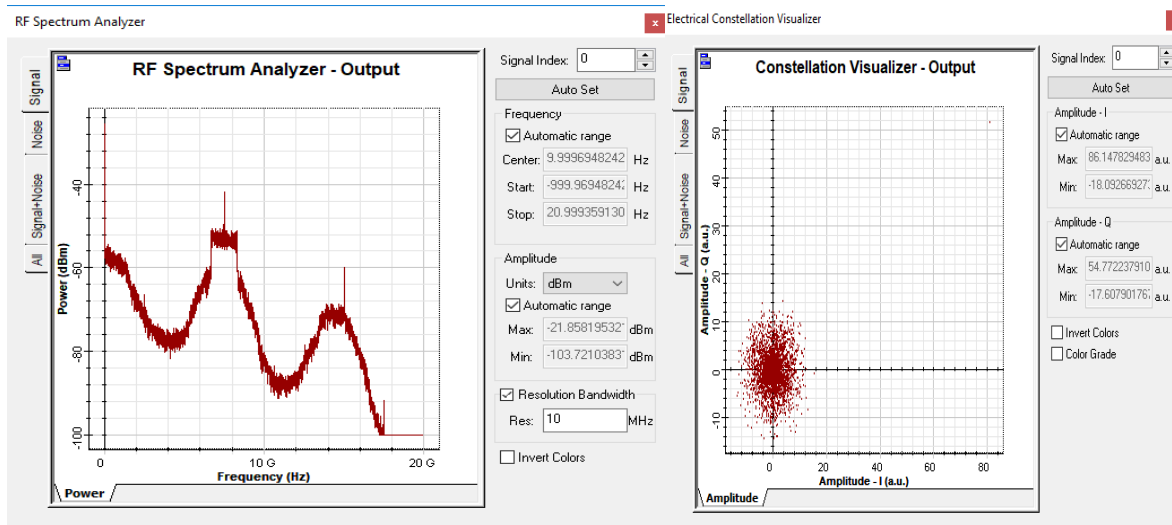


Figure 4.39: RF spectrum of optical link and constellation of OFDM signal of 64-QAM

After modulation and demodulation, three parameters will be checked to assess the signal's performance and quality. The BER, Quality factor, and Eye diagram are the metrics in question. The quality factor reflects the signal's quality, and the bit error rate (BER) is the ratio of bits with errors to total bits received, and it's used to determine the quality of an optical connection. So the figure bellow show that the quality factor is constant for certain time and then increases. But decreases when we increase the length of transmission due to different attenuation, dispersion and the noise that are produced from detectors such as thermal noise.

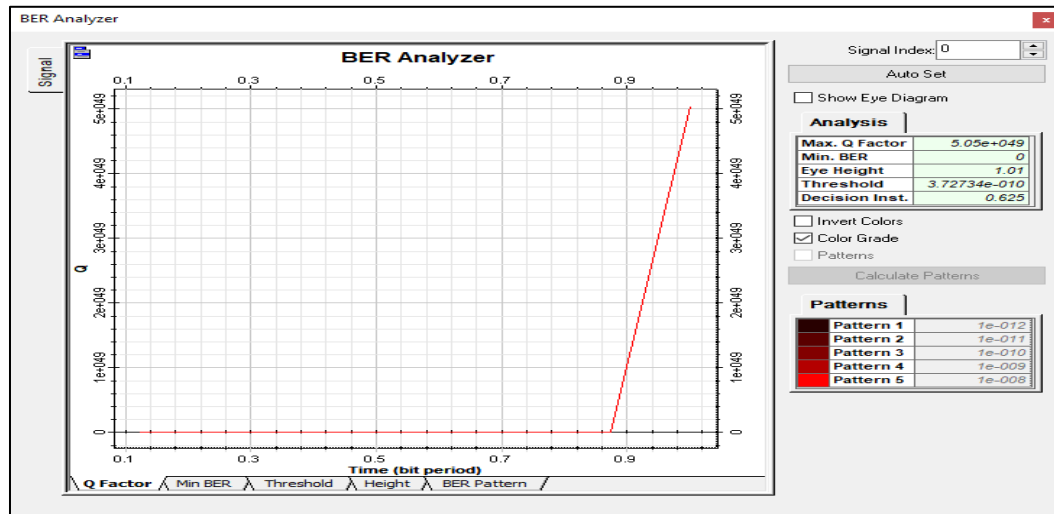


Figure 4.40: The diagram of Quality factor

The table 4.1 show that the signal details at 4-QAM OFDM at receiver part

Table 4.1: Signal details at 4-QAM OFDM at receiver part

Parameter	Value
Max. Q factor	5.05×10^{49}
Min. BER	0
Eye height	1.01
Threshold	3.72734×10^{-10}
Decision Inst.	0.625

The figure 4.41 shows that the decreasing threshold frequency of the signal, which indicates that, the minimum frequency of radiation that will, produces a photo electric.

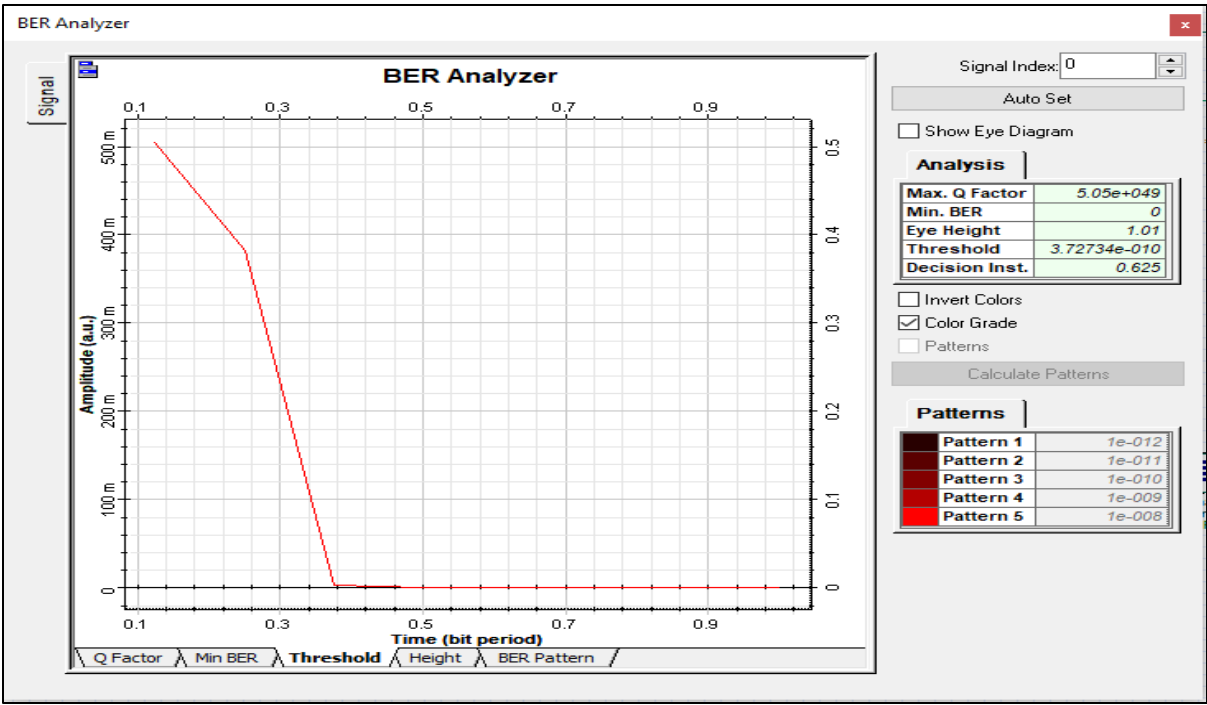


Figure 4.41: The diagram of threshold frequency

The figure 4.42 show that the minimum BER, so we observed the best bit error rate short distances but as transmission distances increases our BER is increase and signal noise decreases.

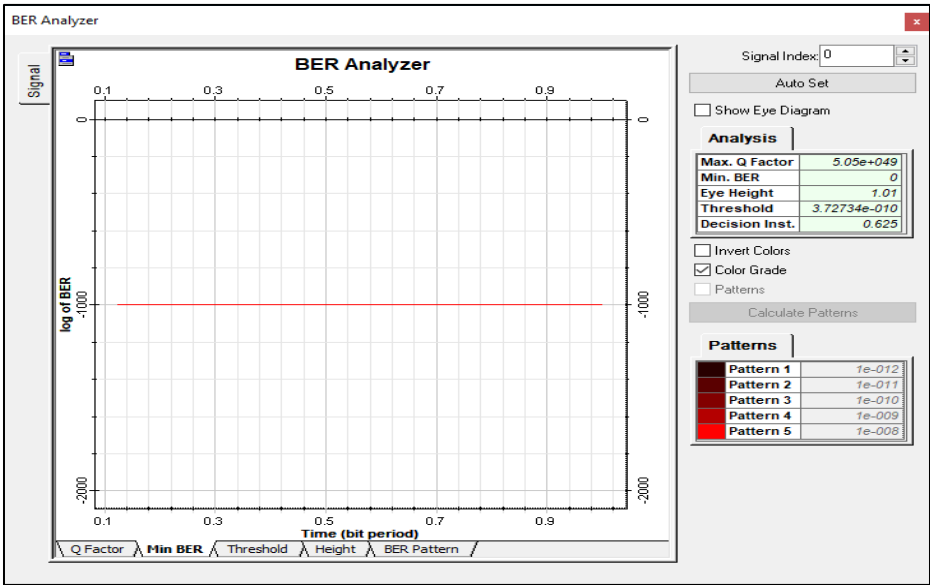


Figure 4.42: The Diagram of Min. BER

Figure 4.43 indicates that the signal strength of message signal or the light intensity of the transmitted signal.

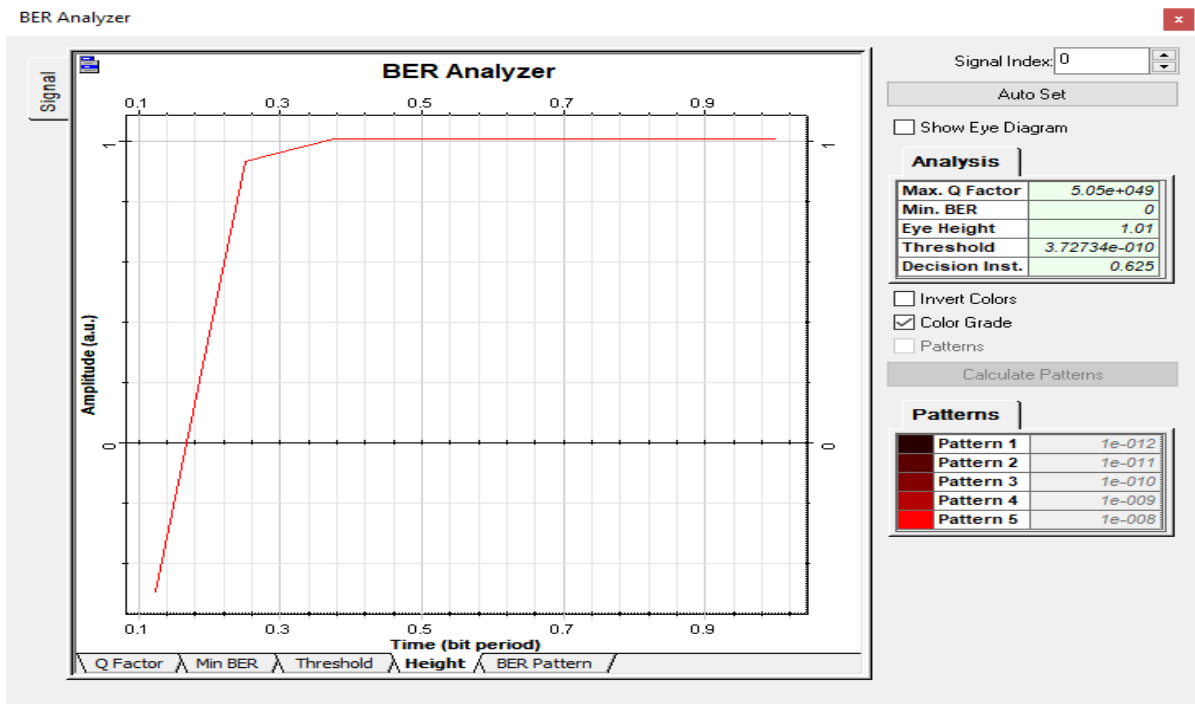


Figure 4.43: The Diagram of Amplitude of the signal

The eye diagram, which is a common indicator of signal quality in high-speed digital transmissions, is shown in the figures below. An oscilloscope creates an eye diagram by superimposing sweeps of several portions of a continuous data stream powered by a master clock. As a result, the width of the eye opening determines the time interval over which the received signal can be sampled without error owing to interference from adjacent pulses, which is referred to as ISI. The degree of distortion is determined by the vertical distance between the top of the eye opening and the highest signal level. The more one's eye closes, the more difficult it is to tell the difference between them. To verify that signals are of adequate quality to sustain communications, they are evaluated and validated using an eye pattern approach. As a result, one of the basic parameters used to investigate the system is the eye diagram, which depicts the noise in the signal and how to distinguish logic 0 from logic 1. An eye diagram depicts the signals' relative performance. The vertical and horizontal apertures of the eye give important information about the receiver's capacity to appropriately detect 1 and 0 bits. The eye opening should be as

large and open as feasible for a good transmission mechanism. So the figure 4.44 shows that the eye diagrams in terms of different parameters such as Quality factor and BER respectively.

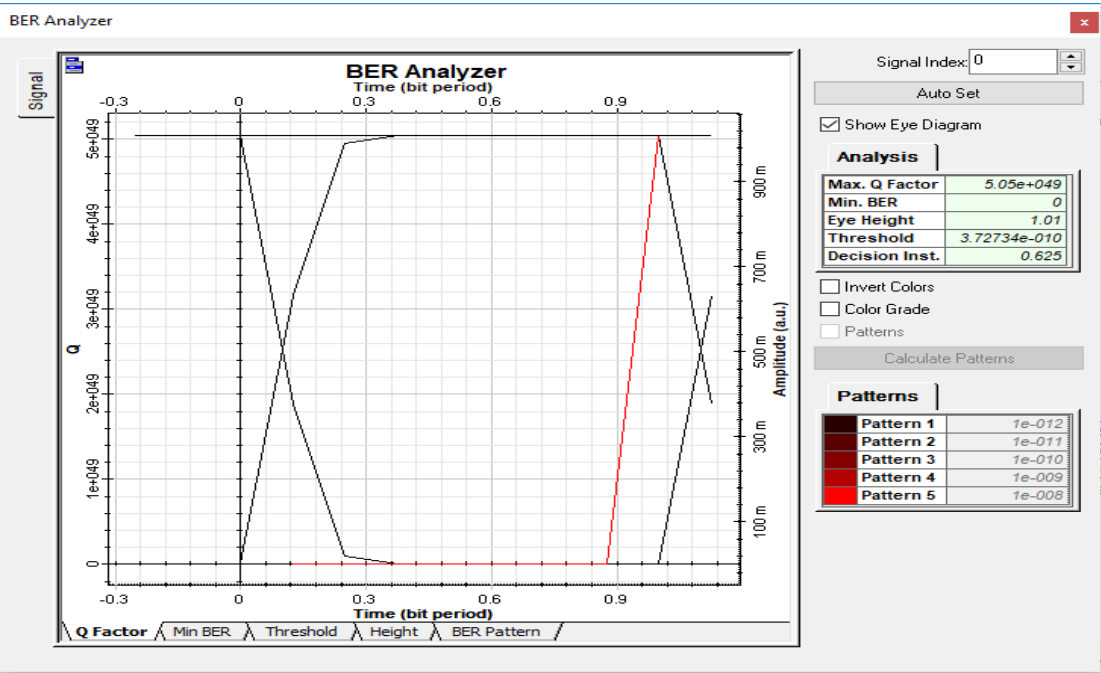


Figure 4.44: Eye diagram in terms Quality factor

And the figure 4.45 is shows the eye diagram in terms of minimum BER

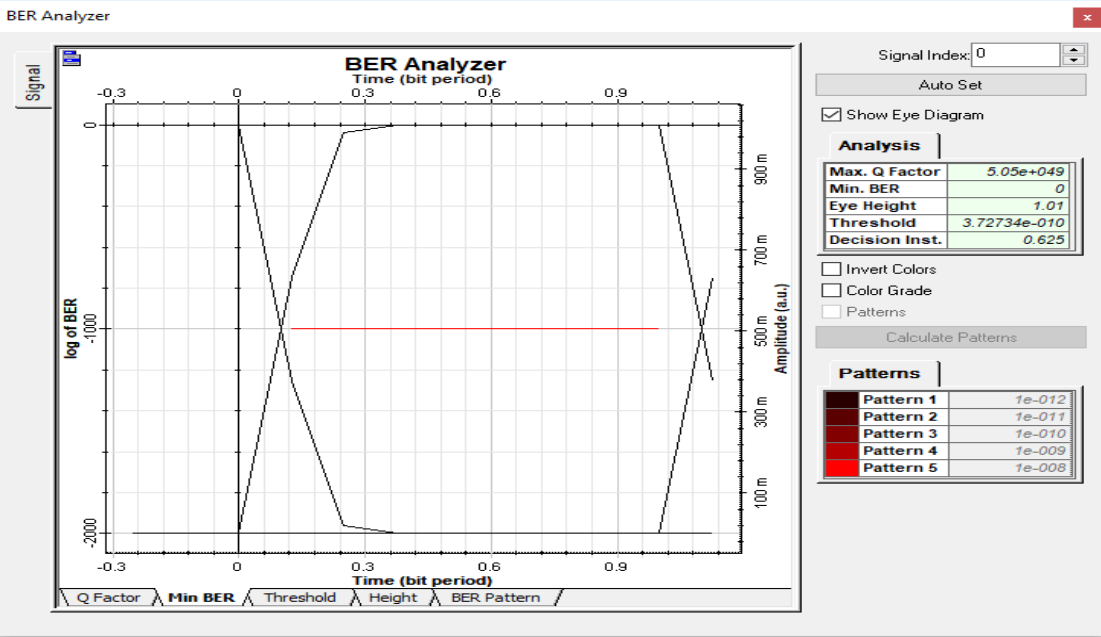


Figure 4.45: Eye diagram in terms of Min. BER

The bellow figure 4.46 show that the Eye diagram in terms of BER pattern

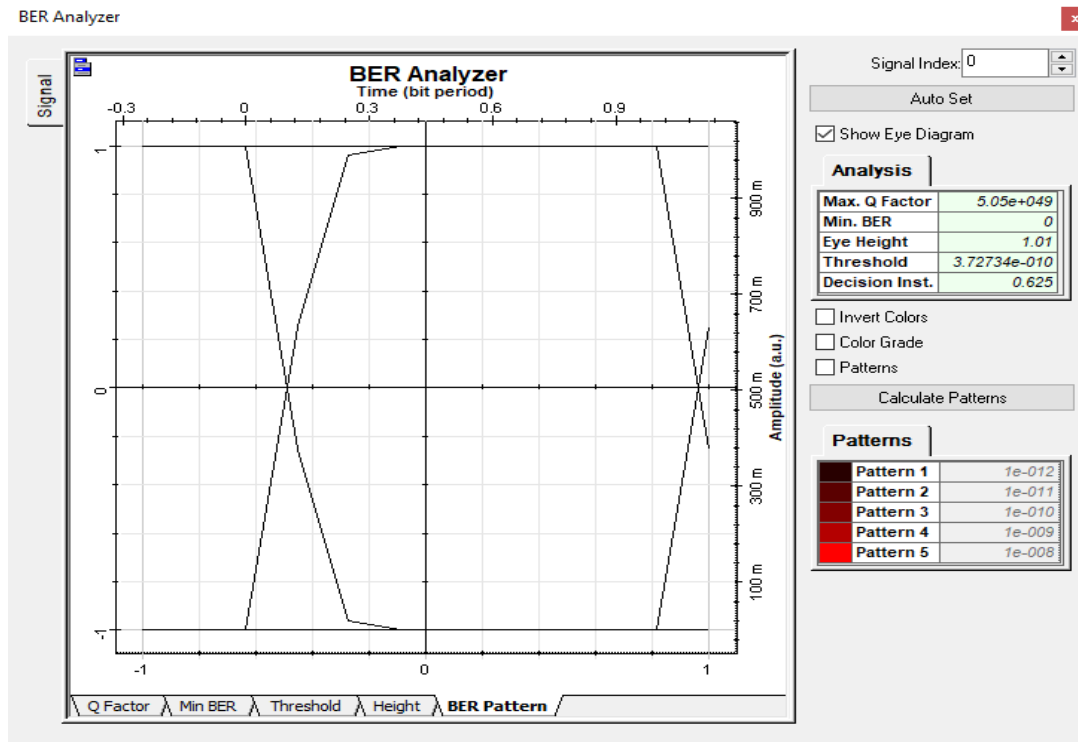


Figure 4.46: Eye diagram in terms of BER pattern

Finally, we analyzed the performance of the system at different transmission length in terms of BER and OSNR as we observed above we got the better error rate at short distance which approximately zero but as the transmission distance is increase the BER also increases.

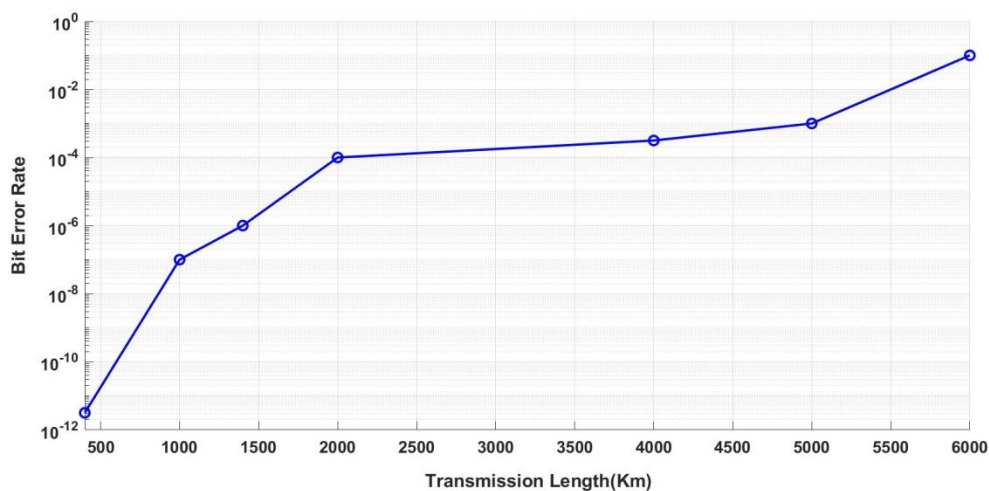


Figure 4.47: The Relationship between BER and transmission distance

Again to analyze the performance of the system we have to study the relationship between BER and OSNR with respect transmission distance. So the figure bellows show that the relationship between OSNR and BER which indicates as the transmission distances increases.

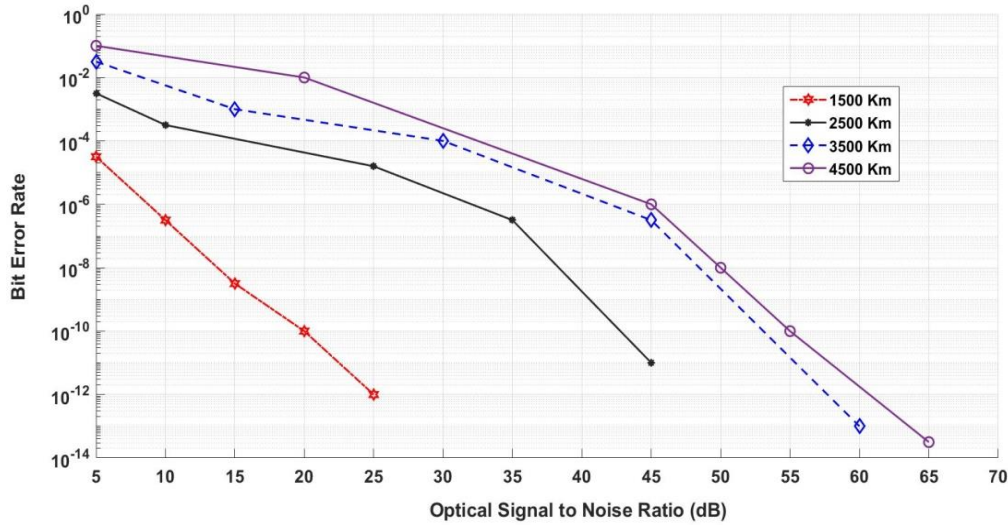


Figure 4.48: The Relationship between BER and OSNR as the transmission length increases

As we observed from the above figure we conclude that the larger OSNR is required as the transmission distance is increase to maintain BER. But to increase the OSNR values we have to add the launched power and increasing of the OSNR is must be limited because increasing the power above the limit point will increase the nonlinear impairment which makes our system again worse. The figure 4.49 shows the relationship of launched power and BER at 4500km

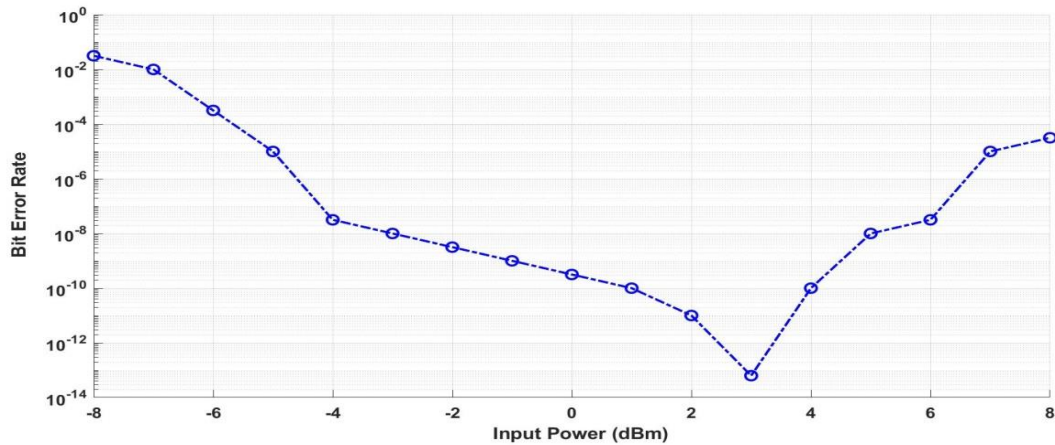


Figure 4.49: The BER of CO-OFDM system with different launched power

Finally, we compare and contrast for 4-QAM, 16-QAM, 32-QAM and 64-QAM of Coherent Detection OFDM in terms of their value of BER and OSNR value. So as we use high order modulation even though constellation error or data error is increase the spectral efficiency is increase and OSNR is again increase that can make the value of BER is approximately going to be decrease. The figure 4.50 is shows the relationship between BER and OSNR for 4-QAM CO-OFDM, 16-QAM CO-OFDM, 32-QAM CO-OFDM, 64-QAM CO-OFDM.

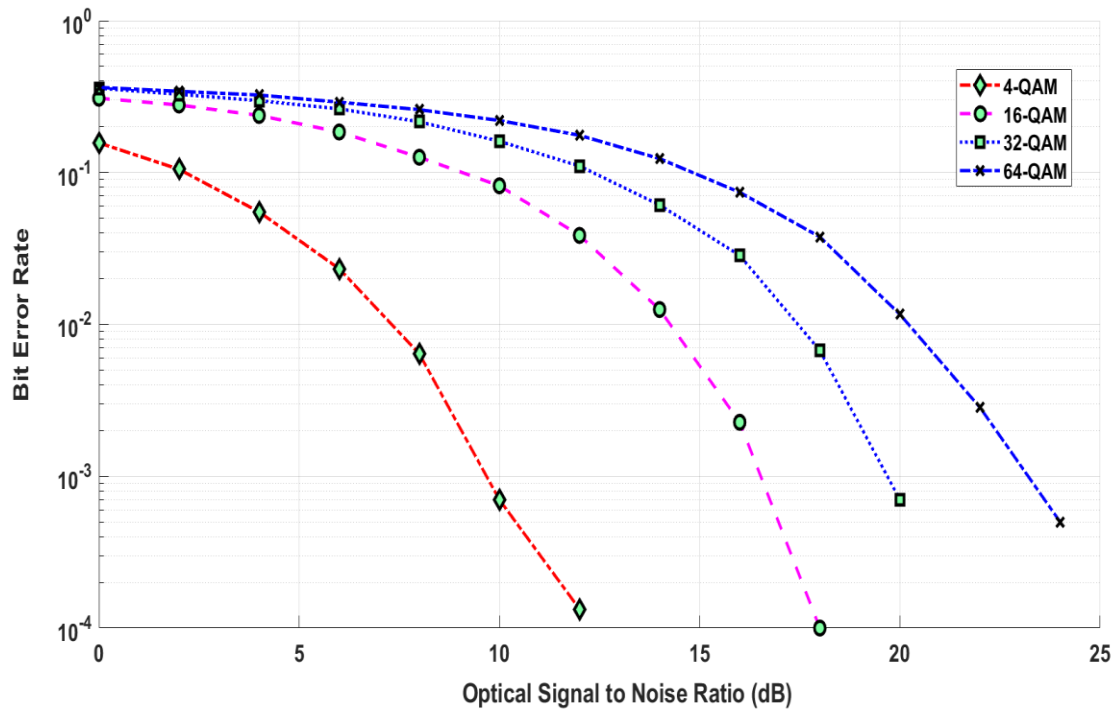


Figure 4.50: The relation between BER and OSNR for M-Modulation formats at 4500 Km.

5. Conclusion and Recommendation

5.1. Conclusion

Finally this thesis is to decrease or minimize the dispersion such as chromatic dispersion (CD) and polarization mode dispersion (PMD) that are occurred during signal transmission through optical channel. In optical communication as the transmission distance is increase the signal overlaps with the neighboring pulses and results the signal becomes broadening. To minimize this problem, the coherent detection OFDM and direct detection OFDM has been employed. Since coherent Detection OFDM is the future technology in optical communication because coherent detection OFDM is integrates both the advantages of coherent detection system and OFDM technology and it has been considered as a promising technology for the next generation of high capacity of optical networks. So in this thesis, we modeled coherent detection OFDM with 4-QAM, 16-QAM, 32-QAM, and 64-QAM for single mode fiber on different length of transmission. In this work, the performances of coherent detection OFDM and direct detection for different distance have evaluated and analyzed using Eye diagram, Quality factor, BER and OSNR with help of oscilloscope visualizer. The spectrum property of signal has demonstrated using RF spectrum analyzer and optical spectrum analyzer. The simulated results have shown that the coherent detection OFDM and direct detection OFDM with considered QAM provides best value of BER and Quality of the signal at specific distance.

5.2. Recommendation

In this thesis, the focus has been made on analysis and design of coherent detection OFDM and direct detection OFDM with QAM to minimize dispersion. If the length of the transmission is increased to a great extent, the signal gets dispersed which can be explored as future work. The quality of the signal, signal to noise ratio also decreases as the distances increases as well as BER increases as the transmission distances increases, so to minimize this the further work should be done by using higher order modulation techniques such as 256-QAM and 1024-QAM to analyze the performance and to maintain OSNR and decrease BER as much as possible. Again the modification will be required for EDFA and DCF which can be explored as future work.

6. REFERENCE

- [1] S. Makovejs(2011), “High-speed optical fibre transmission using advanced modulation formats,” *PhD thesis*, no. July, p. University College London.
- [2] D. O. F. Philosophy and V. Tiwari(2016), “Design and Performance analysis of High speed optical communication links,” .
- [3] D. Cotruta(2011), “Ultra High Data-Rate Optical Transmission Networks,” [Online]. Available: <https://escholarship.mcgill.ca/concern/theses/wd376186t>.
- [4] G. Pandey and A. Goel(2017), “Performance Analysis of Long-Reach Coherent Detection OFDM-PON Downstream Transmission Using m-QAM-Mapped OFDM Signal,” *Journal of Optical Communications*, vol. 38, no. 4. pp. 461–469.
- [5] T. J. Prins(2019), “UCLA UCLA Electronic Theses and Dissertations Title,” [Online]. Available: <https://escholarship.org/uc/item/0th2s0ss>.
- [6] R. S. Romaniuk(2010), “WILGA Photonics and Web Engineering,” *Photonics Appl. Astron. Commun. Ind. High-Energy Phys. Exp.* vol. 7745, no. September 2010, p. 774503, 2010, doi: 10.1117/12.872187.
- [7] X. Luo(2019), “The application of OFDM in optical fiber communication systems,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 332, no. 4, doi: 10.1088/1755-1315/332/4/042010.
- [8] O. D. Chinenye(2017), “Enhancing Signal Production For Promulgating Information in a Fiber Optic Communication System American Journal of Engineering Research (AJER),” no. 11, pp. 105–110.
- [9] S. A. Mohammed, H. Abdullahi, M. M. Babangida, and M. G. Mustapha(2018), “ANALYSIS OF LINEAR AND NON LINEAR EFFECT OF DISPERSION,” vol. 4, no. 6, pp. 106–123.
- [10] P. K. Dubey and V. Shukla(2014), “Dispersion in Optical Fiber Communication,” vol. 3, no. 10, pp. 2012–2015.
- [11] B. SorabhBathla, “*Performance Analysis of Different Dispersion Compensation Techniques in Fiber Optics Communication System.*” .
- [12] S. Devra and G. Kaur(2011), “Different Compensation Techniques To Compensate Chromatic Dispersion In Fiber Optics,” vol. 3, no. May, pp. 1–4, [Online]. Available: https://www.researchgate.net/publication/275517786_Different_Compensation_Techniques_To_Compensate_Chromatic_Dispersion_In_Fiber_Optics.

- [13] P. F. I. D. E. Carrera(2010), “New Methods for Measuring and Monitoring Chromatic Dispersion in Optical,” *Analysis*, pp. 1–125.
- [14] J. Ishiwu, J. Yahya, D. O. Oguche, and B. Andrew(2017), “Efficient Chromatic and Residual Dispersion Postcompensation for Coherent Optical OFDM,” *Int. J. Sci. Eng. Appl.*, vol. 6, no. 12, pp. 372–381.
- [15] K. Puntsri(2014), “Investigation of Receiver Concepts for Coherent Optical Orthogonal Frequency Division Multiplexing Communication Systems,”.
- [16] M. A. Reimer(2007), “Modeling and Simulation of Polarization Mode Dispersion and Polarization Dependent Loss,” 2007.
- [17] C. M. Clayton(1993), *Applications of nonlinear optics*.
- [18] S. P. Singh(2007), “Progress In Electromagnetics Research, PIER 73, 249–275, 2007,” pp. 249–275.
- [19] Y.-K. Wong, S. M. Idrus, and I. A. Ghani(2012), “Performance Analysis of the OFDM Scheme for Wirelessover Fiber Communication Link,” *Int. J. Comput. Theory Eng.*, no. October 2012, pp. 807–811, 2012, doi: 10.7763/ijcte.2012.v4.583.
- [20] M. Anjaley, J. John, and P. G. Gokul(2015), “Performance Evaluation and Simulation of OFDM in Optical Communication Systems,” vol. 5, no. 2, pp. 1–4.
- [21] S. Trehan(2015), “Comparative Analysis of Single Span Long Haul Optical Fibre Link using Different Modulation Format (OPTICAL FIBRE),” no. May, 2015.
- [22] A. H. A. Kareem(2020), “Design and comprehensive investigation of high capacity communication system based on all optical orthogonal frequency division multiplexing processing,” *Int. J. Intell. Eng. Syst.*, vol. 13, no. 4, pp. 66–76, doi: 10.22266/IJIES2020.0831.07.
- [23] Bobby barua(2018) “SPACE OPTICAL COMMUNICATION SYSTEMS OVER TURBULENT DOCTOR OF PHILOSOPHY DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING,” no. October, 2018.
- [24] F. Mohammed Ali, E. Al-Hilo, and M. Gamil Tarbul9(2018), “Performance Analysis of Radio over Optical Fiber System with OFDM Using Multiplexing Techniques,” *Int. J. Appl. Eng. Res.*, vol. 13, no. 12, pp. 10831–10844, [Online]. Available: <http://www.ripublication.com>.
- [25] Juan Miguel Pérez Rosas(2013), “Optical Orthogonal Frequency Division Systems with

- Direct Detection Receivers,” 2013.
- [26] S. M. S. Kenshil(2018), “Digital Commons @ DU Study of Optical OFDM System for Wireless LAN Applications,” .
 - [27] B. J. C. Schmidt, A. J. Lowery, and J. Armstrong(2008), “Experimental demonstrations of electronic dispersion compensation for long-haul transmission using direct-detection optical OFDM,” *J. Light. Technol.*, vol. 26, no. 1, pp. 196–203, doi: 10.1109/JLT.2007.913017.
 - [28] N. LaSorte, W. J. Barnes, and H. H. Refai(2008), “The history of orthogonal frequency division multiplexing,” *GLOBECOM - IEEE Glob. Telecommun. Conf.*, no. January, pp. 3592–3596, 2008, doi: 10.1109/GLOCOM.ECP.690.
 - [29] B. R. Ballal, A. Chadha, and N. Satam(2014), “Orthogonal Frequency Division Multiplexing and its Applications,” no. January 2013, 2014.
 - [30] R. Amasa(2009), “Inter Carrier Interference Cancellation In OFDM Systems Inter Carrier Interference Cancellation,” *Thesis Master Technol. Electron. Commun. Eng. Natl. Inst. Technology*.
 - [31] I. I. Jude, Y. Adamu, M. Luka, and A. Baams(2018), “Optical-OFDM Detection Techniques,” *Int. J. Sci. Eng. Appl.*, vol. 7, no. 3, pp. 023–033, doi: 10.7753/ijsea0703.1001.
 - [32] R. No-(2010), “OFDM SYSTEMS AND PAPR REDUCTION TECHNIQUES IN OFDM SYSTEMS A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of,” no. 10609015, pp. 0–40.
 - [33] Y. J. Qazi, “Performance Evaluation of Error Correcting Techniques for OFDM Systems.”
 - [34] F. Almasoudi, K. Alatawi, and M. A. Matin(2013), “Study of OFDM Technique on RoF Passive Optical Network,” *Opt. Photonics J.*, vol. 03, no. 02, pp. 217–224, doi: 10.4236/opj.2013.32035.
 - [35] T. a Eriksson(2014), “Multidimensional Modulation Formats for Coherent Optical Communication Systems Coherent Optical Communication Systems,” p. 90.
 - [36] A. Dhingra, S. Kumar(2018), . P., D. Sharma, and S. Dahiya, “A Comprehensive Review of QAM-OFDM Optical Networks,” *Int. J. Comput. Sci. Eng.*, vol. 6, no. 11, pp. 811–817, doi: 10.26438/ijcse/v6i11.811817.
 - [37] W. Henkel, G. Tauböck, P. Ödling, P. O. Börjesson, N. Petersson, and A.

- Johansson(2002), "The cyclic prefix of OFDM/DMT - An analysis," *2002 Int. Zurich Semin. Broadband Commun. Access - Transm. - Netw. Meet. Chall. High-Speed Commun. IZS 2002 - Proc.*, no. May, pp. 22–24, 2001, doi: 10.1109/IZSBC.2002.991762.
- [38] S. Bashir, S. Ali, S. Ahmed, and V. Kakkar(2017), "Analog-to-digital converters: A comparative study and performance analysis," *Proceeding - IEEE Int. Conf. Comput. Commun. Autom. ICCCA 2016*, no. May 2016, pp. 999–1001, doi: 10.1109/CCAA.2016.7813861.
- [39] T. Jaemkarnjanaloha, R. Maneekut, and P. Kaewplung(2016), "Long-haul coherent optical OFDM point-to-point transmission using optical phase conjugation," *ICETE 2016 - Proc. 13th Int. Jt. Conf. E-bus. Telecommun.*, vol. 3, no. Icete, pp. 43–47, doi: 10.5220/0005963700430047.
- [40] S. Sharma, D. Parkash, and S. Singh(2020), "Analysis and design of WDM optical OFDM system with coherent detection using different channel spacing," *Lect. Notes Electr. Eng.*, vol. 597, no. March, pp. 365–376, doi: 10.1007/978-3-030-29407-6_27.
- [41] A. Khaled(2013), "High Data Rate Coherent Optical Ofdm System for Long Haul Transmission," *Thesis*, no. November, 2013.
- [42] L. Coelho(2010), "Modeling, Simulation and Optimization of Optical Communication Systems Using Advanced Modulation Formats," *Design*, [Online]. Available: <http://d-nb.info/1010439243/34>.
- [43] X. Li, J. Vucic, V. Jungnickel, and J. Armstrong(2012), "On the capacity of intensity-modulated direct-detection systems and the information rate of ACO-OFDM for indoor optical wireless applications," *IEEE Trans. Commun.*, vol. 60, no. 3, pp. 799–809, doi: [10.1109/TCOMM.2012.020612.090300](https://doi.org/10.1109/TCOMM.2012.020612.090300).
- [44] M. Chen, J. Yu, and X. Xiao(2017), "Real-Time Q-Band OFDM-RoF Systems with Optical Heterodyning and Envelope Detection for Downlink Transmission," *IEEE Photonics J.*, vol. 9, no. 2, pp. 8–12, doi: 10.1109/JPHOT.2017.2671870.
- [45] N. Albakay(2018), "Design and Analysis of Binary Driven Coherent M- ary Qam Transmitter for Next Generation Optical Networks," .
- [46] S. Mhatli and M. A. Jarajreh(2014), "Performances comparison of a coherent optical OFDM system Performances comparison of a coherent optical OFDM system," no. September 2015, 2014.

- [47] Z. Liu, J. Y. Kim, D. S. Wu, D. J. Richardson, and R. Slavik(2015), “Homodyne OFDM with optical injection locking for carrier recovery,” *J. Light. Technol.*, vol. 33, no. 1, pp. 34–41, doi: 10.1109/JLT.2014.2369994.