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HIGH DATA RATE COHERENT OPTICAL OFDM SYSTEM FOR LONG-HAUL TRANSMISSION

A Thesis

Presented to

The Faculty of The Daniel Felix Ritchie School of Engineering & Computer Science

University of Denver

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Khaled Alatawi

November 2013

Advisor: Dr. Mohammed Matin

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Title: High Data Rate Coherent Optical OFDM System for Long-Haul Transmission

Advisor: Dr. Mohammad Matin

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Abstract

The growth in internet traffic has driven the increase in demand for bandwidth and high data rates. Optical Orthogonal Frequency Division Multiplexing is considered as a promising technology to satisfy the increased demand for bandwidth in broadband services. Optical OFDM received a great attention after proposing it as a modulation technique for the long-haul transmission in both direct and coherent detection. However, Coherent Optical OFDM (CO-OFDM) is the next generation technology for the optical communications, since it integrates the advantages of both coherent systems and OFDM systems. It has the ability to overcome many optical fiber restrictions such as chromatic dispersion (CD) and polarization mode dispersion (PMD). Moreover, Integrating the Coherent Optical OFDM with Wavelength Division Multiplexing (WDM) systems will provide the transmission system with a high bandwidth, a significant data rates, and a high spectral efficiency without increasing the cost or the complexity of the system. WDM systems help to enhance the capacity and the data rate of the system by sending multiple wavelengths over a single fiber.

This research focuses on the implementation and performance analysis of high data rate coherent optical OFDM for long-haul transmission. The study starts with a single user and extends to the implanting of the WDM system. “OptiSystem-12” simulation tool is fully used to design and implement the system. The system utilizes to carry range of data rates start from 10 Gbps to 1 Tbps, 4-QAM (2 bits-per-symbol) is

used a modulation type for the OFDM signal, Optical I/Q modulation is employed at the transmitter and coherent detection is employed at the receiver. The performance of the system is studied and analyzed system in terms of Bit-Error-Rate (BER), the effect of the transmission distance on the Optical-Signal-to-Noise-Ratio (OSNR), and the relation of BER and OSNR with regard to the transmission distance.

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Abbreviations

WDM “Wavelength Division Multiplexing”

ADC “Analog to Digital Converter”

DAC “Digital to Analog Converter”

OFDM “Orthogonal Frequency Division Multiplexing”

CO-OFDM “Coherent Optical OFDM”

PMD “Polarization Mode Dispersion”

CD “Chromatic Dispersion”

ISI “Inter-Symbol Interference”

BER “Bit Error Rate”

OSNR “Optical Signal to Noise Ratio”

LED “Laser Emitting Diode”

MZM “Mach-Zehnder Modulator”

SPM “Self-Phase Modulation”

XPM “Cross-Phase Modulation”

FWM “Four-Wave Mixing”

SRS “Stimulated Raman Scattering”

SBS “Stimulated Brillouin Scattering”

DCF “Dispersion Compensation Fiber”

FBG “Fiber Bragg Grating”

CFBG “Chirped Fiber Bragg Grating”

SMF “Single Mode Fiber”

DWDM “Dense Wavelength Division Multiplexing”

CWDM “Coarse Wavelength Division Multiplexing”

MCM “Multicarrier Modulation”

DAB “Digital Audio Broadcasting”

DVB “Digital Video Broadcasting”

WLAN “Wireless Local Area Network”

FDM “Frequency Division Multiplexing”

DFT “Discrete Fourier Transform”

LAN “Local Area Network”

PAN “Personal Area Network”

MMF “Multimode Fiber”

FFT “Fast Fourier Transform”

QAM “Quadrature Amplitude Modulation”

PSK “Phase Shift Keying”

IFFT “Inverse Fast Fourier Transform”

CP “Cyclic Prefix”

DD-OOFDM “Direct Detection Optical OFDM”

EDFA “Erbium Doped Fiber Amplifier”

E/O “Electrical to Optical Converter”

O/E “Optical to Electrical Converter”

LPF “Low-Pass Filter”

MAN “Metropolitan Area Network”

PRBS “Pseudo Random Binary Sequence”

TDM “Time Division Multiplexing”

ICI “Inter Carrier Interference”

LTE “Long Term Evolution”

QPSK “Quadrature Phase Shift Keying”

RF “Radio Frequency”

WiMAX “Worldwide Interoperability for Microwave Access”

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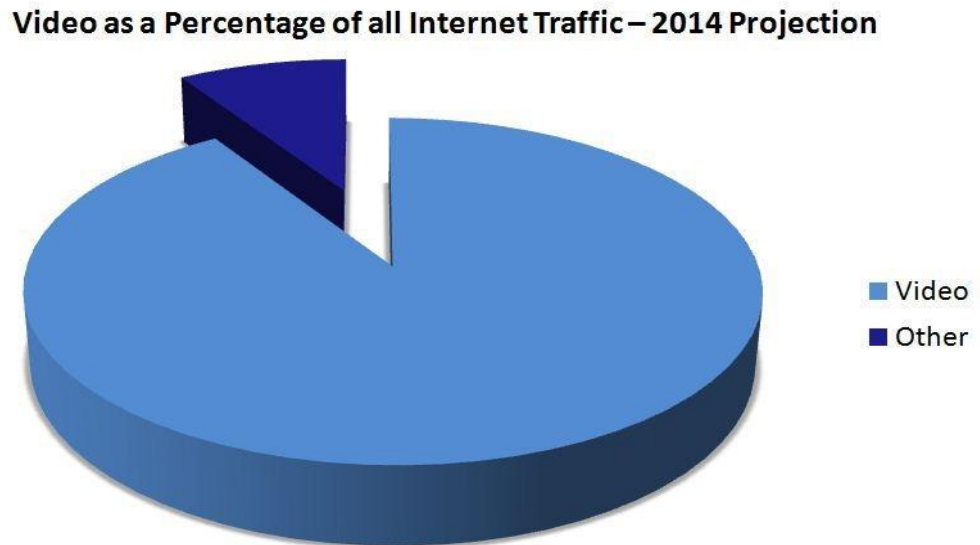
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Chapter One: Introduction

1.1 Overview

The growth in internet traffic, which includes data, voice, and video services, has driven the increased demand in bandwidth and high data rates. According to Cisco Visual networking index, the internet traffic from 2009 to 2014 will quadruple [1]. This increase in internet traffic is driven by the explosion in online videos. Figure 1.1 shows as a 2014 projection of the video services as a percentage of all internet traffic [1]. In addition, a wide range of online applications are in development and there is an increase in distance learning. All of this will increase the bandwidth demands in the future [1].



Source: Cisco Visual Networking Index (VNI) Global Forecast, 2009-2014

Figure 1.1: 2014 Projection of Video Services Percentage of Internet Traffic [1]

Worldwide research and development efforts are being conducted to meet the high capacity demand in transport network, mainly for 100 G Ethernet and beyond. The two main issues that need to be identified to increase the data rate to 100 Gb/s per wavelength are [2]:

- Bandwidth expansion

One direct approach to increase the capacity of a system is to increase the transmission bandwidth per wavelength either optically or electronically. In optical communication, there two widely used techniques to increase the capacity of the transmission [2]. The first technique is to extend the bandwidth by adding several optical carriers. This technique has already been studied and deployed and it is known as Wavelength Division Multiplexing (WDM). WDM can help to extend the transmission bandwidth by adding multiple transceivers for the existing optical fiber links without the need to install other fiber links [2]. WDM is considered one of the most cost efficient approaches to increase the optical fiber link throughput [3]. The second technique is to extend the electronic bandwidth per wavelength relying on the CMOS technology. However, the current digital to analog converters (DAC)/ (ADC) can only support a 6 GHz bandwidth. It is a challenge to realize 100 Gb/s transmission in a cost effective manner [4] [5]. But, recently DAC/ADC achieved more than 30 GS/s with more than a 20 GHz analog bandwidth. This can support a 100 Gb/s transmission [6].

- Enhancing the spectral efficiency

In optical communications, the spectral efficiency, which is the information capacity per unit bandwidth, is the most important figure of merit. Currently, optical networks use intensity modulation and direct detection for transmission, and also use binary modulation to reduce the transceiver complexity. However, with binary modulation, the spectral efficiency will not exceed 1 bits/s/Hz [7]. Recently, many advanced modulation formats in signal amplitude, phase, and polarization have been investigated to increase the capacity of the system. Coherent detection when combined with the advance modulation technique can easily reach the spectral efficiency of several bits/s/Hz [8]. One of these advanced techniques is the optical OFDM. The research on it can be traced back 20 years [9]. Optical OFDM received great attention after it was proposed as a modulation technique for the long-haul transmission in both direct and coherent detection. The integration between OFDM and coherent optical communication brings two main benefits to communication systems [10]. The coherent system brings linearity to the OFDM in both RF to optical up conversion and optical to RF down conversion [11]. The OFDM provides the coherent system with high spectral efficiency and simple channel and phase estimation.

Coherent Optical OFDM (CO-OFDM) is the next generation technology for optical communications since it integrates the advantages of both coherent systems and OFDM systems. CO-OFDM can utilize a high bandwidth and high spectral efficiency [12]. The CO-OFDM system has the ability to overcome many optical fiber restrictions such as chromatic dispersion (CD) and polarization mode dispersion (PMD) [12-14].

Moreover the system is resistant to inter-symbol interference (ISI) because of the cyclic prefix code.

1.2 Problem Statement

As mentioned previously, the growth in internet traffic which includes data, voice, and video services, has driven the increased demand for bandwidth and high data rates. The OFDM system can provide a high spectral efficiency to the system and the coherent optical system can enhance the receiver sensitivity. CO-OFDM is the solution for long-haul transmission because of its tolerance to the CD and PMD issues. In addition, WDM system is proposed as a solution to maximize bandwidth usage, increase the capacity of the system, prevent any cross-talking in a single fiber, and increase the data rate of the system.

1.3 Thesis Objectives

The first objective of this research is to investigate the integration of the coherent optical system and OFDM for one user. The second objective is to investigate and simulate the CO-OFDM for long-haul transmission over 6000 km for a single user using the OptiSystem simulation tool v.12. The third objective is to investigate and simulate the CO-OFDM with the WDM system over a long-haul transmission over 6000 km to increase the overall data rate to up to 1 Tb/s. Also, it is to analyze the CO-OFDM WDM long-haul system by studying the constellation diagram of the system. Finally, it is to analyze and the study the system in terms of Bit-Error-Rate (BER), the effect of the

transmission distance on the Optical-Signal-to-Noise-Ratio (OSNR), and the relation of BER and OSNR with regard to the transmission distance.

1.4 Scopes of Thesis

The scopes of the thesis are:

1. a literature study of the basic principles of a fiber optics communication system, the OFDM system, and the WDM system;
2. to investigate, design, and simulate the CO-OFDM system for the long-haul transmission for a single user and for the WDM system using OptiSystem simulation tool v.12;
3. analyze and the study the system in terms of Bit-Error-Rate (BER), the effect of the transmission distance on the Optical-Signal-to-Noise-Ratio (OSNR), and the relation of BER to OSNR regarding the transmission distance.

1.5 Methodology

The OptiSystem simulation tool v.12 is used to build the models of the CO-OFDM for a single user and for the WDM system. It is also used to build models for a long-haul transmission system. In addition, it used to fully analyze and study the system performance in terms of Bit-Error-Rate (BER), and the effect of the transmission distance on the Optical-Signal-to-Noise-Ratio (OSNR). The thesis methodology is described in Figure 1.2.

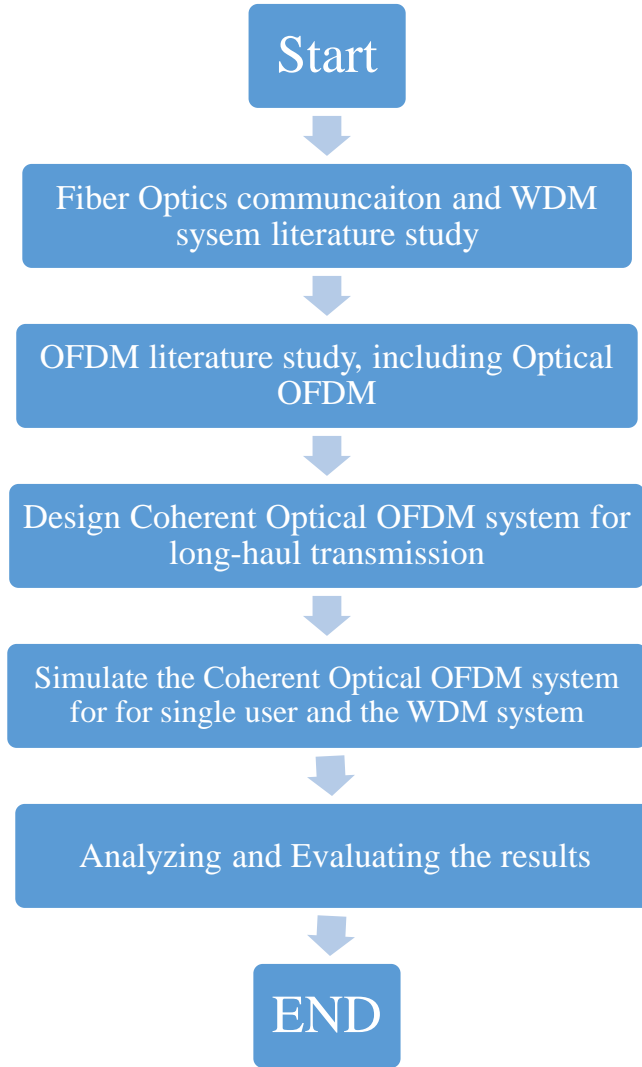


Figure 1.2: Thesis Flow Chart

1.6 Thesis Outline

This thesis is comprised of five chapters which are organized as follows:

Chapter 1 presents the introduction which consists of the research overview, problem statement, objectives, methodology, and finally, the thesis structure;

Chapter 2 presents the literature review of the fiber-optics communication systems. This chapter explains the optical transmission link and the problems that can be faced such as linear and nonlinear impairments, and the solution for such problems. It also illustrates the optical modulation and the WDM system;

Chapter 3 presents the literature review of Orthogonal Frequency Division Multiplexing (OFDM). This chapter consists of a background history of the OFDM, basic principles of the OFDM system, an explanation of optical OFDM including direct and coherent detection, and a comparison between direct and coherent optical OFDM;

Chapter 4 discusses the methodology of this thesis in terms of integrating OFDM with an optical coherent for long-haul transmission. Also discussed is the integration of the coherent optical OFDM with the WDM system to reach significantly high data rates. The OptiSystem simulation tool v.12 is used to fully implement and simulate the system. In addition, this chapter discusses the simulation results and the analysis of the proposed system;

Chapter 5 provides the conclusion of the whole thesis and the future works needed to develop and improve the system.

Chapter Two: Fiber-Optic Communication

Optical fiber communication is like any other communication system. It consists of three main components which are a transmitter, a receiver, and a communication channel. The difference between the fiber-optic communication system and other communication systems is the communication channel is an optical fiber and the optical the transmitter and the receiver are designed to meet the requirements of this communication channel Figure 2.1 [15]. The communication system can be classified as a long-haul > 100 km and a short-haul < 50 km system. However, the fiber-optic communication technology is driven by long-haul applications because of its high data rates.

The main purpose of the optical communication channel is to transmit the signal without distortion and with small loss. The optical fiber can transmit the lightwave with loss (attenuation) equal to 0.2dB/km. However, for long haul applications, the fiber loss (attenuation) increases every 100 km by 1%. So, in the design of an optical fiber, the fiber loss (attenuation) must be considered to determine the space between repeaters or amplifiers for the system.

Another optical fiber drawback that must be considered in the design of the system is the fiber dispersion. This leads to the light pulse broadening while it travels

along the fiber and makes it overlap with the closer pulses. Eventually, this will make it hard to recover the original signal accurately [15]. The fiber dispersion can occur in a severe way in the multimode fiber but less in the case of a single mode fiber, which makes the single mode fiber more suitable for the communication systems design, especially for the long-haul applications [16].

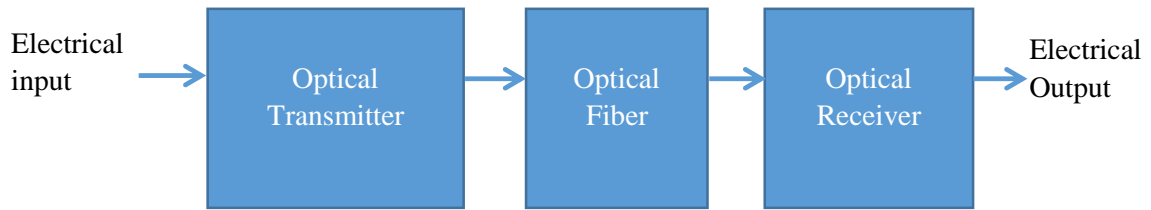


Figure 2.1: Optical Communication System

The main purpose of the optical transmitter is to convert the electrical signal to an optical signal and to launch the resulting signal into the optical fiber. The optical transmitter consists of an optical source and an optical modulator as shown in Figure 2.2. The optical source can be a laser-emitting diode (LED) and the optical modulator can be direct or external modulator. An example of external modulator is a Mach-Zehnder modulator [16].

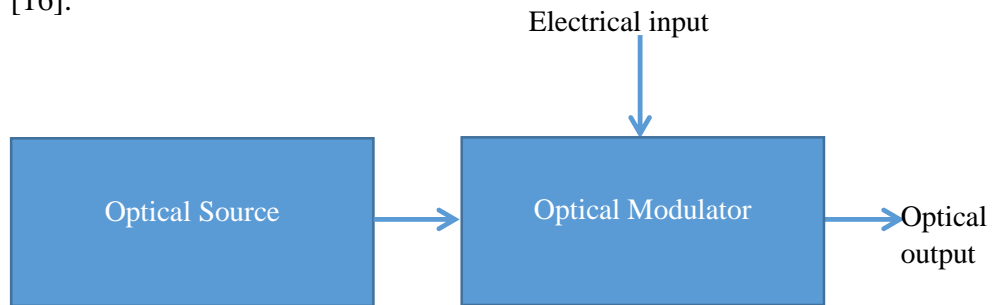


Figure 2.2: Optical Transmitter

The main purpose of the optical receiver is to detect the signal and convert the received signal from optical back to electrical. The optical receiver consists of a photodiode, which converts the optical signal to electrical, and an electrical demodulator, which extracts the original electrical signal that was sent, as shown in Figure 2.3 [16].

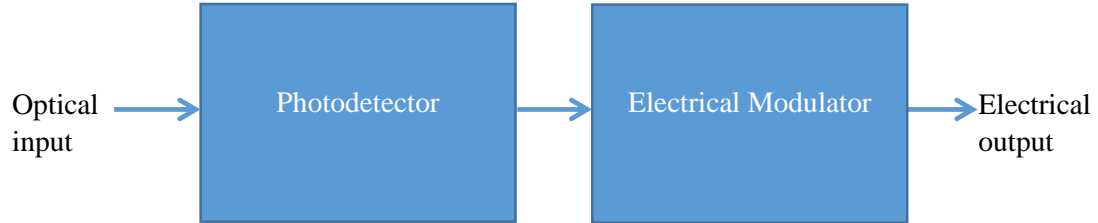


Figure 2.3: Optical Receiver

2.1 Fiber Attenuation

Attenuation, also known as fiber loss, transmission loss, and power loss, means the reduction of the intensity of the light or the light power as it travels along the fiber. An attenuation unit is dB/km and, in an optical fiber, the main cause of attenuation is scattering and absorption. Attenuation can be expressed as the ratio of input optical power and output optical power after L length of optical fiber. This ratio is a function of wavelength and can be expressed as [16]:

$$\alpha = \frac{10}{L} \log \left(\frac{P_{out}}{P_{in}} \right) \quad (2.1)$$

2.1.1 Absorption

As mentioned above, the main cause of attenuation is scattering and absorption. The main absorption factor in fiber is the presence of impurities in the fiber material such as OH ions (water). These ions enter the fiber either during the chemical manufacturing process or from the environmental humidity [15]. High levels of OH ions occur at 725,

950, 1240 and 1380 nm which will lead to large absorption peaks (water peak) [15]. The low absorption regions are between these wavelengths. For standard single-mode fiber, at 1310 nm, the attenuation is 0.4dB/km and, at 1550nm, the attenuation is 0.25dB/km. Both frequencies lie at the low water peak regions. However, for standard single-mode fiber at around 1440nm, the E-band water molecules cause high attenuation (high water peak) as shown in Figure 2.4 [15]. In past years, fiber manufactures worked to produce a low-water-peak-fiber to minimize the water peak area especially at the E-band (1360-1460 nm).

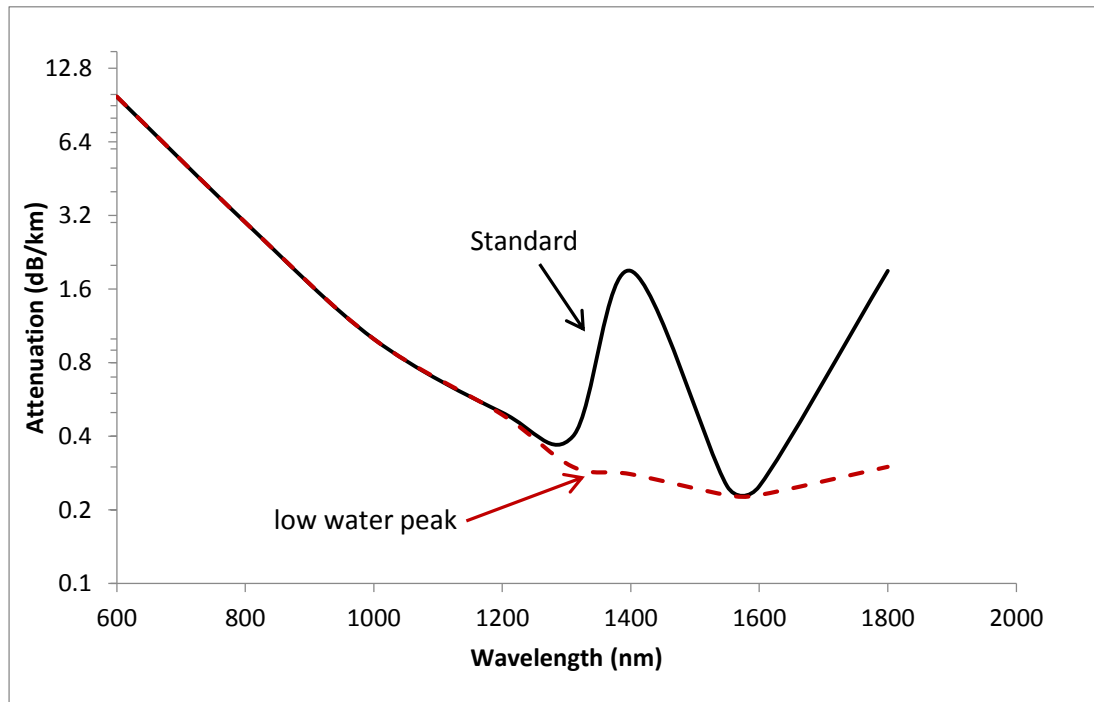


Figure 2.4: Relationship of Attenuation and Wavelength for Standard Fiber and Low-Water-Peak Fiber.

2.1.2 Rayleigh-Scattering

Scattering losses occurs from material density microscopically variations, compositional fluctuations, and from defects during fiber producing process [15,17]. The collision between the light wave and the molecules of the fiber will result in the escape of the light from the fiber waveguide or in it reflecting back to the source. This is known as scattering [15,17]. Rayleigh-scattering in glass is the same principle as the Rayleigh-scattering of sunlight in the atmosphere which causes the sky to appear blue. It is hard to have accurate calculations for attenuation caused by the scattering because of the random molecular nature of glass. But it can be approximated using equation 2.2 for a specific wavelength (λ) [15].

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_T \quad (2.2)$$

where n is the refractive index, k_B is the Boltzmann's constant, p is the photoelastic coefficient, T_f is the fictive temperature, and β_T isothermal compressibility.

2.2 Fiber Dispersion

Fiber dispersion is the broadening of the light pulse while it travels along the fiber. This will lead the pulse to overlap with the closer pulses and eventually make it hard to recover the original signal accurately [15]. There are different types of signal dispersion that can occur during the transmission of a signal such as Intermodal dispersion, Intramodal dispersion (chromatic dispersion), and polarization-mode dispersion [16].

2.2.1 Intermodal Dispersion

Intermodal dispersion or modal delay appears because each mode of the signal at a single frequency has a different group velocity value as the signal travels through the fiber [15]. This difference in group velocities will cause the signal to broaden and will lead eventually to signal distortion [16]. Intermodal dispersion increases as the length of the fiber increases and it appears only in multimode fibers because the single-mode fiber has only one mode.

2.2.2 Chromatic Dispersion (Intramodal Dispersion)

Chromatic dispersion is the pulse broadening that happens in a single mode. The main cause for this broadening is the finite spectral width of the optical source. Chromatic dispersion depends on the wavelength and therefore increases with the spectral width of the optical source [15,16]. There two causes for chromatic dispersion: material dispersion and waveguide dispersion. Chromatic dispersion can be defined as [15]:

$$D = \frac{1}{L} \frac{d\tau_g}{d\lambda} = \frac{d}{d\lambda} \left(\frac{1}{V_g} \right) = - \frac{2\pi c}{\lambda^2} \beta_2 \quad (2.3)$$

where D is the dispersion, L is the pulse traveling distance, $\frac{d\tau_g}{d\lambda}$ is the delay difference per wavelength to propagate the distance L , V_g is the group velocity, c is the speed of light, and β_2 is the GVD (Group Velocity Dispersion) parameter. It is $\beta_2 = \frac{d^2\beta}{d\omega^2}$ where β is the wave propagation constant and the ω is the angular frequency [15].

2.2.2.1 Material Dispersion

Material dispersion arises as a result of the variation of the refractive index of the core material of a fiber with the change of the optical wavelength. The main cause of material dispersion is that the index of refraction is a function of the wavelength [15-17]. Figure 2.5 shows that the index of refraction of the core material of a fiber is a function of wavelength and its variation decreases as the wavelength increases [15-17].

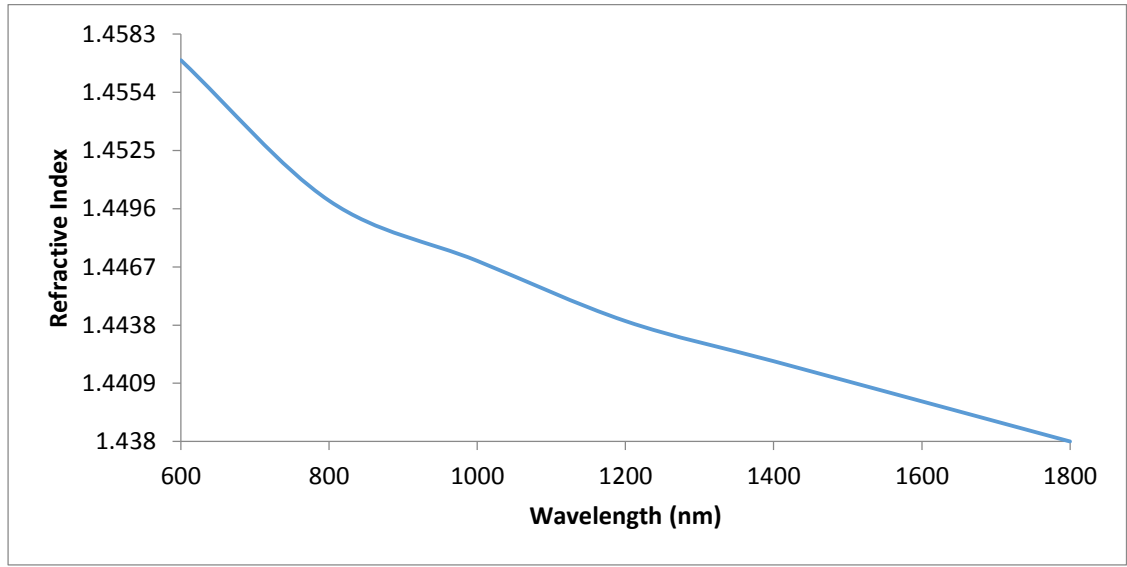


Figure 2.5: Variation of Refractive Index as a Function of Wavelength

Material dispersion can be defined as [15]:

$$|D_{mat}| = \frac{\lambda}{c} \left| \frac{d^2 n}{d\lambda^2} \right| \quad (2.4)$$

where D_{mat} is the material dispersion and n is the refractive index of the core [15].

2.2.2.2 Waveguide Dispersion

Waveguide dispersion is another is a type of chromatic dispersion. It is the material dispersion that will cause the spreading of the signal. However, waveguide dispersion depends on the fiber core diameter and it causes signals of different wavelengths to travel at different velocities which will spread the pulse and make it overlap with neighboring pulses [15, 16]. Waveguide dispersion can be defined as [17]:

$$D_{wg} = -\frac{n_1 \lambda \Delta}{c} \frac{d^2 b}{d\lambda^2} \quad (2.5)$$

2.2.3 Polarization-Mode Dispersion (PMD)

Polarization mode dispersion is caused by a fiber birefringence which affects the polarization state of the optical signal and causes a pulse broadening [15]. Many factors can cause fiber birefringence such as: imperfections from the manufacturing process, the bending or twisting of the fiber, or weather conditions [15-17]. At specific wavelengths, signal energy takes two polarization modes and, because of the birefringence along the fiber, the two polarization modes will travel with different velocities. The difference of propagation time $\Delta\tau_{PMD}$ between the two polarization modes will produce pulse spreading [15].

$$\Delta\tau_{PMD} = \left| \frac{L}{V_{gx}} - \frac{L}{V_{gy}} \right| \quad (2.6)$$

where L is the distance that the pulse travels, and the group velocities of the two polarization modes are V_{gx} and V_{gy} . The polarization-mode dispersion can be calculated by [15]:

$$D_{PMD} \approx \frac{\Delta\tau_{PMD}}{\sqrt{L}} \quad (2.7)$$

2.3 Fiber Nonlinear Impairments

The fiber dispersion is a major factor that can degrade the optical signal and affect the transmission. However, it is not the only factor. The optical signal can be subject to fiber nonlinearity which can affect the transmission. Fiber nonlinear impairments can be divided into two types: the Kerr nonlinearity and the stimulated elastic scattering process. The Kerr nonlinearity comes from the fiber refractive index which is dependent on the intensity of the propagated signal. This can be defined as [18]:

$$r(\omega, |E|^2) = n(\omega) + n_2 |E|^2 \quad (2.8)$$

where the nonlinear index coefficient is n_2 , and ω is the angular frequency. The kerr nonlinearity is comprised of three important nonlinear effects: Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM) [18]. The second type, the stimulated elastic scattering, helps the energy transfer from the optical field to the medium. It includes two types: Stimulated Raman Scattering (SRS), and Stimulated Brillouin Scattering (SBS) [18].

2.3.1 Self-Phase Modulation (SPM)

SPM mostly takes place during the propagation of an ultra-short pulse through the single mode fiber, and will produce a varying medium refractive index. Due to this variation, phase shift on the pulse will occur. This will lead to a change in the pulse's frequency spectrum. The nonlinear phase shift is proportional to the optical intensity and given by [19]:

$$\phi_{NL}(l, T) = n_2 k_0 l |E(l, T)|^2 \quad (2.9)$$

where ϕ_{NL} is the nonlinear phase shift, n_2 is the kerr coefficient (nonlinear refractive index), l is the length of the fiber, $E(l, T)$ is the electrical field at l distance, and $k_0 = \frac{2\pi}{\lambda_0}$, where λ_0 is the wavelength of the signal. SPM does not change the shape of the optical pulses but broadens the optical pulses spectrum. This broadening will generate a frequency chirp which will add a new frequency to the pulse [19].

2.3.2 Cross-Phase Modulation (XPM)

XPM is similar in behavior to SPM, but it occurs when two or more optical pulses affect the phase and intensity of each other while broadening. When two optical fields, E_1 at frequency ω_1 and E_2 at frequency ω_2 , propagate through the fiber at the same time, the nonlinear phase shift is given by [20]:

$$\phi_{NL}(l, T) = n_2 k_0 l (|E_1|^2 + |E_2|^2) \quad (2.10)$$

2.3.3 Four-Wave Mixing (FWM)

FWM takes place when three wavelengths interfere with each other producing refractive index gratings. The gratings will interact with the signals and result in new frequencies, producing the fourth wavelength [19].

2.3.4 Stimulated Raman Scattering (SRS)

SRS occurs when the molecules vibrate and get excited by the light particles travelling through a single mode fiber. As a result, the light particles will be scattered, which is known as SRS. This can happen in both forward and backward directions [20].

2.3.5 Stimulated Brillouin Scattering (SBS)

SBS happens when the optical input power in the optical fiber is high. It generates a beam of light that propagates in the backward direction. Practically, the SBS effect is negligible when the input power is low but it becomes significant with high input power [20].

2.4 Dispersion Compensation

Optical amplifiers solve the problem of attenuation in the fiber but it makes the fiber dispersion worse. However, fiber dispersion can be compensated by different techniques such as: Dispersion Compensation Fiber (DCF), Fiber Bragg Grating (FBG), and Chirped FBG [16, 17, 21]. These techniques help control the dispersion and extend the transmission distance. The following sections describe these techniques.

2.4.1 Dispersion Compensation Fiber (DCF)

The demand of high data rates and long transmission distance in optical communication require compensation of the chromatic dispersion in the optical fiber. One of the techniques to compensate dispersion is the Dispersion Compensation Fiber (DCF). DCF is an effective technique to overcome the fiber dispersion because of its cost effectiveness and temperature stability [16, 17]. DCF can be designed to compensate for the dispersion of an optical fiber. This is by utilizing negative dispersion coefficients that can reach up to -80 ps/nm to cancel the positive dispersion coefficients of the fiber.

DCF can balance the dispersion for the single bands which are S-band (1460-1530 nm), C-band (1530-1565 nm), and L-band (1565-1625nm). It is not effective, however, for the lower band (the E-band (1360-1460nm)). DCF has one disadvantage. It has a higher attenuation than the single mode fiber (SMF) which will produce high insertion loss to the system [21]. One way to overcome this disadvantage is to increase the signal power. However, increasing the signal power will increase the nonlinear impairments of the system and will lead to signal distortion. Therefore, increasing the power can be acceptable in only a limited way [15].

2.4.2 Fiber Bragg Grating

As previously mentioned, DCFs suffer from high insertion loss to the system and from enhancing nonlinear impairments for the long haul communication systems. These issues can be solved by using Fiber Bragg Grating (FBG) for dispersion compensation [16,22]. FBG is a structure that when placed in the optical fiber will affect the refraction

index of the core to change periodically. Therefore, specific wavelengths will be transmitted and all others will be reflected [22]. Any light with a wavelength that satisfies the Bragg condition will be reflected. Therefore, FBG can be considered an optical filter. FBG as a filter has many advantages such as low loss, sensitivity to the polarization of the light, and cost effectiveness [22].

FBGs are used widely in the WDM systems and also can be used as tunable filters. Moreover, FBGs can be used for remote monitoring and as laser diode filters [17].

The Bragg condition occurs at reflection wavelength λ_{Bragg} [15]:

$$\lambda_{Bragg} = 2\Lambda n_{eff} \quad (2.11)$$

where n_{eff} is the core effective index.

The maximum reflectivity R_{max} occurs at the reflection wavelength:

$$R_{max} = \tanh^2(kL) \quad (2.12)$$

where L is the grating length and k is the coupling coefficient.

k is given by:

$$k = \frac{\pi \delta n \eta}{\lambda_{Bragg}} \quad (2.13)$$

where η is the optical fiber fraction in the core and can be approximated by:

$$\eta \approx 1 - V^2 \quad (2.14)$$

2.4.3 Chirped Fiber Bragg Grating (CFBG)

Because of CFBG low insertion loss, low nonlinear effects, and its low cost, it is widely used to compensate the chromatic dispersion of the optical fiber and for power loss reduction. CFBG is like the FBG in the structure but it takes different forms and different periods over the length of the grating. CFBG can be symmetrical, linear chirp, or quadratic chirp [23]. In CFBG, different wavelengths can be reflected by different parts of the grating along the fiber and, therefore, can have a different time delay. Thus, the input signal can be affected by this delay to compensate the dispersion that occurred along the fiber [23,24].

2.5 Optical Modulation

To design an optical communication system, the first thing to consider is how to convert the electrical signal to an optical signal. To convert the electrical signal to an optical signal, an optical modulator is needed which can be a direct or an external modulator.

2.5.1 Direct Modulation

Direct modulation occurs when the electrical information stream varies the laser current directly to produce a different optical power as shown in Figure 2.6. Therefore, it will lead the laser to turn on and off and create 1 and 0 bits [15-17]. Direct modulation is suitable for data rates of 2.5 Gbits or less.

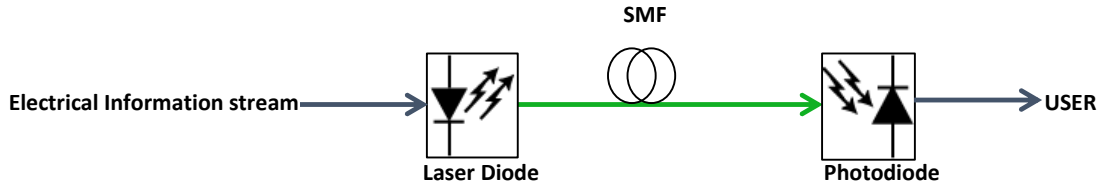


Figure 2.6: Direct Modulation

The main limitation of direct modulation is the broadening in the line width of the laser because of the laser on and off process. This results from the electrical signal that drives the laser source. The broadening of the line width is called *chirp*, and it will lead to degradation in the system performance. Therefore, direct modulation is not suitable for data rates greater than 2.5 Gbits [15,16].

2.5.2 External Modulation

In external modulation, the laser source emits a constant amplitude signal that enters the external modulator such as a Mach-Zehnder modulator (MZM) as shown in Figure 2.7 [15,17]. The electrical signal then enters the external modulator to change the optical power level that the external modulator will transmit, but not change the amplitude of the light that comes originally from the laser to produce optical signal with time variance [15]. The constant amplitude signal from the laser source will help to avoid the chirp of the pulses which will reduce the dispersion and make this process more effective for systems with high data rates of 10 Gbits/s and greater, and for the long-haul communication systems [15,17].

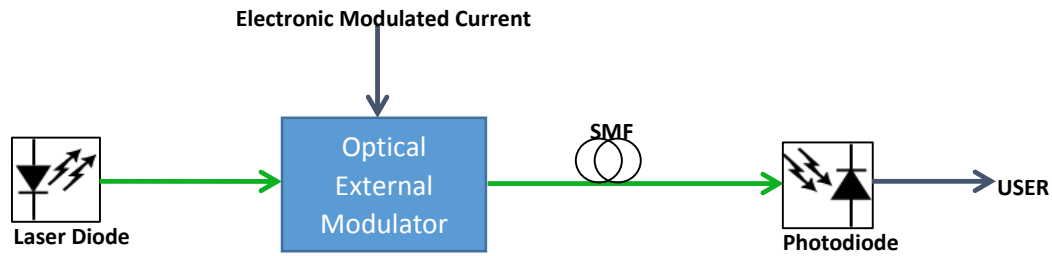


Figure 2.7: Concept of External Modulation

2.6 Wavelength Division Multiplexing (WDM)

The Wavelength Division Multiplexing is an important factor in the development of the optical communications. It has the ability to provide more flexibility to the system and to simplify the design of the network. WDM systems help to enhance the capacity of the system by sending multiple wavelengths over a single fiber [25]. WDM systems provide a significant increase in the data rate that is carried over a single fiber by using multiple wavelengths, where each wavelength carries a separate channel. WDM divides the optical spectrum to smaller channels, which are used to transmit and receive data simultaneously [26].

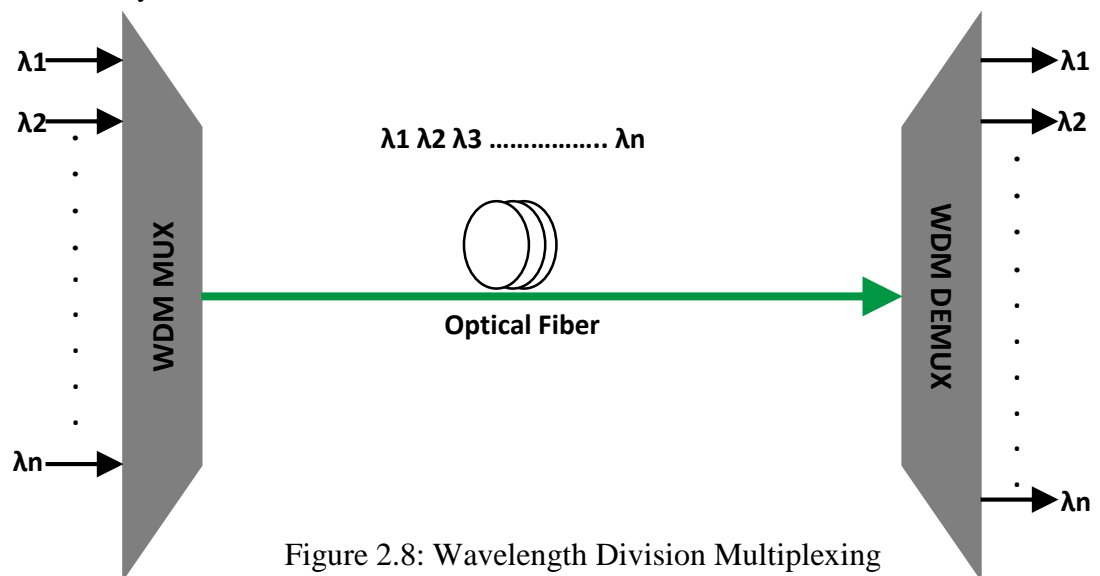


Figure 2.8: Wavelength Division Multiplexing

Figure 2.8 illustrates the optical WDM networks, where wavelength substitutes frequency and each transmitter transmits separated wavelength λ_i , where $i=1,2,3,\dots,N$, to different receivers [25]. For radio broadcasting, this system has the ability to transmit on different frequencies without any interference [26]. WDM systems include two types, Dense Wavelength Division Multiplexing (DWDM) and Coarse Wavelength Division Multiplexing (CWDM).

In Chapter 4 of this thesis the deployment of WDM technology to transmit a long-haul OFDM signal is demonstrated.

2.6.1 Dense Wavelength Division Multiplexing (DWDM)

The solution for the huge demand in capacity in a communication network is the DWDM. Currently, TDM is used to provide internet service to users via cable which restricts the available bandwidth for each user. DWDM connects the users' devices directly to the router which provides greater bandwidth [27]. DWDM can achieve high transmission capacity and distance by minimizing the wavelength spacing. It can reach wavelength spacing of 200-50 GHz (0.4-1.6 nm) in the 1500-1600 nm wavelength area which makes it facilitates 32 to 128 channels per single fiber [28].

On the other hand, temperature rising during operation is the major disadvantage of DWDM systems as this will lead to a decrease in the efficiency of the system [28]. Therefore, it will need a cooling system which consumes more energy and may lead to an increase in cost.

2.6.2 Coarse Wavelength Division Multiplexing (CWDM)

CWDM is another type of WDM which is a cost effective approach because it does not require temperature control. A CWDM grid typically comprises 18 wavelengths with wavelength spacing of 20-40 nm in the 1260-1670 nm band [29]. CWDM is used for short transmission distances of less than 50 km because it is more cost efficient than the DWDM system [30].

Chapter Three: Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation (MCM) technique which uses many subcarriers to carry the information. The main advantage of the OFDM is its ability to overcome channel dispersion [14]. Also, OFDM has the ability to transmit information with high data rates which has made it popular. OFDM has been used in many different applications in the RF domain such as digital audio broadcasting (DAB), digital video broadcasting (DVB), and wireless local area networking (WLAN) [14, 20]. Even with the powerful advantages of OFDM, it has some drawbacks which can affect its applications. High peak-to-average-ratio is one of the main drawbacks in OFDM. Another drawback is its sensitivity to phase and frequency noise [14].

This chapter will start by presenting the historical background of OFDM and a discussion about the OFDM fundamentals. The fundamentals discussion will include OFDM principle, the cyclic prefix, OFDM spectral efficiency, and IFFT. A discussion about optical OFDM is then presented.

3.1 OFDM Historical Background

The concept of OFDM was first discovered at Bell labs in 1966 as a substitute for the frequency division multiplexing (FDM) technique [20,31]. In 1971, a modified

version of OFDM was proposed by Weinstein and Ebert where Discrete Fourier Transform (DFT) is used instead of the sinusoidal modulators. This reduced the OFDM design complexity and still maintained the subcarriers orthogonal [32].

The cyclic prefix was introduced in 1980 by Peled and Ruiz to mitigate the effect of the inter symbol interference (ISI) [32]. Cyclic prefix is a repetition of the last part of an OFDM symbol to the beginning of that symbol which will help to eliminate the ISI and to allow channel estimation and equalization [33].

In the middle of the 1990's, OFDM was used in a wide range of high data rate communication systems [34]. Over the years, OFDM technique has been considered for many applications and standards for cable or wireless communications. Today, OFDM exists in many wireless standards including wireless LAN IEEE 802.11a/g/n, wireless personal area networks (PAN) IEEE 802.15.3a, wireless metropolitan area networks (MAN) 802.16e (WiMax), and the 4G mobile communication (long-term evolution (LTE)) [14][35]. In addition, it exists in many cable standards such as: ADSL, VDSL, digital video broadcasting (DVB), and ITU-T which is a high speed LAN [14].

The application of OFDM was only used for RF communications. It was first used in optical communications in 1996 by Pan and Green and over the following years there was only spasmodic research on optical OFDM [14]. The main advantage of the OFDM, its ability to overcome optical channel dispersion, was not discovered until 2001 by Dixon et al. [14]. Dixon et al. introduced the use of OFDM in optical communications to compensate the dispersion in multimode fiber (MMF), when they discovered that the

multipath fading in wireless was similar to that in an MMF channel [14]. The credit for the large interest in the optical OFDM actually goes to the proposals of the use of optical OFDM in long haul communications.

OFDM is actually a modified version of Frequency Division Multiplexing (FDM). In the FDM technique, different information for different users is transmitted at the same time over different frequency carriers as shown in Figure 3.1 [36]. At the transmitter, each subcarrier is set with a wide guard band after it is modulated by the user's data to prevent it from overlapping with the adjacent subcarriers. However, this guard band will reduce the spectral efficiency of the system. The received signals at the receiver are then demodulated by oscillator banks [20].

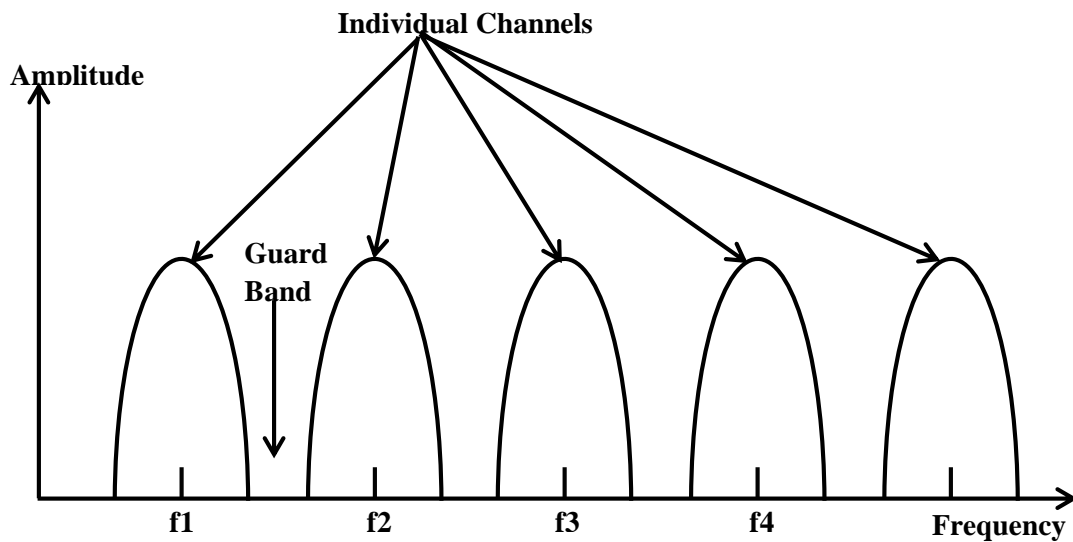


Figure 3.1: FDM Spectral

In the case of the OFDM signal, the use of the Fast Fourier Transform (FFT) and Inverse FFT helps to demodulate and construct the original signal even if there is overlapping between the subcarriers as shown in Figure 3.2 [20, 37, 38].

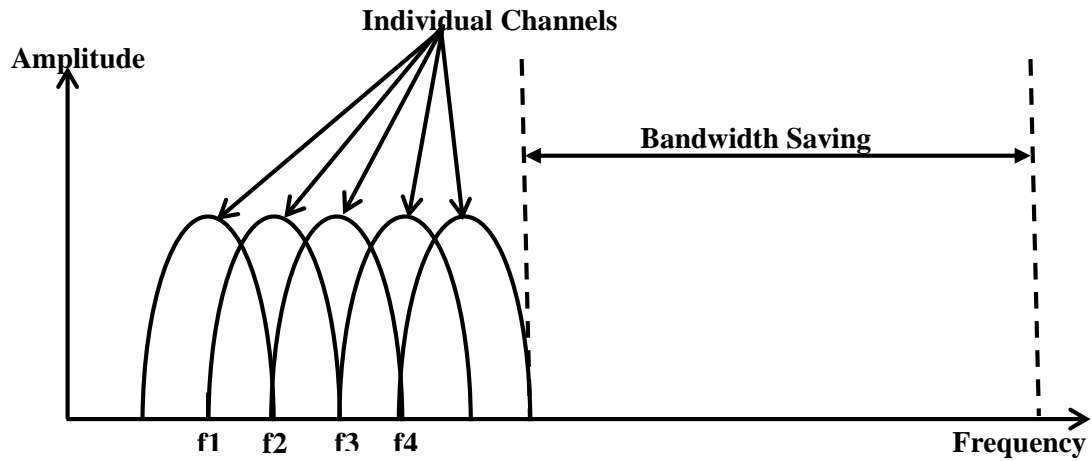


Figure 3.2: OFDM Spectral

3.2 OFDM Modulation Scheme

The OFDM scheme consists of two parts, transmitter and receiver, as shown in Figure 3.3. The transmitter and the receiver consist of number of modules and are illustrated and discussed in detail in this section.

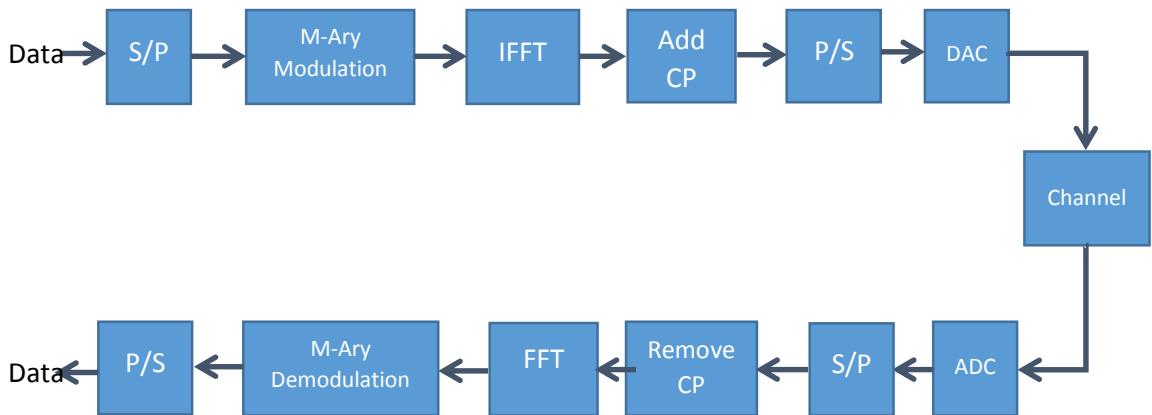


Figure 3.3: OFDM Block Diagram

In the transmitter, the serial input data is first converted to parallel data and mapped by an M-art modulator which could be QAM or PSK. After that, the signal is

processed by IFFT and a guard interval is added to prevent the overlapping between subcarriers. The signal is then sent through the channel after performing a parallel to serial conversion [39].

In the receiver, the received serial data is converted to parallel and the guard interval is removed. It then goes through the FFT operation, and is demodulated using the M-Ary demodulator which could be either QAM or PSK. Finally, the data is converted back to serial to get the original data [40].

3.2.1 Constellation Diagram

A constellation diagram is a two dimensional representation of a signal after it is modulated using digital modulation schemes such as: PSK or QAM. The modulated signal symbols are mapped as points in the complex plane. The y-axis represents the imaginary part of the symbols and the x-axis represents the real part. Constellation diagrams can be used to identify the distortion that occurs in the signal and determine the type of interference. Each different modulation scheme has a different format of constellation diagram. Figure 3.4 shows the constellation diagram of the QPSK modulation. Figure 3.5 shows the constellation diagram of 4-QAM. Figure 3.6 shows the constellation diagram of 8-PSK. Figure 3.7 shows the constellation diagram of 16-QAM.

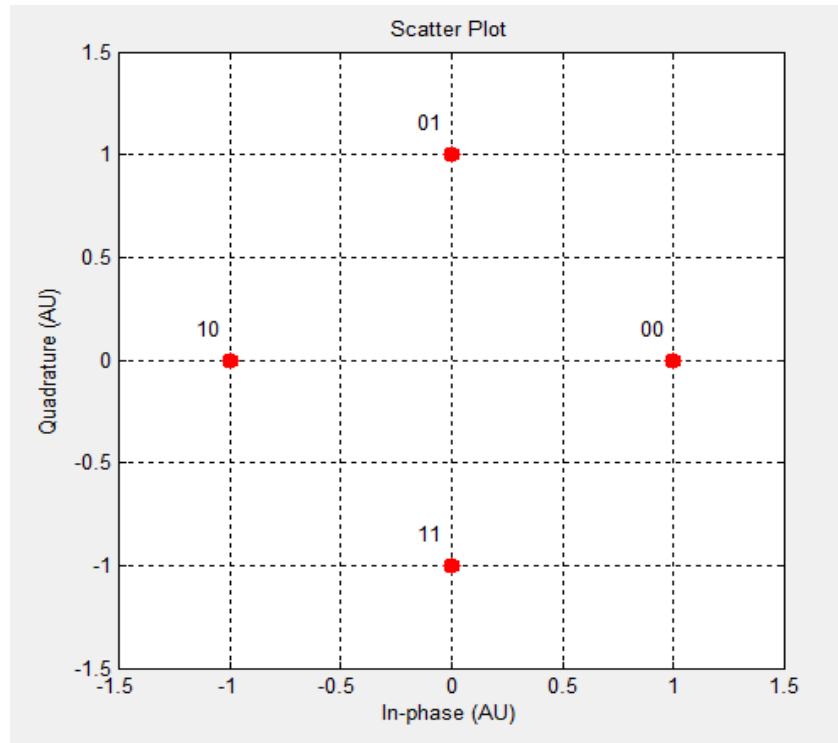


Figure 3.4: QPSK Constellation Diagram

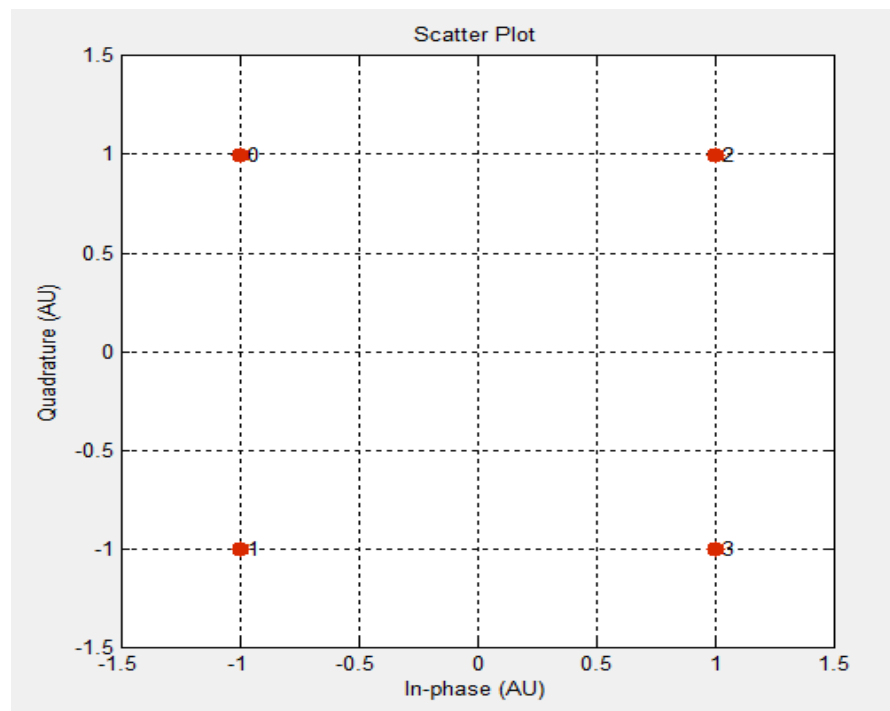


Figure 3.5: 4-QAM Constellation Diagram

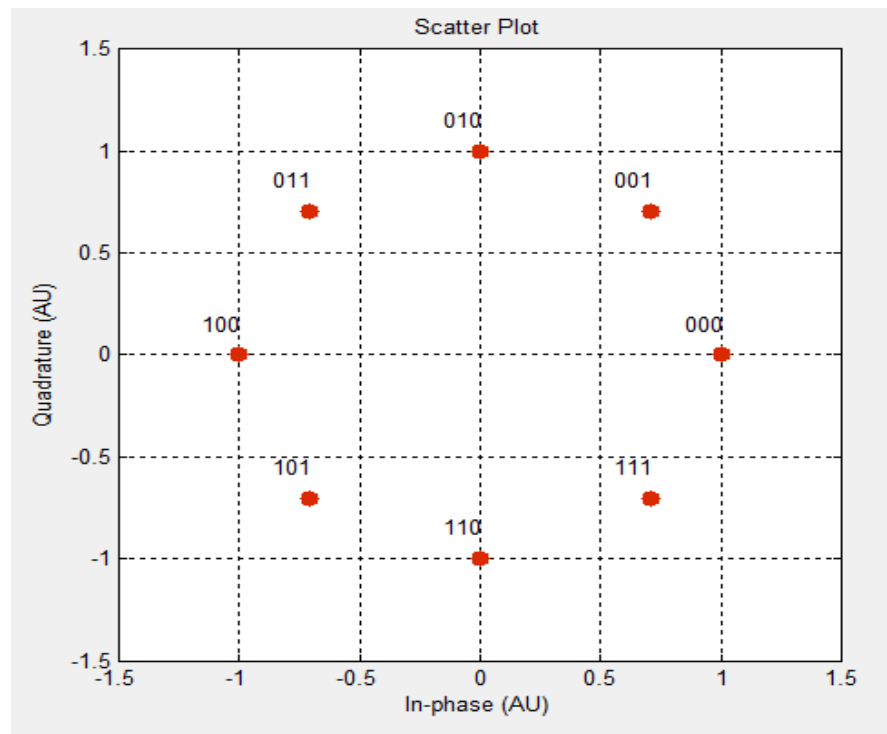


Figure 3.6: 8-PSK Constellation Diagram

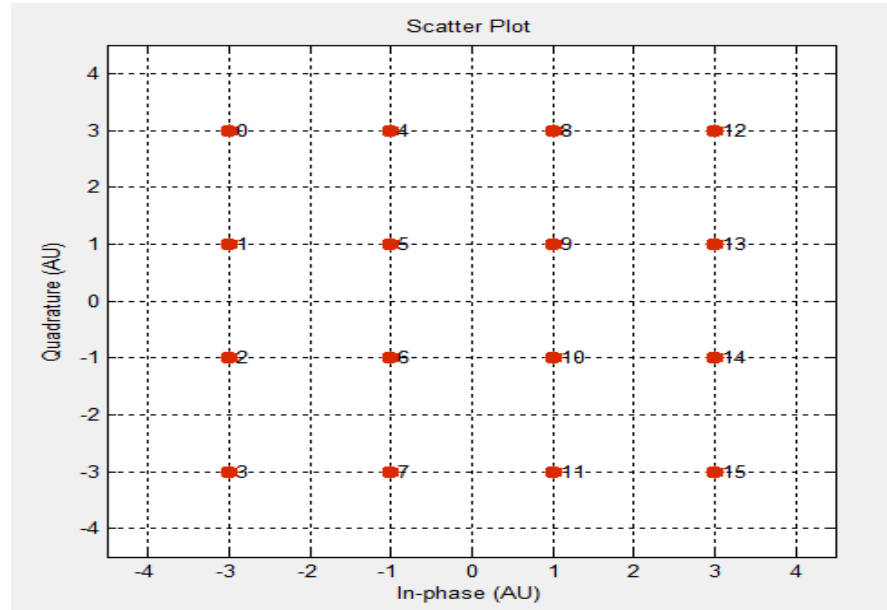


Figure 3.7: 16-QAM Constellation Diagram

3.2.2 Symbol Mapping

In OFDM, the basic function that is usually used is a sinusoidal signal:

$$\phi_n(t) = A(t) \exp(2\pi f_n t) \quad 3.1$$

where f_n is the frequency of the signal, n subcarriers number, and A is the amplitude.

We can rewrite equation 3.1 to be:

$$\phi_n(t) = A(t) \cos(2\pi f_n t) + jA(t) \sin(2\pi f_n t) = I(t) + jQ(t) \quad 3.2$$

where $I(t)$ is the in-phase component and $Q(t)$ is the quadrature component.

Using equation 3.2, the input data is represented by an in-phase and quadrature form. To better illustrate the idea of the I/Q component, take Binary phase shift keying (BPSK) and Quadrature phase shift keying (QPSK) as examples. In the case of BPSK, only one binary value is used each time, so it will have a value of either 0 or 1. The values of the I and Q components are represented in Table 3.1.

Binary	I(t)	Q(t)
0	1	0
1	-1	0

Table 3.1: I/Q Components for BPSK

3.2.3 Serial to Parallel Conversion

After converting the binary values to complex values, the data signals must pass through a serial to a parallel converter to convert them to parallel symbols. These symbols must be arranged into subsets and each subset will carry a number of symbols which is determined by the number of subcarriers.

3.2.4 Inverse Fast Fourier Transform (IFFT)

The use of Inverse Fast Fourier Transform (IFFT) is the advantage of modern OFDM. IFFT has the ability to perform the frequency up converting and the multiplexing of the complex subcarriers in an efficient and accurate way. Furthermore, at the receiver side, the FFT is used for processing the demodulation and the de-multiplexing. So, the core component of the OFDM transceiver is the IFFT/FFT digital process.

The FFT algorithms will ensure the orthogonality of the subcarriers in the OFDM transceivers and will help to avoid any interference. The main point for maintaining orthogonality between subcarriers is to keep the subcarrier center frequency from overlapping with other subcarriers while the subcarrier spectrum overlaps. This will give us overlapped but orthogonal signal sets [41]. This orthogonality occurs from direct correlation between any two subcarriers is given by [14,42]:

$$\frac{1}{T_s} \int_0^{T_s} \exp(j2\pi(f_k - f_l)t) dt = \exp(j2\pi(f_k - f_l)T_s) \frac{\sin(\pi(f_k - f_l)T_s)}{\pi(f_k - f_l)T_s} \quad (3.3)$$

where f_k and f_l are the subcarriers frequencies, and T_s is the symbol period. If the condition:

$$f_k - f_l = m \frac{1}{T_s} \quad (3.4)$$

is satisfied, the two subcarriers are orthogonal to each other. This orthogonality condition will help to recover the signal without Intercarrier Interference (ICI), regardless of the strong overlapping of the signal spectral. Figure 3.8 illustrates power signals where their spectrums are overlapping but their centers are spaced equally.

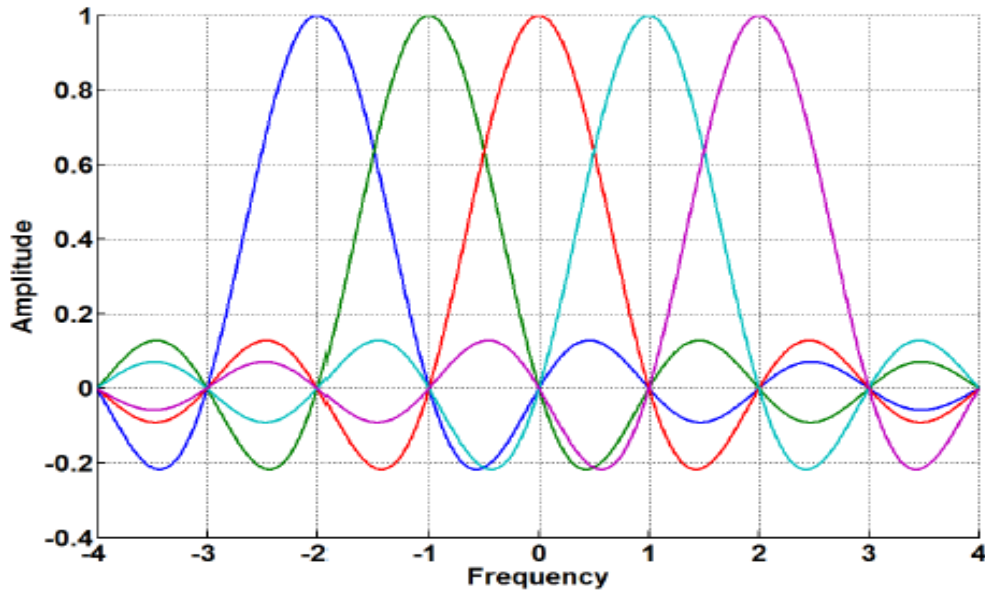


Figure 3.8: OFDM Power Spectrum

3.2.5 Guard Interval

Inserting guard intervals between the OFDM symbols is essential to preventing Inter-symbol Interference (ISI) and maintaining orthogonality. ISI occurs when there is a

delay in the transmitted OFDM symbol, which will cause this symbol to interfere with the next OFDM symbol. The guard intervals provide a period of protection to keep the transmitted OFDM symbol apart from the next OFDM symbol. A guard interval could be zero padding, cyclic prefix, or cyclic suffix.

3.2.6 Cyclic Prefix (CP)

CP is used to reduce the effect of the ISI and to improve the multipath propagation problem robustness. This technique involves copying the last fraction of each OFDM symbol and adding it to the front of the symbol. Figure 3.9 illustrate the concept of CP.

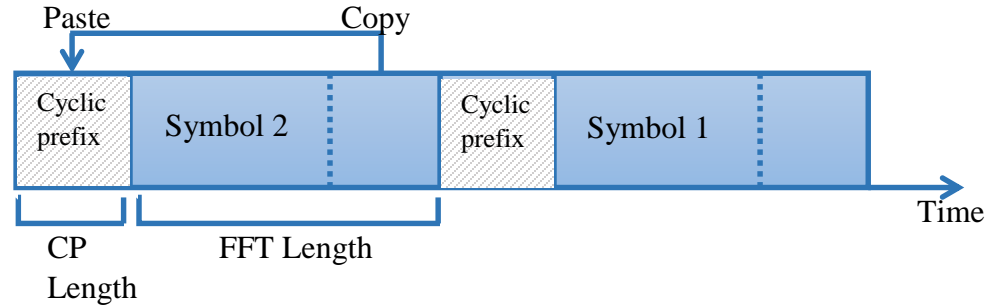


Figure 3.9: OFDM Cyclic Prefix

The CP operator is defined by:

$$\eta = \frac{T_p}{T_s - T_p} \quad (3.5)$$

where the length of the CP is T_p , T_s is the symbol length after adding the CP, and $T_s - T_p$ is the FFT length [20].

The CP length should be selected carefully to maintain the minimum ISI effect. The CP length should be longer or at least the same length as the multipath channel

delay. If the CP length is shorter than the multipath channel delay, the OFDM symbol tail will be affected by the next OFDM symbol head which will cause ISI [43].

After inserting the CP, the OFDM signals pass through a parallel to serial converter to convert the parallel OFDM symbols to serial symbols. After this conversion, the OFDM signals are prepared for the up conversion process.

3.3 OFDM Demodulation

At this stage, assuming a perfect estimation for the receiver is done, the guard interval can be removed. To get the original OFDM signal, the cyclic prefix, which was inserted at the transmitter side, should be removed. CP removal is an easy process as shown in Figure 3.10, where the CP length of T_p should be removed to get the original OFDM symbol.

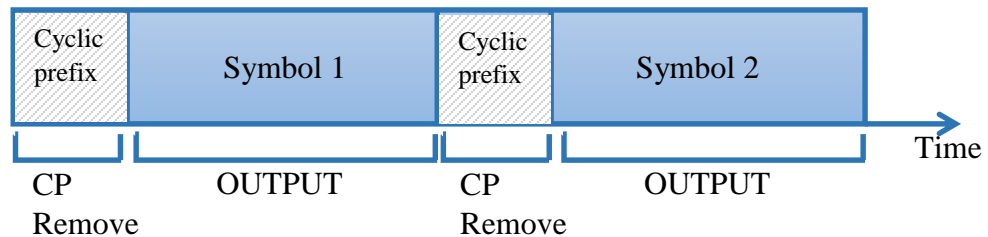


Figure 3.10: OFDM Cyclic Prefix Removal

3.3.1 Fast Fourier Transform (FFT)

After removing the guard intervals, the OFDM symbols are applied to the FFT process to convert the real values to the frequency domain. FFT can recover the subcarriers in one step without the need of a large number of oscillators and filters. After down converting the signal, the digital signal can be represented by:

$$r(k) = \exp\left(j \frac{2\pi k v}{N_{FFT}}\right) \sum_{p=0}^{k-1} h_p s(k - \eta) + n(k) \quad (3.6)$$

where v is the carrier spacing offset, complex gain is represented by h_p , the path time delay is represented by η , and $n(k)$ is the AWGN.

3.3.2 Symbol Demapping

In this stage, the input binary information is recovered. As mentioned previously, the original binary input was mapped to complex-valued signals. Depending on the modulation type of the transmitter, the same input information can be recovered using the same modulation type at the receiver. To illustrate, if the binary input is modulated using 4-QAM, there are four complex valued signals on the constellation diagram. Thus, before the demapping stage, the received signal will have four complex valued signals. The received signal will have some noise and will not be the exactly the same as the transmitted signal, due to equalization errors and phase shift.

3.4 Optical OFDM

Having discussed the general blocks of OFDM system in the previous sections, optical OFDM is being discussed in this section. OFDM was introduced to optical domain in 2005, and has since been studied and investigated in two main techniques classified according to the detection scheme [14]. The first technique is the direct detection optical OFDM (DD-OOOFDM) and the second technique is the coherent optical OFDM (CO-OFDM).

3.4.1 DD-OOOFDM

Figure 3.11 shows the block diagram of the DD-OOOFDM system which consists of a DD-OOOFDM transmitter, optical fiber link, and DD-OOOFDM receiver.

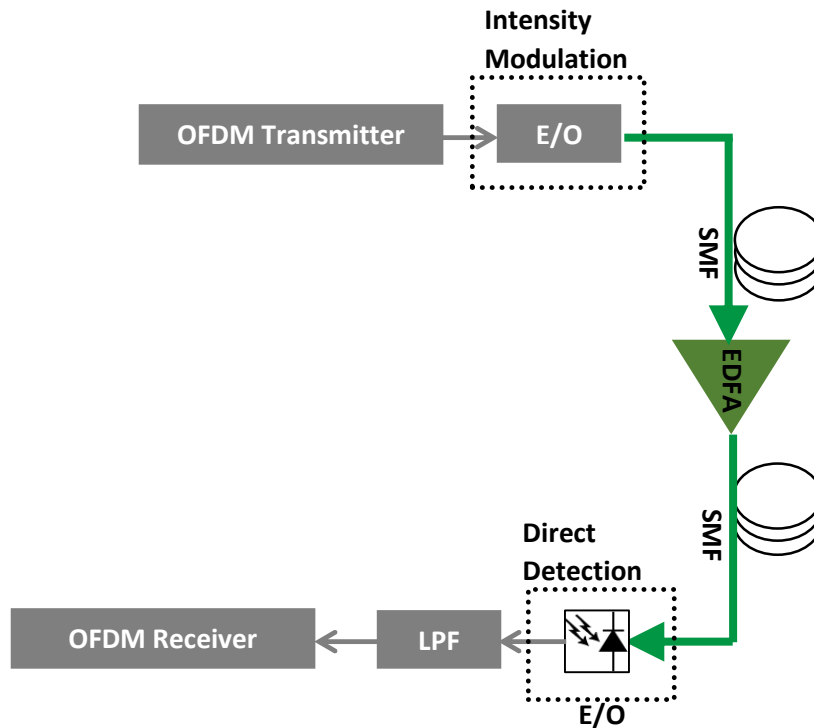


Figure 3.11: DD-OOOFDM Block Diagram

At the transmitter, the OFDM transmitter produces the electrical OFDM signal which is up converted into the optical domain by the electrical to optical (E/O) up converter which does intensity modulation. The resulting optical signal is transmitted through the optical fiber link and an EDFA is used to compensate for the loss in the fiber. At the receiver, the incoming optical signal is converted to the electrical domain by an optical to electrical (O/E) converter, which is in this case a photodiode [44]. The received electrical signal is given by:

$$A_e(t) = |A_0(t)|^2 \otimes h_e(t) + w(t) \quad (3.7)$$

where $A_e(t)$ is the electrical signal received, the optical OFDM signal is $A_0(t)$, the impulse response in the electrical domain for the link is $h_e(t)$, and the system noise is $w(t)$. After down converting the signal, it passes through a low-pass filter (LPF) and is transmitted to the OFDM receiver to get the original signal.

3.4.2 Coherent Optical OFDM (CO-OFDM)

Figure 3.12 shows the block diagram of CO-OFDM system. As can be seen from the figure, the CO-OFDM system is similar to the DD-OFDM system except for the real/imaginary (I/Q) modulator and the local oscillator. An optical local oscillator is used in optical coherent systems to generate optical signals at specific wavelengths. According to the frequency of the local oscillator, the optical coherent detection can be classified into two categories, heterodyne detection and homodyne detection.

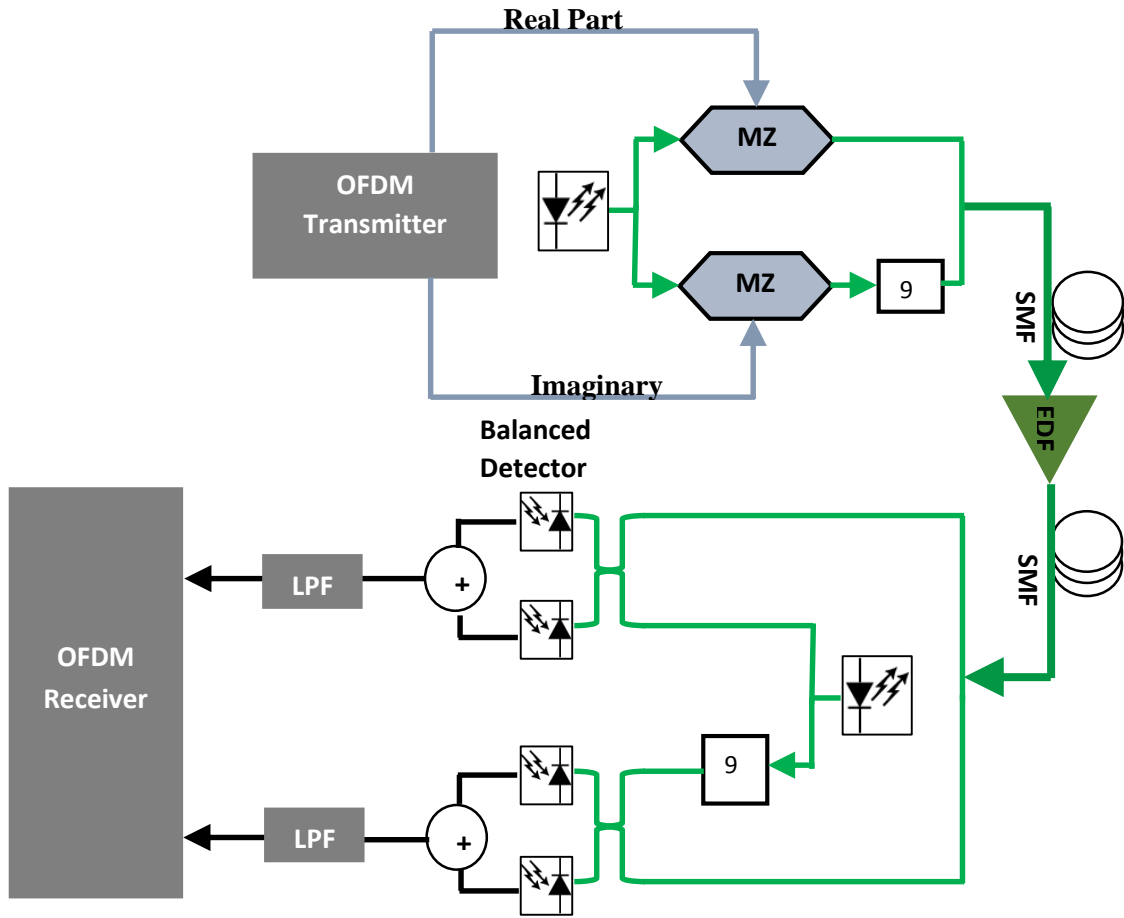


Figure 3.12: CO-OFDM Block Diagram

Heterodyne detection is where the local oscillator frequency does not match the incoming signal frequency. At the photodiode, when the two signals are mixed, a new frequency is generated. The new frequency is an intermediate frequency (IF) which is the difference between the two frequencies [45]. This technique will reduce the thermal noise and the shot noise which will lead to improved SNR performance. However, the optical source frequency tends to drift over time. As a result, the IF has to be regularly

monitored, and the local oscillator must be changed correspondingly to maintain the IF constant.

Homodyne detection, which is used in this research, is where the local oscillator frequency is the same as the incoming signal.

The other additional component in the optical coherent system is the I/Q modulator. The I/Q components of the digital signal are converted to an analogue signal by two DACs at the OFDM transmitter. The I/Q modulator, which consists of two Mach-Zehnder modulators (MZMs), up converts the complex OFDM signal (I/Q components) to the optical domain. As a result, the modulated signal can be written as:

$$E(t) = x(t)\exp(j\omega_{LD1}t + \phi_{LD1}) \quad (3.8)$$

where $x(t)$ is the transmitted electrical signal, ω, ϕ respectively are the angular frequency, and the phase of the transmitter laser diode. The signal at the receiver is represented by:

$$E_r(t) = E(t) \otimes h(t) + w(t) \quad (3.9)$$

where $h(t)$ is the channel impulse response and $w(t)$ is the channel noise. The incoming signal is detected by two identical pairs of balanced coherent detectors and an optical 90° hybrid to perform the I/Q optical to electrical conversion. Each detector consists of two couplers and two PIN photodiodes. The output of the four 90° optical hybrid ports is given by [46]:

$$E_1 = \frac{1}{\sqrt{2}}[E_r + E_{LD2}] \quad (3.10)$$

$$E_2 = \frac{1}{\sqrt{2}}[E_r - E_{LD2}] \quad (3.11)$$

$$E_3 = \frac{1}{\sqrt{2}}[E_r - jE_{LD2}] \quad (3.12)$$

$$E_4 = \frac{1}{\sqrt{2}}[E_r + jE_{LD2}] \quad (3.13)$$

where E_{LD2} is the electrical signal from the local oscillator at the receiver. In addition, as can be seen from Figure 3.12, two photodiodes (PD₁ and PD₂) are used to recover the I component which can be represented by:

$$I_1 = |E_1|^2 = \frac{1}{2}[|E_r|^2 + |E_{LD2}|^2 + 2\text{Re}(E_r E_{LD2}^*)] \quad (3.14)$$

$$I_2 = |E_2|^2 = \frac{1}{2}[|E_r|^2 + |E_{LD2}|^2 - 2\text{Re}(E_r E_{LD2}^*)] \quad (3.15)$$

where the real component is represented by Re. The photocurrent of the real components can be represented by [42]:

$$I_I(t) = I_1 - I_2 = 2\text{Re}(E_r E_{LD2}^*) \quad (3.16)$$

The noise $w(t)$ is suppressed because of the balanced detection which is the main advantage of the coherent detection.

Similar to the I component, two photodiodes (PD₃ and PD₄) are used to recover the Q component which can be represented by:

$$I_Q(t) = I_3 - I_4 = 2\text{Im}(E_r E_{LD2})^* \quad (3.17)$$

where the imaginary component is represented by Im . Therefore, the total complex signal $I(t)$ can be represented by:

$$I(t) = I_I + jI_Q = E_r E_{LD2}^* \quad (3.18)$$

Therefore, the detected OFDM signal is:

$$y(t) = I(t) = x(t) \exp(j\Delta\omega t + \Delta\phi) \otimes h(t) + w(t) \quad (3.19)$$

where $\Delta\omega$ is the angular frequency difference between the laser diode at the transmitter and the local oscillator, and the $\Delta\phi$ is the phase difference between them which can be expressed as [47]:

$$\Delta\omega = \omega_{LD1} + \omega_{LD2}, \quad (3.20)$$

$$\Delta\phi = \phi_{LD1} + \phi_{LD2}, \quad (3.21)$$

After completing the optical detection, the signal is transmitted to the OFDM receiver to extract the original signal.

3.4.3 Comparison between DD-OOFDM and CO-OFDM

When compared to DD-OOFDM, CO-OFDM provides great robustness against CD and PMD. This advantage is because of the linear coherent detection technique which enhances the receiver sensitivity. Therefore, in theory, CO-OFDM provides unlimited dispersion tolerance. In contrast, the DD-OOFDM tolerance to CD and PMD is limited because of the nonlinear direct detection [48-50].

However, CO-OFDM requires frequency offset compensation because of the use of the local oscillator which complicates the receiver when compared to the DD-OOFDM. Also, the CO-OFDM is mainly used in long-haul applications due to the expensive and complex equipment used in the E/O and O/E conversion. On the other hand, DD-OOFDM is a cost effective solution for cost sensitive applications such as LANs and MANs [48-50].

Chapter Four: System Design, Simulation and Results Discussion

In order to reach the design of the high data rate and long-haul Coherent Optical OFDM system, a design and performance investigation have been carried of one user CO-OFDM with 4-QAM for long-haul transmission. The design of the one user CO-OFDM system is fully designed and investigated by using OptiSystem Simulation software V.11.

The simulation tool OptiSystem, from Optiwave Company, is used by telecommunication companies around the world such as Alcatel, Huawei. A huge selection of optical and wireless components are offered for planning and implementing a full optical network by this tool, which is a low cost and time-saving approach, allowing the researcher to work in a highly effective manner.

4.1 One User CO-OFDM System with SMF

The CO-OFDM system design consists of a CO-OFDM transmitter, a fiber link, and a CO-OFDM transmitter. Figure 4.1 shows the system design of the one user CO-OFDM system with a Single Mode Fiber (SMF) of 100 Km. The CO-OFDM transmitter is built with a Pseudo Random Binary Sequence (PRBS) to generate a bit sequence that will approximate the random data characteristics, and a 4-QAM (2 bit per symbol) encoder. The 4-QAM signal is connected to an OFDM modulator with a 512 subcarrier

and 1024 FFT points. The in-phase (I) and quadrature (Q) of the resulting signal from the OFDM modulator is transmitted to the direct I/Q optical modulator which consists of two lithium Niobate (LiNb) Mach-Zehnder modulators (MZM). The MZM will modulate the electrical signal from the OFDM modulator to the optical carrier with a laser source of 193.05 THz. The power of the laser source is -5 dBm [52, 53]. The resulting optical signal from the two LiNb MZMs is then transmitted through the SMF with an attenuation of 0.2 dBm/km, a dispersion of 16 ps/nm/km, a dispersion slope of 0.08 ps/nm²/km and a nonlinearity coefficient of 2.6×10^{-20} . An Erbium Doped Fiber Amplifier (EDFA) is used to amplify the signal and to compensate for the loss [52, 53].

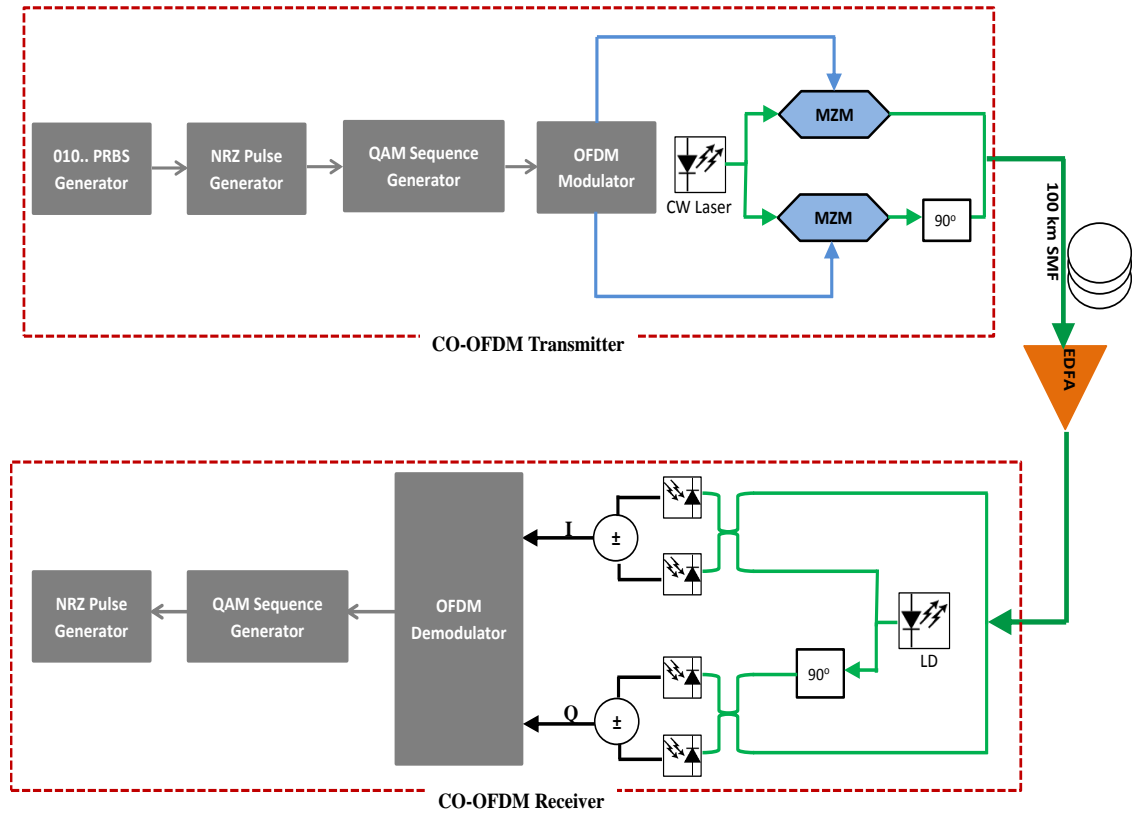


Figure 4.1: One-User CO-OFDM System with 100 km SMF

At the receiver side, the incoming optical signal is detected by two identical pairs of balanced coherent detectors with a local oscillator (LO) to perform the I/Q optical to electrical conversion and cancel the noise. Each detector consists of two couplers and two PIN photodetectors. Each PIN photodetector has a dark current of 10 nA, a responsivity of 1 A/W, thermal noise of $100e^{-24}$ W/Hz, and a center frequency of 193.05 THz. After detecting the signal by the balanced detectors, the signal is sent to the OFDM demodulator which has similar parameters as the OFDM modulator, and the guard interval is removed. Finally, the resulting signal is fed into a 4-QAM decoder to create a binary signal [52, 53].

Global Parameters	
Sequence length	16384 Bits
Samples per bit	8
Number of samples	131072

Table 4.1: Simulation Global Parameters

4.1.1 Simulation Results and Discussion

The simulation results of the long-haul CO-OFDM for different transmission lengths start from 100 km to 400 km are presented and discussed in this section.

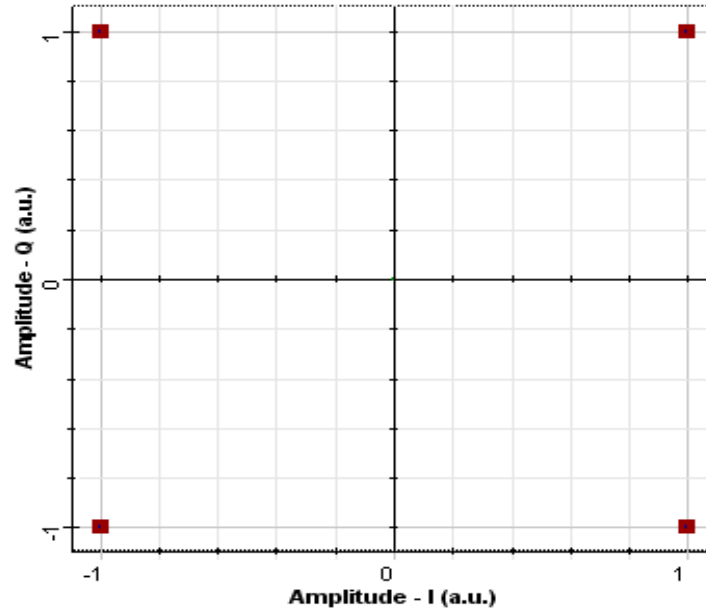


Figure 4.2: Constellation Diagram of 4-QAM at the CO-OFDM Transmitter

Figure 4.2 shows a clear constellation diagram of the 4-QAM modulator signal transmission at the transmitter side. The input OSNR is 56.94 dB. The constellation diagram displays the modulated signal as a two dimensional scatter diagram which helps to identify the distortion and interference that occurs in the signal.

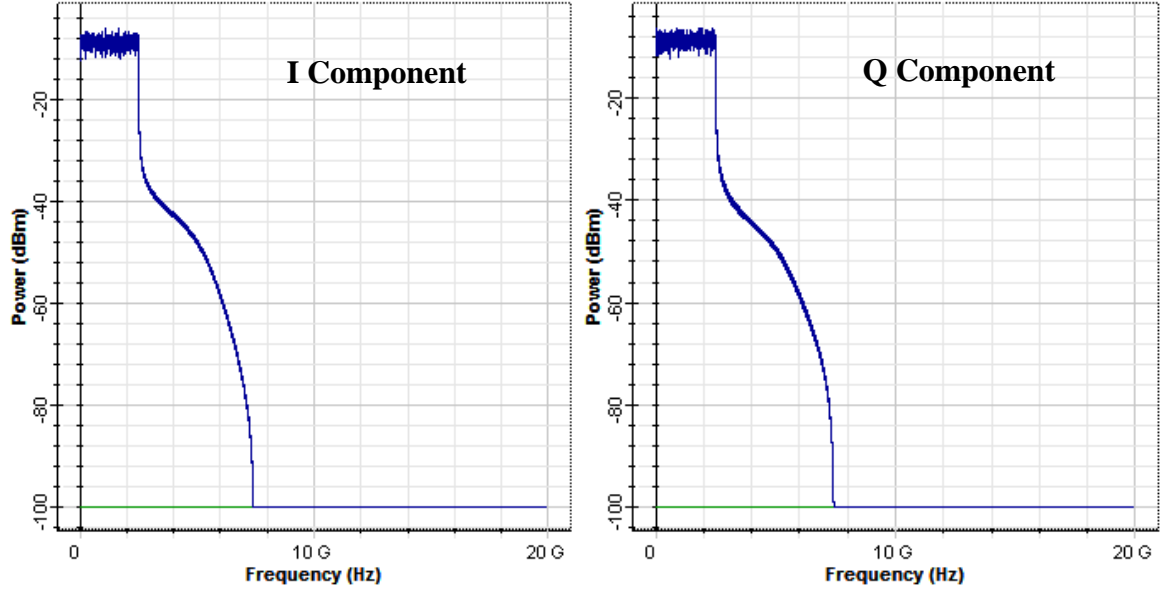


Figure 4.3: RF OFDM Spectrum I/Q Components [52]

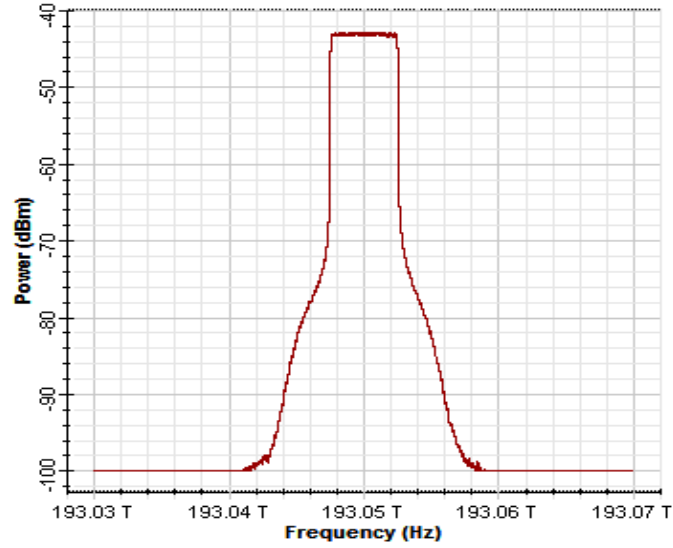


Figure 4.4: Optical OFDM Spectrum after the Two MZM Modulation

Figure 4.3 shows the RF spectrum for the I/Q component of the system at the CO-OFDM transmitter. The RF power is measured at almost -10 dBm. Figure 4.4 shows the optical signal spectrum, after modulating the electrical signal with the optical carrier using two MZMs.

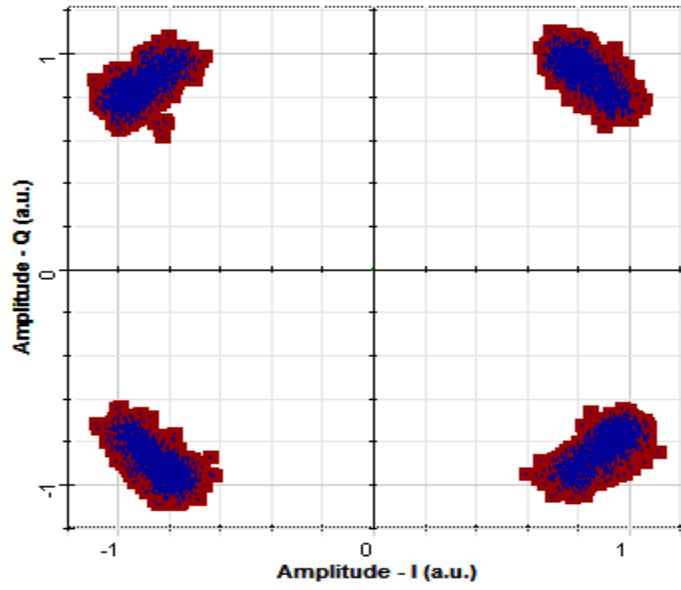


Figure 4.5: Constellation Diagram of the 10 Gbps One User CO-OFDM System at the Receiver Side after SMF of 100 km

Figure 4.5 shows the constellation diagram of the system after 100 km SMF with EDFA of 20 dB at the CO-OFDM receiver side. Compared to Figure 4.3, the signal becomes somewhat unclear and the OSNR is degraded to 25.75 dB because of attenuation, noise, and chromatic dispersion. In the constellation diagram, the blue represents the thermal and shot noise from the laser source, the thermal noise from the photodetectors, and the fiber dispersion.

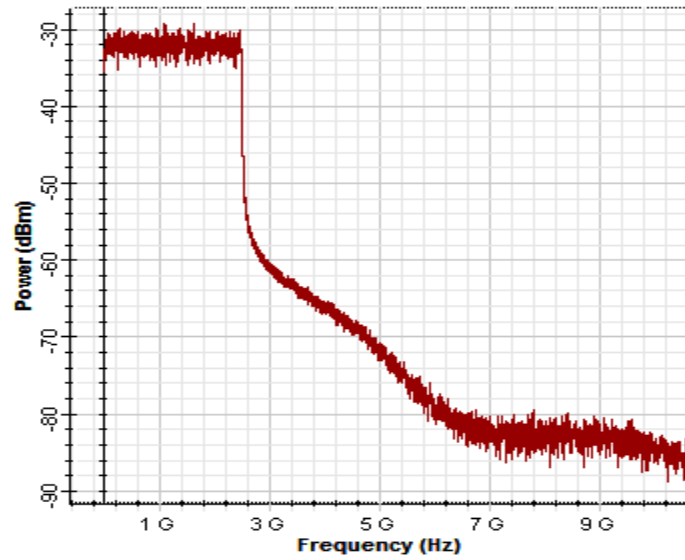


Figure 4.6: RF Spectrum at the CO-OFDM Receiver

Figure 4.6 shows the RF spectrum of the system at the CO-OFDM receiver side after 100 km SMF. The RF power is measured at -30 dBm.

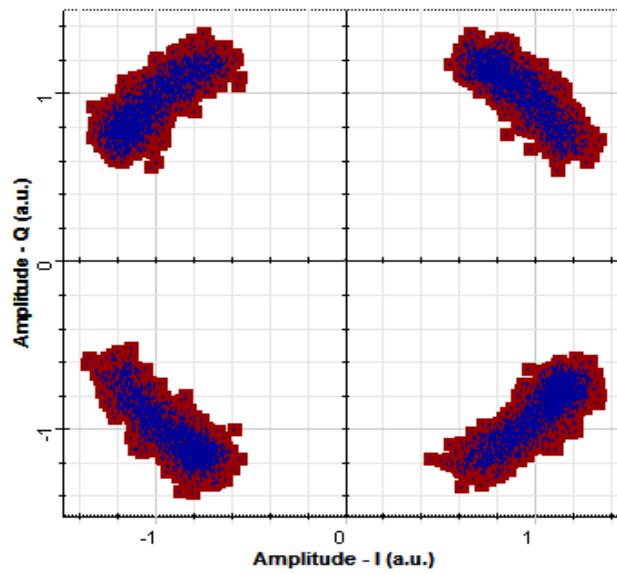


Figure 4.7: Constellation Diagram of the 10 Gbps One User CO-OFDM System at the Receiver Side after SMF of 200 km

Figure 4.7 shows the constellation diagram of the system after 200 km SMF at the CO-OFDM receiver side after increasing the power of the EDFA to 35 dB. It shows some distortion in the signal. When compared to Figure 4.5 ,the distortion is increased because of attenuation, noise, and chromatic dispersion which increases as the fiber length increases. The blue color represents the noise and the red color represents the signal.

The broadening of the light is caused by the chromatic dispersion while the light is traveling along the fiber. This will lead the pulse to overlap with the closer pulses and eventually make it hard to recover the original signal accurately. Therefore, applying dispersion compensation to SMF is essential to control the dispersion for long distances.

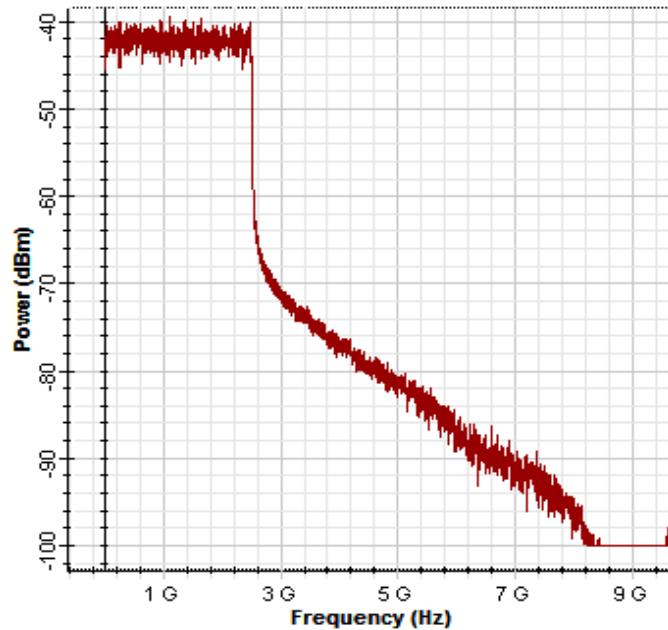


Figure 4.8: RF Spectrum at the CO-OFDM Receiver after 200 km

Figure 4.8 shows the RF spectrum of the system at the CO-OFDM receiver side after 200 km SMF. The RF power is measured at -42 dBm. As the RF power was -30dBm at 100 km, It shows that as the distance increases the power decreases.

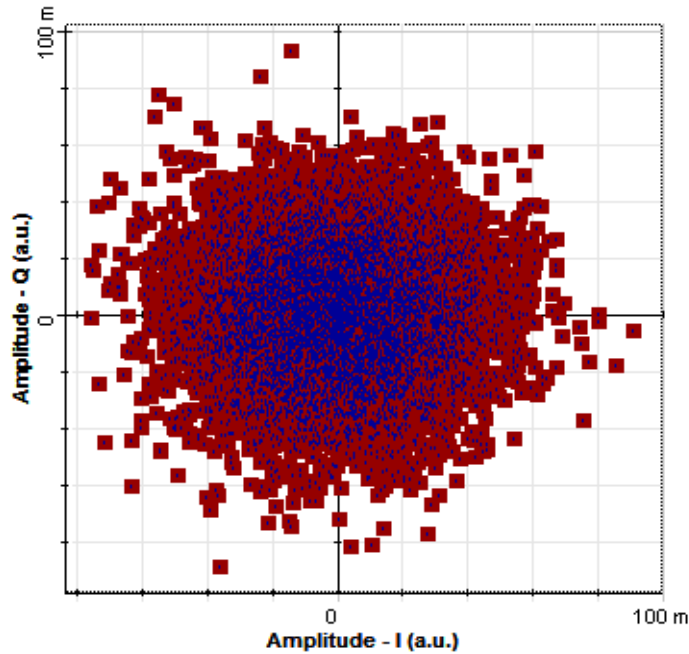


Figure 4.9: Constellation Diagram of the 10 Gbps One User CO-OFDM System at the Receiver Side after SMF of 400 km

Figure 4.9 shows the constellation diagram of the system after 400 km SMF at the CO-OFDM receiver side. It can be seen that the signal is distorted and corrupted. As mentioned before, Chromatic Dispersion causes the broadening of the signal after long distances and the attenuation increases. To solve this problem, the power of the EDFA is increased to amplify the signal in the 1550 nm region where the SMF loss is minimal. Therefore, for the 400 km SMF, the power of the EDFA increased from 35 dB in previous lengths to 60 dB.

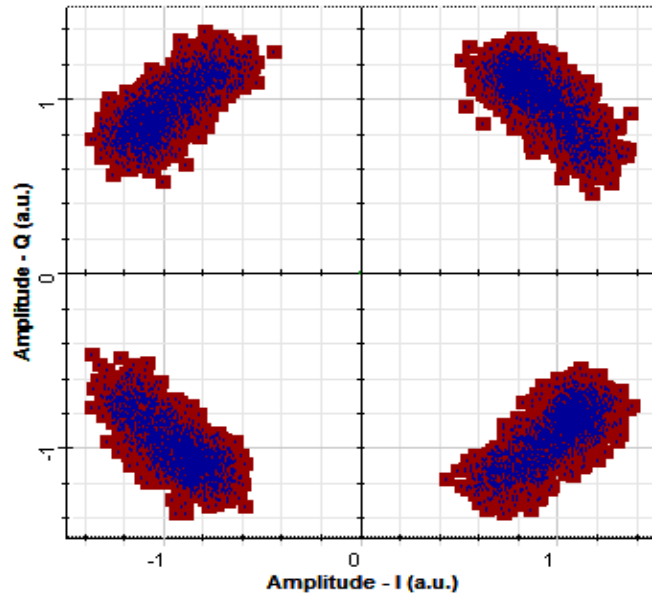


Figure 4.10: Constellation Diagram of the 10 Gbps One User CO-OFDM System at the Receiver Side after SMF of 400 km with EDFA of 60 dB

Figure 4.10 shows the constellation diagram of the system with 400 km SMF at the CO-OFDM receiver side after increasing the power of the EDFA to 60 dB. As can be seen from the figure the signal is clear and improved after increasing the power when compared to Figure 4.9.

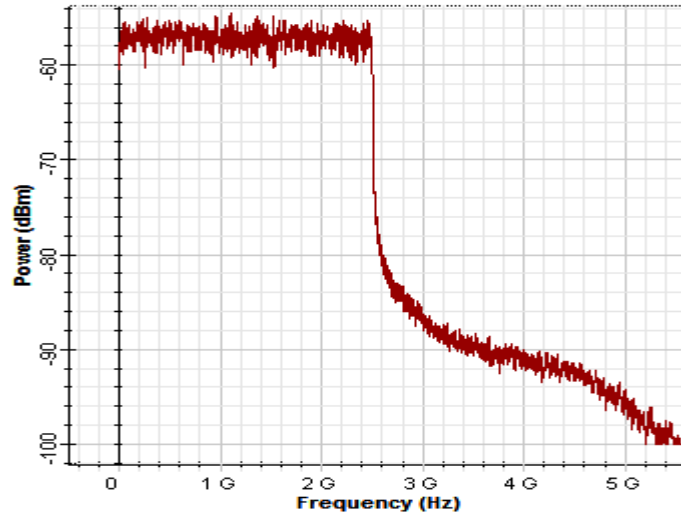


Figure 4.11: RF Spectrum at the CO-OFDM Receiver after 400 km

Figure 4.11 shows the RF spectrum of the system at the CO-OFDM receiver side after 400 km SMF. The RF power is decreased because of the increase of the distance from -42 at 200 km to -56 dBm at 400 km.

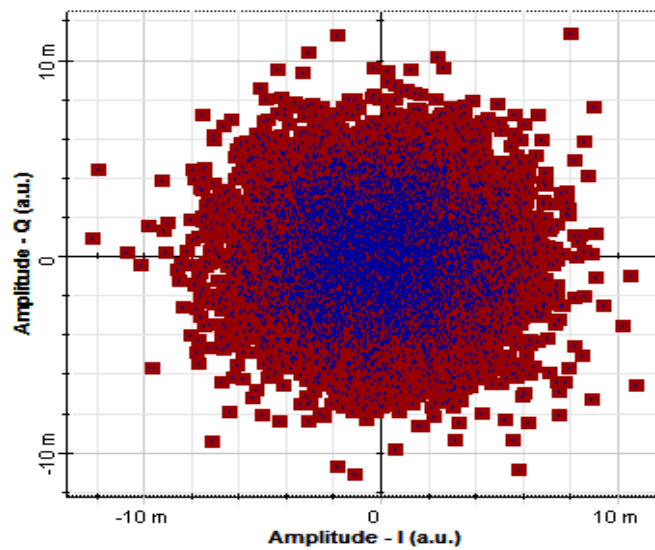


Figure 4.12: Constellation Diagram of the 10 Gbps One User CO-OFDM System at the Receiver Side after SMF of 500 km

Figure 4.12 shows the constellation diagram of the system after 500 km SMF at the CO-OFDM receiver side with EDFA power of 60 dB. Even when the power of the EDFA is increased to more than 60 dB, the signal is still distorted, corrupted, and nothing changed. Thus, the power of the EDFA cannot affect the signal with SMF length of 500 km because the EDFA works effectively when the signal has low power loss. To compare, when the transmission length is 200 km, the EDFA power increases from 20dB to 35dB, but when the transmission length increases to 400 km, the EDFA power increases from 35 dB to 60 dB to improve the signal quality and to overcome the signal attenuation. However, when the transmission length increases to 500 km, the signal is weak and, even with the increase in the power of the EDFA, the signal does not improve. Therefore, to help improve the signal for SMF over 500 km without the need to increase the power of the EDFA, a Dispersion Compensation Component must be added to the system. In the next section, a Dispersion Compensation Fiber (DCF) is proposed as a solution to help improve the quality of the signal and increase the transmission distance without the need of increasing the power of the EDFA.

4.2 CO-OFDM with Dispersion Compensation Fiber (DCF)

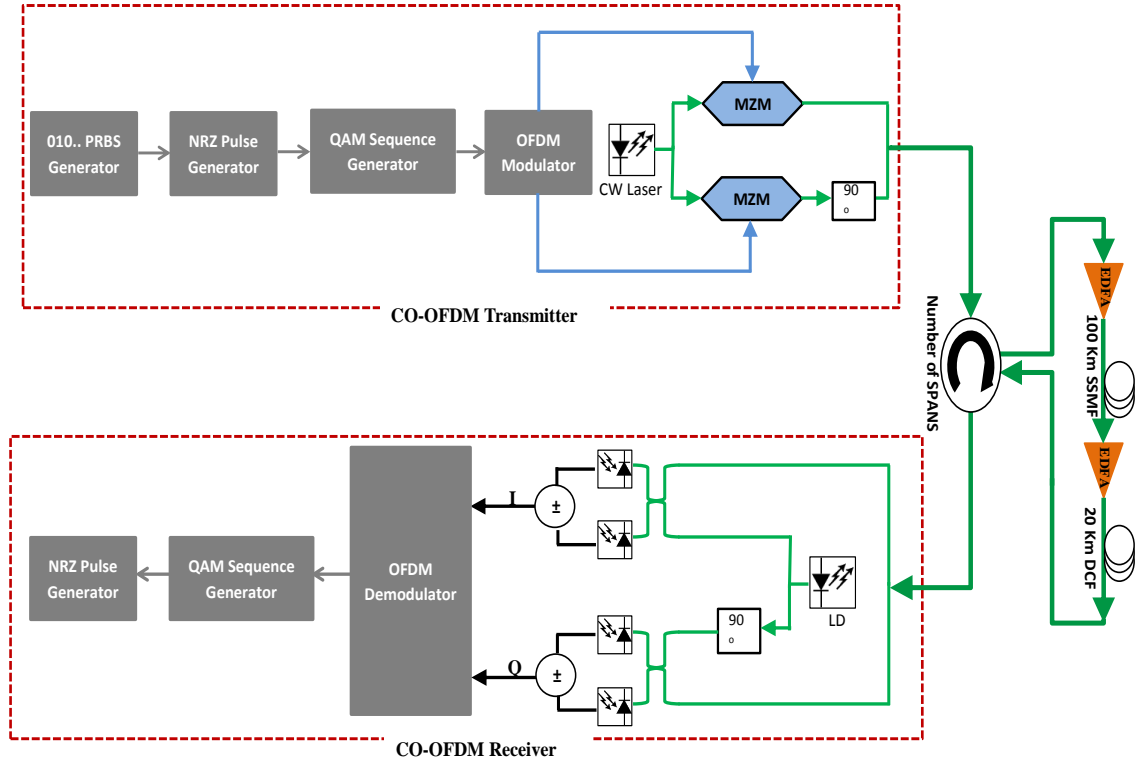


Figure 4.13: System Design of One User CO-OFDM with SMF-DCF [52,53]

Figure 4.13 shows the system design of the one user CO-OFDM system with a SMF-DCF. The CO-OFDM transmitter is built with a Pseudo Random Binary Sequence (PRBS), to generate a bit sequence that will approximate the random data characteristics, and a 4-QAM (2 bit per symbol) encoder. The 4-QAM signal is connected to an OFDM modulator with a 512 subcarrier and 1024 FFT points. The in-phase (I) and quadrature (Q) of the resulting signal from the OFDM modulator is transmitted to the direct I/Q optical modulator. The direct I/Q modulator consists of two lithium Niobate (LiNb) Mach-Zehnder modulators (MZM) and will modulate the electrical signal from the

OFDM modulator to the optical carrier with a laser source of 193.05 THz. The power of the laser source is -5 dBm [52, 53].

The resulting optical signal from the two LiNb MZMs is then transmitted through the SMF-DCF system. The DCF is used to compensate for the fiber dispersion. The SMF attenuation is 0.2 dB/km and the DCF attenuation is 0.4 dB/km. The SMF dispersion is 16 ps/nm/km for 100 km. The SMF will produce a dispersion of $16 \times 100 = 1600$ ps/nm. Therefore, to compensate the dispersion of the 100 km SMF, a 20 km long DCF is needed with dispersion of -80 ps/nm/km. This will produce a dispersion of $-80 \times 20 = -1600$ ps/nm, which will be negative to cancel the positive dispersion of the SMF. An Erbium Doped Fiber Amplifier (EDFA) is used with 20 dB power to amplify the signal and to compensate for the loss [52, 53].

At the receiver side, the incoming optical signal is detected by two identical pairs of balanced coherent detectors with a local oscillator (LO) to perform the I/Q optical to electrical conversion and to cancel the noise. Each detector consists of two couplers and two PIN photodetectors. Each PIN photodetectors has a dark current of 10 nA, a responsivity of 1 A/W, thermal noise of $100e^{-24}$ W/Hz, and a center frequency of 193.05 THz. After detecting the signal by the balanced detectors, the signal is sent to the OFDM demodulator. The OFDM demodulator has similar parameters to the OFDM modulator. The guard interval is then removed. Finally, the resulting signal is fed into a 4-QAM decoder to create a binary signal [52, 53].

SMF	
Dispersion	16 ps/nm/km
Dispersion Slope	0.08 ps/nm ² /km
PMD Coefficient	0.2 ps/km
Effective area	80 μm^2
Nonlinearity Coefficient	2.6×10^{-20}
Attenuation	0.2 dB/km

Table 4.2: SMF Parameters

DCF	
Dispersion	-80 ps/nm/km
Dispersion Slope	-0.45 ps/nm ² /km
PMD Coefficient	0.2 ps/km
Effective area	30 μm^2
Nonlinearity Coefficient	2.6×10^{-20}
Attenuation	0.4 dB/km

Table 4.3: DCF Parameters

4.2.1 Simulation Results and Discussion:

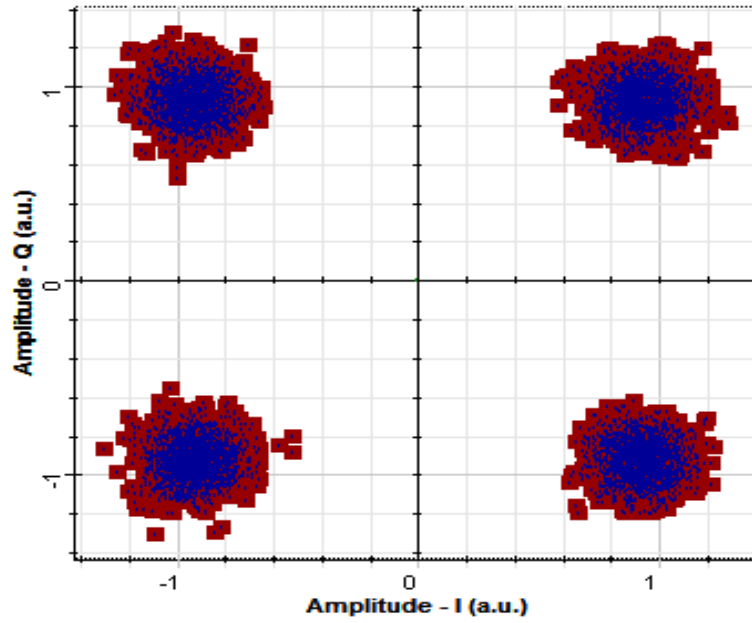


Figure 4.14: The Constellation Diagram of the 10 Gbps One User CO-OFDM System after using the DCF for Fiber Length of 840 km

Figure 4.14 shows the constellation diagram of the system at the CO-OFDM receiver side after 840 km of fiber length using seven spans for both the SMF of 100 km and the DCF 20 km. The EDFA power is 41 dB which is the same amount of power used to transmit over 400 km. A further increase in the transmission distance is required since one of the main goals of this research is the long-haul transmission system. Therefore, the distance is increased to the maximum distance that this setup can handle. Usually, with the increase in distance, the power of the EDFA needs to be increased.

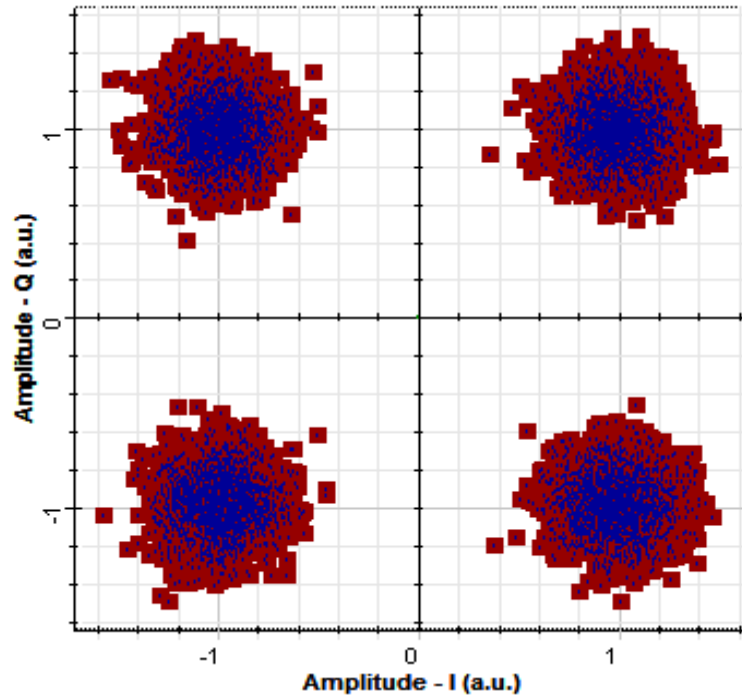


Figure 4.15: The Constellation Diagram of the 10 Gbps One User CO-OFDM System after using the DCF for Fiber Length of 3000 km

Figure 4.15 shows the constellation diagram of the system at the CO-OFDM receiver side after 3000 km of fiber length using 25 spans for both the SMF of 100 km and the DCF 20 km. The EDFA power is 41 dB which is the same amount of power used to transmit over 840 km. When comparing Figure 4.15 to Figure 4.14 slight increase in the noise is apparent in Figure 4.15 due to the increase of the transmission distance. Also, the signal power becomes weak because of the noise the attenuation of the DCF. Therefore, to reduce these effects, the power of the EDFA needs to be increased.

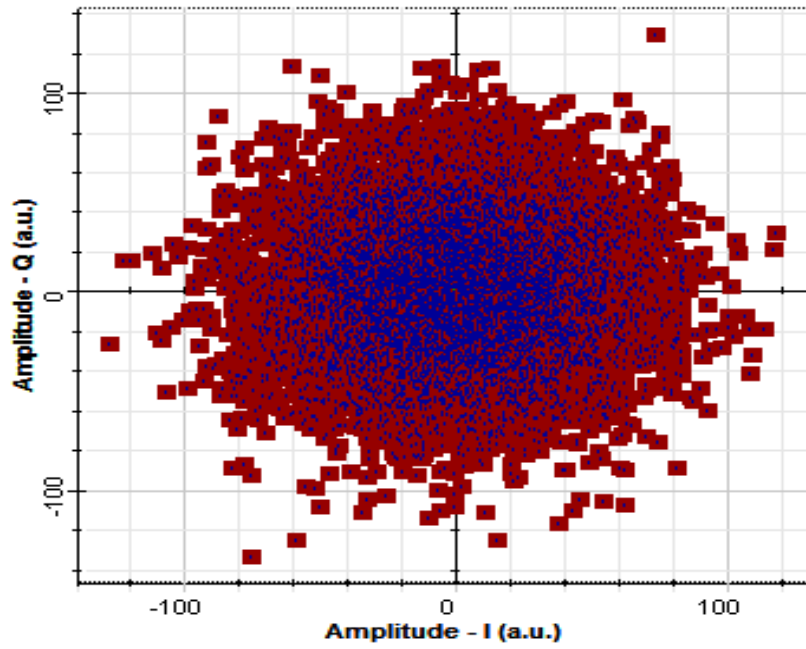


Figure 4.16: The Constellation Diagram of the 10 Gbps One User CO-OFDM System after using the DCF for Fiber Length of 6000 km with EDFA power of 41 dB

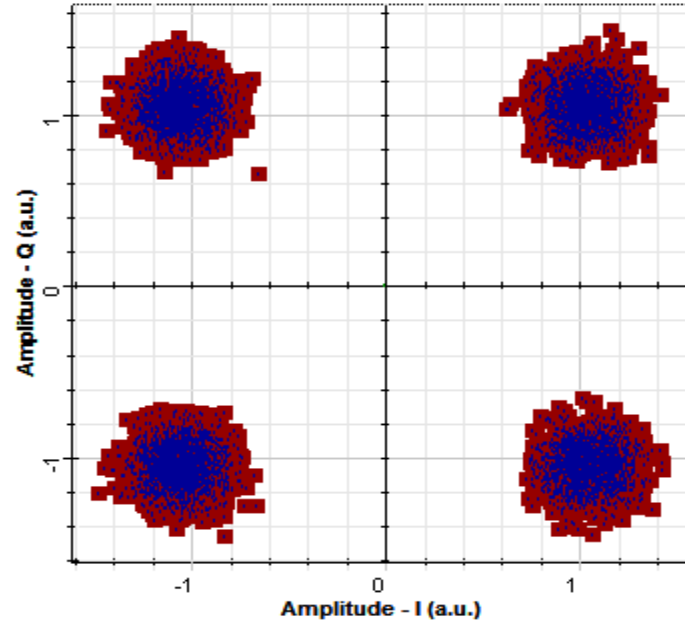


Figure 4.17: The Constellation Diagram of the 10 Gbps One User CO-OFDM System after using the DCF for Fiber Length of 6000 km with EDFA Power of 60 dB

Figure 4.16 shows the constellation diagram of the system at the CO-OFDM receiver side after 6000 km of fiber length using 50 spans for both the SMF of 100 km and the DCF 20 km. The EDFA power is 41 dB which is the same amount of power used to transmit over 3000 km. As can be seen, the signal is totally corrupted and cannot be recovered due to the high amount of noise and attenuation caused by the long distance which weakens the signal. Therefore, the power of the EDFA needs to be increased to compensate for the loss and the signal amplified to successfully transmit the signal over the 6000 km of fiber length. Figure 4.17 shows the constellation diagram of the system at the CO-OFDM receiver side after 6000 km of fiber length using 50 spans for both the SMF of 100 km and the DCF 20 km. The EDFA power is 60 dB. When comparing Figure 4.17 to Figure 4.16 it is apparent that the signal is improved by the increase in the EDFA power. The 6000 km fiber length is the maximum transmission distance for this setup. Even if the EDFA power is increased, the signal will still be corrupted, because of the long transmission distance and the increase in the nonlinear effects due to the high increase in power.

4.3 CO-OFDM for High Data Rates

The main goal for using coherent Optical OFDM is to reach high data rates. In this section, a one user CO-OFDM system design is implemented to reach a high data rate for the long-haul transmission of 6000 km SMF with DCF that was designed in the previous section.

The high data rate design of the CO-OFDM System is the same design as in the previous section. The design consists of a CO-OFDM transmitter, a CO-OFDM Receiver and an Optical Fiber link as shown in Figure 4.13. In this design, the bit rate was increased from 10 Gbps to 20 Gbps, 30 Gbps, 50 Gbps, and 100 Gbps.

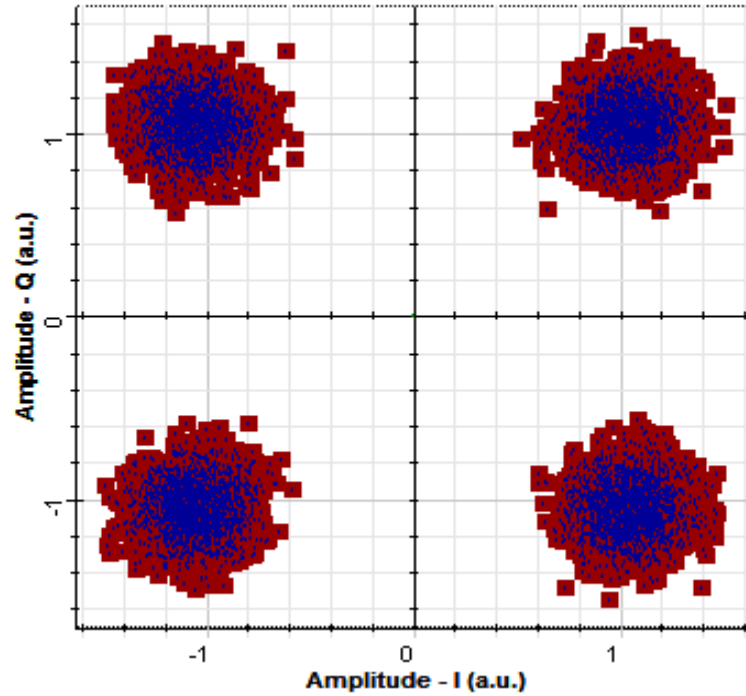


Figure 4.18: The Constellation Diagram of the 20 Gbps One User CO-OFDM System after using the DCF for Fiber Length of 6000 km

Figure 4.18 shows the constellation diagram is of the 20 Gbps one user CO-OFDM System after using the DCF for fiber length of 6000 km. As can be seen from the figure, the signal is clear. But when compared to Figure 4.17, the noise increased in the signal because of the increase in the data rate.

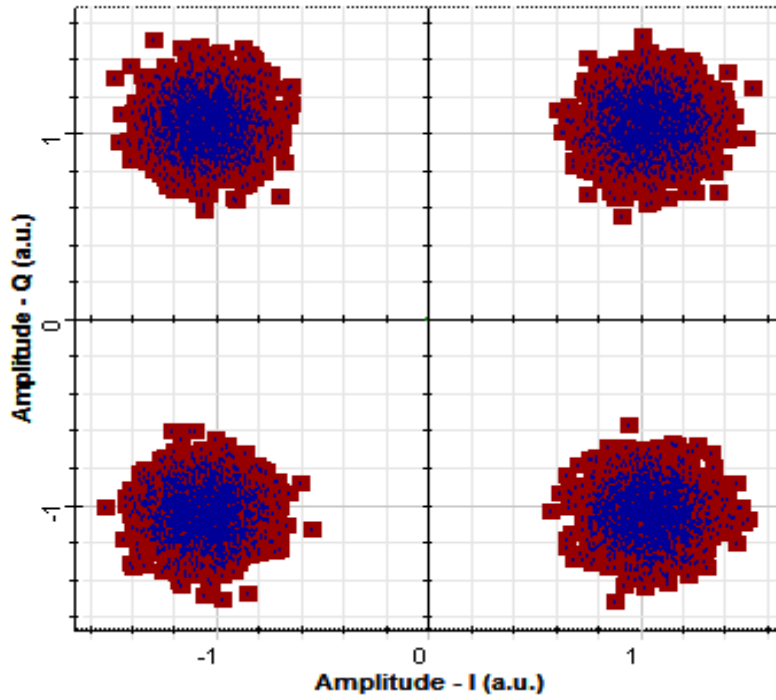


Figure 4.19: The Constellation Diagram of the 30 Gbps One User CO-OFDM System after using the DCF for Fiber Length of 6000 km

Figure 4.19 shows the constellation diagram of the 30 Gbps one user CO-OFDM System after using the DCF for fiber length of 6000 km. As can be seen from the figure, the signal is clear. But when compared to Figure 4.18, the noise increased in the signal because of the increased in the data rate.

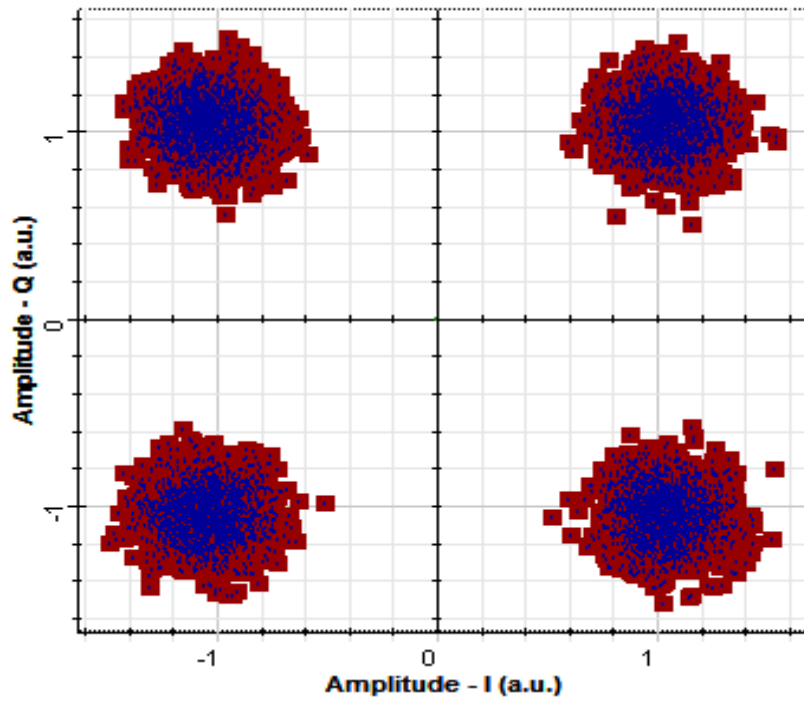


Figure 4.20: The Constellation Diagram of the 50 Gbps One User CO-OFDM System after using the DCF for Fiber Length of 6000 km

Figure 4.20 shows the constellation diagram of the 50 Gbps one user CO-OFDM System, after using the DCF for fiber length of 6000 km as can be seen from the figure, shows the signal is clear. But when compared to Figure 4.19 for the 30 Gbps data rate, the noise increased in the signal because of the increase in the data rate.

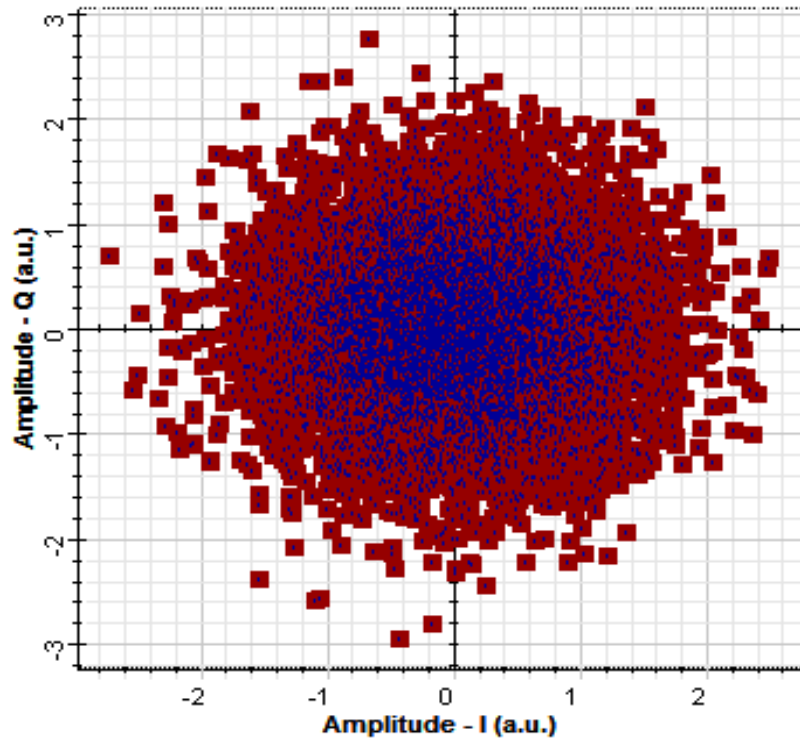


Figure 4.21: The Constellation Diagram of the 100 Gbps One User CO-OFDM System after using the DCF for Fiber Length of 6000 km

Figure 4.21 shows the constellation diagram of the 100 Gbps one user CO-OFDM System, after using the DCF for fiber length of 6000 km. as can be seen from the figure, the signal is totally corrupted. This is due to the increase in the noise and the nonlinear impairments because of the large increase in the data rate. As a result, the one user design of the CO-OFDM can handle only 50 Gbps, and anything over 50 Gbps will be corrupted. To overcome this problem, a Wavelength Division Multiplexing (WDM) can be used to increase the capacity of the system and increase the data rate. The integration of the optical OFDM and the WDM produce a significantly higher data rate which will be presented in the next section.

4.4 Integration of WDM with Coherent Optical OFDM for Long-Haul High Data Rate Transmission

The Wavelength Division Multiplexing (WDM) is an important factor in the development of optical communications. It has the ability to both provide more flexibility to the system and to simplify the design of the network. WDM systems help to enhance the capacity of the system by sending multiple wavelengths over a single fiber. In optical OFDM, WDM helps to increase the capacity of the system and provide a significant increase in the data rate that is carried over a single fiber. This is by using multiple wavelengths, where each wavelength carries a separate channel. WDM divides the optical spectrum to smaller channels, which are used to transmit and receive data simultaneously [52, 53].

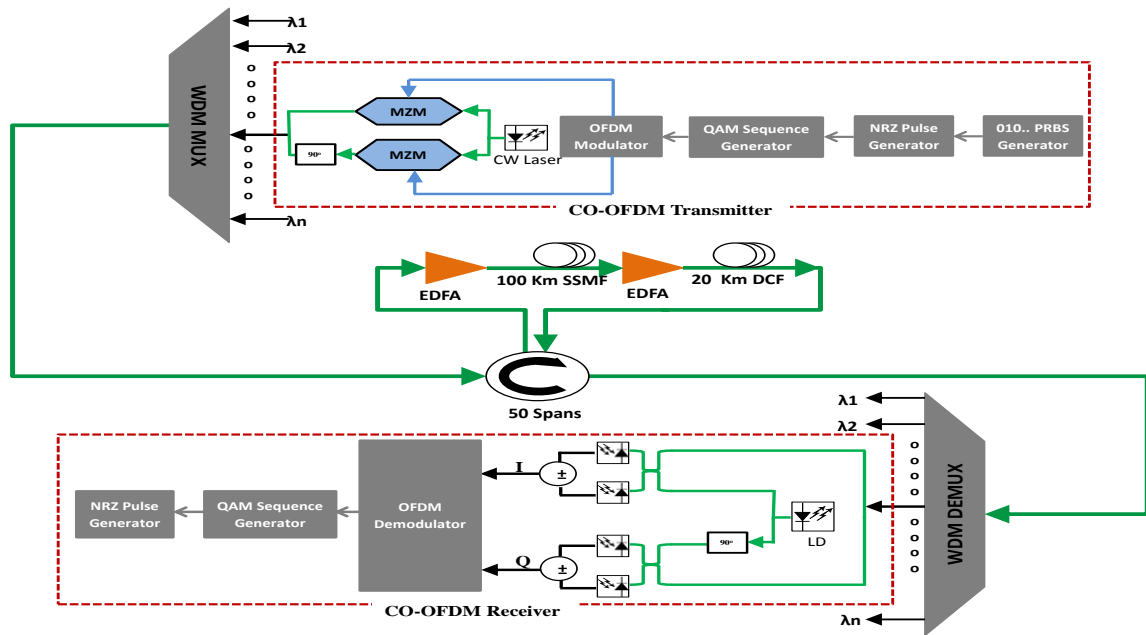


Figure 4.22: Block Diagram of WDM CO-OFDM System with SMF-DCF of 6000 km [52, 53].

Figure 4.22 shows the system design of WDM -CO-OFDM system with a SMF-DCF of 6000 km length. The CO-OFDM transmitter is built with a Pseudo Random Binary Sequence (PRBS) to generate a bit sequence that will approximate the random data characteristics. It is also built with a 4-QAM (2 bit per symbol) encoder. The 4-QAM signal is connected to an OFDM modulator with a 512 subcarrier and 1024 FFT points. The in-phase (I) and quadrature (Q) of the resulting signal from the OFDM modulator is transmitted to the direct I/Q optical modulator. The I/Q optical modulator consists of two lithium Niobate (LiNb) Mach-Zehnder modulators (MZM) which will modulate the electrical signal from the OFDM modulator to the optical carrier. In this scenario, to support 1 Tbps twenty OFDM signals are needed, which means twenty OFDM receivers all have the same design and parameters. The exception is the optical carrier which has a laser wavelength which starts from 193.05 to 194.00 THz with a space of 50 GHz.

The WDM system consists of twenty channels to support the twenty OFDM bands with channel space of 50GHz. Each OFDM signal has a 50 Gbps bitrate which will provide an overall data rate of 1 Tbps. The resulting signals from the OFDM transmitters are launched into the WDM MUX and filtered by a Gaussian optical filter. The twenty different wavelengths are merged to produce one signal to be launched on a single fiber.

The resulting optical signal of the WDM MUX is then transmitted through the SMF-DCF system. The DCF is used to compensate for the fiber dispersion. The SMF attenuation is 0.2 dB/km and the DCF attenuation is 0.4 dB/km. The SMF dispersion is 16 ps/nm/km for 100 km. SMF which will produce a dispersion of $16 \times 100 = 1600$

ps/nm. Therefore, to compensate for the dispersion of the 100 km SMF, a 20 km long DCF is needed with dispersion of -80 ps/nm/km which will produce a dispersion of $-80 \times 20 = -1600$ ps/nm. This dispersion will be negative to cancel the positive dispersion of the SMF. An Erbium Doped Fiber Amplifier (EDFA) is used with 20 dB power to amplify the signal and to compensate for the loss.

The incoming optical signal from the optical fiber link is separated into twenty wavelengths by the WDM DEMUX and each wavelength is detected by its designed receiver. Twenty receivers are designed to have the same parameters except for the center frequency of the receiver and the local oscillator which will be identical to the wavelength of the laser transmitter. Each receiver consists of two identical pairs of balanced coherent detectors with a local oscillator (LO) to perform the I/Q optical to electrical conversion and cancel the noise. Each detector consists of two couplers and two PIN photodetectors. Each PIN photodetector has a dark current of 10 nA, a responsivity of 1 A/W, and thermal noise of $100e^{-24}$ W/Hz. After detecting the signal by the balanced detectors, the signal is sent to the OFDM demodulator which has similar parameters to the OFDM modulator. The guard interval is then removed. Finally, the resulting signal is fed into a 4-QAM decoder to create a binary signal.

4.4.1 1 Tbps WDM CO-OFDM System Simulation Results and Discussion

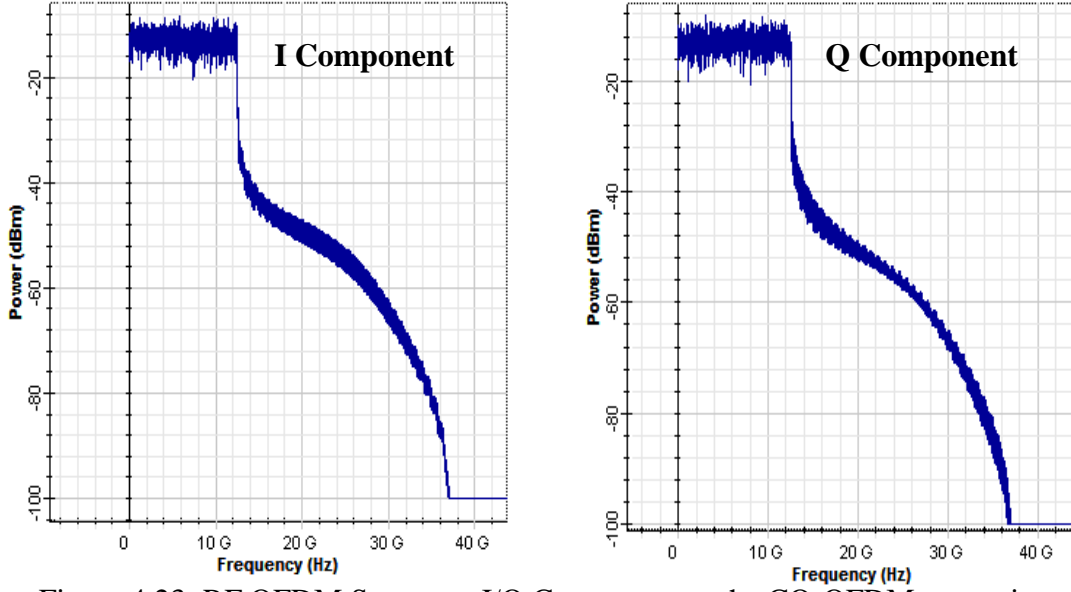


Figure 4.23: RF OFDM Spectrum I/Q Component at the CO-OFDM transmitter [52].

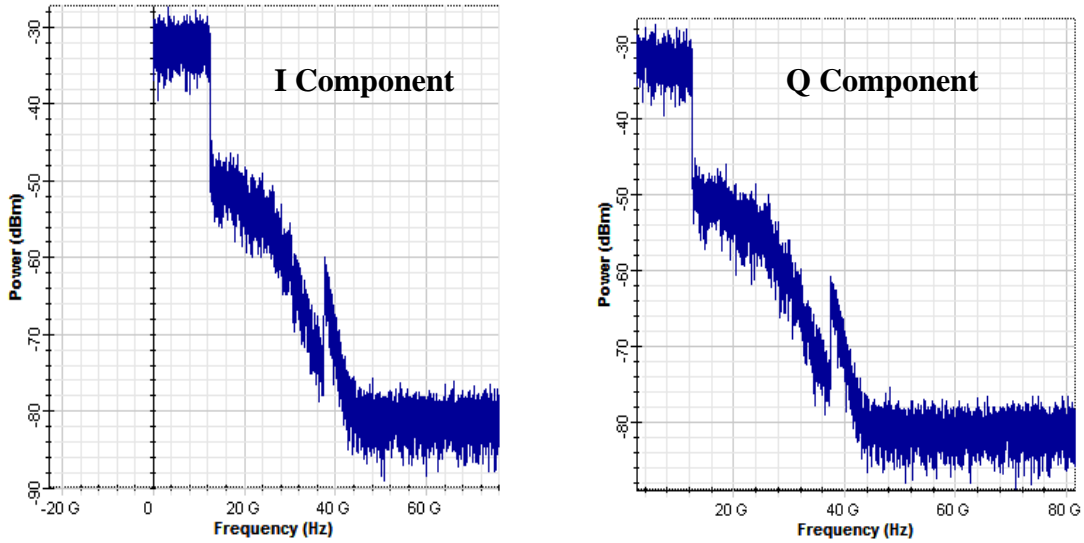


Figure 4.24: RF OFDM Spectrum I/Q Component at the CO-OFDM Receiver [52].

Figure 4.23 shows the RF spectrum of the I/Q component of the CO-ODM WDM system at the transmitter side. The RF power is measured at almost -14 dBm. Figure 4.24

shows the RF spectrum of the I/Q component of the CO-OFDM WDM system at the receiver side. The RF power is decreased to -30 dBm when compared to Figure 4.23, which is good for the long-haul transmission of 6000 km.

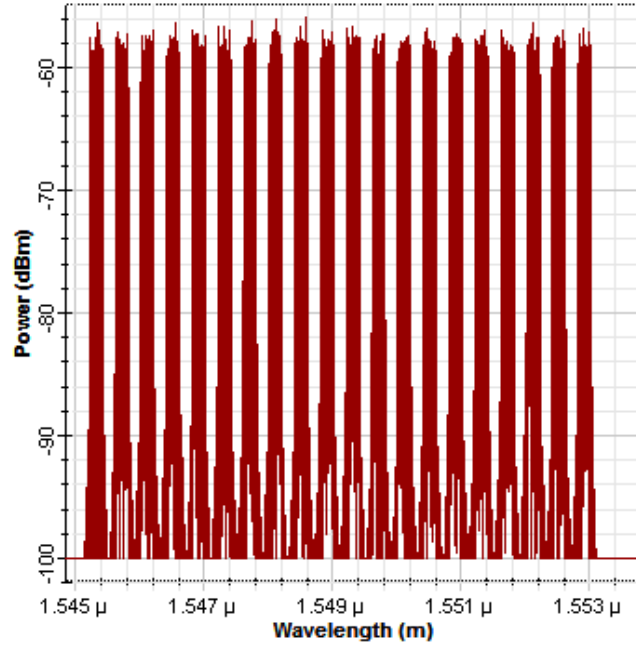


Figure 4.25: 20 OFDM Signal after Optical after WDM with 20 WDM Channels [52].

Figure 4.25 shows the twenty OFDM spectrums after the WDM system. Twenty WDM channels start at 193.05 THz up to 194 THz with channel spacing of 50 GHz.

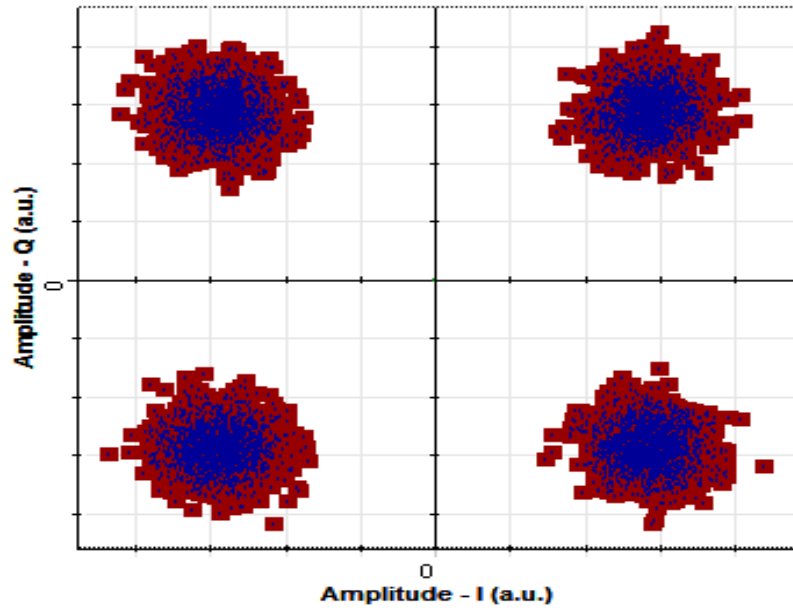


Figure 4.26: The Constellation Diagram of 1 Tbps WDM CO-OFDM System after 6000 km Long-Haul Transmission [52]

Figure 4.26 shows the constellation diagram of the 1 Tbps WDM CO-OFDM system after a long-haul transmission of 6000 km with dispersion compensation. As can be seen from the figure, the transmission is successful and the signal is clear with OSNR of 60 dB and BER of 10^{-13} [52, 53].

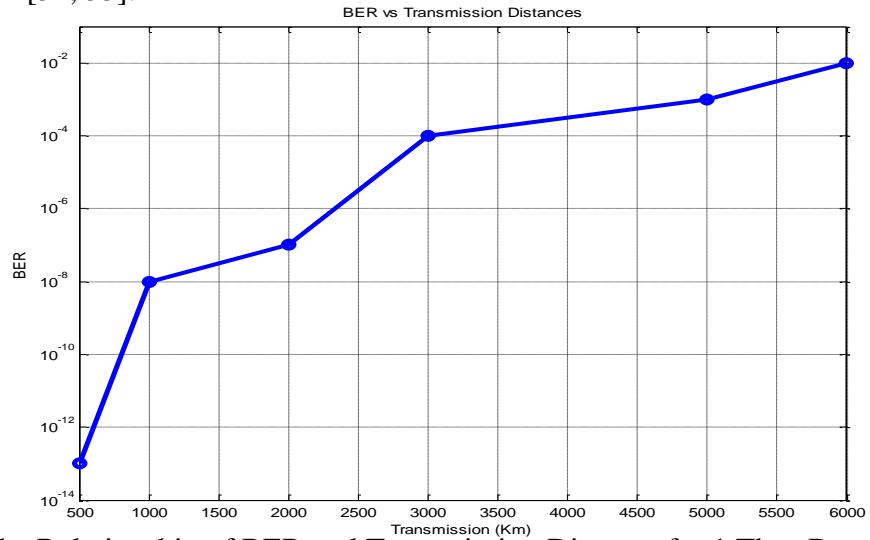


Figure 4.27: The Relationship of BER and Transmission Distance for 1 Tbps Data Rate with 21 dB OSNR [52]

Figure 4.27 shows the BER performance of the OSNR at 21 dB with different transmission distances. As can be seen from the figure, the BER increases as the transmission distance increases, and this increase in BER is due to the increase in fiber loss as the fiber length increases [52, 53].

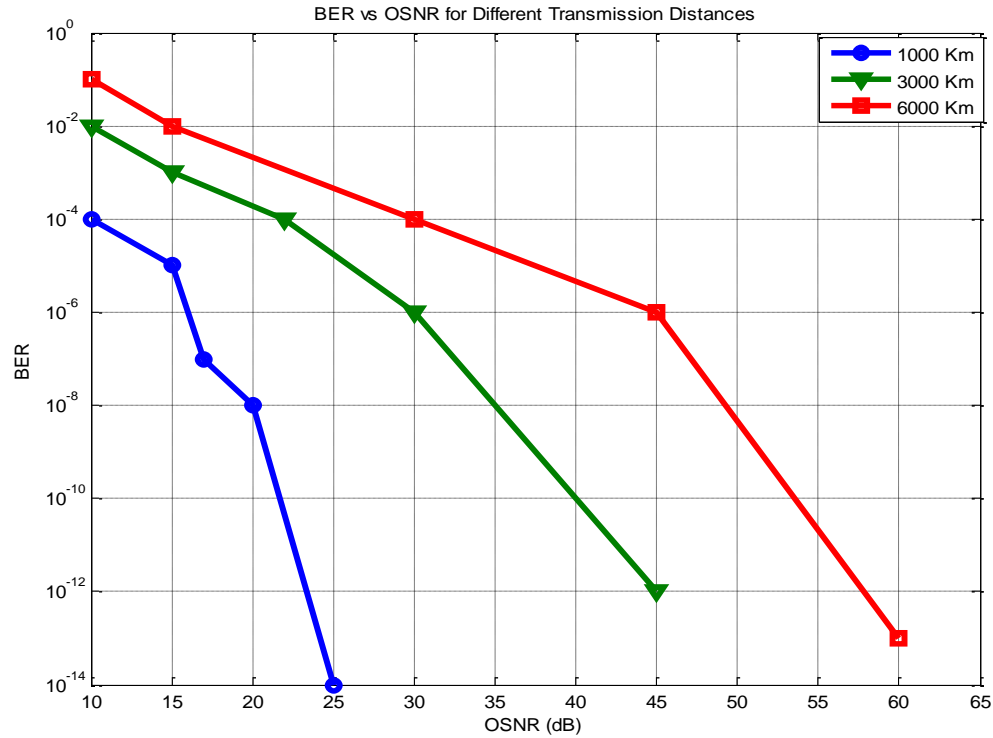


Figure 4.28: The Relationship of BER and OSNR for Different Transmission Distances at 1 Tbps Data Rate [52].

Figure 4.28 shows the performance of BER for different transmission distances with different values of OSNR. As can be seen from the figure, larger OSNR values are needed as the transmission distances increase to maintain BER in the region of less than 10^{-3} . However, the OSNR increase must be limited because increasing the power beyond

the limit will increase the nonlinear effect of the fiber and will make the system worse [52, 53].

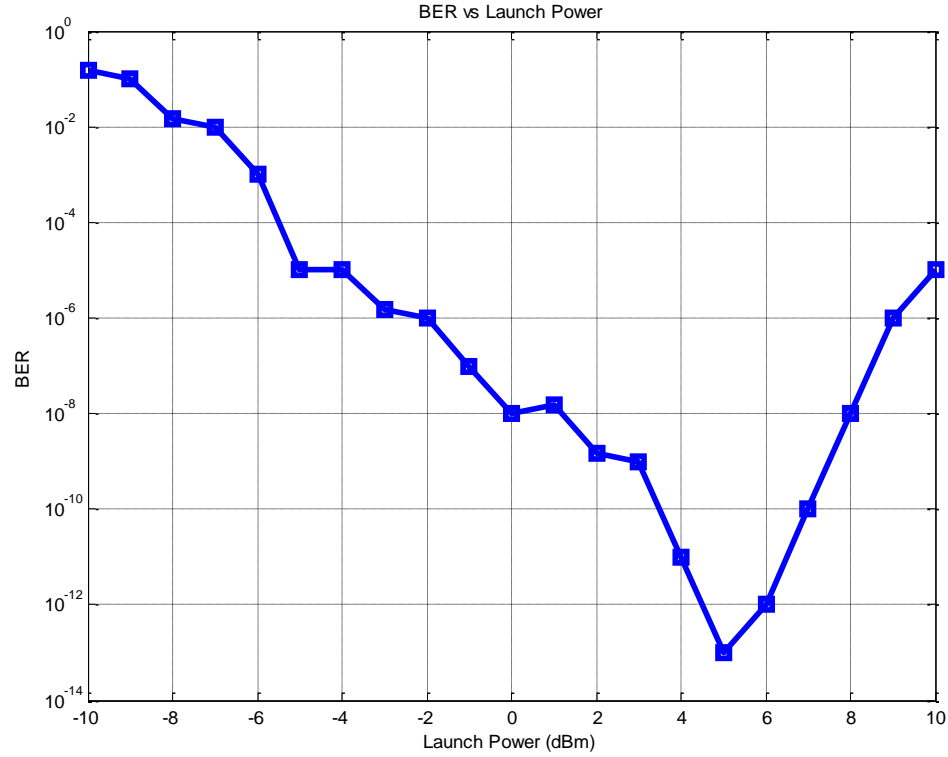


Figure 4.29: BER of the 1 Tbps CO-OFDM WDM System with Different Launch Power for 6000 km

Figure 4.29 shows the performance of the BER with a different launch power for 6000 km. As can be seen from the figure, increasing the launch power will decrease the BER. The lowest BER the system can get is around 5 dBm. However, increasing the launch power more than 5 will lead to an increase in the OSNR. This leads to a drop in the signal quality and increases the BER due to the increase of the nonlinear impairments of the optical fiber.

Chapter Five: Conclusion and Future Work

5.1 Conclusion

This thesis aimed to find a solution for the increased demand for bandwidth and high data rates in today's communication transmission. Coherent Optical OFDM (CO-OFDM) is the next generation technology for the optical communications, since it integrates the advantages of both coherent systems and OFDM systems. It has the ability to overcome many optical fiber restrictions such as chromatic dispersion (CD) and polarization mode dispersion (PMD). Moreover, integrating the coherent optical OFDM with Wavelength Division Multiplexing (WDM) systems will provide a transmission system with a high bandwidth, a significant data rates, and a high spectral efficiency without increasing the cost or the complexity of the system. Integration of CO-OFDM and WDM has been proposed as a solution for the increased demand in bandwidth and the data rates.

First, the performance of a one user CO-OFDM system for short distance was proposed, simulated, and analyzed. A DCF system was then proposed to increase the transmission distance to 6000 km and to overcome the long-haul transmission limits caused by the fiber dispersion with data rates starting at 10 Gbps to 50 Gbps. The results show that the system is reliable and can provide a good transmission. However, one user

CO-OFDM cannot handle more than 50 Gbps which urges the use of a WDM system to increase the capacity and the data rate of the system.

Second, the performance of the integration of CO-OFDM system with WDM system for long-haul transmission of 6000 km with high data rate of 1 Tbps was proposed, simulated, and analyzed. The WDM system consists of twenty channels to support the twenty OFDM bands with channel space of 50GHz. Each OFDM signal has a 50 Gbps bitrate which will provide 1 Tbps overall data rate. The results show that the system is reliable and can provide significant high data rates with BER of 10^{-13} and with OSNR of 60 dB. Also, the results show that the BER increases as the transmission distance increases and, to maintain an acceptable BER, the OSNR should be increased. But, the OSNR increase must be limited because increasing the power beyond the limit will increase the nonlinear effect of the fiber and will make the system worse.

5.2 Future Work

Although the simulation of CO-OFDM with WDM over a long-haul transmission in this thesis showed promising results, there are still a number of issues related to the CO-OFDM long-haul transmission worth studying in the future.

- **Investigating the use of CO-OFDM with WDM passive optical networks (PONs)**

PONs are considered as a solution for the LAN and MAN networks, due to its cheap Electrical to optical E/O and Optical to Electrical O/E conversion. Although, the

PONs were extensively researched, their deployment in coherent optical networks has not been investigated.

- **Exploring the use of Wavelet Transform (WT) CO-OFDM**

OFDM modulation and demodulation is implemented electronically by IFFT/FFT. On the other hand, this modulation and demodulation can be implemented in a fashion similar to the FFT OFDM by using WTs, where the wavelets are the basic function instead of the sinusoids. In WTs, the subcarriers orthogonality can still be maintained because the signal is expanding in the Wavelet, which is an orthogonal set [51]. Unlike the sinusoids, which have infinite length, the WTs have finite length. This means WTs have localization in both frequency and time [51]. In addition, WTs can provide much better spectral roll-off, which eliminates the need for the cyclic prefix.

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Appendix A: List of Publications

Optics and Photonics Journal (OPJ)

DOI: [10.4236/opj.2013.35051](https://doi.org/10.4236/opj.2013.35051),

Volume 3, Issue 5 (September 2013), PP 330-335

Performance Study of 1 Tbits/s WDM Coherent Optical OFDM System

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Abstract

This Paper investigates the architecture of Tbits/s Wavelength Division Multiplexing (WDM) system by using a Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) with 4-QAM for long haul transmissions of 1800 Km SM. A simulation of 20 WDM channels spaced at 50 GHz, and 20 OFDM signals each with 50 Gbits/s bitrate to produce data rate of 1 Tbits/s are built. The system performance is studied by observing the constellation diagram of the signal and the relationship of BER and OSNR with regard to transmission distance. The results show that the BER is increased as the transmission distance increases. Also, as the transmission distance increased, the OSNR need to be increased to maintain BER less than 10^{-3} .

Keywords: WDM; QAM; CO-OFDM; BER; OS

1. Introduction

The demand for high data rate and high capacity in the optical communications field have motivated researchers to try different modulation formats that can support this demand. Among this was Coherent Optical OFDM which got special attention due to its tolerance to Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) [1]. In addition, CO-OFDM has great potential when it comes to receiver sensitivity and spectral efficiency. Tbits/s transmission rate is available through the WDM (Wavelength Division Multiplexing) transmission system; but, this system has a low spectral efficiency due to wavelength spacing [2-4]. However, integrating WDM with CO-OFDM will produce a system with high spectral efficiency; better tolerance to PMD and CD; and, significantly high data rate. Because of the great potential of CO-OFDM, it is considered the solution to upgrade today's 10 Gbits/s transmission rate to beyond 100 Gbits/s[5-8].

This paper demonstrates the architecture of Tbits/s WDM-CO-OFDM system. In this experiment we studied a WDM system by using CO-OFDM with 4-QAM (Quadrature Amplitude Modulation). 20 WDM channels are used with a 50 GHz wavelength space and 20 OFDM signals, each with 50 Gbits/s to produce a net data rate of 1 Tbits/s. To study the

performance of the system, we focused on the constellation diagram of the system and the relationship of the BER (Bit Error Rate) and the OSNR (Optical Signal to Noise Ratio) with regard to transmission distance.

2. System Design

The WDM CO-OFDM system is simulated and studied using an OptiSystem V.11 simulation tool. The simulation diagram is shown in **Figure 1**. The design consists of three main parts: CO-OFDM Tx (Transmitter), optical fiber link and CO-OFDM Rx (Receiver). In the WDM system, 20 channels with 50 GHz channel spacing are used to support 20 OFDM bands, each with a 50Gbits/s bitrate to reach 1 Tbits/s data rate. Important simulation parameters are shown in **Table 1**.

Table 1: Simulation global parameters

Global Parameters	
Sequence length	16384 Bits
Samples per bit	8
Number of samples	131072

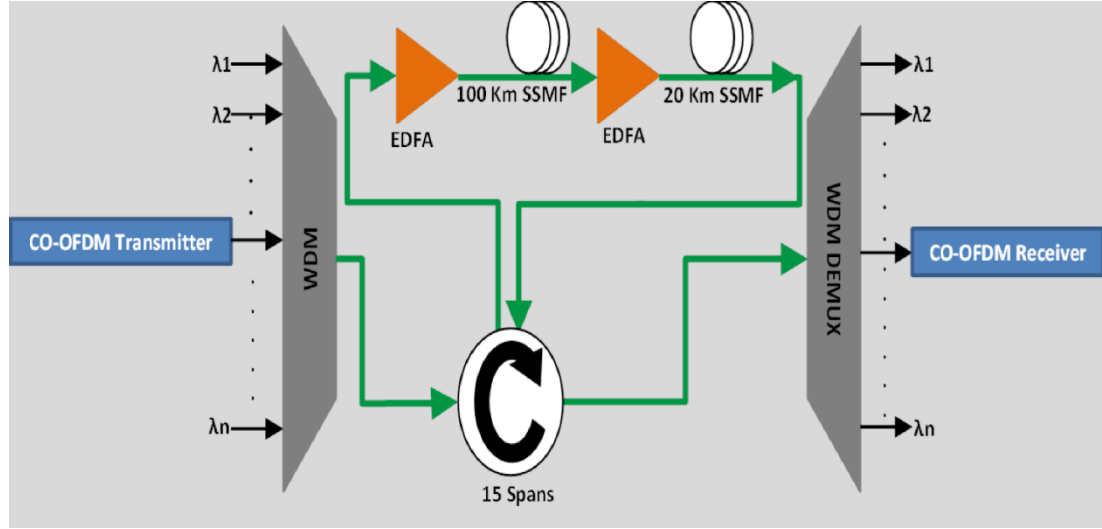


Figure 1: WDM CO-OFDM System design

2.1. CO-OFDM Tx Design

Figure 2 shows the CO-OFDM transmitter design; the bit stream is generated by a PRBS generator and mapped by a 4-QAM encoder. The resulting signal is modulated by an OFDM modulator; the parameters are shown in **Table 2**. After that, the resulting electrical signal is modulated to the optical signal using a pair of Mach-Zehnder modulators (MZM). **Figure 3** shows the in-phase and quadrature parts of the OFDM signal, where **Figure 4** shows the signal after the two MZMs which will be fed to the optical link. The laser source has a line width of 0.15 MHz and launch power of -5 dBm [9-10].

Table 2: OFDM Parameters

OFDM Modulator	
Number of subcarrier	512
IFFT	1024
guard interval	1/8

2.2. Optical Fiber Link

The optical link consists of 15 spans of 100 Km SMF, with a dispersion coefficient of 16 ps/nm/Km, nonlinearity coefficient of 2.6×10^{-20} ; and, attenuation of 0.2 dB/Km. SMF parameters are shown in **Table 3**. Fiber dispersion is compensated by the Dispersion Compensation

Fiber (DCF) of 20 Km with a -80 ps/nm/Km coefficient in each span; DCF parameters are shown in **Table 4**. The attenuation of SMF and DCF are balanced by optical amplifiers with 4 dB noise figure in each span.

Table 3: SMF Parameters

SMF	
Dispersion	16 ps/nm/km
Dispersion Slope	0.08 ps/nm ² /km
PMD Coefficient	0.2 ps/km
Effective area	80 μm^2
Nonlinearity Coefficient	2.6×10^{-20}
Attenuation	0.2 dB/km

Table 4: DCF Parameters

DCF	
Dispersion	-80 ps/nm/km
Dispersion Slope	-0.45 ps/nm ² /km
PMD Coefficient	0.2 ps/km
Effective area	30 μm^2
Nonlinearity Coefficient	2.6×10^{-20}
Attenuation	0.4 dB/km

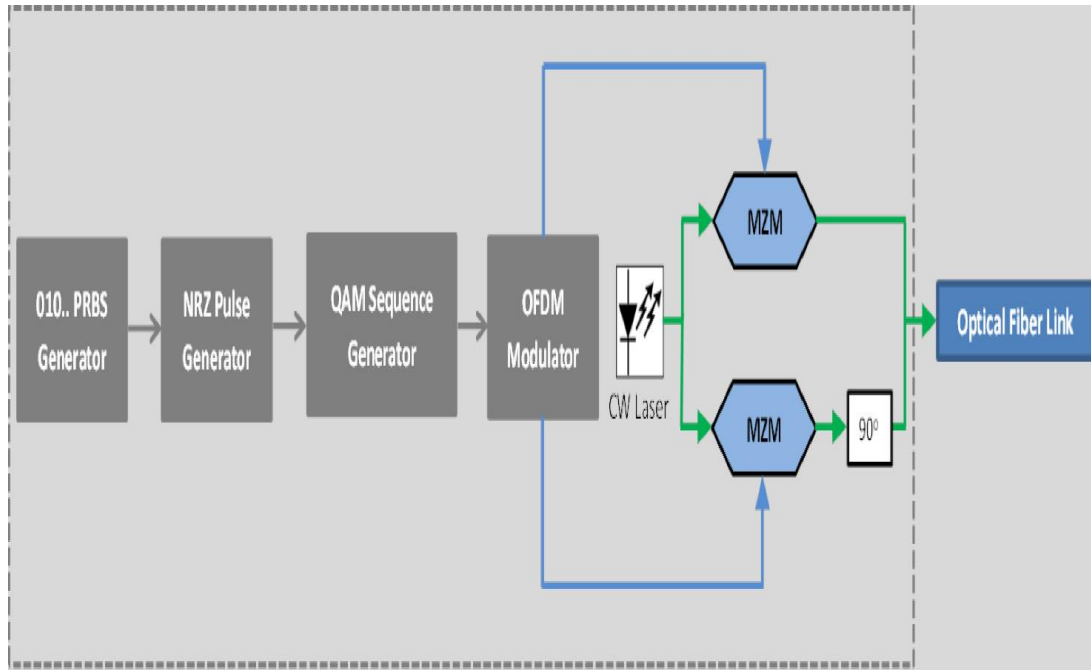


Figure 2: CO-OFDM Transmitter Design

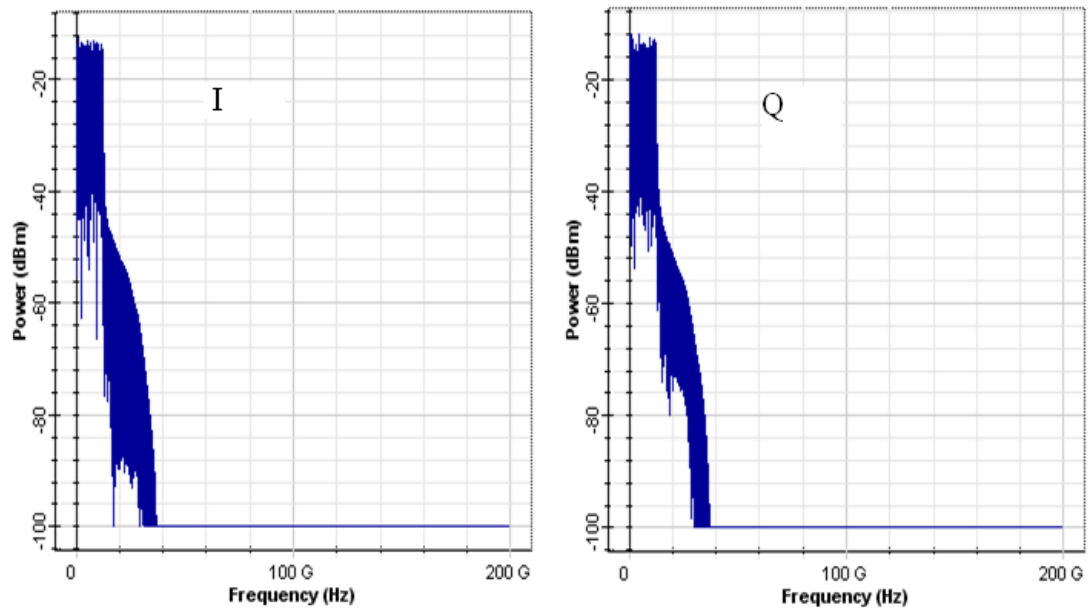


Figure 3: OFDM I/Q Spectrum

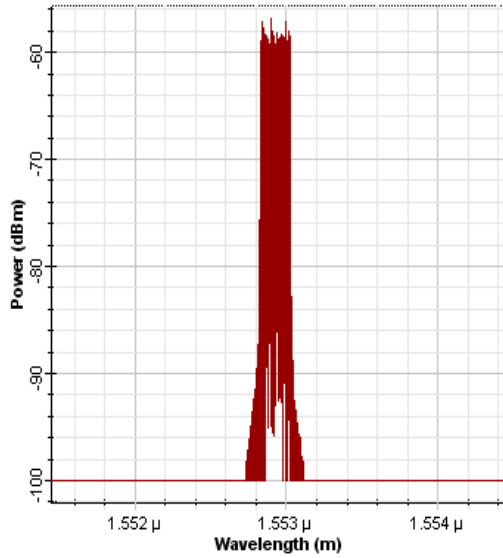


Figure 4: OFDM Signal after the two MZMs

2.3. CO-OFDM Rx Design

Figure 5 shows the CO-OFDM receiver design; to recover the I/Q component of the OFDM signal, two pairs of balanced PIN photodetectors and LO (Local Oscillator) lasers are used. The balanced detectors perform the I/Q optical to electrical detection and help perform the noise cancellation. Electrical amplifiers are used to adjust the signal intensity [11-12]. After the balanced detectors the resulting signal is demodulated using the OFDM demodulator with similar parameters as the OFDM modulator, the guard interval is removed. After that the signal is fed into a 4-QAM decoder, and the BER is calculated at the end [12-16].

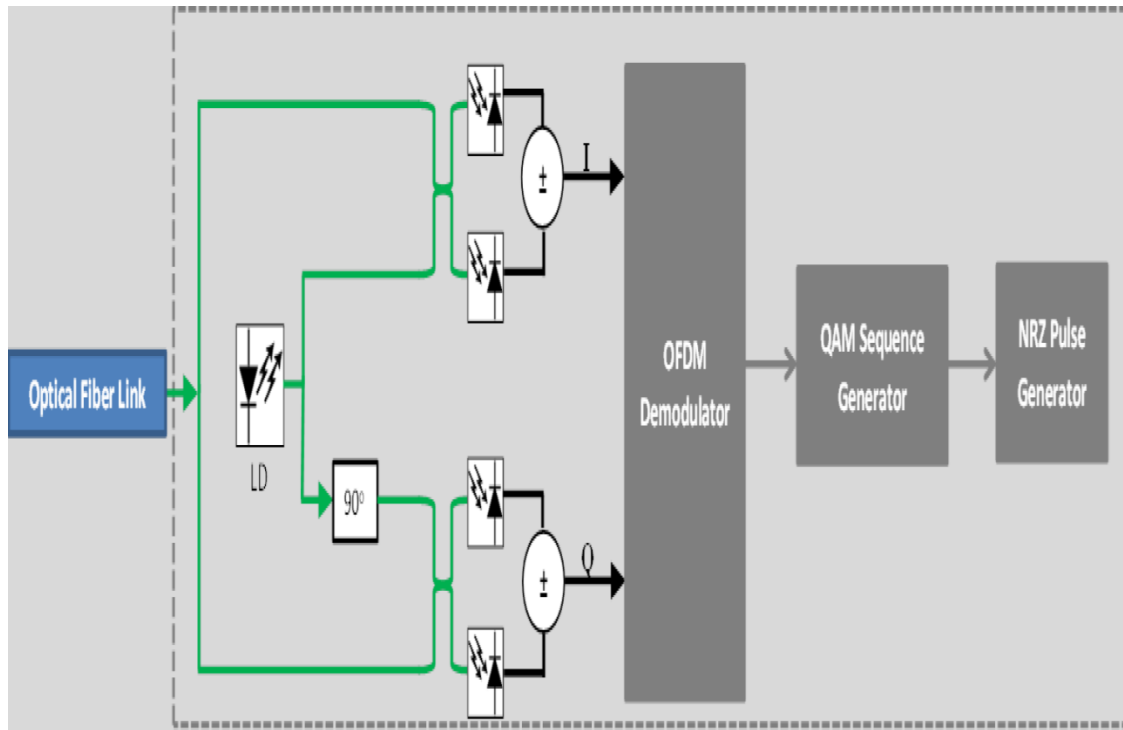


Figure 5: CO-OFDM Receiver Design

3. Results and Discussion

Figure 6 shows the RF spectrum of the signal at the transmitter side, where the power of the RF is approximately -12 dBm. **Figure 7** shows the RF spectrum at the receiver side after 1800 Km SMF. The power of the RF is decreased to -22 dBm, this decrease in power is because of the increase in fiber length which increases the attenuation.

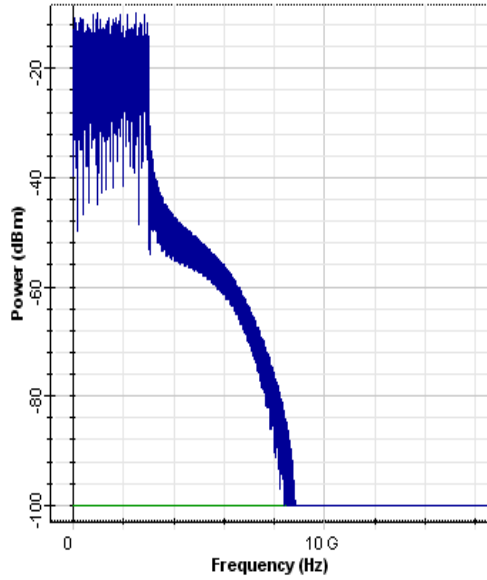


Figure 6: RF spectrum of the signal at the transmitter side

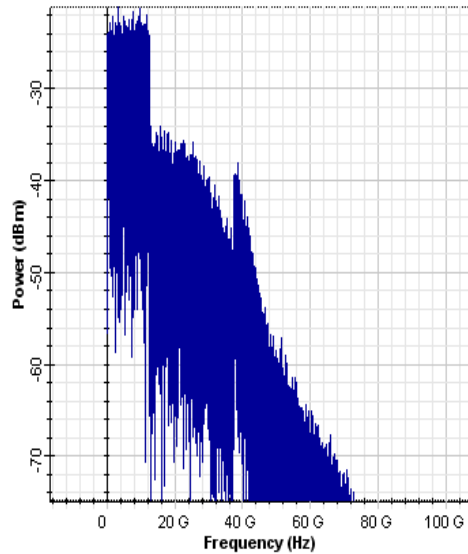


Figure 7: RF spectrum of the signal at the receiver side

Figure 8 shows the spectrum 20 OFDM signal after the WDM multiplexer. 20 WDM channels start from 193.05 THz to 194 THz with 50 GHz of channel space.

The constellation visualizer is an important tool to find if the signal is recovered correctly. The constellation diagram can determine the interference and distortion that happened to the signal. **Figure 9** shows the electrical constellation diagram of the 4-QAM digital modulator at the transmitter side.

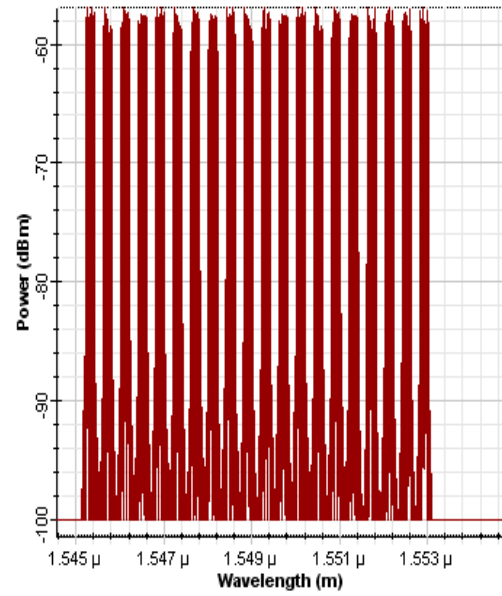


Figure 8: 20 WDM CO-OFDM Channels

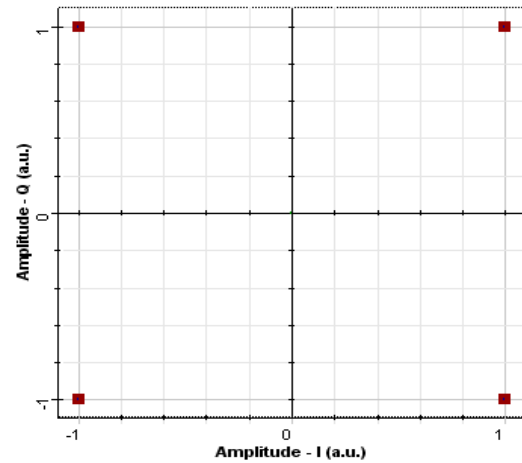


Figure 9: 4-QAM constellation diagram at the transmitter side

Figure 10 shows the constellation diagram after 1800 SMF and before using the DCF. It is clear

that the chromatic dispersion and the nonlinearity impairments affect the system. So, to improve the signal and remove chromatic dispersion that occurs because of the increase in transmission distance and the data rate, DCF is used. **Figure 11** shows the constellation diagram of the signal after using the DCF.

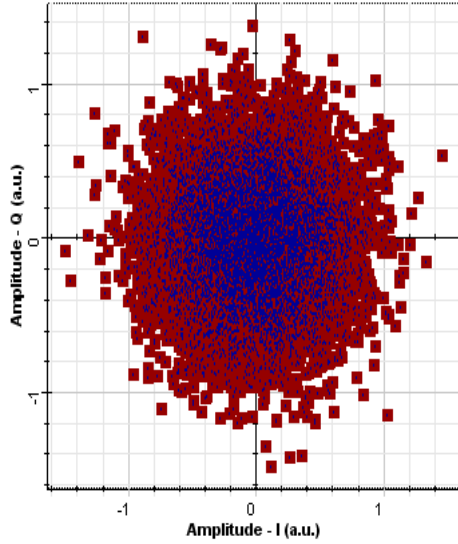


Figure 10: Constellation diagram after 1800 Km before using the DCF

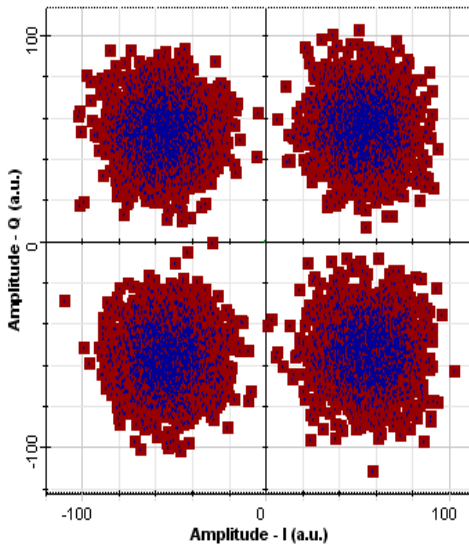


Figure 11: Constellation diagram after 1800 Km after using the DCF

To study the performance of the system for the high data rate, the relationship of the BER and the OSNR with regard to the transmission distance is

studied. **Figure 12** shows the relationship of the BER and the transmission distance. As can be seen, the BER of short distances is good. However, the BER increases as the transmission distance increases. This happens because of the fiber dispersion which causes the optical pulse to be broadened and produces Intersymbol Interference.

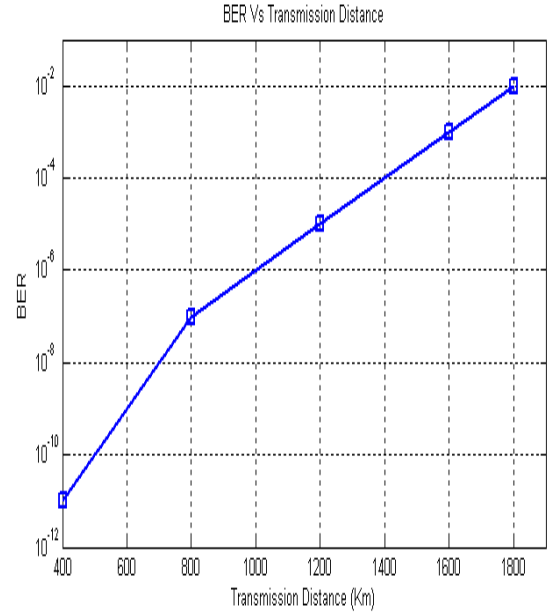


Figure 12: The relationship of BER and transmission distance

Figure 13 shows the relationship of the BER and the OSNR for different transmission distances. As can be seen from the figure, as the transmission distance increases, larger OSNR is required to maintain a BER of less than 10^{-3} . However, increasing the OSNR will increase the nonlinearity effects in the fiber which will make the system worse.

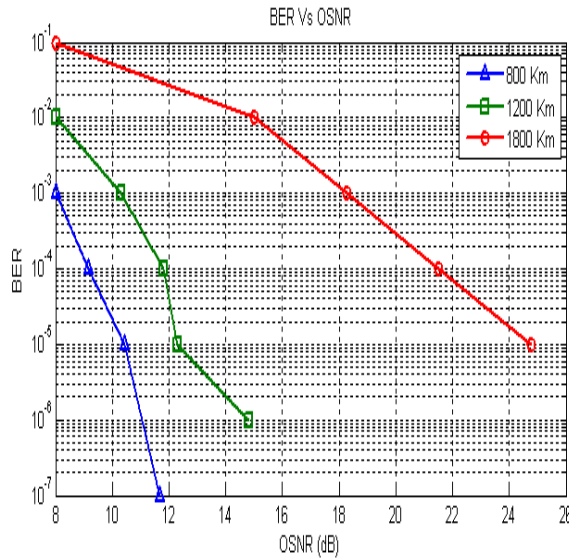


Figure 13: The relationship of BER and OSNR for different transmission distance

4. Conclusion

In this paper the architecture of Tb/s WDM systems are studied by using Co-OFDM. The simulation was designed by 20 WDM channels spaced at 50 GHz, and 20 OFDM signals, each with 50 Gbits/s bitrate to produce 1 Tbits/s data rate. The proposed system gives clear results and proved that it is reliable. The results shows that as the transmission distance increased the BER increased. Also, when the transmission distance increased, larger OSNR is needed to maintain a BER of less than 10^{-3} . However, increasing the OSNR will increase the nonlinear effects on the fiber. In the future study of the system higher order modulation such as: 16-QAM and 32-QAM will be used to improve the system performance.

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Integration of Coherent Optical OFDM with WDM

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ABSTRACT

This paper proposes a system design that integrates CO-OFDM with WDM to reach a data rate of 400 Gbits/s over 1000 Km Single Mode Fiber (SMF). The 400 Gbits/s signal is generated by multiplexing eight OFDM with 50 Gbits/s for each OFDM. We present the performance of CO- OFDM WDM back to back design by measuring the BER and the OSNR (Optical Signal to Noise Ratio) and the constellation diagram of each user. We will also show the performance of CO-OFDM WDM for 1000 Km SMF by measuring the BER and the OSNR of different WDM channels and studying the constellation diagram of each user.

Keywords: OFDM, CO-OFDM, WDM, OSNR, BER, IFFT, QAM, DCF.

1. INTRODUCTION

The need for high data rates has led the increased interest in Orthogonal Frequency Division Multiplexing (OFDM) in optical communication [1]. OFDM is intended to be used as the modulation technique in the next generation broadband wireless networks because it supports increased robustness with respect to narrowband interference and frequency selective fading [2]. Also, OFDM has the ability to deal with the delay spread of the multi-path. The principle of operation of OFDM is that it divides high data rate streams into lower data rate streams. Then, the entire low data rate stream is transmitted at the same time over a number of sub-carriers. Because of this the duration of symbol is increased [2]. Therefore, the amount of dispersion generated from delay spread of the multi-path will be reduced significantly.

As mentioned before, OFDM uses a number of subcarriers to send parallel low data rate streams. The sub-carriers of the OFDM can be modulated by using different types of modulation, such as Quadrature Amplitude Modulation (QAM) or Phase Shift Keying (PSK) [3]. After that, the subcarriers are carried over a high frequency carrier (e.g. 7.5 GHz). The Fast Fourier Transform (FFT) and the Inverse Fast Fourier Transform (IFFT) are very effective algorithms that can be used in the OFDM transceivers. These effective algorithms prove that OFDM has higher scalability above the data rate and the channel dispersion [3].

In optical fiber communication systems, OFDM has received great attention as an effective modulation technique to overcome different restrictions in the optical fiber transmission systems, such as relative intensity noise, modal dispersion, , chromatic dispersion (CD), polarization mode dispersion (PMD) [4]. Coherent optical OFDM (CO-OFDM) has emerged as an efficient technique for high data rates beyond 100 Gbps. CO-OFDM integrate the advantages of OFDM modulation technique and coherent detection technique and have many benefits that are crucial for the future of high-speed fiber optic transmission systems [4].

One of the main advantages of using CO-OFDM in the optical fiber communication system is its ability to reduce the effect of the chromatic dispersion (CD) and the polarization mode dispersion (PMD) [5]. Also, it can give high spectral efficiency because the OFDM subcarriers spectra are incompletely overlapped. Moreover, the electrical bandwidth of the CO-OFDM transceiver can be considerably reduced by using direct up/down conversion. These features are greatly appealing for designing high-speed circuits. CO-OFDM is a technology that has a great potential for getting high speed data rates in today's transmission systems [5].

Theoretical principles for OFDM:

The OFDM modulation technique is used in this design to modulate the electrical signal. A multi carrier modulation (MCM) signal at transmitter side can be described as follow [5][6]:

$$s(t) = \sum_{l=-\infty}^{+\infty} \sum_{k=1}^N c_{kl} s_k(t - iT_s) \quad (1.1)$$

$$s_k(t) = \Pi(t) e^{2\pi j f_k t} \quad (1.2)$$

$$\Pi(t) = \begin{cases} 1, & 0 < t \leq T_s \\ 0, & \text{otherwise} \end{cases} \quad (1.3)$$

The subcarrier is denoted by s_k and c_k represents the information of k th subcarriers. N stands for the subcarriers number. The subcarrier frequency is represented by f_k . The symbol period is denoted by T_s and $\Pi(t)$ represents the function of the pulse shaping. The m th sample of $s(t)$ with sampling period of T_s/N can be described as [5][6]:

$$s_m = \sum_{k=1}^N c_k \cdot e^{j2\pi f_k(m-1)T_s/N} \quad (1.4)$$

In the OFDM system, a number of subcarriers frequencies are selected, where all subcarriers are orthogonal to each other. To maintain the orthogonality in the OFDM subcarriers, the following equation should be satisfied [6]:

$$f_k = \frac{(k-1)}{T_s} \quad (1.5)$$

By substituting the value of f_k in Eq.1.4, we get the following equation [6]:

$$s_m = \sum_{k=1}^N c_k \cdot e^{j2\pi(m-1)(k-1)/N} \quad (1.6)$$

It is noticed that s_k is the Inverse Fourier Transform (IFT) of the input signal c_k . The recovered signal \hat{c}_k can be defined as the Fourier transform of \hat{s}_k , which is the received signal [6].

$$\hat{c}_k = \frac{1}{\sqrt{N}} \sum_{m=1}^N \hat{s}_m \cdot e^{-j2\pi(m-1)(k-1)/N} \quad (1.7)$$

It is clear that from Eq.1.6 the OFDM signal is consisting of a summation of many subcarriers. Subsequently, OFDM signal will have high peak to average power ratio (PAPR) compared to single carrier (SC) signals [6].

$$PAPR = \frac{\max\{|s(t)|^2\}}{E\{|s(t)|^2\}}, t \in [0, T_s] \quad (1.8)$$

2. SYSTEM DESIGN

This paper concentrates on the integration between CO-OFDM and WDM to reach high data rates (400 Gbps). Figure 1 shows the conceptual system design of the system. The design consists of three main parts: CO-OFDM transmitter, optical fiber link, and CO-OFDM receiver. Wavelength Division Multiplexing (WDM) is used to support the high data rate with eight channels spaced at 50 GHz to support eight OFDM signals each with 50 Gbps to reach 400 Gbps data rate.

OptiSystem V.11 simulation tool is used to fully design, implement, and study the system. Some important parameters are shown in Table 1, which must be taken into consideration to make the system work properly and to get the right results [7].

Table 1: Simulation Global Parameters

Global Parameters	
Sequence length	16384 Bits
Samples per bit	8
Number of samples	131072

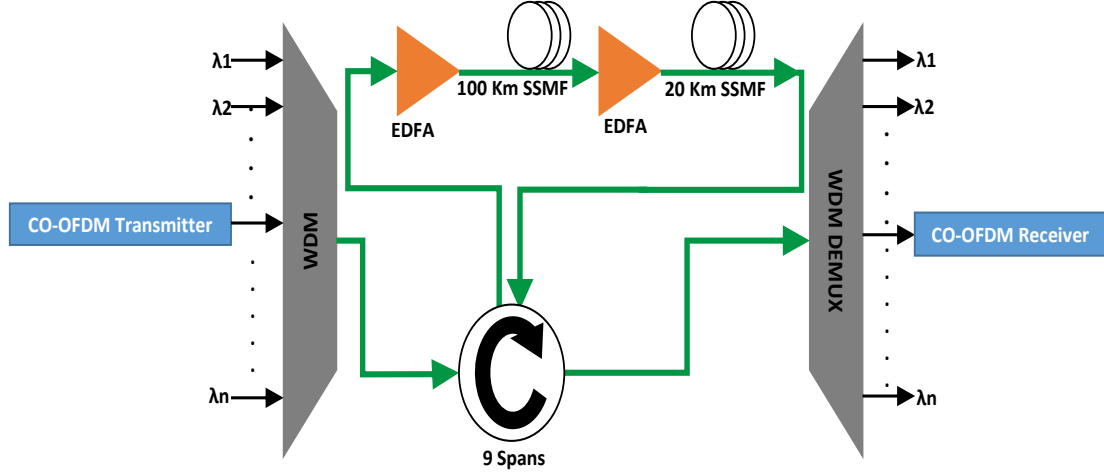


Figure 1: the conceptual system design of the system

2.1. CO-OFDM Transmitter

Figure 2 shows the design of CO-OFDM transmitter; the input signal is connected to a 4-QAM sequence generator and modulated by the OFDM modulator. The OFDM subcarrier is 512, the number of FFT points is 1024 and the guard interval is 1/8. The resulting signal from the OFDM modulator is transmitted to direct I/Q optical modulator, which consist of an optical power splitter, two Mach-Zehnder Modulators (MZMs) and a power combiner [8-10]. The laser source is connected to the power splitter and the output signals are fed to the two MZMs which are driven by the components of the OFDM. The resulting signals from the two MZMs are combined to be transmitted to the optical fiber link [11-12].

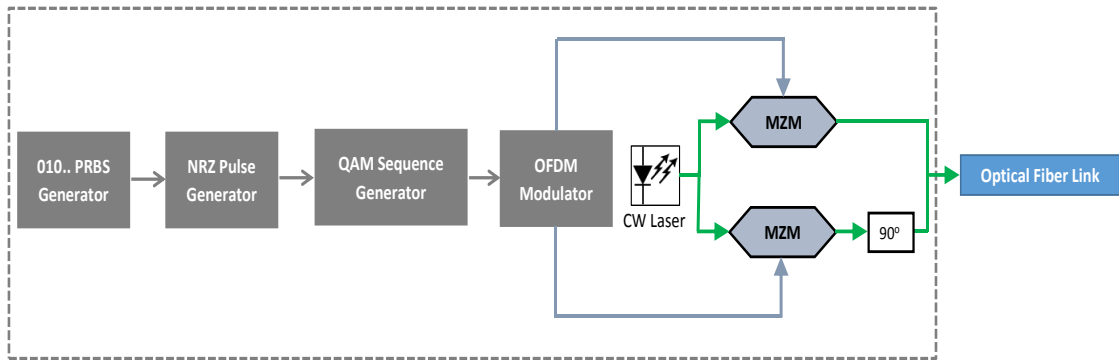


Figure 2: CO-COFDM transmitter.

2.2. Optical Fiber Link

Before the optical fiber, the eight OFDM signals are multiplexed using eight channels WDM and then launched to the optical fiber link. A multi-span optical fiber is used, which consist of 9-spans of 100 Km Single Mode Fiber (SMF), the SMF parameters are shown in Table 1. The dispersion of the fiber is compensated using DCF (Dispersion Compensation Fiber) of 20 Km in each span; Compensation parameters are shown in Table 2 [13] [14]. Two EDFAs are used in the fiber link to compensate the loss.

Table 2: SSMF Parameters

SSMF	
Dispersion	16 ps/nm/km
Dispersion Slope	0.08 ps/nm ² /km
PMD Coefficient	0.2 ps/km
Effective area	80 μm^2
Nonlinearity Coefficient	2.6×10^{-20}
Attenuation	0.2 dB/km

Table 3: Compensation Parameters

DCF	
Dispersion	-80 ps/nm/km
Dispersion Slope	-0.45 ps/nm ² /km
PMD Coefficient	0.2 ps/km
Effective area	30 μm^2
Nonlinearity Coefficient	2.6×10^{-20}
Attenuation	0.4 dB/km

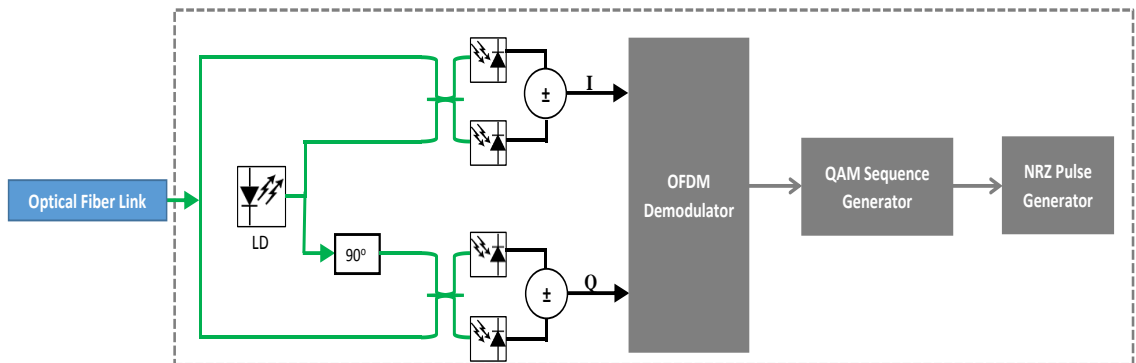


Figure 3: CO-OFDM Receiver.

2.3. CO-OFDM Receiver

Figure 3 shows the design of the CO-OFDM receiver which consists of four balanced PIN photodetectors and a local laser with a wavelength equal to the center of each band. Noise cancellation is performed by using the balanced detectors [15]. The output signal from the optical fiber link is received by the four balanced receivers to perform I/Q optical to electrical detection. The resulting signal is transmitted to OFDM demodulator to be demodulated and to remove the guard interval. After that, the resulting signal is transmitted to the 4-QAM sequence generator [15][16].

3. RESULTS and DISCUSSION

The undistorted RF spectrum of CO-OFDM transmitter is shown in Figure 4. The power of RF is measured at -12 dBm. Figure 5 shows the RF spectrum of CO-OFDM receiver; the signal is spread over 1000 km SMF. The power of RF is decreased to -34 dBm, this degrades the power occurred because of the attenuation increase due to the high increase of the fiber length. Figure 6 shows the eight OFDM spectrums after the WDM system. Eight WDM channels start at 193.05 THz up to 193.4 THz with channel space of 50 GHz.

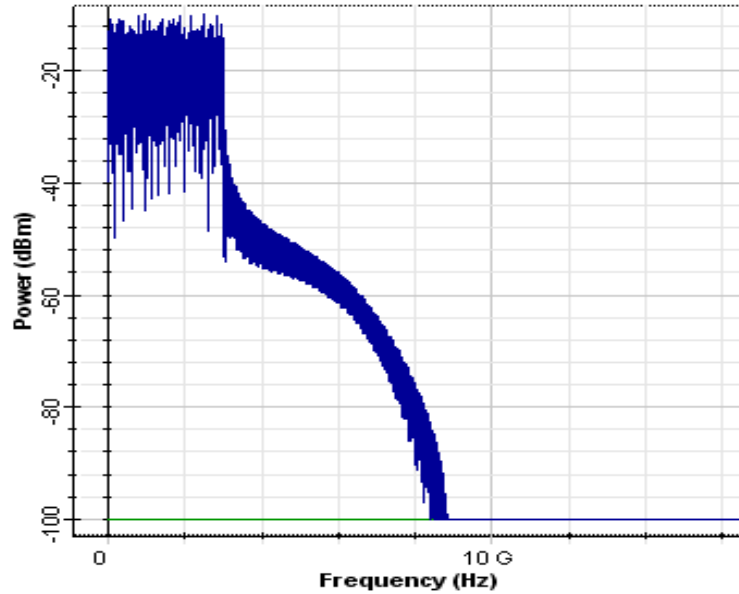


Figure 4: RF spectrum for CO-OFDM at the transmitter.

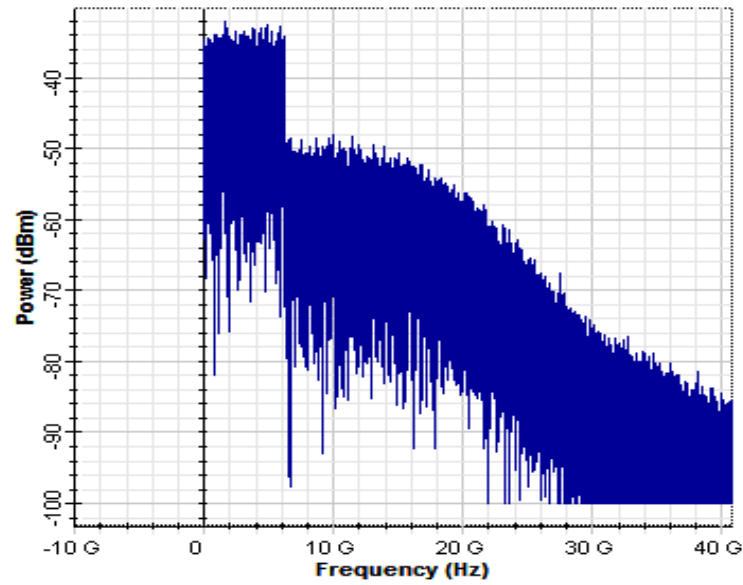


Figure 5: RF spectrum for CO-OFDM at the receiver.

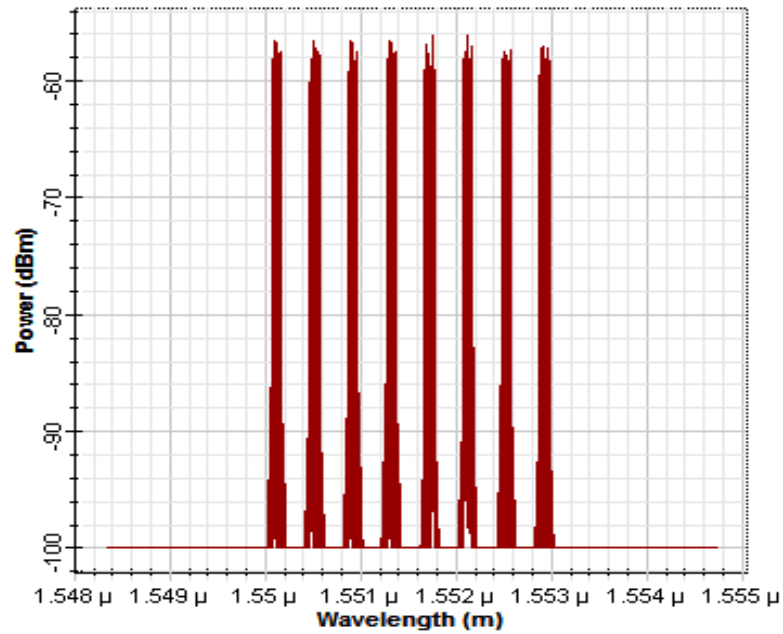


Figure 6: the spectrum of the 8 CO-OFDM signals after the WDM multiplexer.

The constellation diagram demonstrates a signal that is digitally modulated and displays it as a two-dimensional scatter diagram. The measurements of the constellation diagrams determine the effect of distortion and interference in a signal. In Figure 7, the transmitted signal is clearly shown by the electrical constellation diagram for 4-QAM digital modulator at the CO-OFDM transmitter.

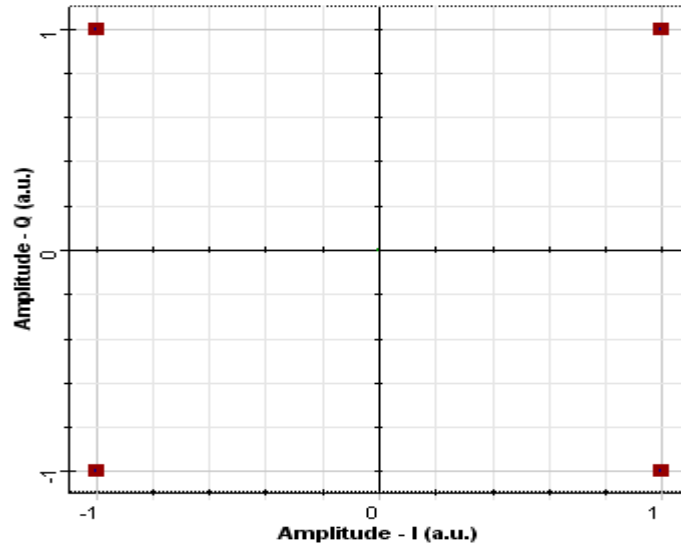


Figure 7: the constellation diagram at CO-OFDM transmitter

Figure 8 shows the constellation diagram of the back-to-back CO-OFDM system with no fiber in use; as can be seen from the figure the signal is delivered successfully. Figure 9 shows the constellation diagram of the system after 1000 Km SMF, as can be seen from the figure the signal is distorted when compared to Figure 8 B2B constellation diagram; this distortion of the signal occurred because of the chromatic dispersion and the nonlinear effects due to the increase of the data rate and the transmission distance. To overcome this problem Dispersion Compensation Fiber is used; Figure 10 show the constellation diagram of the system at the transmitter side after using the DCF to compensate the fiber dispersion.

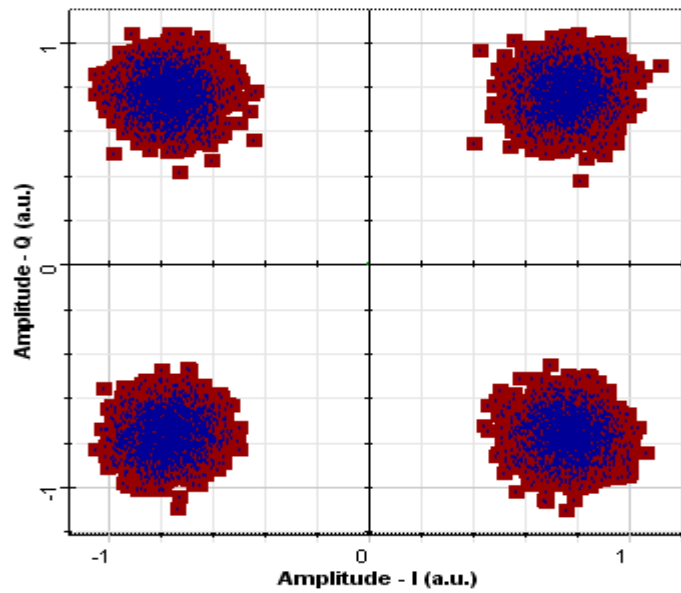


Figure 8: the constellation diagram of B2B CO-OFDM at receiver

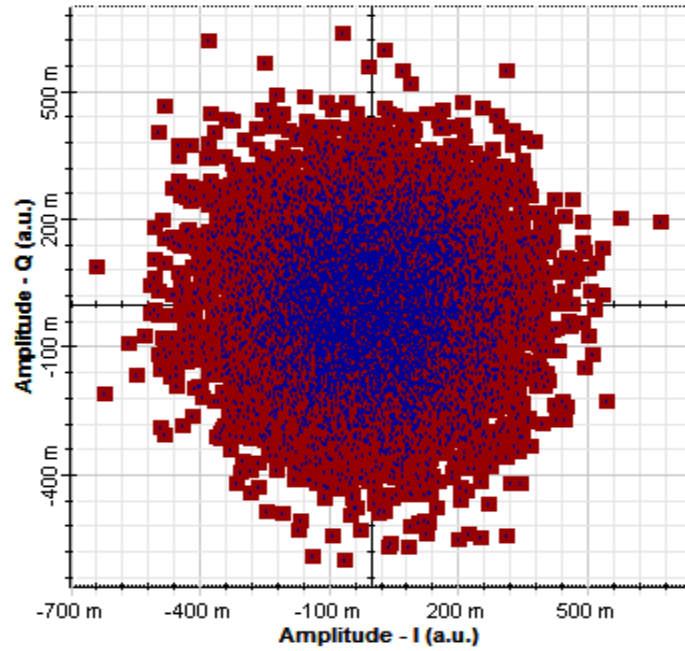


Figure 9: the constellation diagram of CO-OFDM at receiver after 1000 Km and before using DCF.

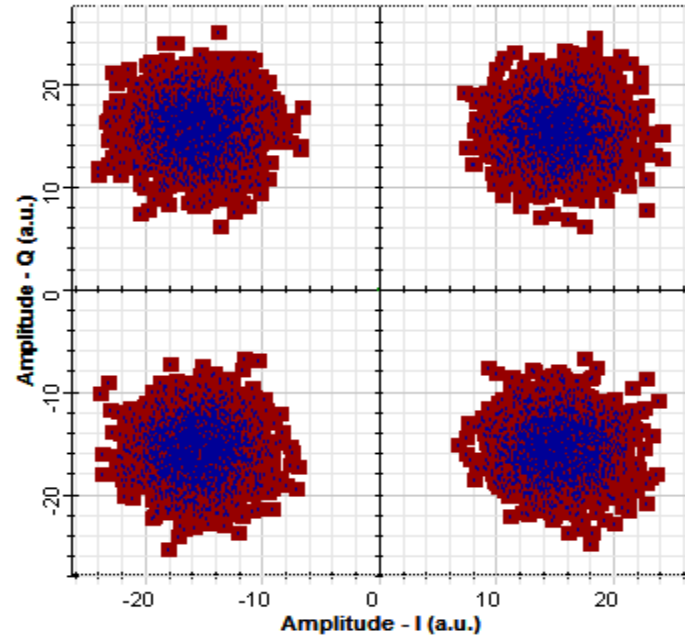


Figure 10: The constellation diagram of CO-OFDM at receiver after using DCF.

The high data rate long-haul system performance is studied by observing and analyzing the relationship of Bit Error Rate (BER) and transmission distance. Also, by studying the effect of the Optical signal to Noise Ratio (OSNR) on the system performance and the BER. Figure 11 displays the effect of the transmission distance on the BER. As can be seen in Figure 11, as the transmission distance increases the BER increases due to the increase of the fiber dispersion which will produce Intersymbol Interference that will affect the transmission of the signal.

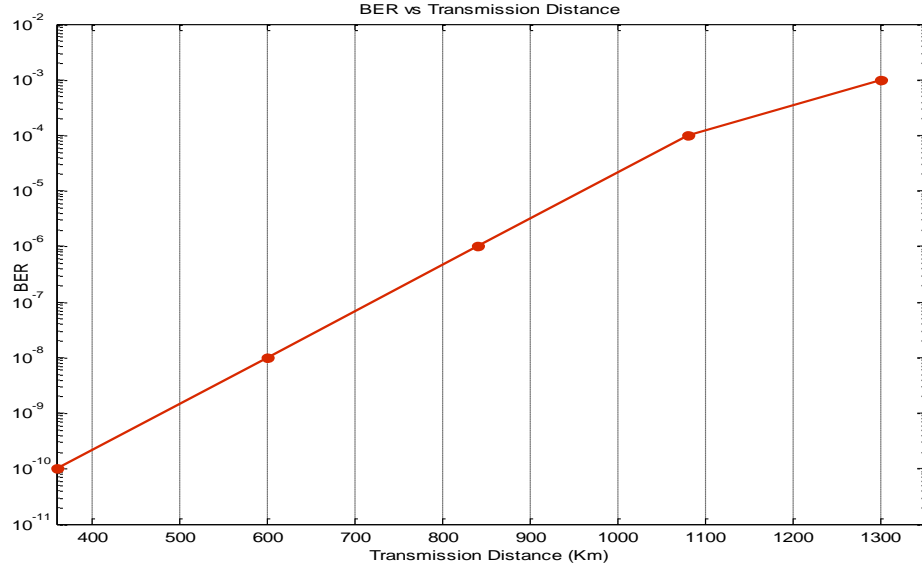


Figure 11: the relationship of BER and transmission distance

Figure 12 displays the effect of the OSNR on the BER of the system for the targeted transmission distance which is 1080 Km. As can be seen from Figure 12, increasing the OSNR will maintain BER less than 10^{-3} , however, increasing the OSNR should be limited because high OSNR will increase the nonlinear impairments on the system which will eventually affect the transmission of the signal and make it difficult to recover the original signal.

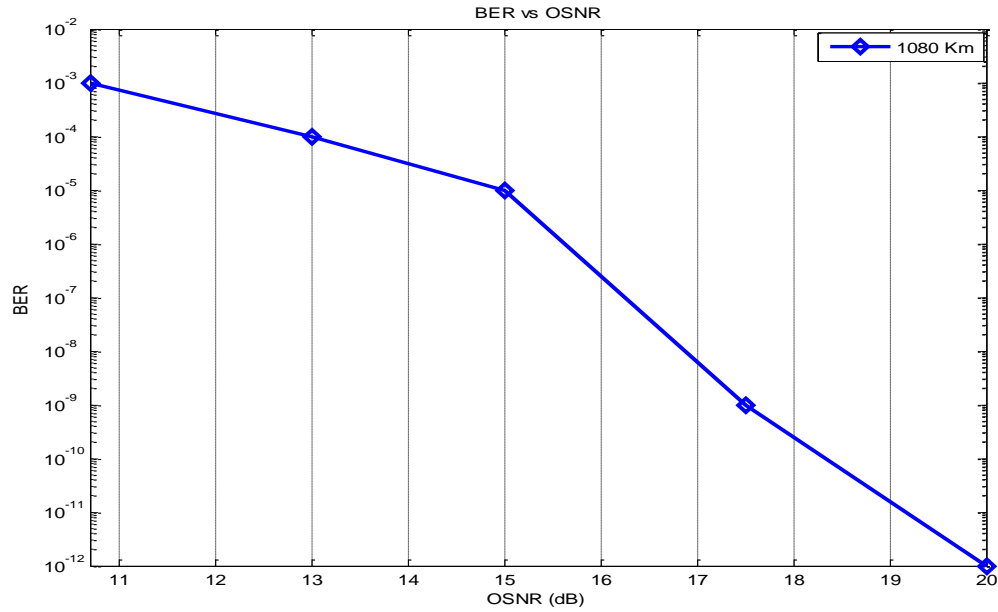


Figure 12: The relationship of BER and OSNR for 1080 Km

4. CONCLUSION

In this paper, the integration of the Coherent Optical OFDM with WDM has been studied and analyzed. The use of WDM helped to increase the capacity of the system and to reach a high data rate of 400 Gbits/s. The system was designed by eight channels spaced at 50 GHz to support eight OFDM signals each with 50 Gbps to reach 400 Gbps data rate. The proposed system gives clear results and the results proved that the system is reliable. The resulting data proved the effectiveness of the CO-OFDM-WDM system which can provide significantly high data rates. The results show that when increasing the fiber length the BER will increase and larger OSNR is required to keep the BER less than 10^{-3} . In the future study of the system, different modulation techniques, such as 16-QAM, and 64 QAM will be used to enhance system performance.

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Study of OFDM Technique on RoF Passive Optical Network

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Abstract

The combination of radio over fiber (RoF) and orthogonal frequency division multiplexing (OFDM) techniques has resulted in a high-data-rate. This paper investigates the use of the OFDM as a modulation technique for radio over fiber (RoF) in passive optical network (PON). A laser source of 1550 nm wavelength was used with 100Km, 140 Km and 288 Km single mode fiber. In the OFDM-PON a passive optical splitter of ratio 1:2 is used to connect two optical network units (ONUs). A 10 Gbits/sec transmission bit rate is used to simulate the ROF- OFDM-PON system. The proposed system can provide a flexible, cost effective and significant high data rate.

Keywords: OFDM, RoF, PON, ONU, RoF-OFDM, ISI, ICI, QA

1. Introduction

The demand for high speed data rate and high capacity of bandwidth has increased due to recent advances in technology in the access networks bandwidth. The integration of wireless communication networks and fiber optic networks has provided a large number of advantages such as a high data rate, larger bandwidth and low consumption of power. One of the promising techniques to support high data rates and bandwidth is with the use of passive optical network (PON). OFDM is a practical technique used to improve the efficiency of the PON used in the long haul application. OFDM is an efficient technique when used in fiber optical networks due to its ability to reduce chromatic dispersion in the optical fiber [1]. Because of its limited Inter Symbol Interference (ISI), and lower computational complexity OFDM has been widely used in the field of wireless communication. OFDM affords the high transmission rate and the preferred spectrum utilization with low cost optical components by using different types of M-array modulation, such as Quadrature Amplitude Modulation (QAM) or Phase-Shift-Keying (PSK) [2].

OFDM is established on the parallel transmission in frequency domain. ISI can be cancelled in OFDM because the symbols are long. The modulator in the OFDM contains an M-point of inverse discrete Fourier transform (IDFT), subcarrier mapping, conversion from serial to parallel, and the addition of a cyclic prefix and filter before each OFDM symbol.

A small portion of the last part of the OFDM symbol is duplicated to the prefix of the similar OFDM symbol. The prefix helps to cancel ISI and intercarrier interference (ICI), and to let the channel matrix to be circular. The IDFT in the receiver and its corresponding discrete Fourier transform (DFT) are applied with the inverse fast Fourier transform (IFFT) and the fast Fourier transform (FFT), correspondingly as shown in **Figure 1** [3].

This paper will concentrate on presenting and studying the efficiency of OFDM technique in RoF-PON architecture for downstream through M-array QAM modulation.

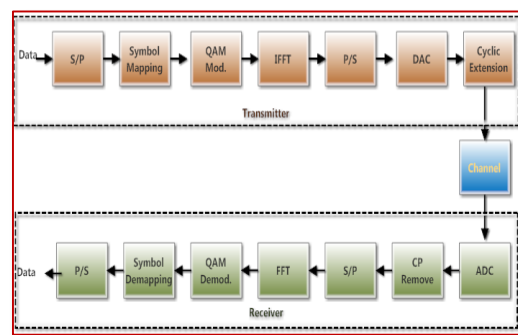


Figure 1: OFDM block diagram

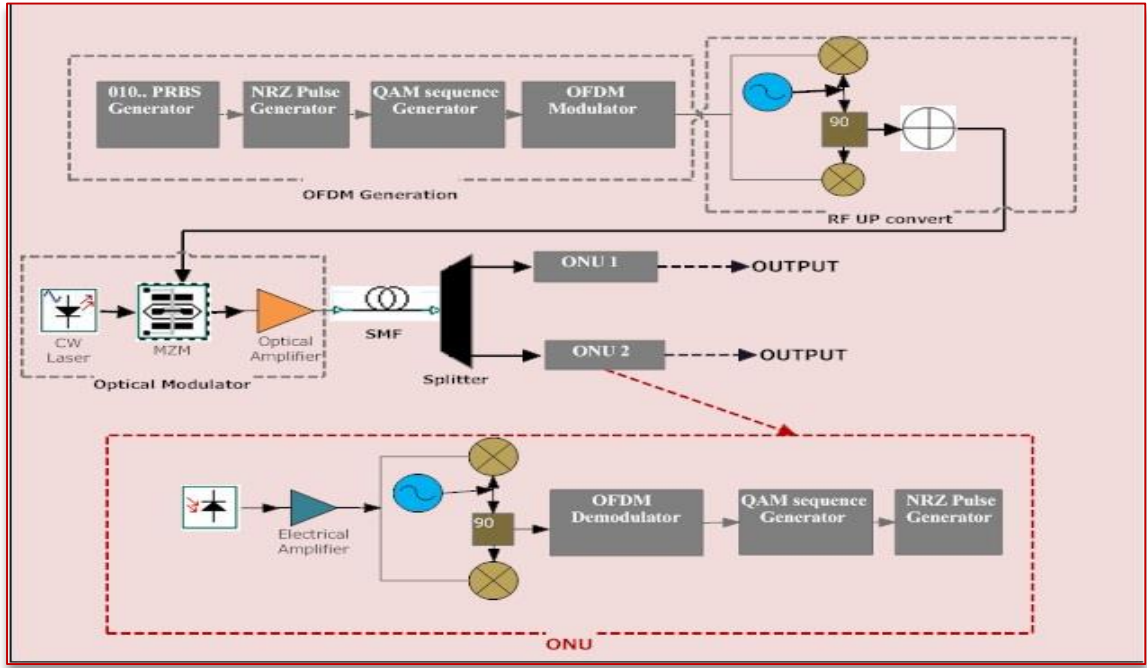


Figure 2: RoF OFDM-PON system design

2. System Design

The main goal of this paper is to investigate the integration of RoF (Radio over Fiber) with OFDM-PON (Passive Optical Network). The system design as shown in **Figure 2** includes three main parts which are the transmission part, the transmission link and the receiver part. For the transmission part, in order to generate OFDM signal, the input signal needs to be connected to M-QAM sequence generator, which is in our case 4-QAM followed by OFDM modulator [4]. After that, to integrate the OFDM signal RF or to convert the OFDM signal to RF, a RF-IQ mixer is used [4-6]. The resulting signal is combined with the light wave from the CW laser through an external modulator, Mach-Zehnder modulator [7-9]. The resulting signal from the modulator is transmitted over single mode optical fiber followed by a 1:2 optical splitter to make the use of the Passive Optical Network. After that, the resulting signal from the splitter is transmitted to two optical network units (ONUs). Each ONU contains a photo detector to convert the optical signal to Electrical signal, RF-IQ demux, OFDM demodulator and 4-QAM sequence generator.

To design and implement the system OptiSystem V.11 simulation software is used [10]. After designing the system, several parameters must be taken under consideration to get the right results, these parameters are defined in **Table 1**.

Table 1: Simulation Global Parameters

Global Parameters	
Bit rate	10 Gbits/s
Sequence length	16384 Bits
Samples per bit	4
Number of samples	65536

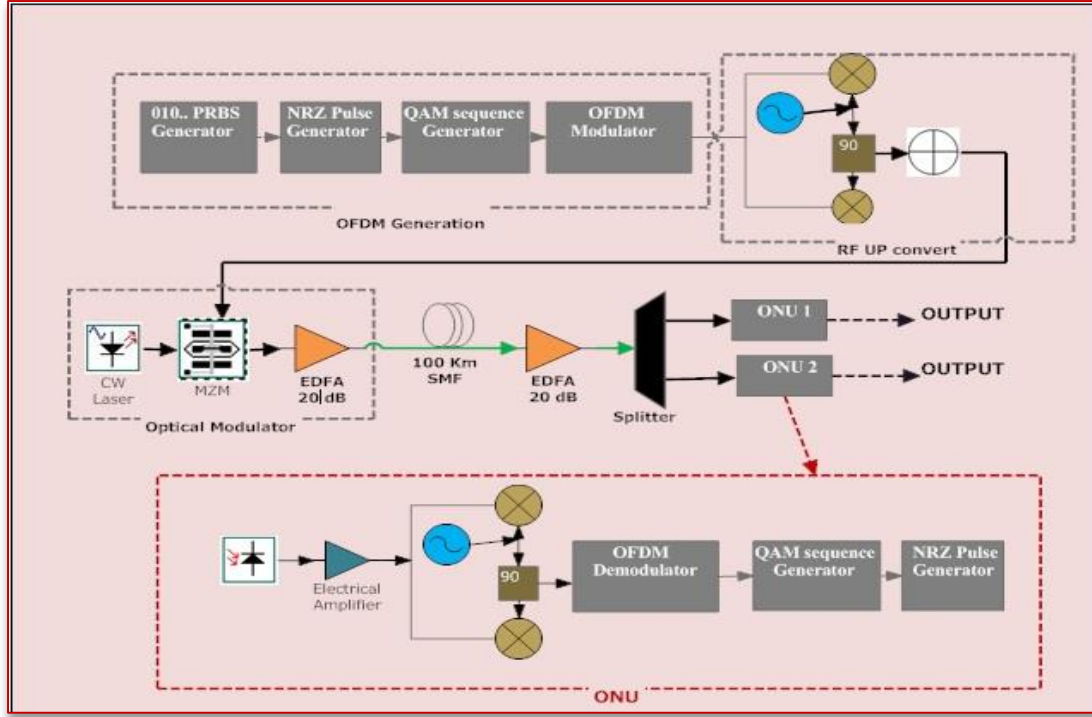


Figure 3: ROF-OFDM-PON-100 Km SMF system Design

2.1 RoF-OFDM-PON-100 Km-SMF System Design

The RoF-OFDM-PON design for 100 Km SMF is shown in **Figure 3**. The OFDM transmitter was defined for 4-QAM (2 bit-per-symbol). The signal from the OFDM generation was modulated by LiNbO₃ Mach-Zehnder modulator with CW laser of 193.1 THz. The modulated signal was transmitted over 100 Km-SMF with EDFA of 20 dB before the SMF and EDFA of 20 dB after the SMF. The signal from the SMF was detected by a photodiode (PD). After that, the RF signal was demodulated by Quadrature demodulator followed by an OFDM Demodulator and 4-QAM decoder to get the data.

2.2 Rof-OFDM-PON-140 Km-SMF System Design

Figure 4 shows the RoF-OFDM-PON design for 140 Km SMF. The OFDM transmitter was defined for 4-QAM (2 bit-per-symbol). The signal from the OFDM generation was modulated by LiNbO₃

Mach-Zehnder modulator with CW laser of 193.1 THz. The modulated signal was transmitted over 140 Km-SMF; however, the signal was corrupted due to dispersion from the long distance. So, in order to solve this problem the EDFA before the SMF was increased to 25 dB and the EDFA after the SMF was increased to 40 dB. After that, the signal from the SMF was detected by a photodiode (PD). After that, the RF signal was demodulated by Quadrature demodulator followed by an OFDM Demodulator and 4-QAM decoder to get the data. After modifying the EDFAs the signal improved significantly.

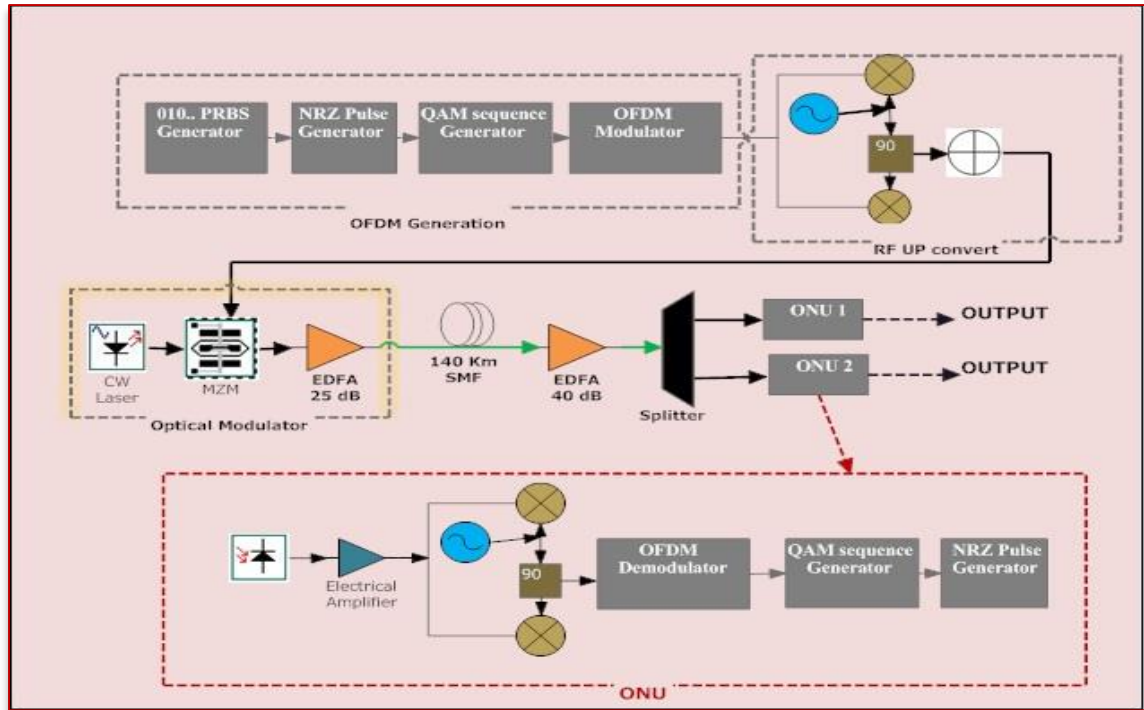


Figure 4: ROF-OFDM-PON-140 Km SMF system Design

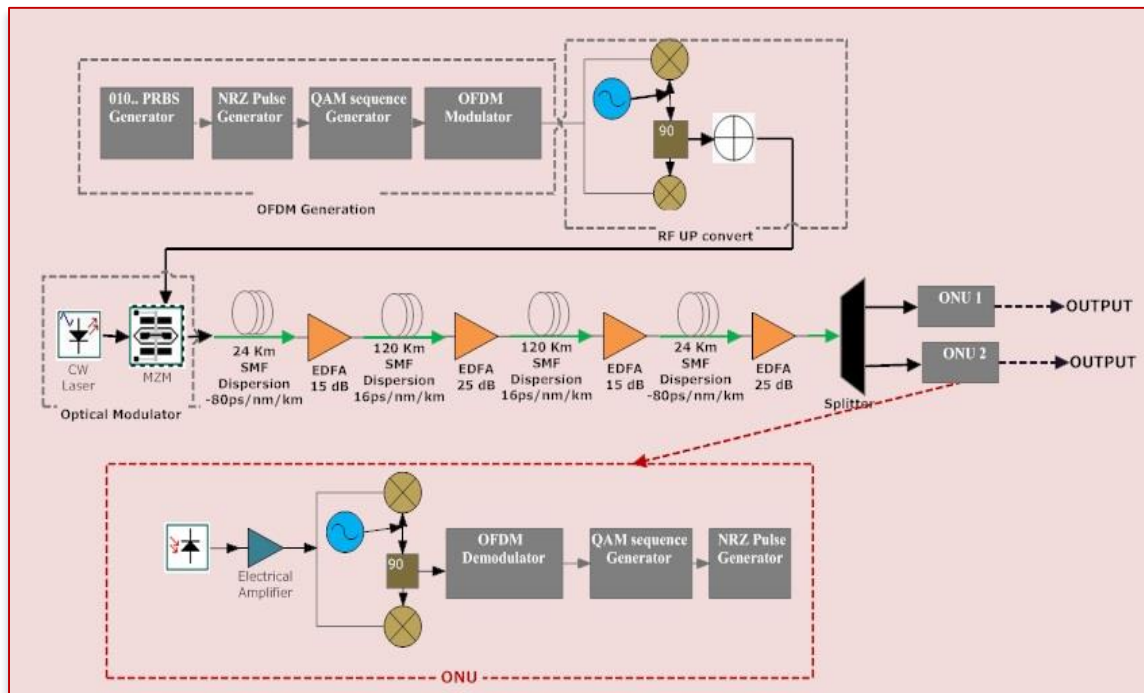


Figure 5: ROF-OFDM-PON-288 Km SMF with DCF system Design

2.3 ROF-OFDM-PON-288 Km SMF with DCF System Design

The RoF-OFDM-PON design for 100 Km SMF is shown **Figure 5**. After increasing the SMF length to 140 Km, different lengths was tested such as: 180-200-288 but even with increasing the EDFAs gain the signal was corrupted. The signal corruption is due to the chromatic dispersion because of the long distance and power attenuation. In order to solve this problem dispersion compensation must be used. So, to extend the transmission distance symmetric Dispersion Compensation Fiber (DCF) of 2XDCF and 2XSMF was designed to compensate the dispersion [12-14]. The SMF dispersion is 16 ps/nm/Km and length of 120 Km. for the DCF the dispersion is -80 ps/nm/Km and length of 24 Km. the SMF is followed by 25 dB EDFA to amplify the signal. The signal from the SMF was detected by a photodiode (PD). After that, the RF signal is demodulated by Quadrature demodulator followed by an OFDM Demodulator and 4-QAM decoder to get the data.

3. Results

The constellation diagram describes the signal that digitally modulated, presenting it as a two-dimensional dispersion diagram. **Figure 6** displays a pure electrical constellation scheme for the signal transmission for 4- QAM digital modulator 2 bits at the transmitter. Constellation diagrams can measure the distortion and interference in a signal.

Figure 7 displays the constellation of the 4QAM signal at the receiver when the length of the fiber is 100km. The signal begins to become indistinct, because Rayleigh scattering, chromatic dispersion, power attenuations, and noise when it is compared with the transmission signal in **Figure 6**. The blue points describe the noise that comes from the laser diode and the red points represent the signal.

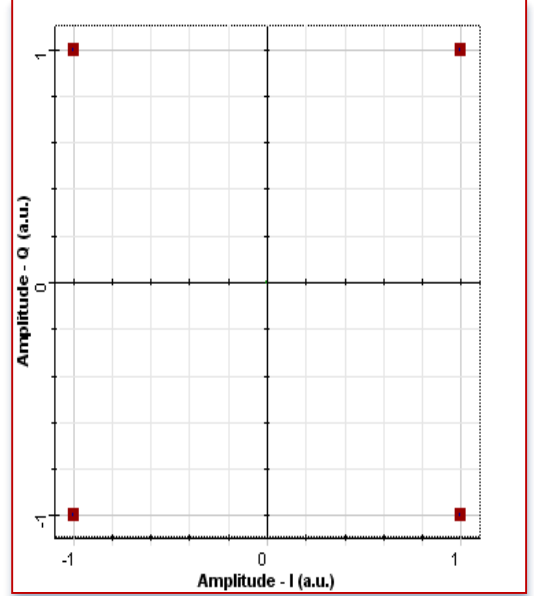


Figure 6: Constellation diagram for 7.5 GHz signal transmissions at transmitter.

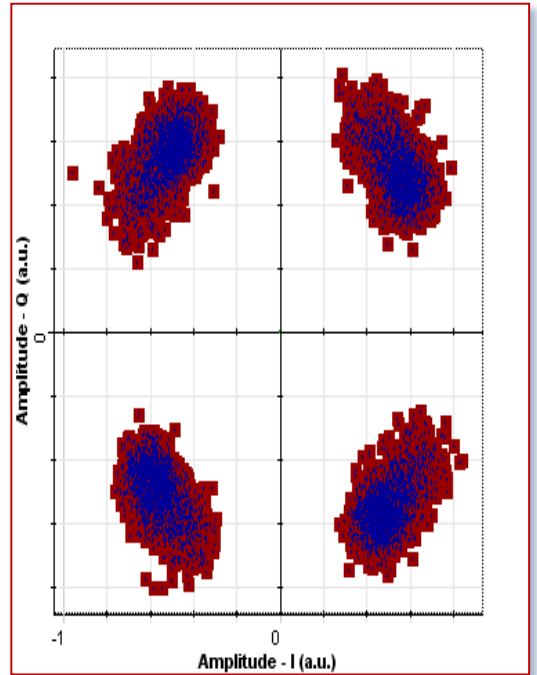


Figure 7: the Constellation diagram for SMF of 100km length.

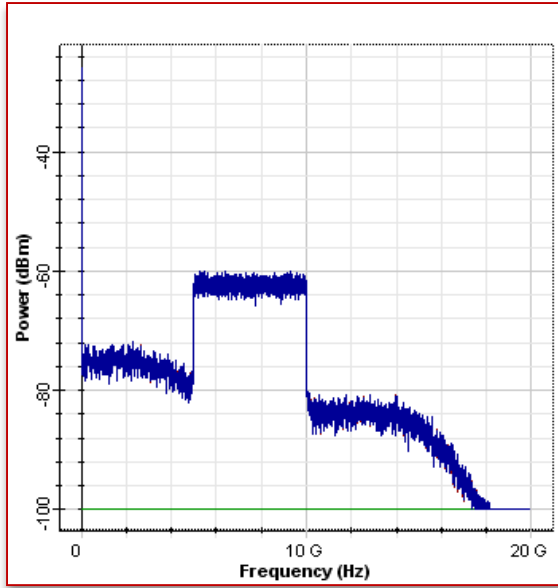


Figure 8: RF spectrum for 100km SMF

The RF spectrum of 4-QAM for 7.5GHz carrier frequency and 10MHz bandwidth is shown in **Figure 8**. The signal is distributed by SMF of 100km length. The photo detector changes the optical signal to an electrical signal. The power of the RF is measured at -60dBm. The noise, which is showed in green color, is measured at -100dB. The signal is showed in blue color.

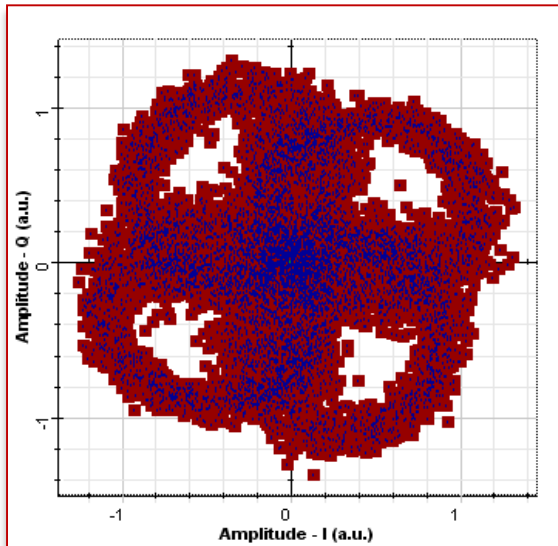


Figure 9: Signal constellation of 140km SMF length

The display of the electrical constellation of the signal after 140km is shown in **Figure 9**, it is clearly shows that the signal is corrupted. The signal started broadening when the length of the fiber exceeds 100km. This broadening occurred in the signal due the positive dispersion in the SMF. The chromatic dispersion is a major issue in the SMF when the signal travels for a long distance. It can affect the quality of the signal and also it can increase the attenuation power.

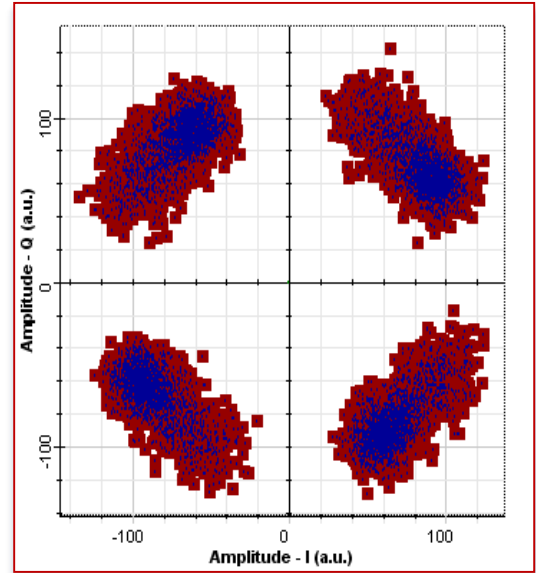


Figure 10: Constellation diagram of 140 km SMF for EDFAs power of 25 and 40dB, respectively.

Figure 10 presents the constellation diagram of the 140 km SMF. The EDFAs gains are increased to 25 and 40 dB, respectively to take off the dispersion from the signal. Consequently, the signal shows a great improvement when it is compared by **Figure 9**.

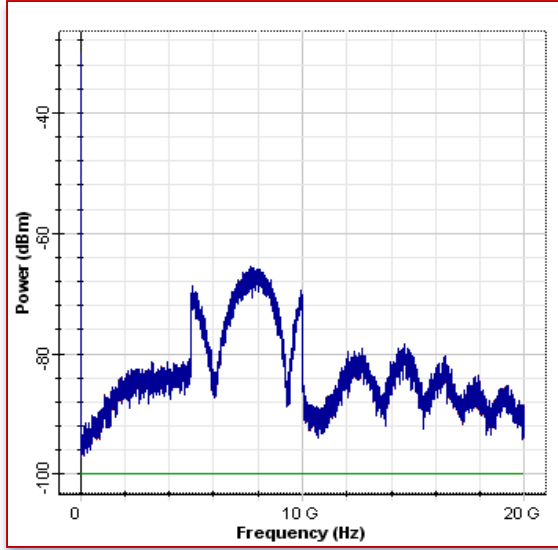


Figure 11: RF spectrum for 140km SMF

Figure 11 presents the RF spectrum of 4-QAM for 7.5GHz carrier frequency and 10MHz bandwidth. The signal is distributed by SMF of 140km length. The result displays that the power is reduced from -60 dBm to -65 dBm when the SMF length is increased to 140km. the reduction in the RF power is because of the attenuation in the SMF.

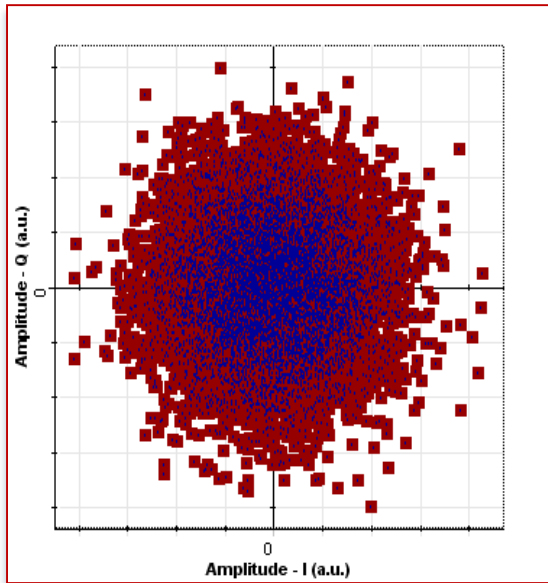


Figure 12: Constellation diagram of 288km SMF

Afterwards, the distance of the signal transmission is increased to 288km fiber length. The power of

the EDFAs is raised to more than 75dB but the corruption of the signal is still has not improved, as displayed in **Figure 12**. This means that increasing the power of the EDFAs cannot affect the quality of the signal or a fiber length of 288km, because the EDFA just amplifies efficiently, when the signal transmitted gets low power.

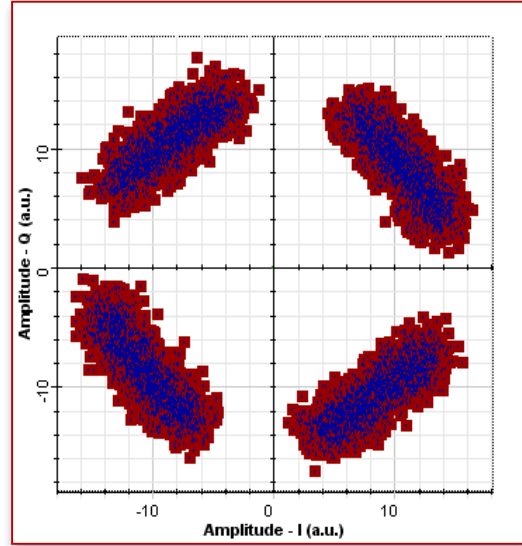


Figure 13: the constellation diagram for RoF (SMF-DCF) for SMF 288km

Figure 13 shows the constellation diagram of 4-QAM for a fiber length of 288km. It is clearly that the quality of the signal is much improved after using dispersion compensation fiber (DCF).

4. Conclusion

In this paper we studied and analyzed ROF OFDM-PON over 100Km, 140 Km, and 288 Km with a DCF single mode fiber by OptiSystem simulation software. In the OFDM-PON a passive optical splitter with a ratio 1:2 was used to connect two optical network units (ONUs). A 10 Gbits/sec transmission bit rate for the total system was used to simulate the OFDM-PON system. To analyze the performance of the system, an oscilloscope visualizer was used. Furthermore, to study a RF signal and the optical signal, a RF spectrum analyzer and optical spectrum analyzer were used. The Quadrature-Phase and In-Phase signals were analyzed using Electrical Constellation visualizer. The resulting data proved the effectiveness of the

ROF OFDM-PON. The study suggests that this system is not only flexible and cost effective, but also provides a significant high data rate.

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1.05Tb/s Optical-OFDM using ROF over 3600km

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Abstract

In this paper, an effort is made to analyze the integration of direct detection optical orthogonal frequency division multiplexing (DD-OFDM) with dense wavelength division multiplexing (WDM) to reach high data rates of 1.050 Tb/s over 3600 km single mode fiber (SMF). The 1.050Tb/s signal is generated by multiplexing 30 OFDM signals with 35 Gb/s for each OFDM. The performance of the system is studied by measuring the optical signal to noise ratio (OSNR) of each WDM channel; signal to noise ratio (SNR); and bit error rate (BER); while analyzing the constellation diagram of all users. Also, the relationship between the OSNR and BER is studied and it is noticed that as the OSNR increased, the BER decreased. As can be seen from the results as the transmission distance increased the BER increases and to keep the BER less than 10^{-3} we need to increase the OSNR.

Keywords: BER; OOFDM; DCF; ICI; ISI;

Introduction

The improvements in high-speed optical components and electronics support new optical communication systems with high data rates. Optical components can be shared between different WDM channels. WDM can increase bandwidth over optical fiber by sending several signals concurrently at different wavelengths [1]. Therefore, it can increase the system capacity while reducing the cost of the system. The possible bit rate for each WDM channel has been increased to more than 40 Gb/s and this implementation gets a high possibility for dispersion [2].

OOFDM is one of the advanced and efficient modulation techniques that have been used in the modern optical communication systems. OOFDM is used as the modulation technique in advanced optical communication systems because it offers robustness to narrowband interference and frequency selective fading [3]. DDO-OFDM when combined with WDM will provide a small increase in the nonlinearity of the optical system even with high number of channels. In addition, the main goal of DDO-OFDM is to have a simple transmitter and receiver which will provide a low cost system when compared to other methods such as Coherent Optical OFDM [3][4]. It is being offered as the premier long-haul transmission

design in direct detection and coherent detection. OOFDM is a part of multicarrier modulation (MCM) where the data information is transmitted over many subcarriers of lower rate. [4]. OOFDM modulation technique provides a number of great advantages when it is used in the optical communication system. It can reduce the amount of dispersion produced by multipath delay spread. Moreover, all OOFDM symbols used a guard interval, which gives the advantage of eliminating Inter-Symbol Interference (ISI) produced by a dispersive channel [5]. Furthermore, the OOFDM symbol is regularly extended to avoid Inter-Carrier Interference (ICI) [6]. In addition, using OOFDM in long-haul systems can compensate the linear distortions in the optical fiber, such as group velocity dispersion (GVD).

OOFDM uses different subcarriers to send low rates in parallel data streams. The M-array Quadrature Amplitude Modulation (QAM) or Phase Shift Keying (PSK) is used to modulate the subcarriers before being transported on a high frequency microwave carrier.

Because the duration of symbol is extremely longer than the root-mean-square (RMS) delay of the optical wireless channel, the multicarrier modulation has strong robustness to ISI. Consequently, OOFDM multilevel quadrature

amplitude modulation (MQAM) encourages the delivering of very high data rates [6], [7], and [8]. In the optical communication system, the information is transmitted on the optical signal intensity and hence it can be only positive (unipolar). In this paper, direct detection is used instead of coherent detection which means that there is no laser at the receiver acting as a local oscillator.

2. System Design

The paper studies the combination between OOFDM and WDM to get high data rates (1,050

Tb/s). **Figure 1** presents the theoretical design of the system-the

design is composed of three major parts: OOFDM transmitter, a fiber optic transmission link, and the OOFDM receiver. The use of WDM is to support a system of high data rates with thirty channels, each with 35 Gb/s and 100 GHz of spacing, to achieve data rates of 1,050 Tb/s.

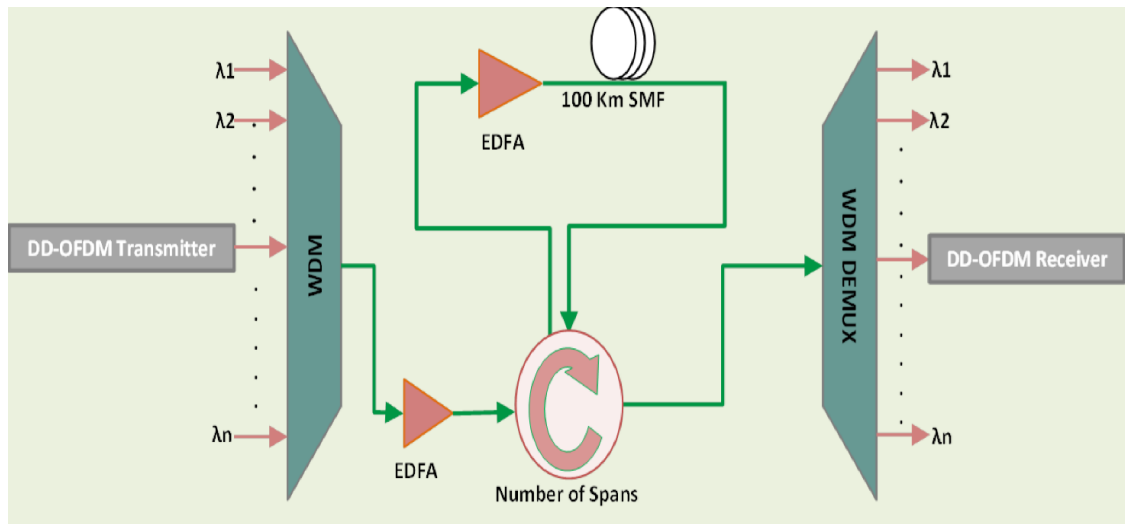


Figure 1: DD-OOFDM-WDM System design

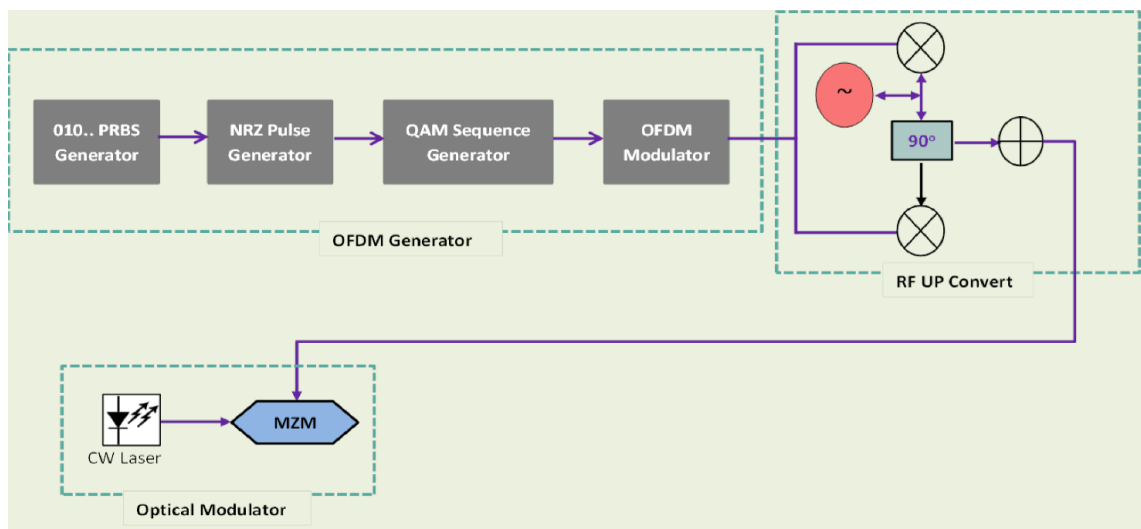


Figure 2: DD-OOFDM transmitter block diagram

2.1 DD-OOFDM Transmitter

A pseudo-random binary sequence (PRBS) block creates a random bit sequence to be the information of the OFDM signal. Then it is connected to a M-ary-QAM sequence generator. In this design, 64-QAM is used and followed by the OFDM modulator [9]. Consequently, the RF-IQ mixer is used to transform the OFDM signal to a radio frequency (RF) [9-11]. The OOFDM parameter is shown in **Table 1**. After that, the signal is mixed with the light wave generated from the continuous wave (CW) laser by an external modulator, which is a Mach-Zehnder modulator (MZM) [12-14]. **Figure 2** shows the design of OFDM transmitter. The signal that is produced from the MZM is connected to a fiber optic transmission link.

Table 1: OFDM Modulator Parameters

Number of subcarrier	512
Number of FFT points	1024
Cyclic Prefix	5/6

Table 1 shows the OFDM transmission parameters consisting of 512 sub-carriers, and a large Fast Fourier Transform (FFT) of 1024 with a bandwidth of 20MHz. The size of the cyclic prefix (CP) is calculated by multiplying CP with the whole number of electrical subcarriers (NFFT).

The output of OOFDM is modulated by a Quadrature modulator corresponding to Eq. (1) [15-16].

$$V_{out}(t) = G[I(t)\cos(2\pi f_c t + \varphi_c) - Q(t)\sin(2\pi f_c t + \varphi_c)] + b \quad (1)$$

Where I and Q are the input electrical signals, G presents Gain, $f_c = 7.5GHz$ is the carrier frequency, b stands for bias, and φ_c is the phase of the carrier.

2.2 Long-Haul Optical Fiber Link

Thirty OOFDM signals are multiplexed by using WDM and then sent to the optical fiber link. In this design, a single-mode fiber (SMF) with a wavelength around 1550 nm is used because it offers low attenuation at 0.2 dB. The total bandwidth provided at 1550 nm is approximately 8 THz. The total available bandwidth is divided into various channels, usually with 100 or 50 GHz bandwidth, and is known as dense wavelength-division multiplexing (DWDM). A multi-span of optical fiber consisting of 30-span of 120 Km SMF is used. Also, two erbium doped fiber amplifiers (EDFAs) are used before and after the optical fiber to compensate for the loss in the fiber. After linking the optical fiber transmission, the signal is connected to a WDM demultiplexer to separate the thirty OFDM signals.

2.3 DD-OOFDM Receiver

As shown in **Figure 3**, the output signal is received from the optical fiber by a PIN photodetector to convert the optical signal to an electrical signal. After that, the OFDM signal is recovered from the RF to a baseband by a Quadrature demodulator and then the signal is transmitted to the OOFDM demodulator. Finally, a QAM sequence decoder is used to decode the signal and to generate a binary signal. **Table 2** shows the OOFDM demodulator parameter.

Table 2: OFDM Demodulator Parameters

Bit rate	Bit rate/6
Number of subcarrier	512
Number of FFT points	1024

The system design is studied and implemented by using a sufficient simulation program called OptiSystem V.11. The global parameter of the system design is shown in **Table 3**.

Table 3: Simulation Global Parameters

Sequence length	16384 Bits
Samples per bit	4
Number of samples	65536

3. Dispersion Compensation Fiber (DCF) Design

One of the significant parameters that affect the quality of the signal over long haul transmission link is the dispersion in the fiber. DCF is a highly efficient technique to compensate the chromatic dispersion (CD) in high-speed transmission systems. DCF is designed to achieve a high negative dispersion of up to -80 ps/nm, which can

adjust the amount of CD in the optical fiber. The dispersion is broadband, so it has the advantage of adjusting multiple WDM channels at the same time without phase distortion [17].

In this paper, the dispersion post-compensation technique is used to compensate the dispersion and support the system to transmit over 3600 km SMF as shown in **Figure 4**.

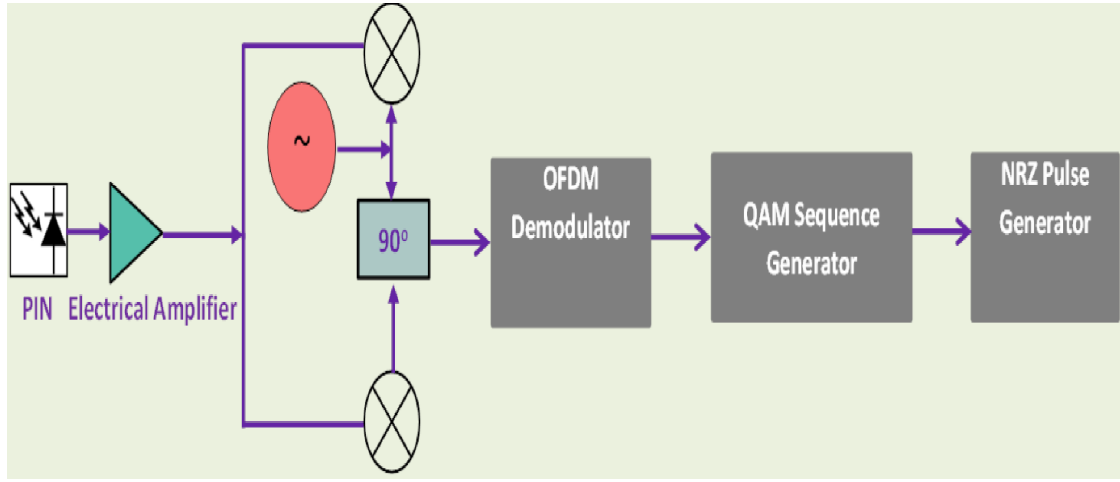


Figure 3: DD-OFDM receiver block diagram

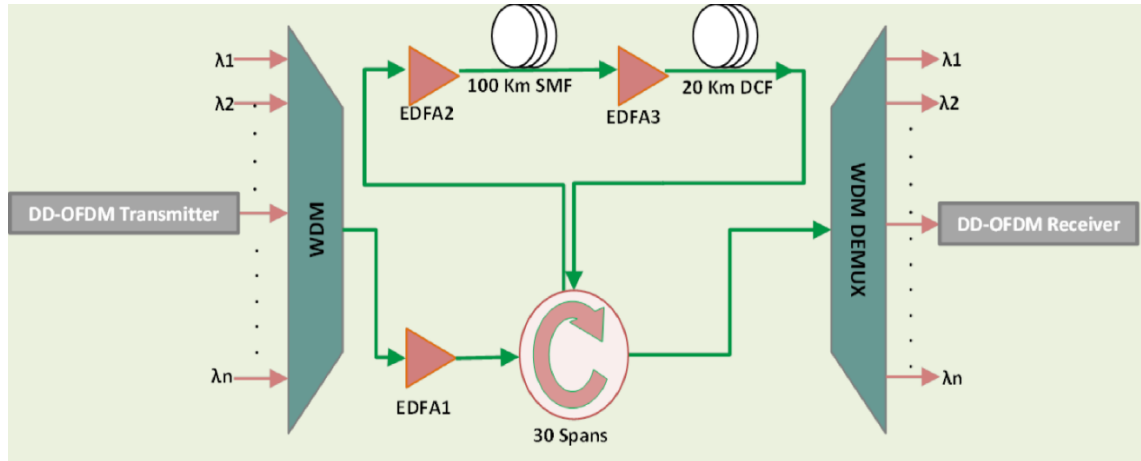


Figure 4: Post compensation fiber design.

4. Results and Discussion

After simulating the design by using Optisystem, many parameters are considered to measure the system performance.

The constellation shows a two-dimensional scatter diagram of the signal. **Figure 5** demonstrates a signal modulated 64-QAM. As can be seen from the graph, all samples are free of interferences and noise.

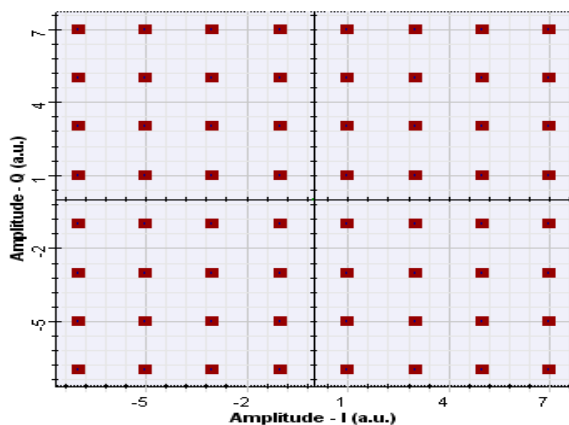


Figure 5: Constellation diagram of 64-QAM OOFDM at transmitter

Figure 6 shows the spectrum of 30 channels of 35 Gb/s each after DWDM, with 100 GHz channel spacing. The modulation parameter of each channel has the same settings. The carrier frequencies of the thirty optical signals starting from 193.1 to 196 THz with a spacing of 0.1 THz and each with an average power of 5 mW and linewidth of 1 MHz.

Figure 7 demonstrates the RF signal and it is clear that the signal is free of noise. The carrier frequency of the signal is 7.5 GHz and the power of the RF spectrum is measured at 7 dBm. The OSNR is measured at 59.2 dB and the maximum value of SNR is measured at 102.23 dB by using an electrical carrier analyzer.

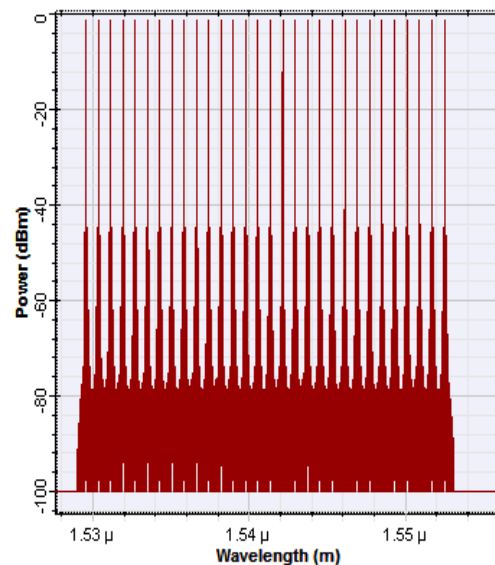


Figure 6: The Spectrum of the signals after WDM

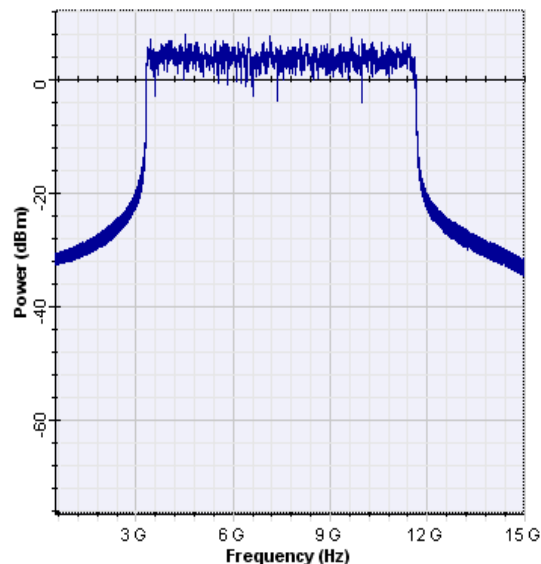


Figure 7: RF spectrum of 64-QAM OOFDM transmitter for 7.5GHz carrier frequency

Figure 8 shows the RF spectrum of the signal after it transmitted over 3600 km SMF. The OSNR measured at a 43.33 dB. It is clear that the OSNR decreased when the signal was transmitted over 3600 km SMF, due to dispersion and noise.

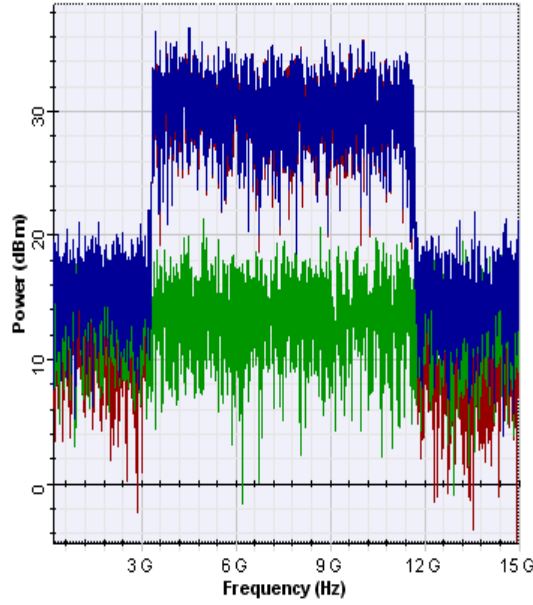


Figure 8: RF spectrum of 64-QAM OOFDM receiver for 7.5 GHz carrier frequency

The parameters of the SMF and DCF are shown in **Table 4**, and **5**, respectively.

Table 4: SMF Parameters

Fiber length (km)	100
Attenuation (dB/km)	0.2
Dispersion (ps/nm/km)	16
Slope (ps/nm ² /k)	0.08
Effective area ($\mu\text{ m}^2$)	80
Nonlinear refractive index n_2 (m^2/w)	2.6×10^{-20}

Table 5: DCF Parameters

Fiber length (km)	20
Attenuation (dB/km)	0.6
Dispersion (ps/nm/km)	-80
Slope (ps/nm ² /k)	-0.45
Effective area ($\mu\text{ m}^2$)	30
Nonlinear refractive index n_2 (m^2/w)	2.6×10^{-20}

Figure 9 represents the electrical constellation diagram without any dispersion compensation. It is clear that the signal is corrupted and can't be recognized. The signal is corrupted because of the huge amount of dispersion, noise, attenuation, and interference when the signal travelled over long transmission distance.

To get rid of the high amount of dispersion and recover the original signal, a post-DCF is placed after the SMF to compensate the positive dispersion of the SMF.

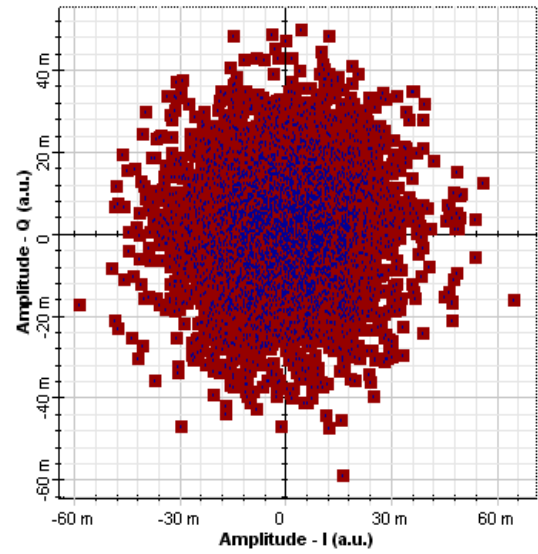


Figure 9: Shows the constellation diagram of the 64-QAM OOFDM signal transmission over 1080km SMF

Figure 10 illustrates the constellation diagram of the 64-QAM OOFDM signal at the receiver after DCF is used. As can be seen from the graph, the red points represent the signal and the noise is represented by blue points. Clearly, the signal is recovered after removing the chromatic dispersion from the optical fiber.

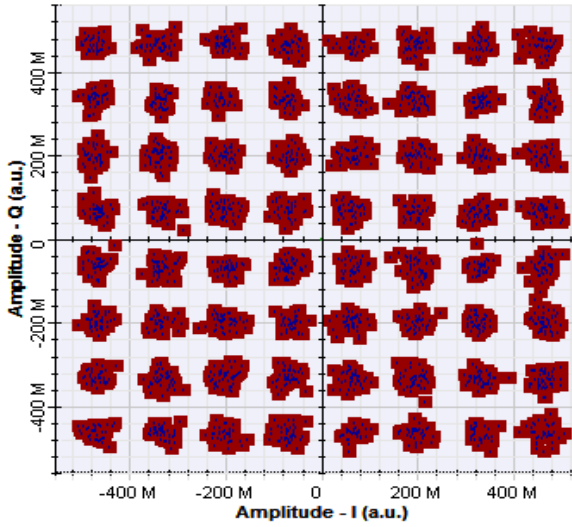


Figure 10: Shows the constellation diagram of the 64-QAM OOFDM signal after the DCF

The performance of the system can be studied by measuring the SNR and the OSNR versus BER. **Figure 11** shows the BER versus OSNR and it is clear that as OSNR increase the BER decrease. So, to get a BER less than 10^{-12} , the OSNR must be greater than 40dB.

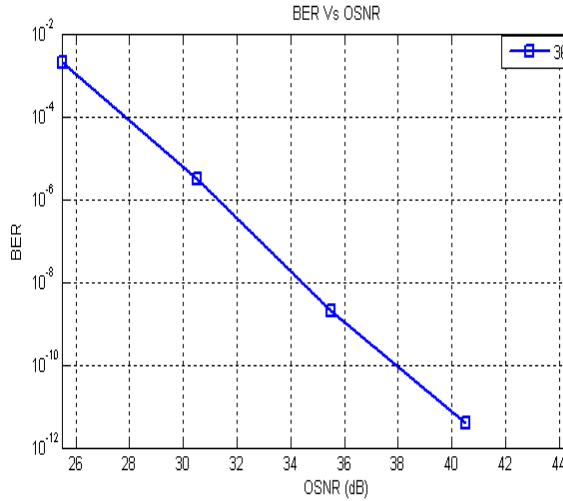


Figure 11: Shows the relationship between BER and OSNR for a transmission length of 3600 km SMF

In **Figure12** the SNR versus BER are plotted where SNR is defined as the ratio of signal power to noise power. It is clear that as the SNR increase the BER decrease. The value

of the SNR must be greater than 30 dB for a BER less than 10^{-12} .

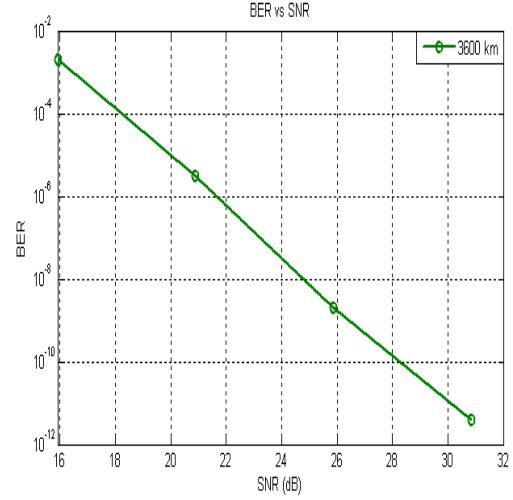


Figure 12: Shows the relationship between BER and SNR for a transmission length of 3600 km SMF

5. Conclusion

In this paper, the combination of OOFDM with DWDM was examined and investigated. DWDM was used to increase the system capacity and support to reach high data rates of 1.05 Tb/s. 30 OFDM signals of 35 Gb/s were multiplexed to generate a data rate of 1.05 Tb/s. According to the result, the system showed a clear constellation diagram of 64-QAM at receiver. The results show that the system has a good performance according to the OSNR, SNR, and BER values. The resulting data demonstrated the efficiency of the OOFDM-WDM system in presenting considerably higher data rates.

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Design of Broadband –RoF PON for the Last Mile

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Abstract

An increase in the demand of broadband service has encouraged research and study to find a solution to offer an adequate amount of service. Living in this digital world with downloading video, voice or data leads us occasionally to have a shortage of bandwidth in the provided data. One of the solutions to cover the huge expected demand in the future is improving the communication systems by adding optical passive components to the Radio over Fiber (RoF) system. This work is mainly to increase the bandwidth that allows the small and single consumer at the last mile. We have shown that by adding the 40-GHz mm-wave to the system, Bit-Error-Rate (BER) has increased while Q-factor has decreased.

Keywords: WDM-PON, MM-wave radio, RoF, Q-factor, BER

1. Introduction

In the modern communication systems, optical fiber is used to promote the efficiency in the transmitting and the receiving signals. This development in the communication system will help to supply enough broadband service to the last point of each individual consumer. Providing broadband service to each single end would not be an easy task to the service providers. Not only does optical fiber have immunity to the electromagnetic field, it also offers a high bandwidth that might be needed at the end of a single terminal. Distributing services to each single end will be costly. However, by using the wavelength division multiplexer (WDM), which works to transmit one signal with many wavelengths, one fiber, is needed to connect the wavelength division multiplexing to the demultiplexing at the end of the transmitter side and the beginning of the receiver side. Fiber to terminal x technology (FTTx) has shown its ability to increase the bandwidth at the last mile terminals such as small businesses and housing customers. The passive optical network (PON), which consists of, the optical line terminal (OLN), the single mode fiber optic (SM), and the optical network terminal (ONT), is simply a

(FTTx) technology. WDM PON systems can also offer symmetric wavelengths, both downstream (from OLN to ONT) and upstream (from ONT to OLN) [1]. Moreover, for the wireless broadband technology mm-wave radio shows it is efficient in supporting the wireless connections. In this paper, we have found the function of WDM-PON systems which requires having all passive optical components and studying the system after adding the optical fiber to the last mile terminal [2]. We also have added mm-wave to the carrier signal in order to take the advantage of mm-wave.

The demand for a high-speed data rate has increased over the last few years. The traditional networks that use coaxial cable and wireless communication have become insufficient to provide high data and large bandwidth. To overcome this problem, an optical fiber must be used because it can provide large bandwidth and a high data transfer rate. The use of the passive optical network (PON) is the most efficient and economic way to solve this problem because of its characteristics. The passive optical network has many advantages. For instance, it does not use active devices such as optical amplifiers, repeaters and active splitters especially between

the central offices and the base stations. Therefore it consumes less power, less space, and less complexity. Because of this it can be expanded cheaply as compared to the active network [3].

2. System Design

The most dominant use of the passive optical network is to provide high speed, large bandwidth, and a high data rate to the end user at the last mile. The demand for using the Internet service for gaming, video calling, and high-definition television has been increased by the end users [1]. Therefore, this will require large bandwidth and a high data rate. The main goal of this project is to provide high-speed Internet services to the last mile by using fiber to the home, which is known as FTTH. In this study we used the broadband passive optical network, which is known as BPON to implement the FTTH network and adding mm-wave to the carrier and finding the effects that mm-wave apply to the output signal.

In this paper we design and analysis a broadband passive optical network (BPON) to achieve a high-speed data rate and large bandwidth. We have built our system without and with adding a mm-wave to the input signal. OptiSystem software version 10 was used to simulate this system. Figure 1 shows the basic Architecture of WDM-PON network. Figure 2, represents our whole model. We use two transmitters that have been used to generate two different wavelengths of 1510 and 1530 nm, respectively. The two wavelengths have been combined using a WDM multiplexer. After that the signal has been inserted in the bidirectional single mode optical fiber. After using the bidirectional SM optical fiber a splitter was used as in Figure 3. The splitter block contains the WDM demultiplexer to separate the two wavelengths in the downstream. For the upstream the splitter block contains WDM in order to combine the wavelengths that will be sent by the end users. For the downstream the two wavelengths that were demultiplexed will be transmitted to the two optical network terminals

(ONTs). Each ONT contains an optical splitter and two optical network units (ONUs). The signal that comes from the splitter block will be inserted into the splitter through 3 Km bidirectional optical fiber, after dividing the signal each output port from the splitter will deliver a signal to an ONU through 50 m bidirectional optical as shown in Figure 4. Each ONU consists of a photodetector with a low pass filter for the downstream and a transmitter for the upstream signals as shown in Figure 5. At each of the ONUs the transmitter's wavelength is 1310 nm. Since we have four transmitters with the same wavelength that may transmit their information at the same time, we take the advantage of time division multiplexing access (TDMA) to design the upstream system. TDMA has been designed by using two dynamic y select that will pass the signal upstream in a determined period of time and will set the rest of the signals to zero Figure 5. The receiver end of the upstream link consists of a buffer selector to select the desired signal. A photodetector with low pass filter is connected to the buffer selector. By using dual-arm MZM in the input side, we have inserted 40 -GHz mm-wave signal based on optical carrier suppression (OCS) to the input signal 1510 and 1530 nm for the downstream link; however, for the upstream link out of MZM was connected to the input of the selectors [3-5].

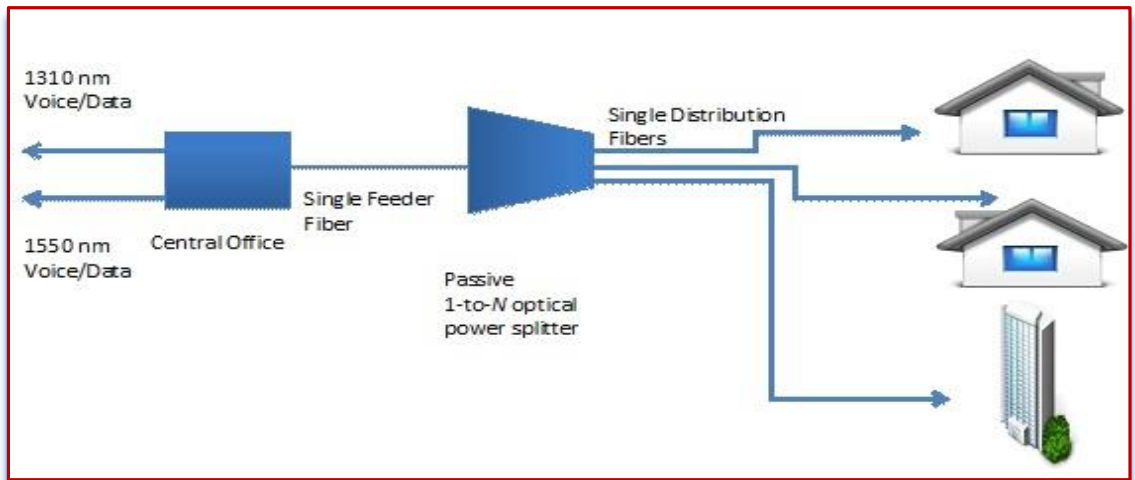


Figure 1: Basic Architecture of WDM-PON network

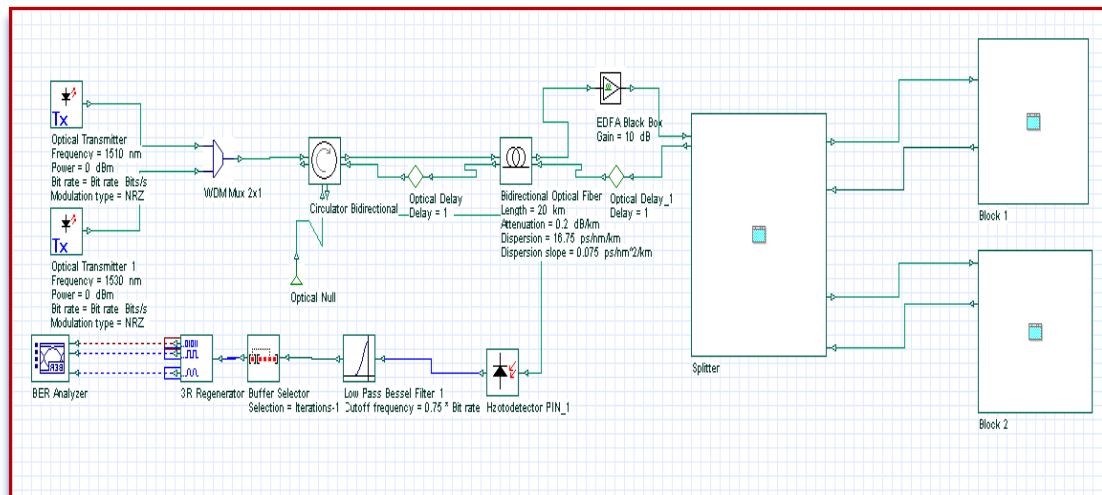


Figure 2: System Model

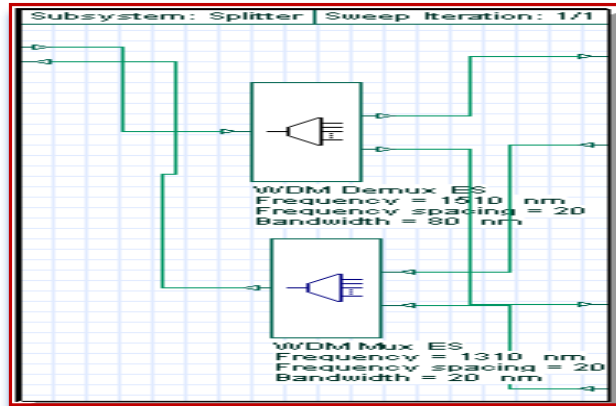


Figure 3: Splitter Circuit with WDM Mux and Demux

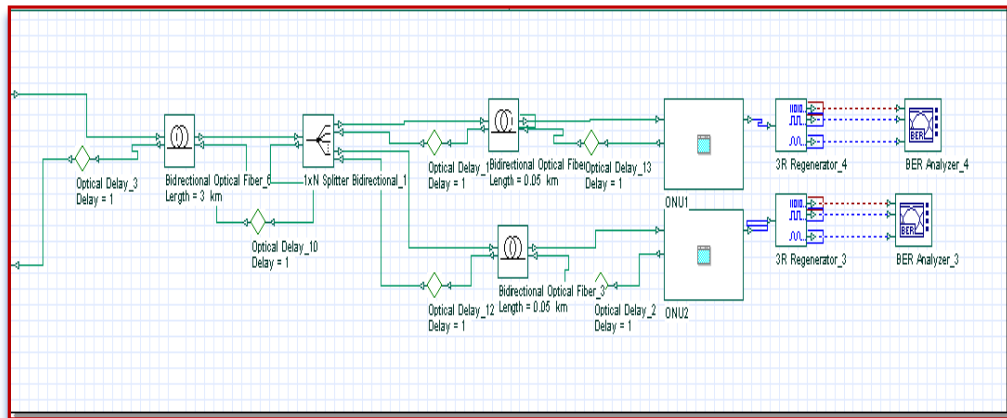


Figure 4: Passive Optical Network for one Block

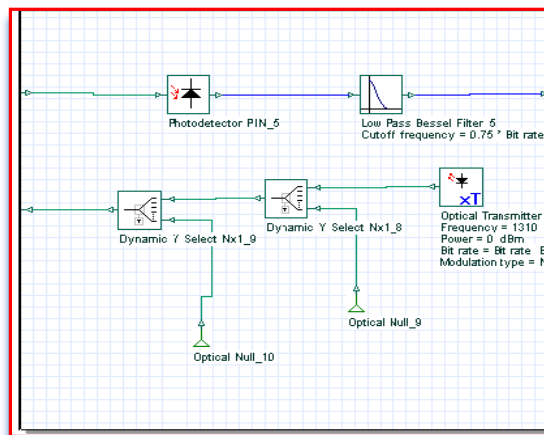


Figure 5: Optical network unit (ONU)

2.1 Design Studying Parameters

After designing the system, three parameters were tested to study the performance of the network and the quality of the signal. These parameters are the Q factor, the bit error rate and the eye diagram. The Q factor is the quality factor; a higher Q factor indicates a higher signal quality. On the other hand, the Bit error rate (BER) is the ratio between the number of the bits with errors and the total number of bits received and it helps to identify the quality of the optical connection. The eye diagram is one of the important methods to study the system. The eye opening can indicate the noise in the signal and how it differentiates the logic 0 from logic 1. The eye width can indicate the jitter effect and the rising or falling edge can indicate the distortion of the signal path [6-7].

clearly seen that the opening eye is large and clear which means this signal is very good with little noise and distortion and it is easy to distinguish between logic 0 and logic 1[8-9].

Table 1. Downstream Signal details with and without 40-GHz mm-wave

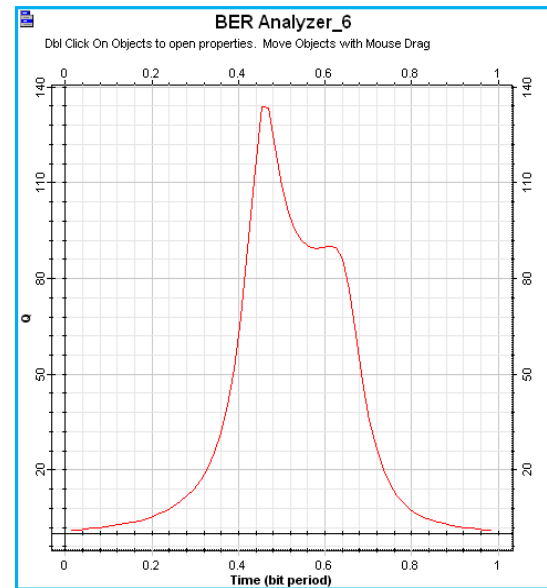
	Without 40-GHz mm-wave	With 40-GHz mm-wave
Max. Q Factor	133.819	67.909
Min. BER	0	0
Eye Height	0.008254238	0.00765657
Threshold	0.00200062	0.00347784
Decision Inst	0.5	0.5

3. Results

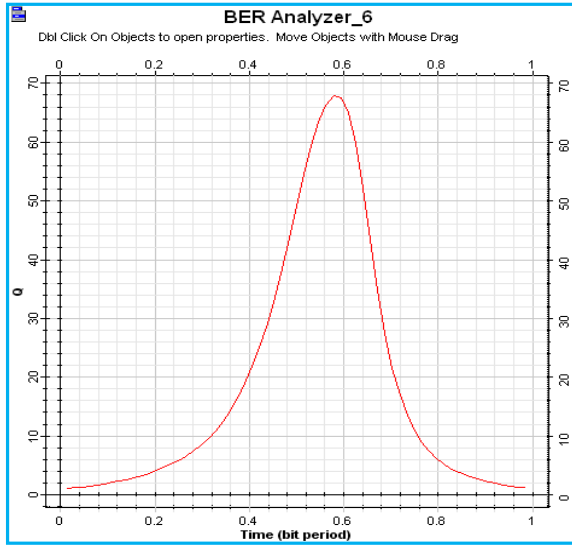
After designing this PON, a number of parameters have to be considered such as bit rate, sequence length, samples per bit and the total samples, as given in Figure 7. In the case we have studied this system is at 2.5 G/s as a bit rate, the sequence length is 128 bits, samples per bit are 64 and the total number of samples is 8192.

3.1 Downstream Design Analysis

For the downstream signal with and without adding mm-wave to the system, Table.1 shows the important output of BER, Q-factor and eye diagram which are at one single user. Because of having almost identical outputs for each one of the four users, we have analyzed the quality of the signals at only one single user. From Figure.6-a, the maximum Q-factor is equal to 133.819; however, after adding 40-GHz mm-wave to the system has the Q-factor is equal to 67.909 as shown in Figure 6-b. These two values of Q-factor are high enough for having a good quality of signal and have achieved the desired value of the Q-factor. BER for the downstream signal is zero which means the Q-factor has reached its maximum. Figure 7, portrays the eye diagram of the downstream signals. From this figure, it can be

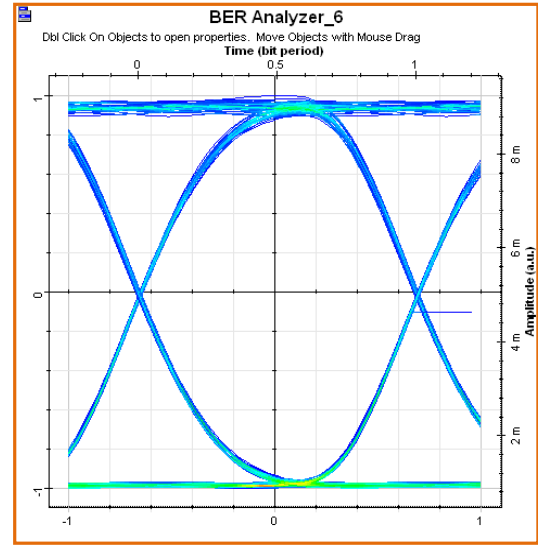


(a)



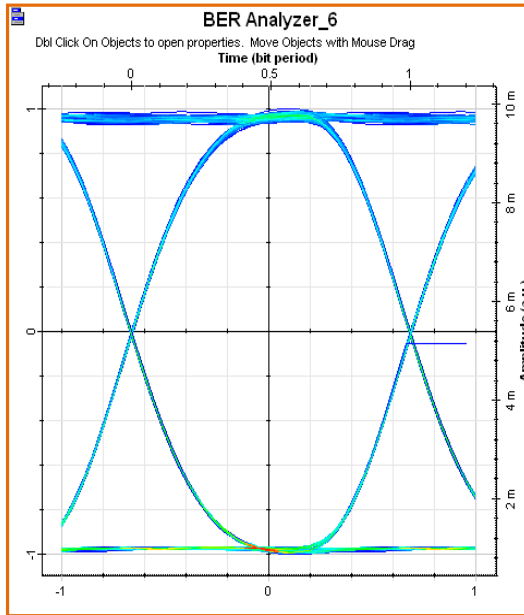
(b)

Figure 6 Q-factor vs. time for downstream signal with (b) and without (a) inserting 40-GHz mm-wave.



(b)

Figure 7. Eye diagram of the downstream signal with (b) and without (a) inserting 40-GHz mm-wave.



(a)

Table.2. Upstream Signal details with and without RF generator.

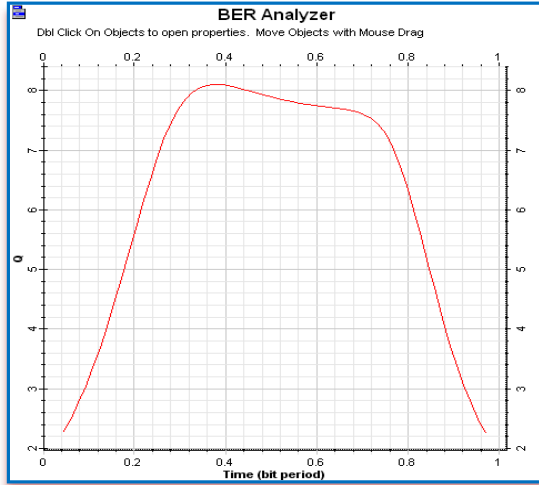
	Without RF Generator	With RF Generator
Max. Q Factor	8.09842	3.90774
Min. BER	1.6922e-016	1.50805e-005
Eye Height	0.000345197	5.84756e-005
Threshold	0.000318945	0.000103043
Decision Inst	0.375	0.359375

3.2 Upstream Design Analysis.

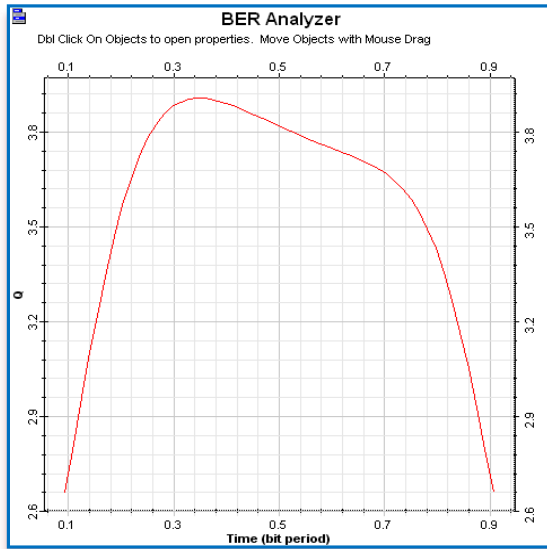
Before running the upstream design, seven iterations have to be set in order to operate the design. Seven iterations are needed because each upstream signal from any individual user will go through seven time delays before reaching the upstream receiver. Table-2 shows the most important details of the upstream signal. From this table, the BER values are larger than the BER values of the downstream signals; however, the Q-factor values are smaller than those of the downstream design as shown as in Figure 8.

This decrease in Q-factor and the increase in BER values lead us to have a signal with lower quality

than the quality of the downstream signals. Even though the upstream signal is a good signal, it is not as good as the downstream signal. The eye diagram of the upstream signals shows in Figure 9, that this signal has noise and distortion which are larger than those of the downstream signal.

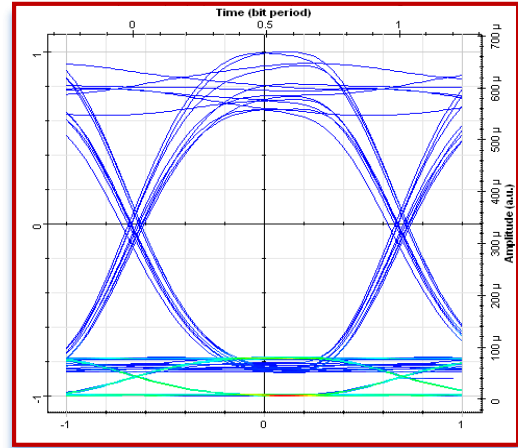


(a)

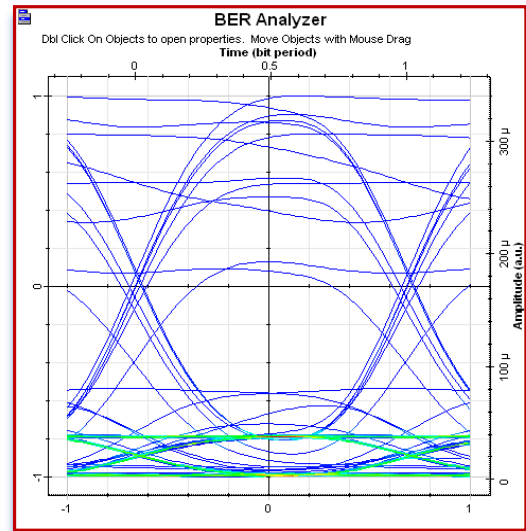


(b)

Figure 8. Q-factor vs. time for upstream signal with (b) and without (a) inserting 40-GHz mm-wave.



(a)



(b)

Figure 9. Eye diagram of the upstream signal with (b) and without (a) inserting 40-GHz mm-wave.

4. Conclusion

The results showed that the BER of the signal was very low and the eye diagram showed the quality of the signal for the downstream was very high before adding the 40-GHz mm-wave; however, after adding the mm-wave to the system BER has increased and Q-factor has decreased as a result the quality of the signal was of equipment was used including amplifiers and filters. The qualities of the signals were decreased after adding the mm-wave; however, there are still acceptable. Building BPON system in general has showed high reliability. In general using PON has a lot of advantages which include allow costs, very low power consumption and flexibility in extending the network.affected by mm-wave. But for the upstream signals, as the eye diagram showed, the quality was good but not as high as the downstream signal because in the downstream a lot

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