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华中师范大学

硕士学位论文

基于OFDM的高速光纤通信系统的建模与仿真

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硕士学位论文
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硕士学位论文
MASTER'S THESIS

Modeling and Simulation of High Speed Optical Fiber Communication System with OFDM

A Thesis

Submitted in Partial Fulfillment of the Requirement

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By

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摘 要

在任何需要将信息从一个地方传输到另一个地方的场景，都可能需要应用到光纤传输。然而，现代通信结构是基于光纤的数据传输，因而必须具有更高的带宽和低衰减特性。在数据接入、企业、地铁、区域和长途运输市场，迫切需要100Gbit/s或更高的数据传输速率。如果继续使用上一代的传输系统，现有的光传输设施将会超负荷运行且无法适应高速传输要求，因此必须建立下一代传输系统。

为了满足在宽带服务中日益增长的带宽需求，将正交频分复用应用在光纤传输中将是未来的发展方向。在使用光通信的社区，正交频分复用技术吸引了越来越多的关注，尤其是在它被作为在长距离通信相关检测和直接探测的制式之后。OFDM能够克服许多光纤传输中的限制，比如光纤色散(CD)和偏振模色散(PMD)。此外，将相干光的 OFDM 与波分复用(WDM)系统集成将使传输系统具有高带宽、高传输数据速率和高频谱效率的特性。

通过在单光纤中传输多波长光谱，能够使WDM系统提高容量和数据传输速率。

本文所主要研究的，是高数据率直接和相干光OFDM在长距离传输中的实现与性能分析。首先从只有单个用户的开始研究，并实现OFDM-WDM系统能够扩展到100Gbits/s的传输。该系统通过OptiSystem仿真软件来进行设计和实现。该系统用于传输的速率范围是从直接检测实现的 10Gbits/s 到通过 OFDM-WDM 实现的100Gbits/s，QAM用于对OFDM信号的调制，IQ调制用于在发送端中进行信号调制，在接收端通过直接和相干检测进行解调。为了对系统的性能和信号的质量进行分析，需要测试三个参数，分别是Q因子、误码率和眼图。

关键词：OFDM；DD-OFDM；CO-OFDM；SMF；WDM CO-OFDM；DCF

Abstract

The application of fiber optic transmission is possible in any area that requires transfer of information from one place to another. However, the modern telecommunications infrastructure is based on optical fibers for data transmission, due to their higher bandwidth and low attenuation.

There is a real need for data rates of 100Gbit/s and beyond in the access, enterprise, metro, regional and long haul markets. Therefore, next generation transmission systems must be employed, otherwise the optical infrastructure will become overloaded and exceed its current capacity.

Orthogonal Frequency Division Multiplexing is considered as a promising technology to satisfy the increased demand for bandwidth in broadband services. Orthogonal Frequency Division Multiplexing gained a grate attention in the optical communication community, especially after proposed as the attractive long haul transmission format in coherent detection and direct detection. OFDM 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.

WDM systems help to enhance the capacity and data rate by sending multiple wavelengths over a single fiber.

This research focuses on the implementation and performance analysis of high data rate direct and coherent optical OFDM for long haul transmission. The study starts with a single user and extends to the implementation of the OFDM-WDM system for 100Gbits/s. Optisystem simulation tool is used to design and implement the system. The system is used for carrying range of data start from 10Gbits/s with direct detection to 100Gbits/s with OFDM-WDM, QAM is used as a modulation type for the OFDM signal, I/Q modulation is employed at the transmitter, direct and coherent detection is used at the receiver. Three parameters were tested to study the performance of the system and the quality of the signal. These parameters are the Q factor, the bit error rate and the eye diagram.

Key words: OFDM,; DD-OFDM; CO-OFDM; SMF; WDM-CO-OFDM; DCF

Contents

Abbreviations

OFDM “Orthogonal Frequency Division Multiplexing”
WDM “Wavelength Division Multiplexing”
DD-OFDM “Direct Detection OFDM”
CO-OFDM “Coherent Optical OFDM”
PMD “Polarization Mode Dispersion”
CD “Chromatic Dispersion”
ISI “Inter-Symbol Interference”
ICI “Inter-Carrier Interference”
QAM “Quadrature Amplitude Modulation”
A/D “Analog to Digital Conversion”
D/A “Digital to Analog Conversion”
S/P “Serial to Parallel Conversion”
P/S “Parallel to Serial Conversion”
MZM “Mach-Zehnder Modulator”
LED “Laser Emitting Diode”
LO “Local Oscillator”
SPM “Self-Phase Modulation”
XPM “Cross-Phase Modulation”
FWM “Four Wave Mixing”
SRS “Stimulated Raman Scattering”
SBS “Stimulated Brillouin Scattering”
SMF “Single Mode Fiber”
DCF “Dispersion Compensate Fiber”
CP “Cyclic Prefix”
MMF “Multimode Fiber”
FFT “Fast Fourier Transform”
IFFT “Inverse Fast Fourier Transform”
MCM “Multicarrier Modulation”
PSK “Phase Shift Keying”
FDM “Frequency Division Multiplexing”
DFT “Discrete Fourier Transform”
E/O “Electrical to Optical Converter”
O/E “Optical to Electrical Converter”
LPF “Low Pass Filter”

BPF “Band-Pass Filter”
PRBS “Pseudo Random Binary Sequence”
RF “Radio Frequency”
BER “Bit Error Rate”
SNR “Signal to Noise Ratio”
I-Q “In-Phase and Quadrature”
MUX “Multiplexers or Multiplexing”
DEMUX “De-multiplexer”
TDM “Time Division Multiplexing”
DWDM “Dense Wavelength Division Multiplexing”
DAB “Digital Audio Broadcasting”
DVB “Digital Video Broadcasting”
LAN “Local Area Network”
WLAN “Wireless Local Area Network”
LTE “Long Time Evolution”
PAPR “Peak to Average Power Ratio”

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Chapter 1 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. Recently, 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 [1]: bandwidth expansion and enhancing the spectral efficiency.

1.1.1 Bandwidth Expansion

One of the approaches to increase the capacity of the 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 [1]. 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 is considered one of the most cost efficient approaches to increase the optical fiber link throughput [2]. 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 [3, 4]. 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 [5].

1.1.2 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 [6]. 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 [7].

One of these advanced techniques is the optical OFDM. Optical OFDM received great attention after it was proposed as a modulation technique for the long-haul transmission in both direct and coherent detection.

1.2 Problem Statement

As mentioned earlier, the advent of the Internet, data traffic involving transmission of video and images has become much more common and by now such traffic consumes more bandwidth than the traditional telephone traffic. The OFDM is seen as the modulation technique for long haul transmission system in both direct and coherent detection, because OFDM 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.

1.3 Historical Perspective of OFDM

The concept of OFDM was first introduced by Chang in a seminal paper in 1966 [8]. In 1967 the scheme was soon analyzed by Saltzberg [9]. The term OFDM in fact is first appeared in a separate patent of his in 1970 [10]. The proposal to generate the orthogonal signals using an FFT came in 1969 [11]. Cyclic prefix was introduced in 1980 by Peled and Ruiz to mitigate the effect of the inter symbol interference (ISI) [12]. In the mid of 1980s OFDM began to be considered for practical wireless applications. In 1985 Cimini of Bell Labs published a paper on OFDM for mobile communications [13].

In 1987, Lassalle and Alard based in France considered the use of OFDM for radio broadcasting and noted the importance of combining forward error correction (FEC) with OFDM[14]. Because of this interrelationship, OFDM is often called Coded OFDM (C-OFDM) by broadcasting engineers. The field of OFDM had long been developed as a peripheral interest in military applications because there was a lack of broadband applications for OFDM and powerful integrated electronic circuits to support the complex computation required by OFDM. However, the arrival of broadband digital applications and maturing of very large scale integrated (VLSI) CMOS chips in the 1990s brought OFDM into the spotlight [15]. In 1995, OFDM was adopted as the European DAB standard, ensuring its significance as an important modulation technology and heralding a new era of OFDM success in a broad range of applications [15]. Over the years, OFDM technique has been considered for many applications and standards for cable and wireless communications; today , OFDM exists in many wireless standards including wireless LAN IEEE 802.11a/g, wireless metropolitan area networks (WiMAX; 802.16e), asymmetric digital sub-carrier line (ADSL; ITU G.992.1) and longtime evolution (LTE) the fourth generation mobile communications technology [15].

The application of OFDM to optical communications has only occurred very recently, but there are an increasing number of papers on the theoretical and practical performance of OFDM in many optical systems including optical wireless [16, 17].

1.4 Thesis Objectives

The first objective of this research is to investigate and simulate the DD-OFDM system to transmit 10 Gbits/s over a different transmission links for single user. The second objective is to investigate and simulate the CO-OFDM system to transmit 40 Gbits/s over 150 km. The third objective is to investigate and simulate the CO-OFDM with WDM system to transmit 100Gbits/s over 120 km with the Optisystem simulation tool. Finally, three parameters were tested to study the performance of the system and the quality of the signal. These parameters are the Q factor, the bit error rate and the eye diagram.

1.5 Thesis Outline

Chapter 1 presents the introduction which consists of the research overview, problem statement, objectives 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;

Chapter 4 discusses the methodology of this thesis in terms of integrating OFDM with DD-OFDM and CO-OFDM for long-haul transmission. Also discusses the integration of the coherent optical OFDM with the WDM system to transmit 100 Gbits/s. The OptiSystem simulation tool 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 conclusions and future works of OFDM.

Chapter 2 Optical Fiber Communications Systems

2.1 Optical Fibers

An optical fiber is a flexible, transparent fiber made of extruded glass (silica) or plastic, slightly thicker than a human hair. It can function as a waveguide, or “light pipe” to transmit light between the two ends of the fiber. The field of applied science and engineering concerned with the design and application of optical fibers is known as fiber optics.

Optical fibers are widely used in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidths (data rates) than wire cables. Fibers are used instead of metal wires because signals travel along them with less loss and are also immune to electromagnetic interference. Fibers are also used for illumination, and are wrapped in bundles so that they may be used to carry images, thus allowing viewing in confined spaces. Specially designed fibers are used for a variety of other applications, including sensors and fiber lasers.

Optical fibers typically include a transparent core (of refractive index n_1) surrounded by a transparent cladding material with a lower index of refraction (n_2) as shown in Figure 2.1. Light is kept in the core by total internal reflection. This causes the fiber to act as a waveguide. Fibers that support many propagation paths or transverse modes are called multi-mode fibers (MMF), while those that only support a single mode are called single-mode fibers (SMF). Multi-mode fibers generally have a wider core diameter, and are used for short-distance communication links and for applications where high power must be transmitted. Single-mode fibers are used for most communication links longer than 1,000 meters (3,300ft).

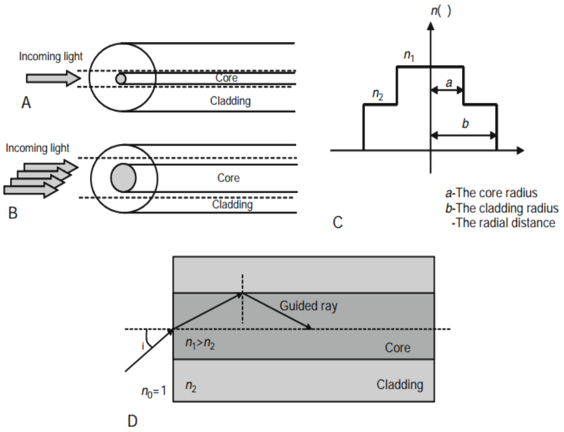


Figure 2.1: Optical fibers: (A) single-mode fiber, (B) multi-mode fiber,
(C) Refractive index profile for step-index fiber, and (D) light confinement in step-index fibers through the total internal reflection.

Optical fiber communication system is like any other communication system. It consists of three main components: 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 transmitter and the receiver are designed to meet the requirements of this communication channel as shown in Figure 2.2 [18].

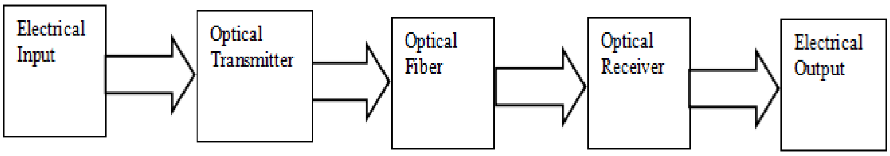


Figure 2.2 General Diagram of Optical Communication System

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 attenuation. The optical fiber can transmit the light wave with attenuation equal to 0.2dB/km. However, for long haul applications, the fiber 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 [18]. The fiber dispersion can occur in a severe way in the multi-mode 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 [19]. 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 2.3. The optical source can be a light-emitting diode (LED) and the optical modulator can be direct or external modulator. An example of external modulator is a Mach-Zehnder modulator [19].

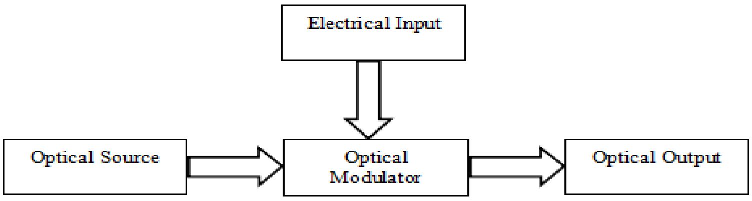


Figure 2.3 Optical Transmitter

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 2.4 [19].

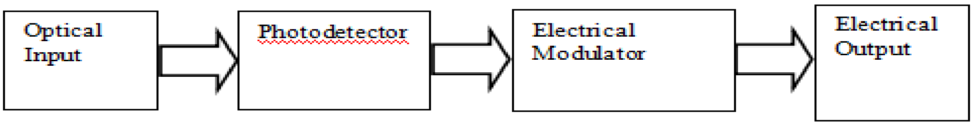


Figure 2.4 Optical Receiver

2.2 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 [19]:

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

2.2.1 Absorption

As mentioned earlier, 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 [18]. High levels of OH ions occur at 725, 950, 1240 and 1380 nm which will lead to large absorption peaks (water peak) [18]. 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 2.5 [18]. 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).

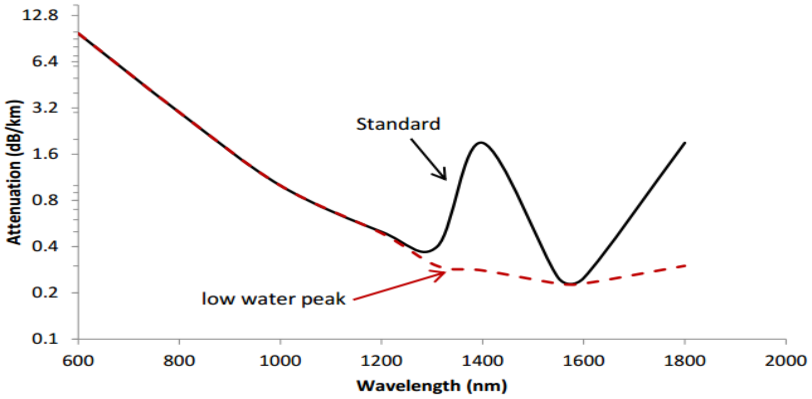


Figure 2.5 Relationship of Attenuation and Wavelength for Standard Fiber and LowWater-Peak Fiber.

2.2.2 Rayleigh Scattering

Scattering losses occurs from material density microscopically variations, compositional fluctuations, and from defects during fiber producing process [18, 20]. 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 [18, 20]. 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 [18].

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

Where (n) is the refractive index, k_B the Boltzmann's constant, p is the photoelastic coefficient, T_f is the fictive temperature, and β_T is Isothermal compressibility.

2.3 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 [18]. There are different types of signal dispersion that can occur during the transmission of a signal such as chromatic dispersion, and polarization-mode dispersion [19].

2.3.1 Chromatic 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 [18, 19]. Chromatic dispersion can be defined as [18]:

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

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, β_2 is the GVD (Group Velocity Dispersion) parameter. $\beta_2 = \frac{d^2\beta}{d\omega^2}$ where β is the wave propagation constant and ω is the angular frequency [18].

There two causes for chromatic dispersion: material dispersion and waveguide dispersion.

(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 [18-20]. Figure 2.6 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 [18-20].

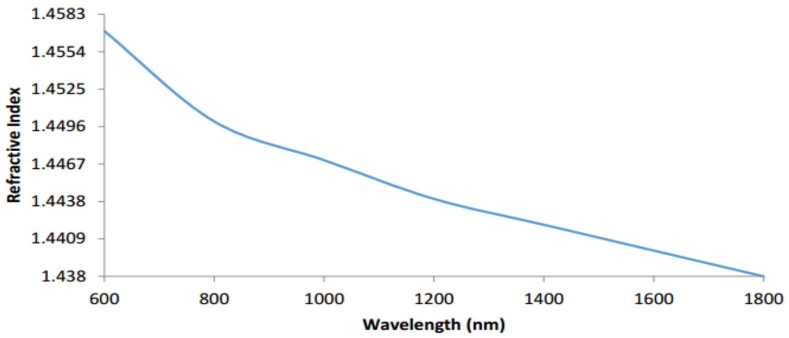


Figure 2.6 Variation of Refractive Index as a Function of Wavelength

Material dispersion can be defined as [8]:

$$|D_{ma}| = \frac{\lambda}{c}\left|\frac{d^2n}{d\lambda^2}\right| \tag{2.4}$$

Where D_{mat} is the material dispersion and n is the refractive index of the core [18].

(2) Waveguide Dispersion

Waveguide dispersion is another 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 [18,1 9]. Waveguide dispersion can be defined as [20]

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

2.3.2 Polarization Mode Dispersion

Polarization mode dispersion is caused by a fiber birefringence which affects the polarization state of the optical signal and causes a pulse broadening [18]. Many factors can cause fiber birefringence such as: imperfections from the manufacturing process, the bending or twisting of the fiber, or weather conditions [18-20]. 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 $\Delta\tau_{PMD}$ between the two polarization modes will produce pulse spreading [18].

$$\Delta_{PMD} = \left| \frac{L}{V_{gx}} - \frac{L}{V_{gy}} \right| \tag{2.6}$$

Where L is the distance that the pulse travels, and the group velocities of the two polarization modes are V_{gx} , V_{gy} . The polarization-mode dispersion can be calculated by[18]

$$D_{PMD} \approx \frac{\Delta\tau_{PMD}}{\sqrt{L}} \tag{2.7}$$

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 [19, 20, 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 [19, 20]. 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 [18].

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 [19, 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. On the other hand, FBGs can be used for remote monitoring and as laser diode filters [20]. The Bragg condition occurs at reflection wavelength λ_{Bragg} [18]

$$\lambda_{Bragg} = 2\Lambda n_{eff} \tag{2.8}$$

Where n_{eff} is the core effective index.

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

$$R_{\max} = \tanh^2(kL) \tag{2.9}$$

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

K is given by: $k = \dfrac{\pi \delta n \eta}{\lambda_{Bragg}}, \eta \approx 1 - V^2$ where η is the optical fiber fraction in the core.

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 2.7. Therefore, it will lead the laser to turn on and off and create 1 and 0 bits [18-20]. Direct modulation is suitable for data rates of 2.5 Gbits or less.

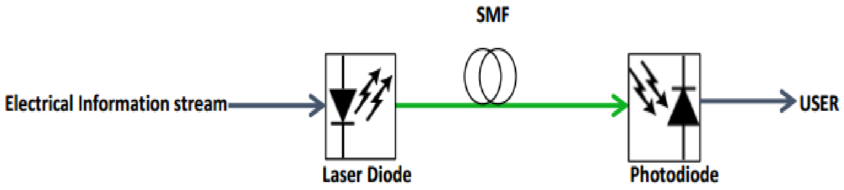


Figure 2.7 Direct Modulation

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 [18, 1 9].

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 2.8 [18-20].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 [18].

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 [18-20].

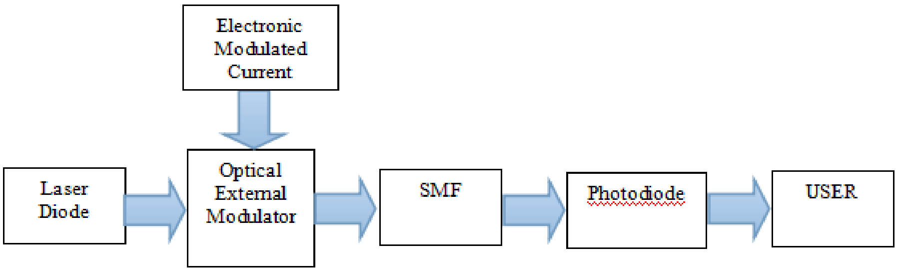


Figure 2.8 External Modulation

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 2.9 illustrates the optical WDM networks, where wavelength substitutes frequency and each transmitter transmits separated wavelength λ_i 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).

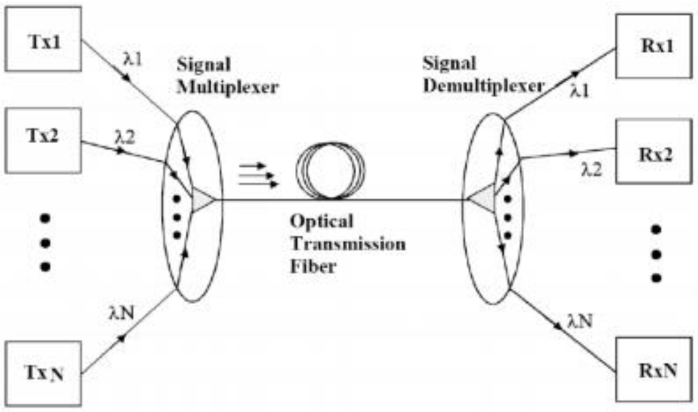


Figure 2.9 Wavelength Division Multiplexing

Chapter 3 Orthogonal Frequency Division Multiplexing Techniques

3.1 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a method of encoding digital data on multiple carrier frequencies. OFDM has developed into a popular scheme for wideband digital communication, used in applications such as television broadcasting and audio broadcasting, DSL Internet access, wireless networks, power-line networks, and 4G mobile communications. Two fundamental advantages of OFDM are its robustness against channel dispersion and its ease of phase and channel estimation in a time varying environment. OFDM is a frequency division multiplexing (FDM) scheme used as a digital multicarrier modulation method. A large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels. Each sub-carrier is modulated with a conventional modulation scheme such as QAM or PSK at a low symbol rate. However, OFDM also has disadvantages, such as high peak to average power ratio (PAPR) and sensitivity to frequency and phase noise.

3.2 OFDM Principles

Figure 3.1 shows the block diagram of transmission system using OFDM. At the transmitter side, the high rate digital data stream is split into N parallel streams. Each stream is mapped to a symbol stream using modulation scheme (QAM, PSK, etc). The symbols are modulated onto the sub-carrier using IFFT to transform the OFDM signal from frequency domain to time domain. After IFFT operation, a cyclic prefix or guard interval is added to prevent the overlapping between sub-carriers, and then the OFDM signal is converted to analog signal by using D/A converter. After that the signal is sent through the channel after performing a P/S conversion. At the receiver side, the received data is converted to parallel and the guard interval or cyclic prefix is removed. Then the signal is demodulated by using FFT algorithm and demodulated using the M-Ary demodulator which could be either QAM or PSK. Finally, the data is converted to serial to get the original data [27].

3.2.1 S/P Conversion

After converting the binary values to complex values, the data signals must pass through a serial to 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 sub-carriers. For example, for a sub-carrier modulation of

16-QAM, each sub-carrier carries 4-bits of data. So for a transmission using 100 sub-carriers using 16-QAM the number of bits per OFDM symbol would be 400 symbols, while the number of parallel symbols entering the IFFT block is 100.

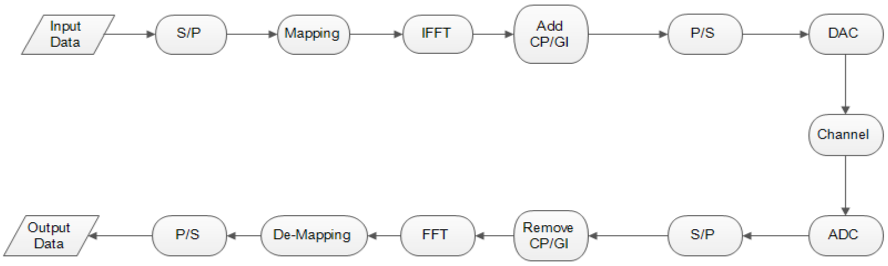


Figure 3.1 OFDM Block Diagram

3.2.2 Mapping

The modulation scheme is mapping the data words to a real (In Phase) and imaginary (Quadrature) constellation, also known as an I/Q constellation.

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

$$\Phi_k(t) = A(t)exp(2\pi f_k t) \tag{3.1}$$

Where (f_k) is the frequency of the signal, (k) is the number of the sub-carriers and (A) is the amplitude.

The above equation (3.1) can be written as:

$$\Phi_k(t) = A(t)cos(2\pi f_k t)+jA(t)sin(2\pi f_k t)= I(t)+jQ(t) \tag{3.2}$$

Where $I(t)$ is the In-Phase component and $Q(t)$ is the Quadrature component.

From equation 3.2, the input signal is represented by an In-phase and Quadrature form. To understand the idea of *I/Q* component, take (8-PSK) as an example. Figure 3.2 illustrate the constellation diagram of 8-PSK. The values of the I/Q components are represented in table 3.1.

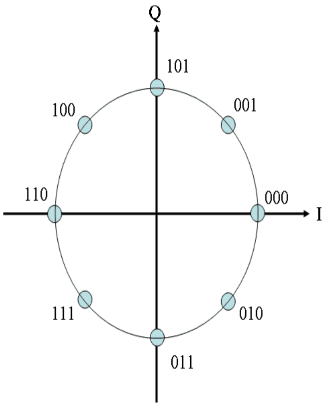


Figure 3.2: The Constellation Diagram of 8-PSK

Table 3.1 I/Q Components for 8-PSK

Input bits	Φ_k	8-PSK	
		I_k	Q_k
000	0	1	0
001	$\pi/4$	$\sqrt{2}/2$	$\sqrt{2}/2$
101	$\pi/2$	0	1
100	$3\pi/4$	$-\sqrt{2}/2$	$\sqrt{2}/2$
110	π	-1	0
111	$5\pi/4$	$-\sqrt{2}/2$	$-\sqrt{2}/2$
011	$3\pi/2$	0	-1
010	$7\pi/4$	$\sqrt{2}/2$	$-\sqrt{2}/2$

At the receiver, the received *I/Q* symbol de-mapped back to get the original signal, this is called demodulation, the cyclic prefix should be removed in this stage.

3.2.3 Inverse Fast Fourier Transform (IFFT)

The use of IFFT is the advantage of modern OFDM. IFFT has the ability to perform the frequency up converting and the multiplexing of the complex sub-carries in an efficient and exact way. Moreover, 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 algorithm will ensure the orthogonality of the sub-carriers in the OFDM transceiver and will help to avoid any interference. Orthogonality between sub-carriers is to keep the sub-carrier center frequency from overlapping with other sub-carriers while the sub-carrier spectrum overlaps. This will give overlapped but orthogonal signal sets [28]. This orthogonality occurs from direct correlation between any two sub-carriers which is given by [29, 30]

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

Where (f_k , f_l) are the sub-carriers frequencies and (T_s) is the symbol period. If the condition: $f_k - f_l = m/T_s$ is satisfied, then the two sub-carriers are orthogonal to each other. This condition help to recover the signal without intercarrier interference (ICI), despite strong signal spectral overlapping.

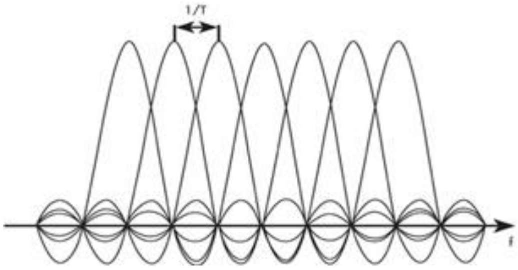


Figure 3.3: OFDM Power Spectrum

3.2.4 Guard Interval or Cyclic Prefix

A guard interval can be added to the start of each OFDM symbol. This guard interval is longer than the maximum delay spread of the channel. The guard interval preserves orthogonality between the sub-carriers by keeping the OFDM symbol periodic over the extended symbol duration, therefore avoiding intercarrier interference (ICI).

Cyclic prefix is added as a guard interval and it was proposed to resolve the channel dispersion induced ISI and ICI [32]. The cyclic prefix is copying the last part of the OFDM symbol and prefixing it as a guard interval at the beginning of the OFDM symbol.

Figure 3.4 shows one complete OFDM symbol composed of an observation period and cyclic prefix. The waveform within the observation period will be used to recover the frequency domain information symbols.

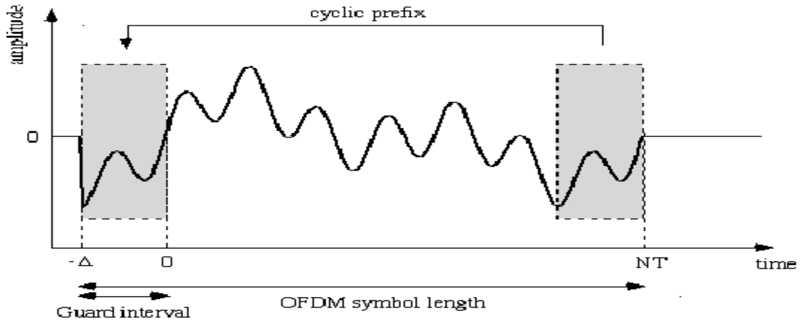


Figure 3.4: Cyclic Prefix in an OFDM Symbol

3.2.5 D/A and A/D Conversion

D/A converter is needed to convert the discrete value of sample to the continuous value, and A/D converter is needed to convert the continuous received signal to discrete sample.

3.2.6 Fast Fourier Transform (FFT)

After removing the guard intervals, the OFDM signals are applied to the FFT process to convert the real values to the frequency domain. FFT can recover the sub-carriers 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

$$r(k) = \exp j\left(\frac{2\pi k\upsilon}{N_{FFT}}\right)\sum_{p=0}^{k-1} h_p s(k-\eta) + n(k) \tag{3.4}$$

Where (υ) is the carrier spacing offset, (h_p) is the complex gain, (η) the path time delay and *n (k)* is the AWGN.

There are two fundamental advantages of FFT/IFFT implementation of OFDM. First, because of the existence of an efficient IFFT/FFT algorithm, the number of complex multiplications for IFFT and FFT is reduced from N^2 to ($N/2\log_2(N)$) almost linearly with the number of sub-carriers N [31]. Second, a large number of orthogonal sub-carriers can be generated and demodulated without restoring to much more complex RF oscillators and filters. This leads to a relatively simple architecture for OFDM implementation when large numbers of sub-carriers are required.

3.3 Optical OFDM

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 [29]. The first technique is the direct detection optical OFDM (DD-OOFDM) and the second one is the coherent detection optical OFDM (CO-OFDM).

3.3.1 DD-OFDM

Figure 3.5 illustrates the block diagram of the DD-OOFDM system which consists of a DD-OOFDM transmitter, optical fiber and DD-OOFDM receiver.

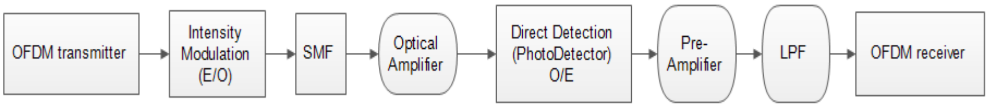


Figure 3.5 DD-OOFDM Block Diagram

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 and an optical amplifier is used to compensate the loss in the fiber.

At the receiver, the incoming signal is converted from optical to electrical domain by using optical to electrical converter (O/E), which is a photo-diode [33].

The received electrical signal is giving by

$$A_e(t) = |A_0(t)|^2 \otimes h_e(t) + w(t) \tag{3.5}$$

Where ($A_e(t)$) is the electrical signal at the receiver, $A_0(t)$ is the optical OFDM signal, $h_e(t)$ is the impulse response in the electrical domain, and $w(t)$ is the system noise. After down converting, the signal will be amplified again and passes through a low-pass filter (LPF) and is transmitted to the OFDM receiver to get the original signal.

3.3.2 Coherent Optical OFDM (CO-OFDM)

Figure 3.6 illustrates the CO-OFDM system. As can be seen, 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 divided into two categories, heterodyne detection and homodyne detection.

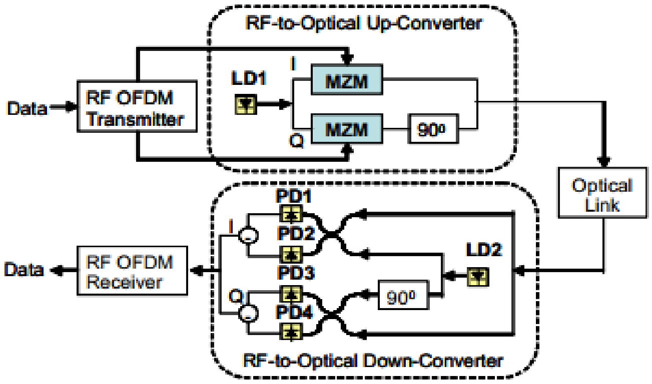


Figure 3.6 CO-OFDM Block Diagram

Heterodyne detection is where the local oscillator does not match the incoming signal frequency. At the photo-diode, when the two signals are mixed, a new frequency is generated. The new frequency is an intermediate frequency (IF) which is the difference between two frequencies [34]. 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 to maintain the IF constant.

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

The other component is I/Q modulator. The I/Q components of the digital signal are converted to an analog signal by two D/A converters at the transmitter. The I/Q modulator, which consists of two MZMs , up converts the complex OFDM signal to optical domain, and the modulated signal can be written

$$E(t) = x(t)\exp j(w_{LD1}t + \phi_{LD1}) \tag{3.6}$$

Where *x (t)* is the transmitted electrical signal, *w*, ϕ are the angular frequency and the phase of the transmitter laser diode respectively. The received signal is represented by

$$E_r(t) = E(t) \otimes h(t) + w(t) \tag{3.7}$$

Where *h(t)* is the channel response and *w(t)* is the channel noise. Then, the incoming signal is detected by two identical pairs of balanced coherent detectors and an optical 90^o hybrid to perform the I/Q optical to electrical conversion. Each detector consists of two couplers and PIN photo-diodes. The output of the four 90^o optical hybrid ports is given by [35]

$$\begin{aligned}
E_1 &= \frac{1}{\sqrt{2}}[E_s + E_{LD2}] \\
E_2 &= \frac{1}{\sqrt{2}}[E_s - E_{LD2}] \\
E_3 &= \frac{1}{\sqrt{2}}[E_s - jE_{LD2}] \\
E_4 &= \frac{1}{\sqrt{2}}[E_s + jE_{LD2}]
\end{aligned} \tag{3.8}$$

Where E_s, E_{LD2} are the incoming signal and local oscillator signal (LO) respectively. On the other hand, the In-Phase signal is recovered by using the two photo-detectors (PD_1, PD_2) whose photo-current can be given by

$$\begin{aligned}
& I_1 = |E_1|^2 = \frac{1}{2}\{|E_s|^2 + |E_{LD_2}|^2 + 2\,\mathrm{Re}\{E_s E^*_{LD_2}\}\} \\
& I_2 = |E_2|^2 = \frac{1}{2}\{|E_s|^2 + |E_{LD_2}|^2 - 2\,\mathrm{Re}\{E_s E^*_{LD_2}\}\} \\
& |E_s|^2 = |E_r|^2 + |n_o|^2 + 2\,\mathrm{Re}\{E_r n_o^*\} \\
& |E_{LD_2}|^2 = I_{LD_2}(1 + I_{rin}(t))
\end{aligned} \tag{3.9}$$

Where L_{LD2} , $I_{rin}(t)$ are the average power and relative intensity noise of the laser diode. Because of the balanced detection, the In-phase component of the photo-current becomes [36]:

$$I_I = 2\,\mathrm{Re}\{E_s E_{LD_1}^*\} \tag{3.10}$$

In the same way, the quadrature component from the other photo-detectors (PD_3, PD_4) can be derived as:

$$I_Q = 2\,\mathrm{Im}\{E_s E_{LD_2}^*\} \tag{3.11}$$

From the equations (3.10) and (3.11) the complex photo-current

$$\widetilde{I}(t) = I_I(t) + jI_Q(t) = 2E_s E_{LD} \tag{3.12}$$

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

3.4 Advantages of OFDM

OFDM has many advantages such as high data rate in mobile wireless channel and it is conveniently implemented using FFT/IFFT algorithm. Many advantages of OFDM are shown below:

1- Makes efficient use of the spectrum by allowing overlap.

2-By dividing the channel into narrow-band flat fading sub-channels, OFDM is more resistant to frequency selective fading than single carrier systems are.

3-Eliminates ISI and ICI through use of a cyclic prefix.

4-Channel equalization becomes simpler than by using adaptive equalization techniques with single carrier systems.

5-OFDM is computationally efficient by using FFT techniques to implement the modulation and demodulation functions.

6-Less sensitive to sample timing offsets

7-Tuned sub-channel receiver filters are not required

3.5 Disadvantages of OFDM

On the other hand, OFDM has many disadvantages. The main disadvantage is the complexity, where OFDM is a multi-carrier modulation which is more complex than the single-carrier modulations as well as OFDM requires more linear power amplifier. The disadvantages of OFDM are shown below and the explanation of some of these disadvantages in next section.

- sensitive to Doppler shift
- sensitive to frequency synchronization problems

- high peak-to-average power ratio (PAPR)

3.5.1 Peak-to-Average Power Ratio

High peak to average power ratio (PAPR) has been recognized as one of the drawbacks of the OFDM modulation. The origin of high PAPR of an OFDM can be understood from its multicarrier nature. Because cyclic prefix is an advanced time-shifted copy of a part of the OFDM signal in the observation period, the transmitted time domain waveform inside the observation period for one OFDM symbol can be given by

$$s(t)=\sum_{k=1}^{N_{sc}} c_k e^{2\pi j f_k t},\ f_k=\frac{k-1}{T_s} \tag{3.13}$$

The PAPR of the OFDM signal is defined as:

$$PAPR=\frac{\max\{|s(t)|^2\}}{E\{|s(t)|^2\}}, t\in[0,T_s] \tag{3.14}$$

For simplicity, we assume that an M-PSK encoding is used, where c_k=1. The theoretical maximum of PAPR is $10\log_{10}(N_{sc})$ in dB, by setting $|c_k=1|$ and t=0 in equation 3.13. For OFDM systems with 256 sub-carriers, the theoretical maximum PAPR is 24 dB, which obviously is excessively high. A better way to characterize the PAPR is to use the complementary cumulative distribution function (CCDF) of, P_c which is expressed as $P_c=P_r\{PAPR > \zeta_p\}$, P_c is the probability that PAPR exceeds a particular value of ζ_p.

CCDF with varying numbers of sub-carriers shows in figure 3.7. We have assumed QPSK encoding for each sub-carrier. It can be seen that despite the theoretical maximum PAPR of 24 dB for the 256-sub-carrier OFDM systems, for more likely probability regimes, such as a CCDF of 10^{-3}, PAPR is approximately 11.3 dB, which is much less than the maximum value of 24 dB. A PAPR of 11.3 dB is still very high because it implies that the peak value is approximately one order of magnitude stronger than the average, and some form of PAPR reduction should be used. It is also interesting to note that the PAPR of an OFDM signal increases slightly as the number of sub-carriers increases. For instance, PAPR increases by approximately 1.6 dB when the sub-carrier number increases from 32 to 256.

There are different solutions to the PAPR problem. The PAPR reduction algorithms proposed so far allow for trade-offs among three figures of merits of the OFDM signal: PAPR, bandwidth efficiency, and computational complexity. The most two popular PAPR reduction approaches are: PAPR reduction with signal distortion in this approach hard clipping the OFDM signal. The consequence of clipping is increased BER and out-of band distortion. The out-of-band distortion can be mitigated through repeated filtering. The second, PAPR reduction without signal distortion in this approach map the original waveform to a new set of wave-forms that have a PAPR lower than the desirable value, most often with some bandwidth reduction. This algorithm include selection mapping,optimization approaches.

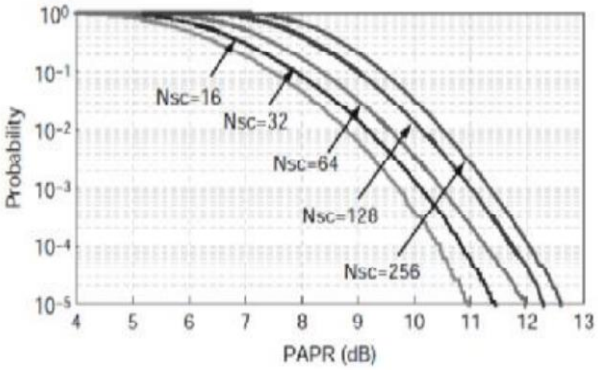


Figure 3.7 CCDF for the PAPR of OFDM Signal with Varying Numbers of Sub-Carriers [40].

3.5.2 Frequency Offset and Phase Noise Sensitivity

Frequency offset and phase noise sensitivity has been recognized as two major disadvantages of OFDM. Both frequency offset and phase noise lead to ICI. Because of its relatively long symbol length compared to that of the single carrier. Frequency offset sensitivity can be mitigated through frequency estimation and compensation [37]. This offset is usually compensated by using adaptive frequency correction (AFC)[38] and phase noise sensitivity is resolved primarily via careful design of RF local oscillators that satisfy the required phase noise specification [37].

3.5.3 Time Offset Error

The time offset error is caused by the incorrect identification of the OFDM symbol boundary at the receiver introducing ISI and ICI. The inclusion of the cyclic prefix makes OFDM relatively more robust to time offset errors. The time offset may vary over an interval equal to the length of the CP without causing ICI or ISI. On the other hand, OFDM is relatively more sensitive to frequency offset errors [38]. The objective of time synchronization is to estimate where the symbol boundary lines, so that an uncorrupted portion of the received OFDM symbol can be sampled for FFT.

Chapter 4 System Design, Simulation and Results Discussion

4.1 Introduction

This chapter presents the simulation results of OOFDM system. The system designed in Optisystem software. Quadrature Amplitude Modulation (QAM) OFDM modulation technique is inserted into system. An Optisystem software will be described, a brief description and explanation of the QAM technique will be discussed.

The OFDM system model will be explained and described; 16QAM OFDM system will be explained and described.

4.2 Optisystem Simulation Software

Optisystem is a comprehensive software design that enables users to plan, test, and simulate optical links in the transmission layer of modern optical networks. 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.

Optisystem enables users to simulate and design

- Access Networks
- Advanced Modulation
- Co-Simulation
- Optical code division multiple access for Passive optical networks
- Dispersion Management
- Fiber Analysis and Design
- Multimode Systems
- Optical Amplifiers, receivers, transmitters

4.3 10Gbits/s DD-OFDM system with SMF

4.3.1 QAM-OFDM System

In this project the OFDM signal generation and decoding using QAM as the modulation technique, 16QAM scheme is used. QAM is both an analog and digital modulation scheme. It conveys two analog message signals, or two digital bit streams by changing (modulating) the amplitudes of two carrier waves, using the amplitude-shift keying (ASK) digital modulation scheme or amplitude modulation (AM) analog modulation scheme. The two carrier waves, usually sinusoids, are out of phase with each other by 90 degree and are thus called quadrature carries or quadrature components.

The modulated waves are summed, and the final waveform is a combination of both PSK and ASK, or (in the analog case) of phase modulation (PM) and amplitude modulation (AM).

In digital QAM case, a finite number of at least two phases and at least two amplitudes are used. PSK modulators are often designed using the QAM principle, but are not considered as QAM since the amplitude of modulated carrier signal is constant.

Figure 4.1 shows the constellation diagrams which show the different positions for the states within different forms of QAM, from 4QAM, 16QAM and 64QAM.

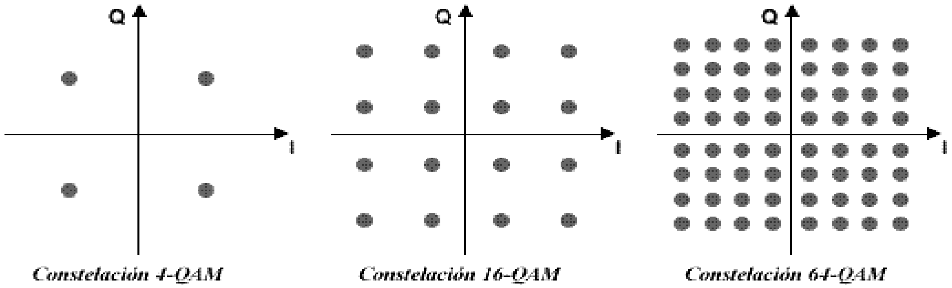


Figure 4.1 Constellation Diagram for Different forms of QAM

In Direct Detection 16QAM-OFDM system the 256 sub-carriers is used to achieve a value of BER of zero. In Coherent detection OFDM and in the integration of WDM with CO-OFDM systems 512 sub-carriers is used to get the best value of BER, the 16QAM-OFDM system will be discussed with more details and explanations.

(1) Radio Frequency Transmitter

The RF transmitter is consisted of four blocks, the figure 4.2 shows all blocks of RF transmitter system as the following:

The first block is a Pseudo Random Binary Sequence Generator to generate a bit sequence that will approximate the random data characteristics. In this simulation the sequence of length is 16384 bits.

The second block is 16-QAM (4 bit per symbol) sequence generator to generate bits per symbol.

The third block is OFDM modulator with 256 sub-carriers and 512 FFT points and low pass roll off filters.

The last block is the quadrature modulator, which is used to up convert the signal at high RF frequency.

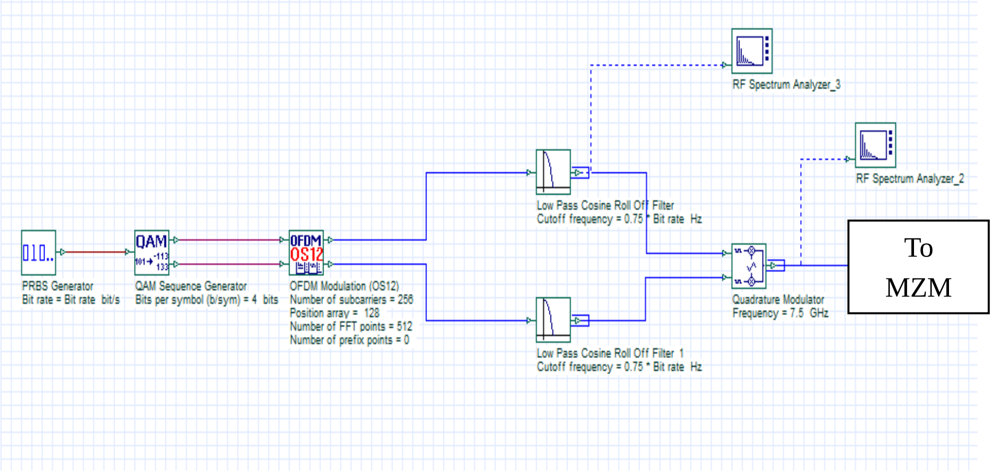


Figure 4.2 Radio Frequency Transmitter

Table 4.1 shows the global parameters setup for 10Gbits/s DD-OFDM system.

Table 4.1 Global Parameters Setup 10Gbits/s DD-OFDM

Parameter	Value
Bit rate	10 Gbit/s
Time window	1.6384×10^{-6} s
Sample rate	40 GHz
Sequence length	16384 bits
Sample per bit	4
Number of samples	65536

(2) Optical Transmitter

The optical transmitter converts the electrical signal into optical signal, and launches the resulting optical signal into the optical fiber and also can called RF to optical up-converter (RTO). The optical transmitter consists of optical source, electrical pulse generator and optical modulator as shown in figure 4.3.

A suitable launched power which indicates how much fiber loss can be tolerated with 0.15MHz line width at 1550nm (193.1 THz) used in this simulation, then the light signal, which was generated by laser, and OFDM symbols will be modulated with $LiNbO_3$ MZM, after that the optical modulated signal is filtered by optical filter at the same window at 193.1 THz frequency with bandwidth of 20 GHz, then to keep signal strong an optical amplifier is used with gain 13dB.

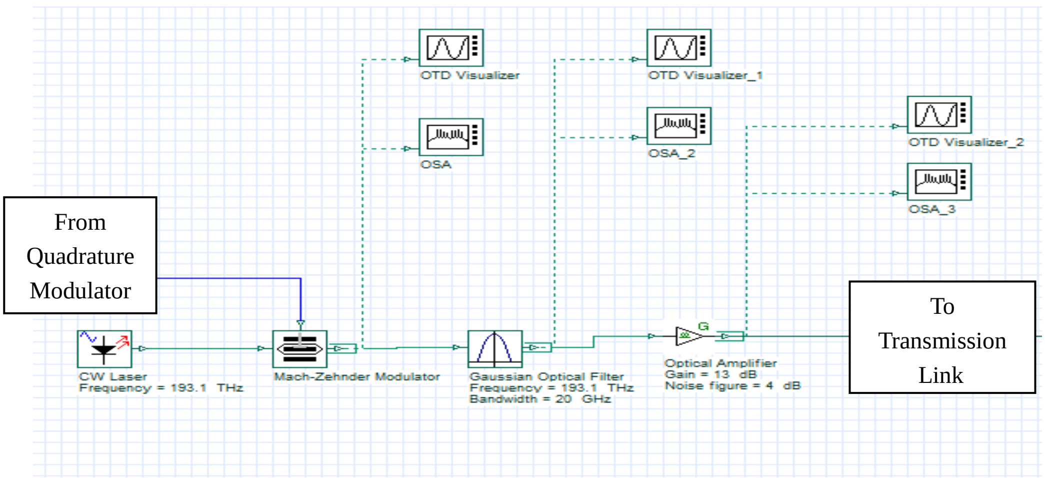


Figure 4.3 Optical Transmitter

4.3.2 The Optical Transmission Link

The transmission link which is shown in figure 4.4 consists of an optical fiber with length of 100 km and attenuation of 0.2 dB/km, a dispersion of 16 ps/(km.nm), a dispersion slope of 0.075 ps/(km.nm^2) and a nonlinearity coefficient 2.6×10^{-20}. An optical amplifier is used to amplify the weak signals and optical signal with the same window of laser, the transmission link repeated twice.

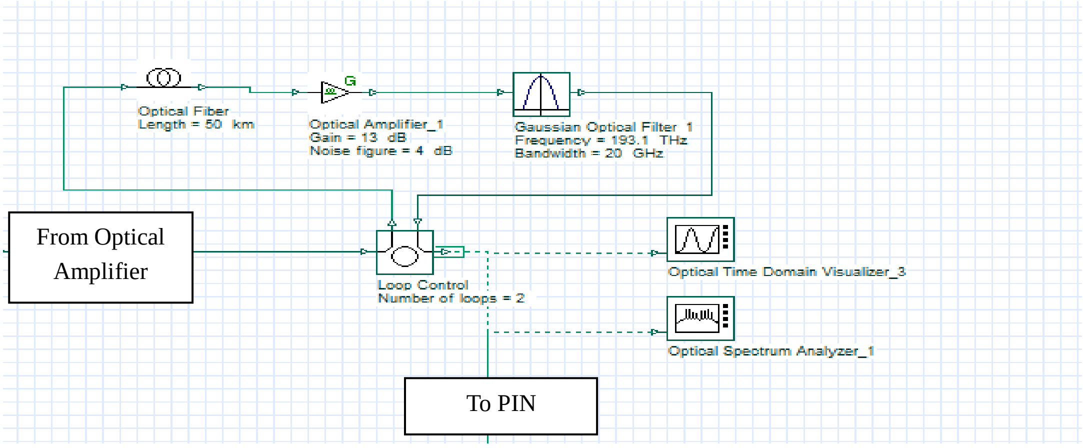


Figure 4.4 Optical Transmission Link

4.3.3 The Receiver Model

The receiver model of OOFDM system is consists of two parts: the optical receiver and RF receiver.

(1) Optical Receiver:

The optical receiver (or optical to RF down-converter OTR) is shown in figure 4.5.

The optical signal sent from laser to receiver by the optical link is detected by photo-detector, which is Positive Intrinsic Negative (PIN) detector with responsivity of 1 A/W, thermal noise of 1×10^{-22} W/Hz, dark current of 10 nA, and a center frequency of 193.1 THz. After that the signal is filtered by band pass filter, which is used to eliminate the noise that added from fiber, this filter has a frequency of the RF signal and bandwidth of half of the bit rate.

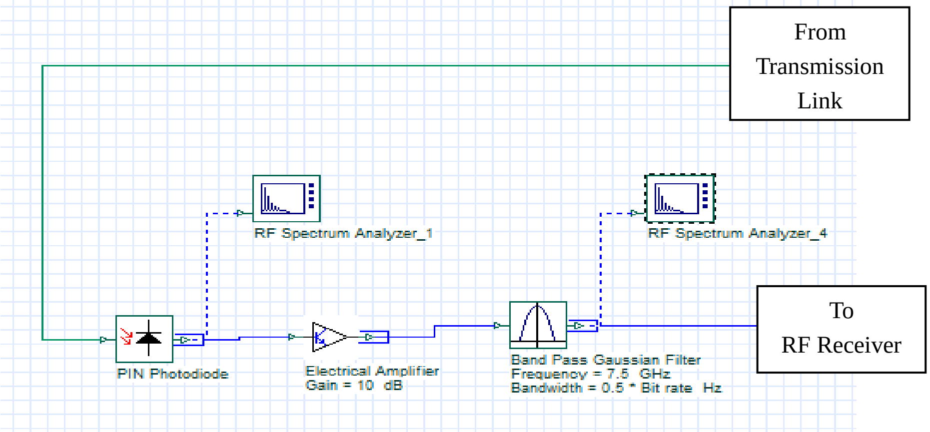


Figure 4.5 Optical to RF Receiver

(2) RF Receiver:

After the optical signal converted to electrical signal and all noise is eliminated, the signal will be demodulated with OFDM demodulator to extract the symbols and then decoded with 16QAM decoder to get the original bits. Figure 4.6 shows the RF receiver.

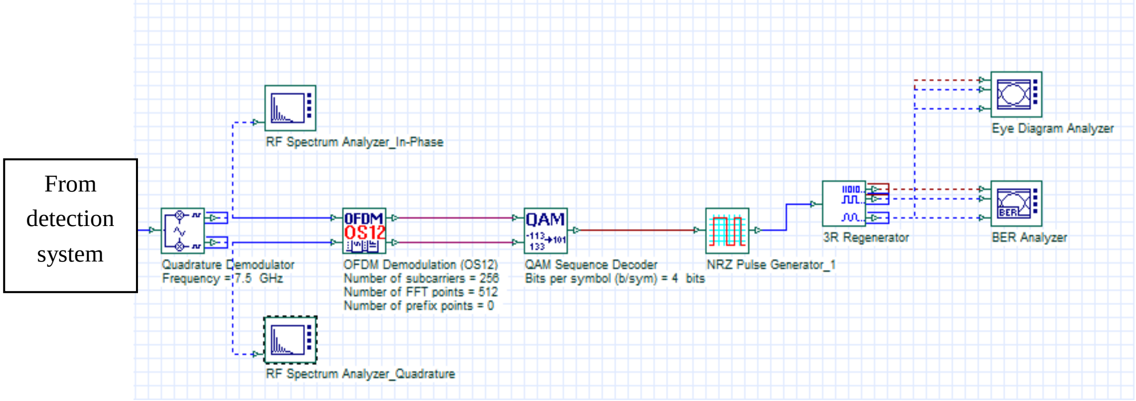
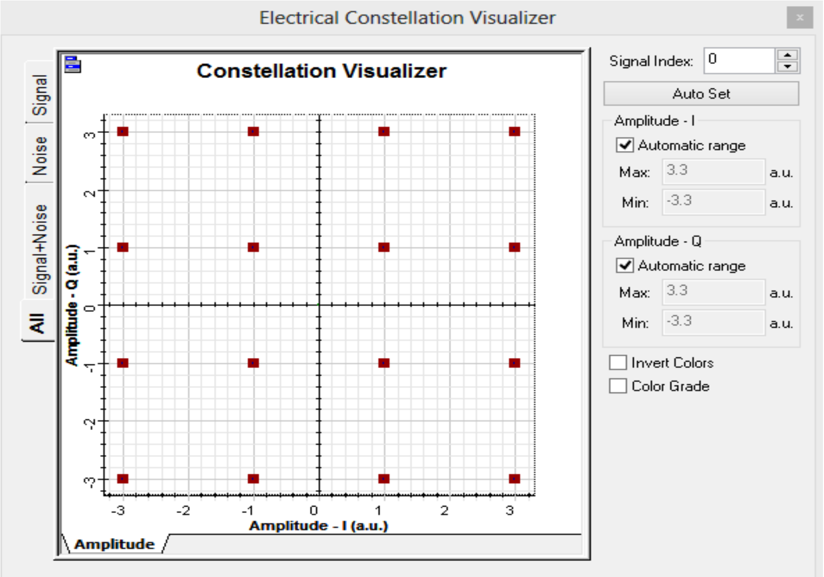


Figure 4.6 RF Receiver

4.3.4 Simulation Results and Discussion

Figure 4.7 illustrate the 16-QAM encoder diagram



Signal Index: 0

Amplitude - I
☑ Automatic range
Max: 3.3 a.u.
Min: -3.3 a.u.

Amplitude - Q
☑ Automatic range
Max: 3.3 a.u.
Min: -3.3 a.u.

☐ Invert Colors
☐ Color Grade

Figure 4.7 16QAM Encoder Constellation Diagram

Figure 4.8 shows the filtered OFDM signal by LP filter.

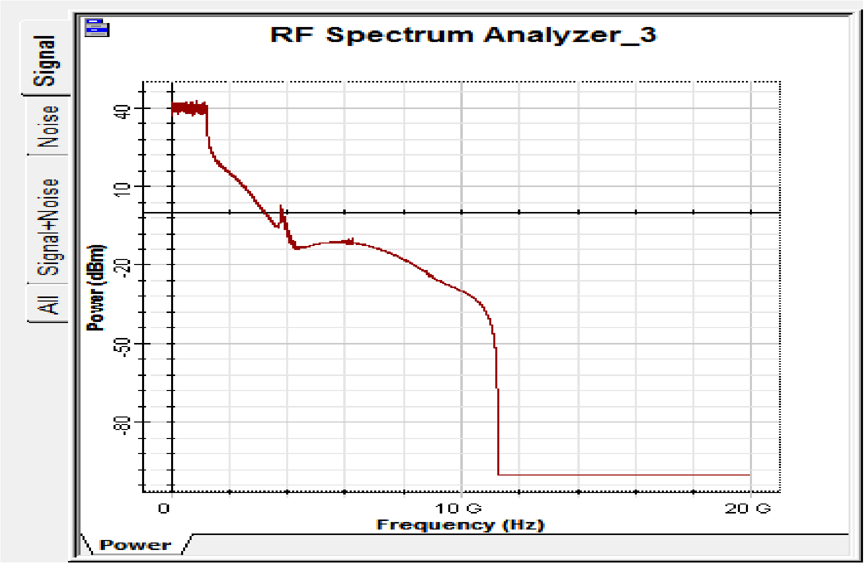


Figure 4.8 Filtered OFDM signal by LP filter

Figure 4.9 shows the modulated OFDM signal after quadrature modulator in the frequency domain. The power of modulated OFDM signal is equal to 40dBm and bandwidth of 12 GHz.

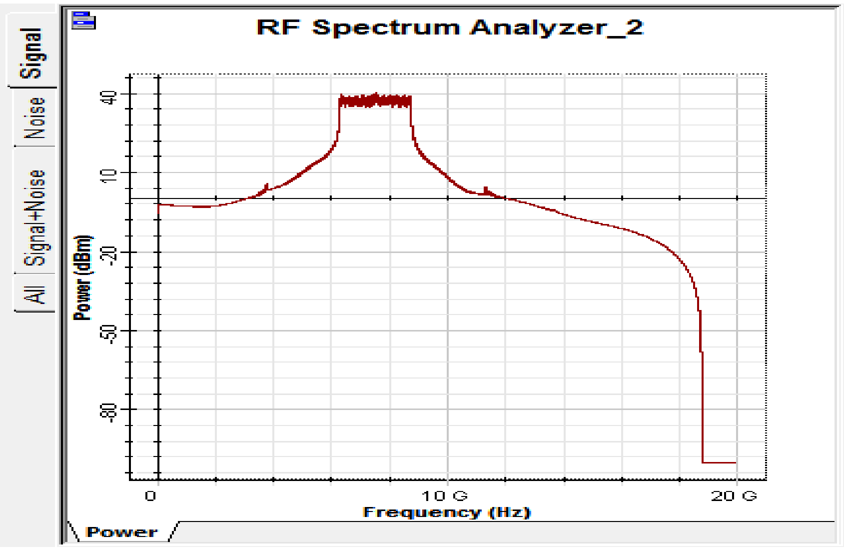
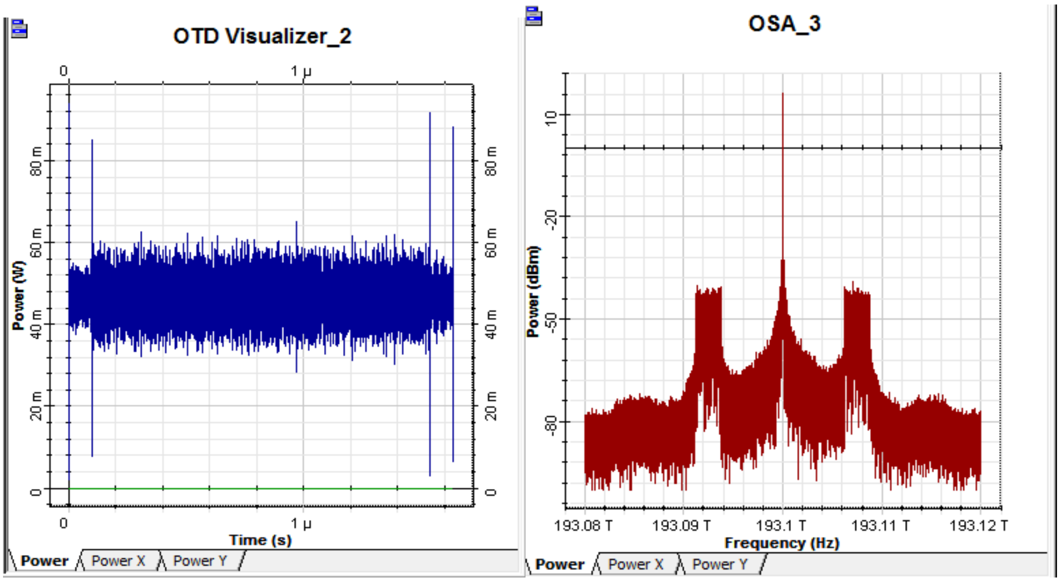


Figure 4.9 OFDM Signal in the Frequency Domain

Figure 4.10 shows the next procedure which is converting the RF OFDM signal to optical signal at window of 1550nm (193.1 THz) using MZM external modulator with suitable power incoming from the laser, the resulted signal in time and frequency domain.



(a) (b)

Figure 4.10 Modulated Optical Signal. (a) Time Domain, (b) Frequency Domain

After that the signal will be propagated through the optical fiber to be received after two loops of 50 km length of fiber. Figure 4.11 shows the modulated OFDM signal after the propagation through the optical link.

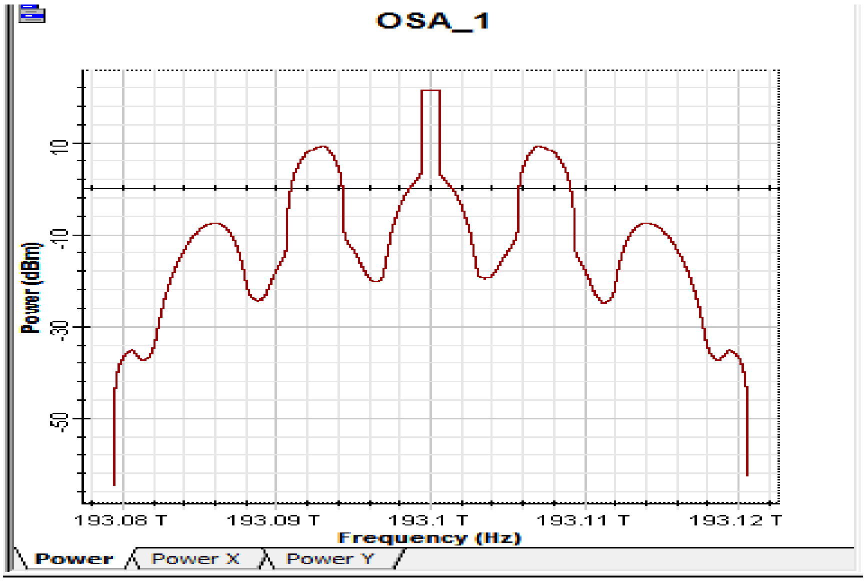


Figure 4.11 OFDM Signal after the Optical Link

Figure 4.12 shows the RF spectrum of system at the DD-OFDM receiver side after two loops of 50 km length of optical link. The RF power is measured at -17 dBm with side noise.

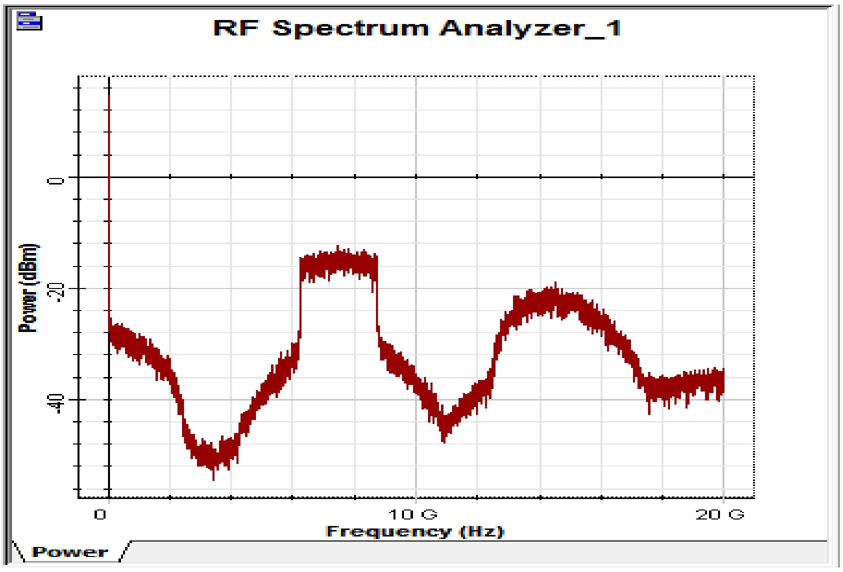


Figure 4.12 Received RF Signal in the Frequency Domain

Figure 4.13 shows the resulted signal after the BPF with 2 GHz bandwidth form two sides of the center frequency at 7.5GHz.

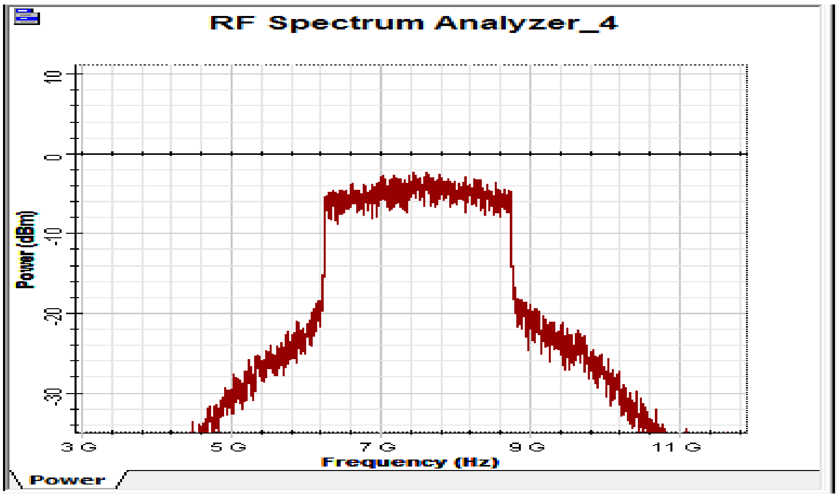
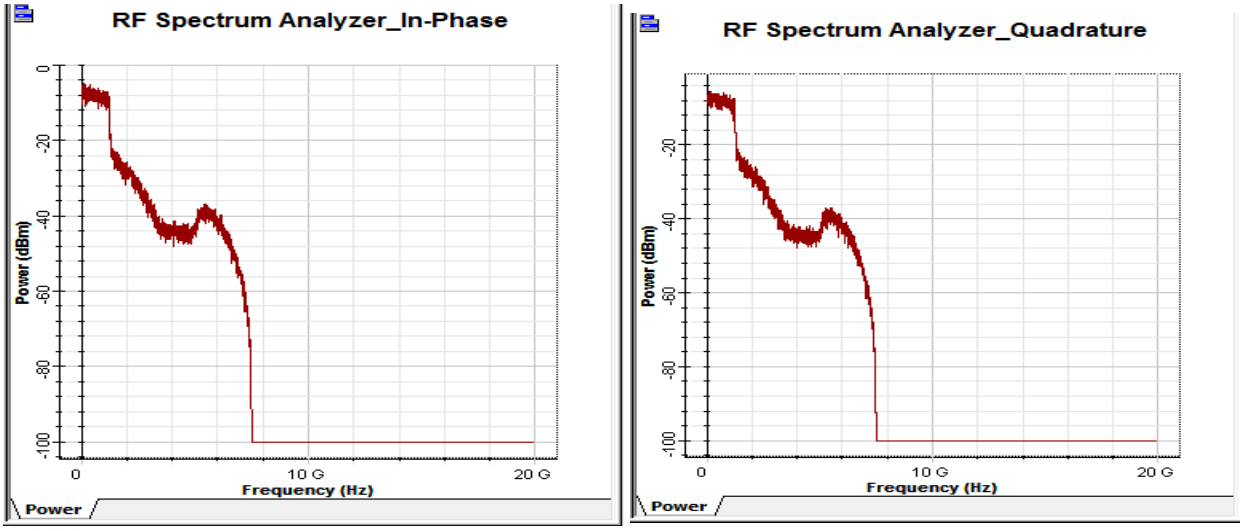


Figure 4.13 RF Signal after BPF

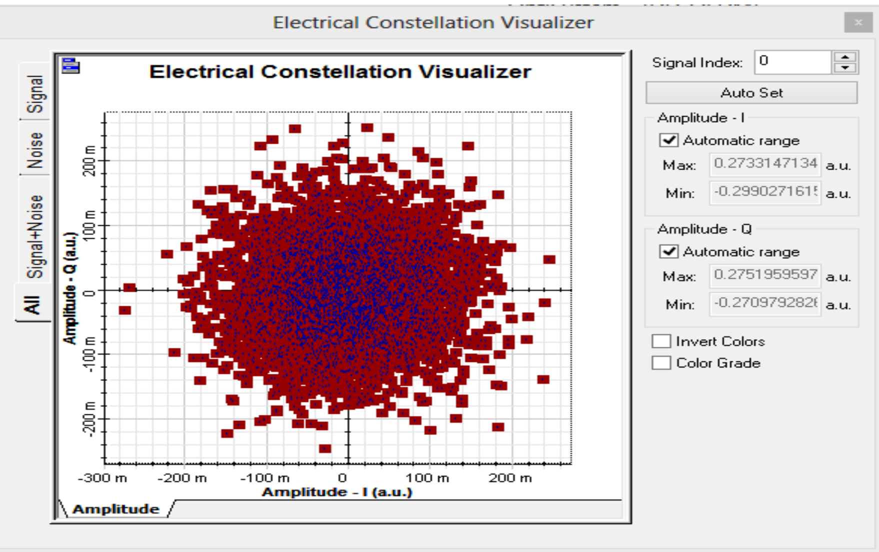
Figure 4.14 shows the RF spectrum at the receiver side after the quadrature demodulator with a measured power at almost -10 dBm.



(a) (b)

Figure 4.14: RF Spectrum after Quadrature Demodulation:(a) In-Phase Spectrum, (b) Quadrature Spectrum

Figure 4.15 shows the constellation diagram of the system after 100 km SMF at the DD-OFDM receiver side. It can be seen that the signal is distorted and corrupted because of the chromatic dispersion.



Signal Index: 0

Amplitude - I

☑ Automatic range

Max: 0.2733147134 a.u.

Min: -0.299027161 a.u.

Amplitude - Q

☑ Automatic range

Max: 0.2751959597 a.u.

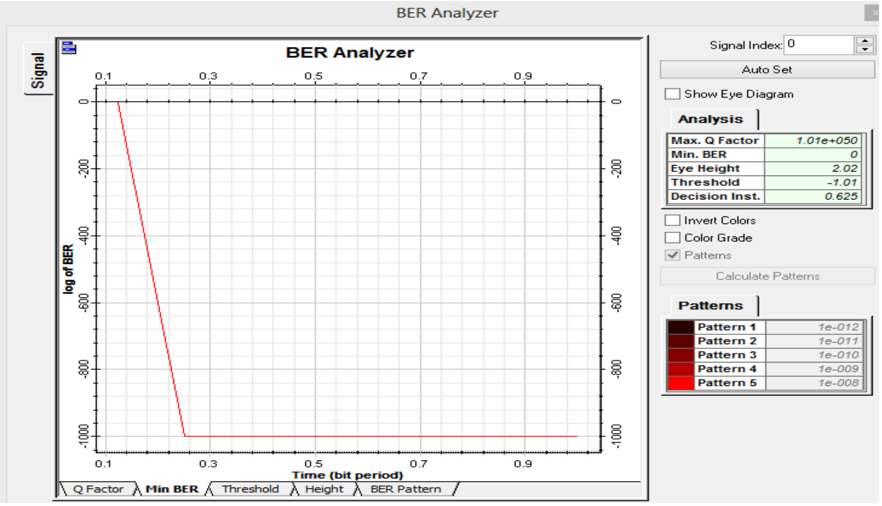
Min: -0.270979282 a.u.

☐ Invert Colors

☐ Color Grade

Figure 4.15 Constellation Diagram of the 10 Gbits/s One Users DD-OFDM at the Receiver Side after SMF of 100 km

After the modulation and demodulation, three parameters were tested to study the performance of the system 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 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. From figure 4.16 the best value of BER of zero is achieved.



Signal Index: 0

☐ Show Eye Diagram

Max. Q Factor	1.01e+050
Min. BER	0
Eye Height	2.02
Threshold	-1.01
Decision Inst.	0.625

☐ Invert Colors

☐ Color Grade

☑ Patterns

■	Pattern 1	1e-012
■	Pattern 2	1e-011
■	Pattern 3	1e-010
■	Pattern 4	1e-009
■	Pattern 5	1e-008

Figure 4.16 BER Analysis

Figure 4.17 shows the high open eye diagram.

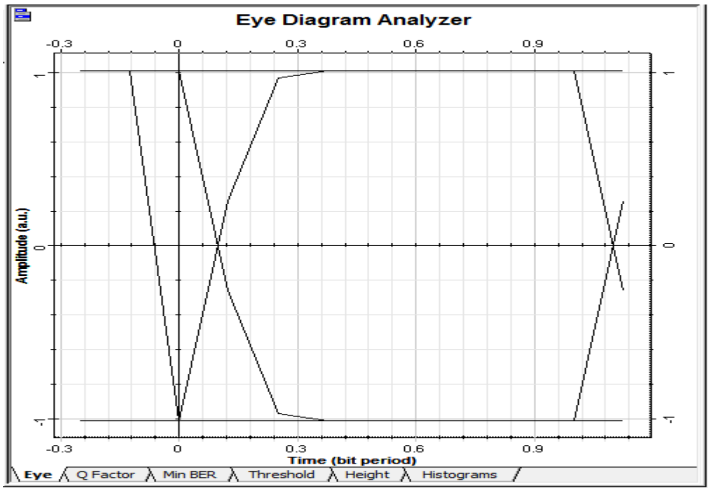
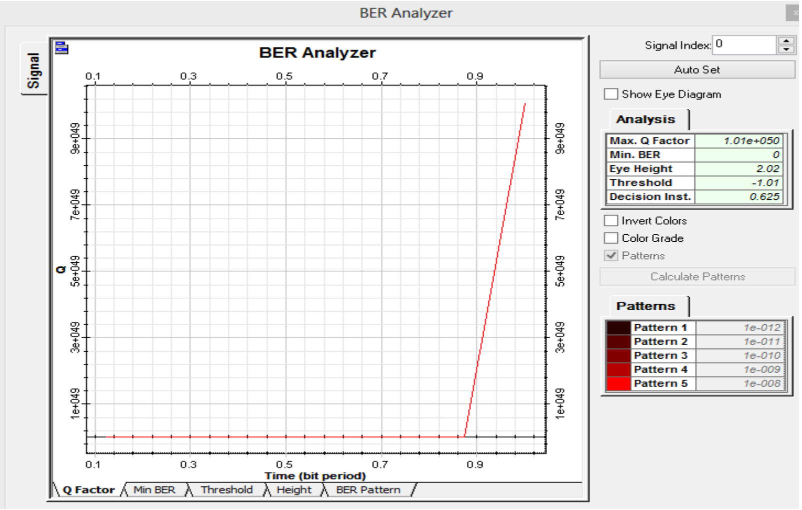


Figure 4.17 Eye Diagram Analyzer

And the Q factor is shown in figure 4.18.



Signal Index: 0

☐ Show Eye Diagram

Analysis

Max. Q Factor	1.01e+050
Min. BER	0
Eye Height	2.02
Threshold	-1.01
Decision Inst.	0.625

☐ Invert Colors
☐ Color Grade
☑ Patterns

Patterns

■	Pattern 1	1e-012
■	Pattern 2	1e-011
■	Pattern 3	1e-010
■	Pattern 4	1e-009
■	Pattern 5	1e-008

Figure 4.18 Q Factor

Table 4.2 gives the signal details at the receiver for 10Gbits/s

Table 4.2 Signal Details at the Receiver for 10Gbits/s

Min. BER	0
Max Q Factor	1.01×10^{50}
Eye Height	2.02
Threshold	-1.01
Decision Inst	0.625

4.4 40Gbits/s CO-OFDM with SMF

Coherent optical OFDM (CO-OFDM) represents the ultimate performance in receiver sensitivity, spectral efficiency, and robustness against polarization dispersion, but it requires the highest complexity in transceiver design.

The CO-OFDM system design consists of a CO-OFDM transmitter, a fiber link and a CO-OFDM receiver. Figure 4.25 shows the system design of one user CO-OFDM transmitter. As can be seen that the CO-OFDM transmitter is built with a Pseudo Random Binary Sequence (PRBS) to generate a bit sequence, and 16QAM encoder. The 16QAM encoder is connected to an OFDM modulator with 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 I/Q optical modulator (RF to optical converter) as shown in figure 4.26 which consists of two lithium Niobate ($LiNbO_3$) Mach-Zehnder modulators (MZM). The MZM will modulate the electrical signal from the OFDM modulator to the optical carrier with a laser source of 193.1 THz. The power of the laser source is -5 dBm.

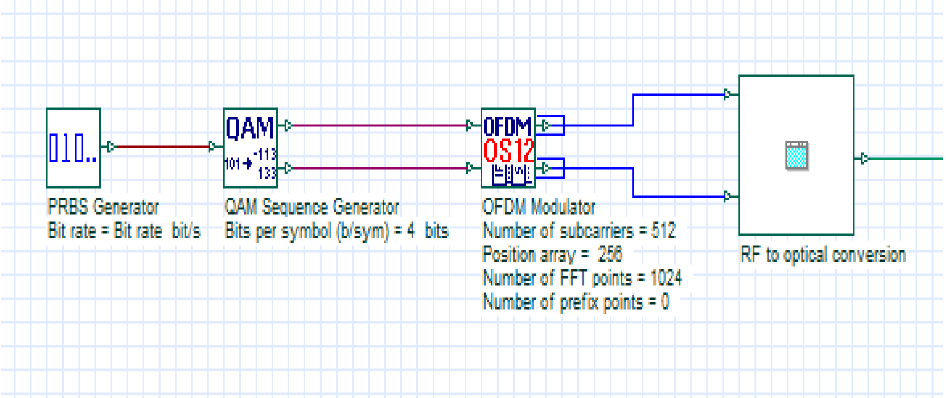


Figure 4.25 OFDM Transmitter with Optical Conversion

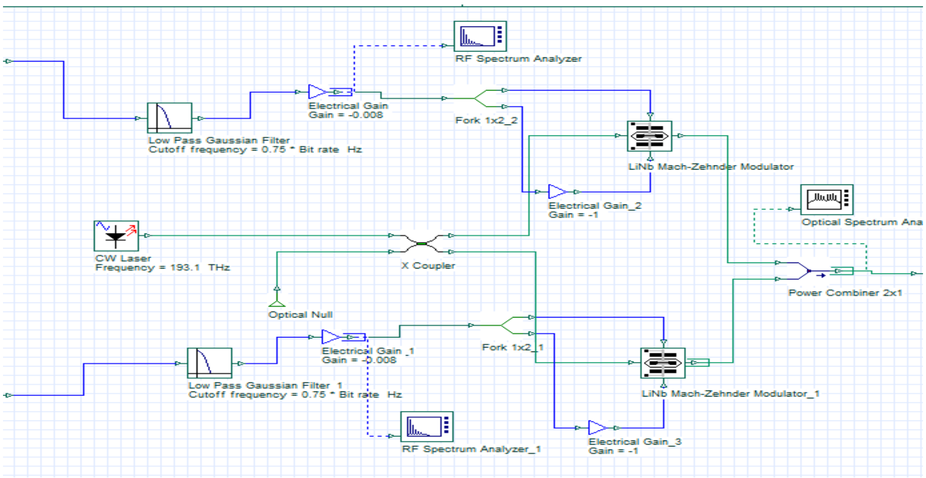


Figure 4.26 RF to Optical Conversion

The resulting signal after the two $LiNbO_3$ MZMs is transmitted through the optical fiber with attenuation of 0.2 dB/km, a dispersion of 16 ps/(nm.km), a dispersion slope of 0.075 ps/(nm^2 .km) and a nonlinearity coefficient of 2.6×10^{-20}. An optical amplifier is used to amplify the signal and to compensate for the loss , the optical link is shown in figure 4.27.

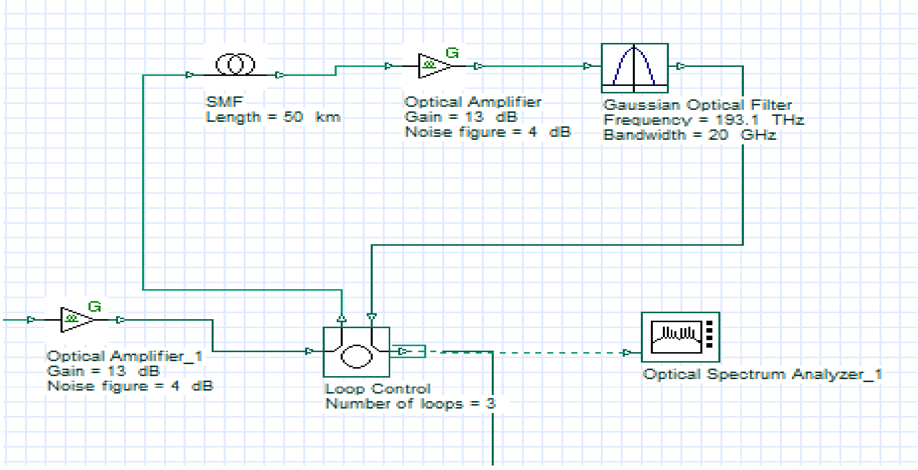


Figure 4.27 Optical Link with 150 km SMF

At the receiver side as shown in figure 4.28, 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 photo-detectors. Each PIN photo-detector has a dark current of 10 nA, a responsivity of 1 A/W, thermal noise of 1×10^{-24} W/Hz and a center frequency of 193.1 THz as shown in figure 4.29. After detecting the signal, 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 16QAM decoder to create a binary signal as shown in the figure 4.28.

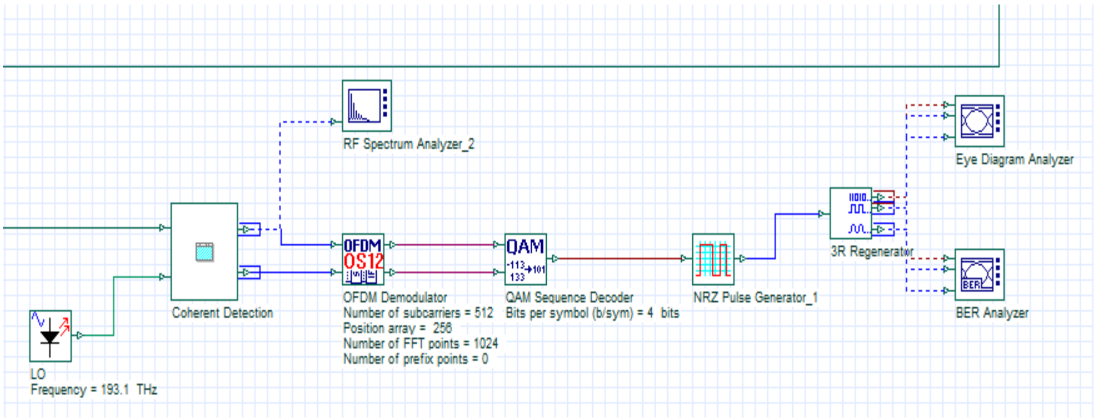


Figure4.28 CO-OFDM Receiver

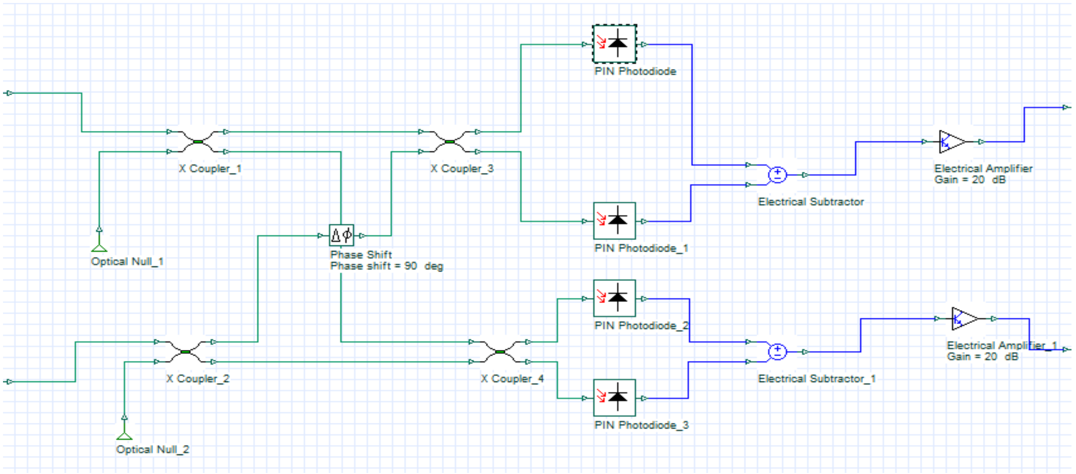


Figure 4.29 Coherent Detection

4.4.1 Simulation Results and Discussion

Table 4.4 gives the global parameters for 40Gbits/s CO-OFDM system.

Table 4.3 Global Parameters Setup for 40Gbits/s

Parameter	Value
Bit rate	40 Gbit/s
Time window	0.4096×10^{-6} s
Sample rate	80 GHz
Sequence length	16384 bits
Sample per bit	2
Number of samples	32768

The simulation results of the long haul CO-OFDM are presented and discussed in this section.

Figure 4.29 shows the RF spectrum for the I/Q signals of the system at CO-OFDM transmitter. The RF power is measured at almost -6 dBm. Figure 4.30 shows the optical signal spectrum, after modulating the electrical signal with the optical carrier using two MZMs. While figure 4.31 shows the OOFDM spectrum after the propagation through the optical link.

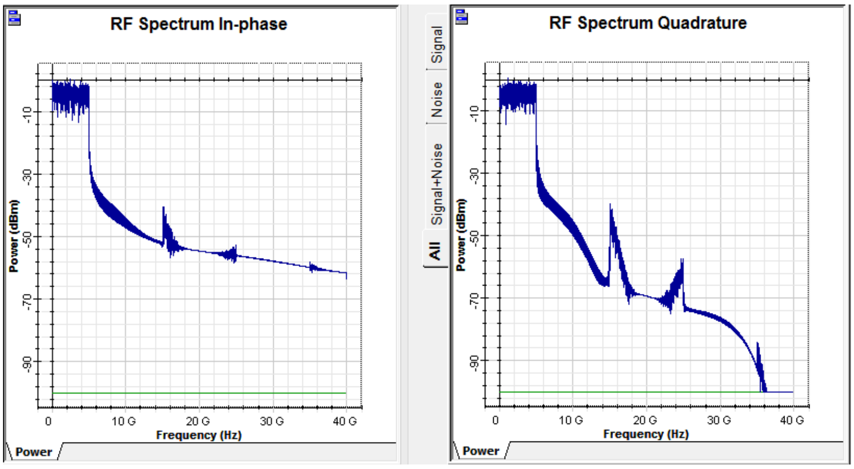


Figure 4.29 RF OFDM Spectrum I/Q

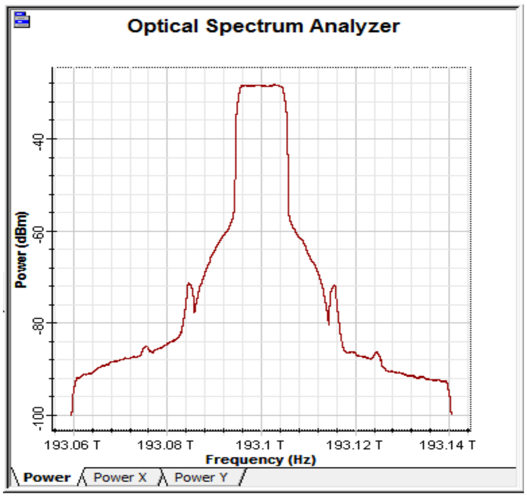
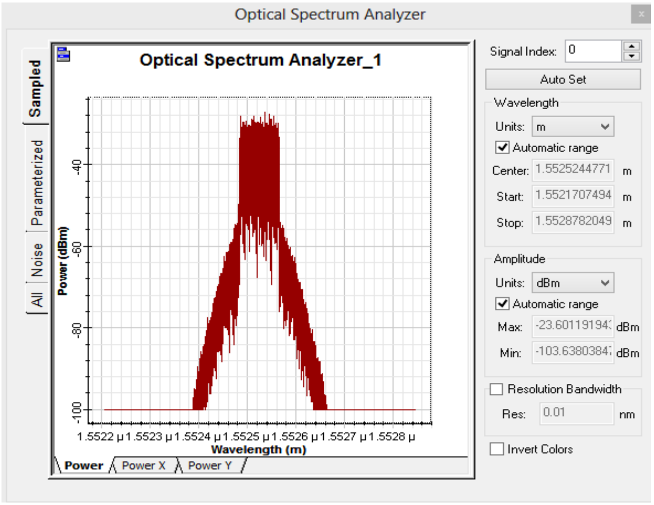


Figure 4.30 Optical OFDM Spectrum after the two MZM Modulators



Signal Index: 0

Wavelength

Units: m

☑ Automatic range

Center: 1.5525244771 m

Start: 1.5521707494 m

Stop: 1.5528782049 m

Amplitude

Units: dBm

☑ Automatic range

Max: -23.60119194 dBm

Min: -103.6380384 dBm

☐ Resolution Bandwidth

Res: 0.01 nm

☐ Invert Colors

Figure 4.31 OOFDM Spectrum after 150 km SMF

Figure 4.32 shows the RF spectrum of the system at the CO-OFDM receiver side after 150 km SMF. The RF power is measured at almost -40 dBm .

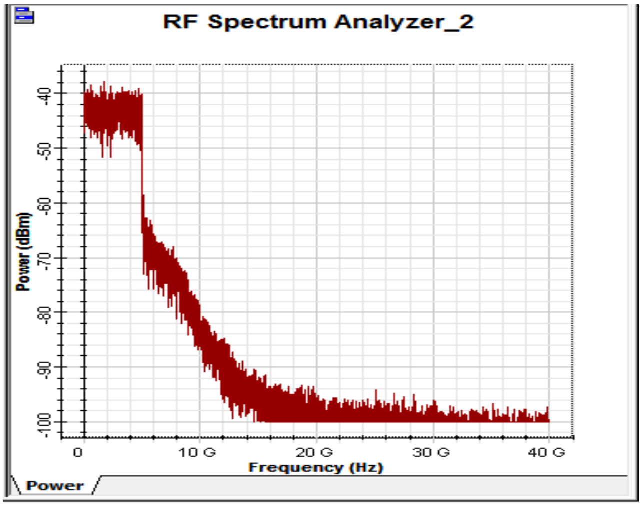
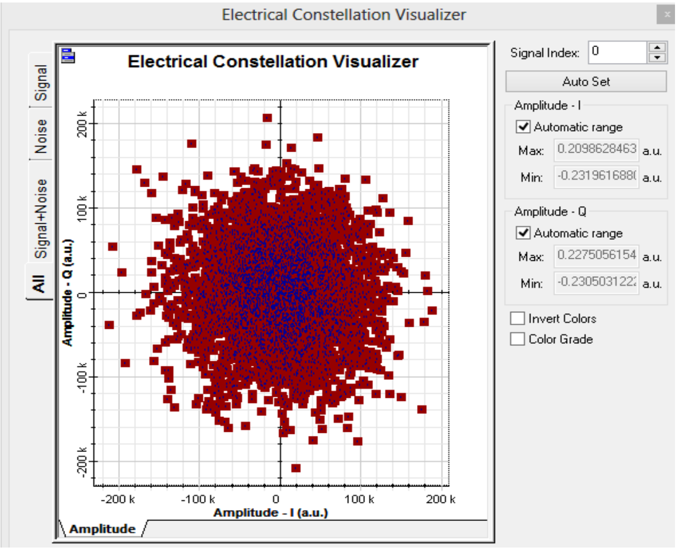


Figure 4.32 RF Spectrum at the CO-OFDM Receiver

Figure 4.33 shows the constellation diagram of the 40 Gbps CO-OFDM system at the receiver side after SMF of 150 km. In the constellation diagram, the blue represent the thermal noise from the photo-detectors and fiber dispersion. It can be seen that the signal is distorted and corrupted.



Signal Index: 0

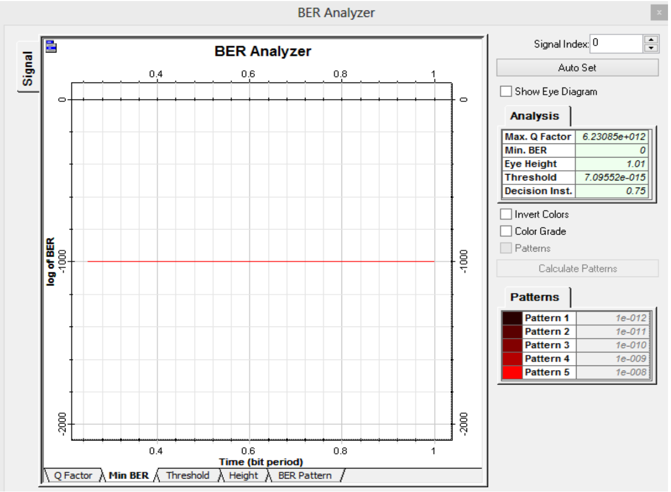
Amplitude - I
☑ Automatic range
Max: 0.2098628463 a.u.
Min: -0.231961688 a.u.

Amplitude - Q
☑ Automatic range
Max: 0.2275056154 a.u.
Min: -0.230503122 a.u.

☐ Invert Colors
☐ Color Grade

Figure 4.33 Constellation Diagram of the 40 Gbps CO-OFDM System

From figure 4.34 the best value of BER of zero is achieved, and the high open eye diagram is shown in the figure 4.35. And the Q factor is shown in figure 4.36.



Analysis	
Max. Q Factor	6.23085e+012
Min. BER	0
Eye Height	1.01
Threshold	7.09552e-015
Decision Inst.	0.75

Patterns	
Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Signal Index: 0

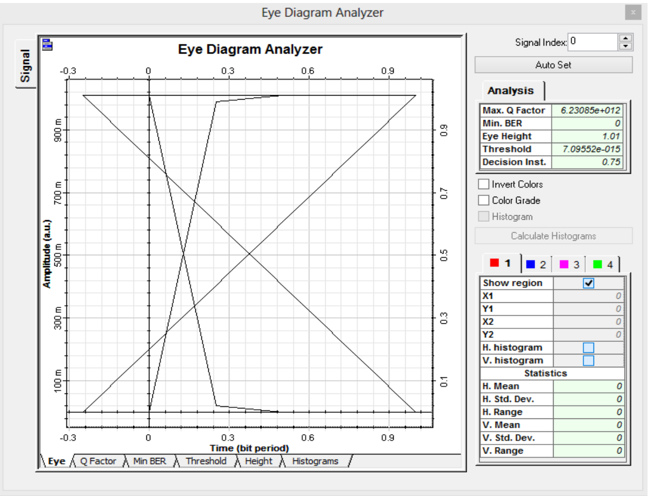
☐ Show Eye Diagram

☐ Invert Colors

☐ Color Grade

☐ Patterns

Figure 4.34 BER Analysis



Analysis	
Max. Q Factor	6.23085e+012
Min. BER	0
Eye Height	1.01
Threshold	7.09552e-015
Decision Inst.	0.75

Signal Index: 0

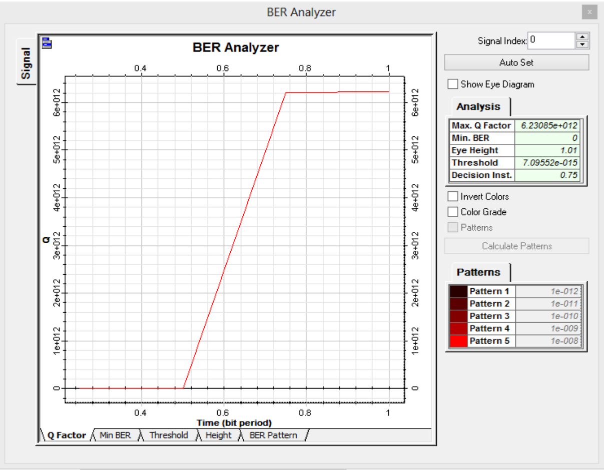
☐ Invert Colors

☐ Color Grade

☐ Histogram

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0

Figure 4.35 Eye Diagram Analyzer



Analysis	
Max. Q Factor	6.23085e+012
Min. BER	0
Eye Height	1.01
Threshold	7.09552e-015
Decision Inst.	0.75

Patterns	
Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Signal Index: 0

☐ Show Eye Diagram

☐ Invert Colors

☐ Color Grade

☐ Patterns

Figure 4.36 Q Factor

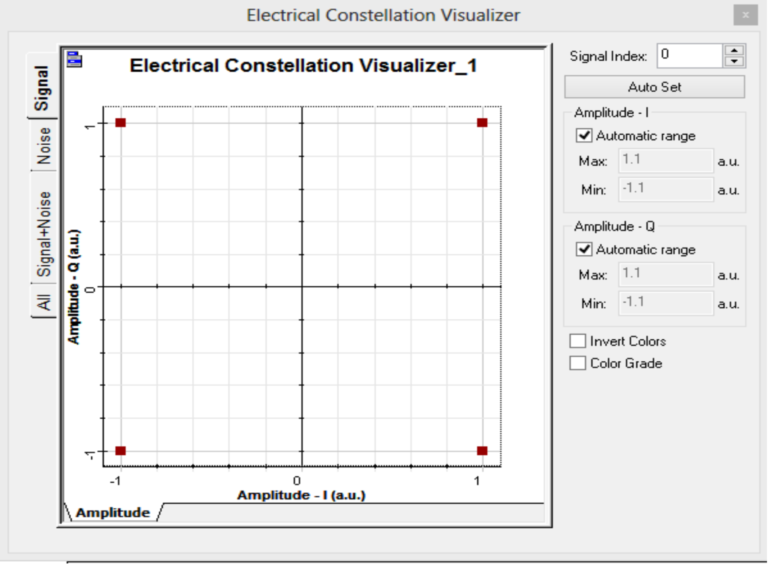
Table 4.5 present the signal details at the receiver side for 40Gbits/s

Table 4.4 Signal Details at the Receiver for 40Gbits/s

Max.Q Factor	6.23085×10^{12}
Min. BER	0
Eye Height	1.01
Threshold	7.09552×10^{-15}
Decision Inst	0.75

4.5 Integration of WDM with CO-OOFDM for long haul high data rate transmission

The wavelength division multiplexing (WDM) is an important factor in the development of optical fiber communication. It has the ability to provide more flexibility to the system and to simplify the design of the network. WDM technique multiplexes a number of optical carrier signals onto a single optical fiber by using different wavelengths or laser light. 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 carriers a separate channel. WDM divides the optical spectrum to smaller channels, which are used to transmit and receive data simultaneously. Figure 4.37 shows the constellation diagram of 4-QAM.



Signal Index: 0

Amplitude - I
☑ Automatic range
Max: 1.1 a.u.
Min: -1.1 a.u.

Amplitude - Q
☑ Automatic range
Max: 1.1 a.u.
Min: -1.1 a.u.

☐ Invert Colors
☐ Color Grade

Figure 4.37 Constellation Diagram of 4-QAM

Figure 4.38 shows the system design of WDM CO-OFDM system with SMF-DCF of 120 km length. The CO-OFDM transmitter is built with a PRBS generator to generate a bit sequence; it is also built with 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 ($LiNbO_3$) Mach-Zehnder modulators (MZM). The optical modulator will modulate the electrical signal from the OFDM modulator to optical signal.

In order to support 100 Gbits/s four OFDM signals are needed, which means four 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 THz to 193.2 THz with a space of 50 GHz. The WDM system consists of four channels to support the four OFDM bands with channel space of 50GHz. Each OFDM signal has a 25 Gbps bit-rate which will provide an overall data rate of 100Gbits/s.

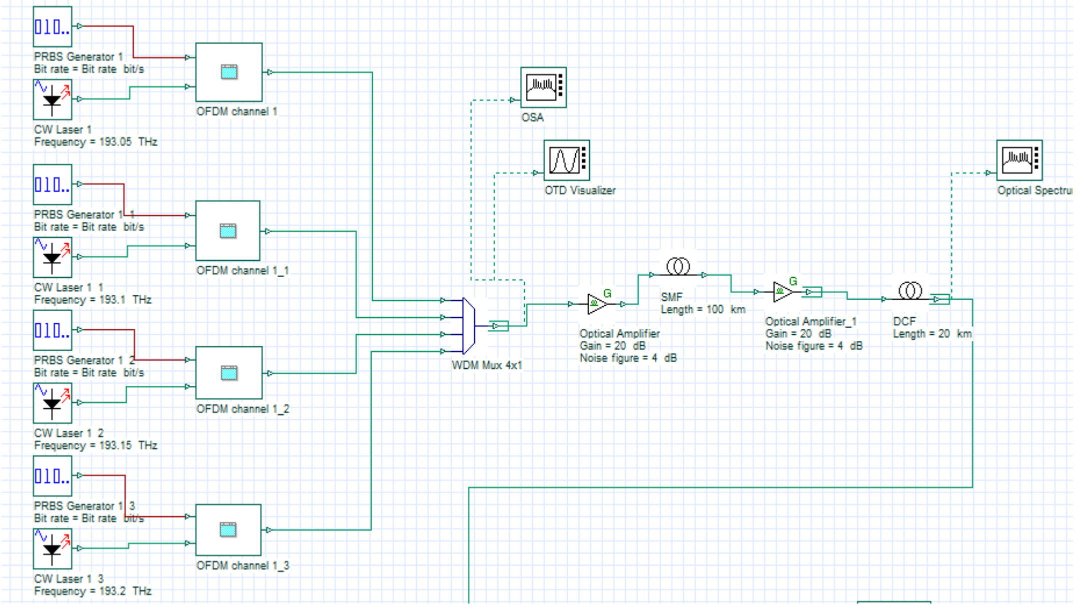


Figure 4.38 Block Diagram of WDM CO-OFDM System with SMF-DCF of 120km

The resulting signals from the OFDM transmitters are launched into the WDM MUX. The four different wavelengths are merged to produce one signal to be launched in the optical fiber. The resulting optical signal of the WDM MUX is then transmitted through the SMF-DCF system. 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 100km. SMF which will produce a dispersion of 1600 ps/nm. Therefore, to compensate for the dispersion of the 100km SMF, a 20 km long DCF is needed with dispersion of -80 ps/(nm.km) which will produce -1600 ps/nm. This dispersion is negative in order to cancel the positive dispersion of the SMF. An optical amplifier is used with 20 dB power to amplify the signal and to compensate for the loss. The parameters of SMF and DCF are given in tables 4.6 and 4.7.

The incoming optical signal from the optical link is separated into four wavelengths by the WDM DEMUX and each wavelength is detected by its receiver. Four 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 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 photo-detectors. Each PIN photo-detector has a dark current of 10 nA, a responsivity of 1 A/W and thermal noise of 1×10^{-22} W/Hz. After detecting the signal, the signal is sent to the OFDM demodulator which has the similar parameters to the OFDM modulator. The guard interval is removed. Finally, the resulting signal is fed into a 4-QAM decoder to create a binary signal.

Table 4.5 SMF Parameters

Fiber length	100 (km)
Attenuation	0.2 (dB/km)
Dispersion	16 (ps/(nm.km))
Slope	0.08 (ps/(nm^2 .km))
Effective Area	80 (µm^2)
Nonlinear refractive index n_2	2.6×10^{-20}

Table4.6 DCF Parameters

Fiber length	20 (km)
Attenuation	0.4 (dB/km)
Dispersion	-80 (ps/(nm.km)
Slope	-0.45(ps/(nm^2 .k))
Effective Area	30 (µm^2)
Nonlinear refractive index n_2	2.6×10^{-20}

4.5.1 100Gbits/s WDM CO-OFDM System Simulation Results and Discussion

Figure 4.39 shows the RF spectrum of the I/Q component of the CO-OFDM WDM system at the transmitter side. The RF power is measured at almost -16 dBm. Figure 4.40 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 almost -39 dBm compared with figure 4.39.

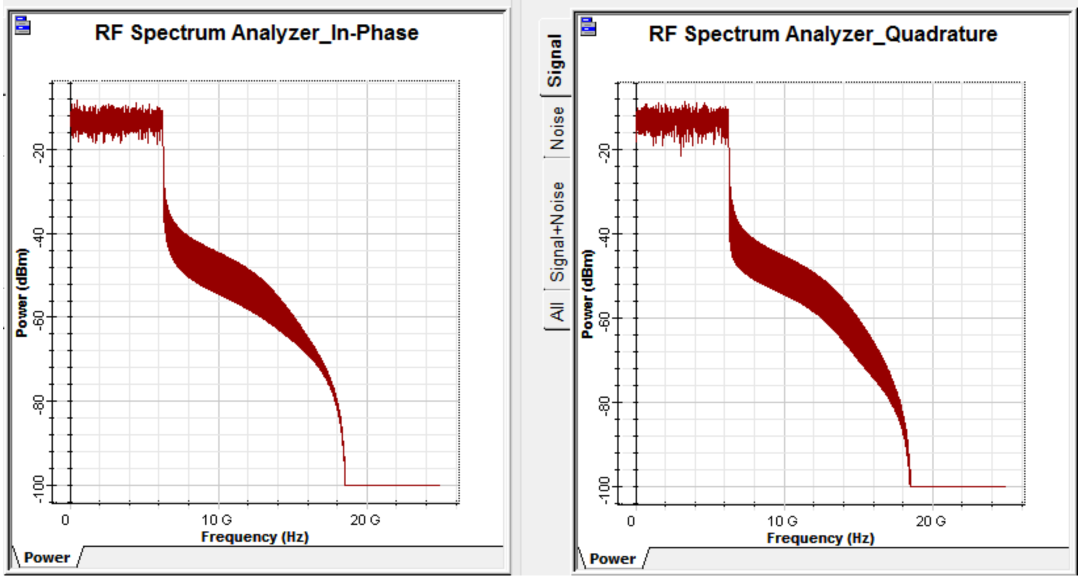


Figure 4.39 RF OFDM Spectrum I/Q Component at the CO-OFDM Channel

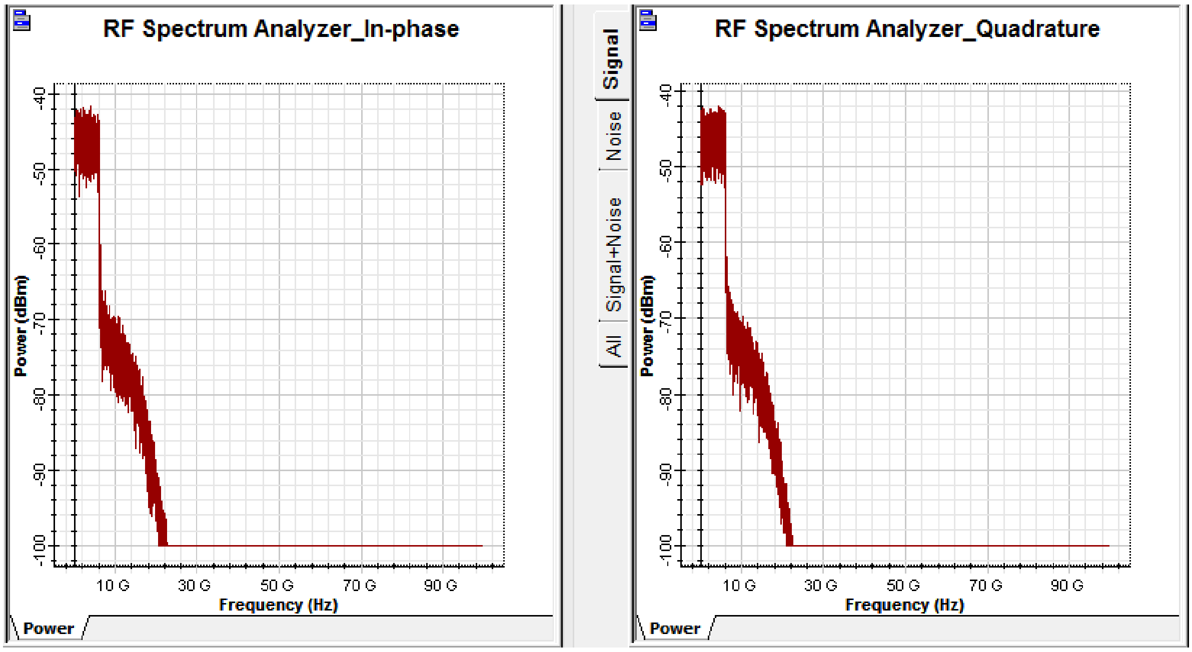
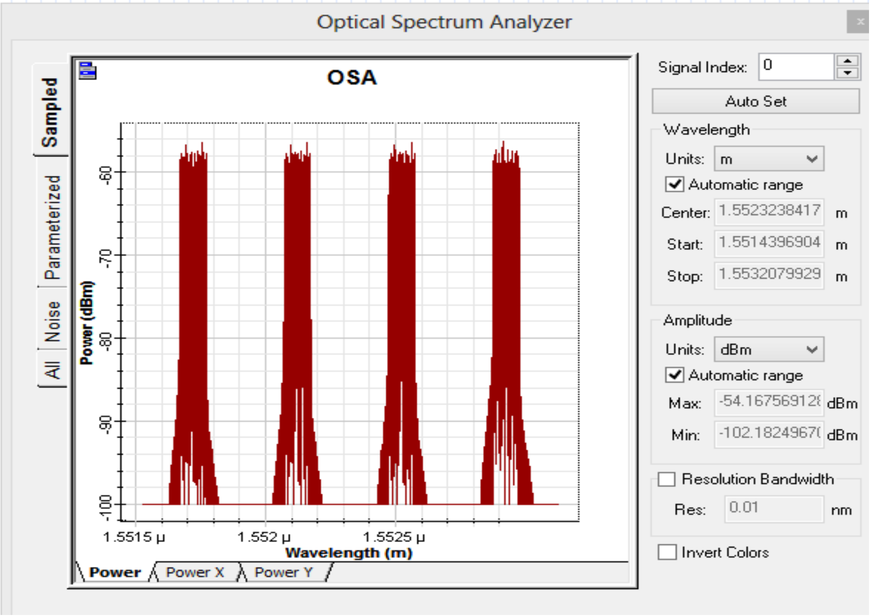


Figure 4.40 RF OFDM Spectrum I/Q Component at the CO-OFDM Receiver

Figure 4.41 shows the four OFDM spectrums after the WDM system. Four WDM channels start 193.05 THz to 193.2 THz with channel spacing of 50 GHz.



Signal Index: 0

Wavelength
Units: m
☑ Automatic range
Center: 1.5523238417 m
Start: 1.5514396904 m
Stop: 1.5532079929 m

Amplitude
Units: dBm
☑ Automatic range
Max: -54.16756912 dBm
Min: -102.1824967 dBm

☐ Resolution Bandwidth
Res: 0.01 nm

☐ Invert Colors

Figure 4.41 4- OFDM Signal after the WDM Channels

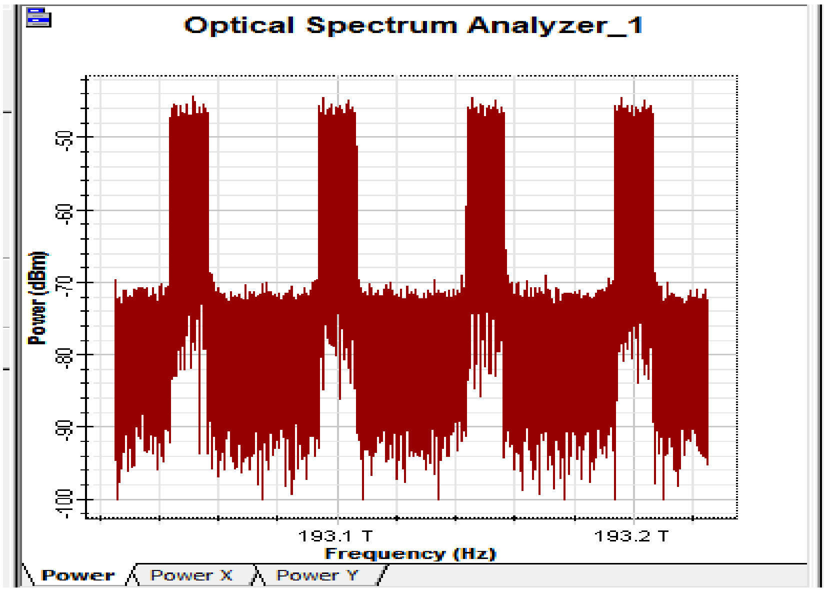


Figure 4.42 4 -OFDM Signal after SMF-DCF Optical Link of 120km

Figure 4.43 illustrate the constellation diagram of the 4-QAM OOFDM signal at the receiver after SMF-DCF optical link. As can be seen from the graph, the red points represent the signal and the blue points represent the noise. Clearly, the signal is recovered after removing the chromatic dispersion from the optical fiber.

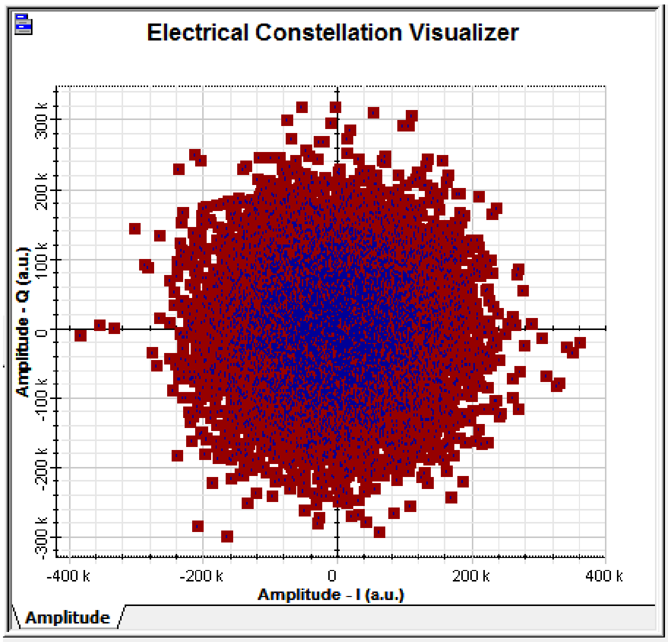


Figure 4.43 The Constellation of 100Gbps WDM CO-OFDM System after 120km

After designing the system, Q factor, bit error rate and eye diagram were tested to study the performance of the system and the quality of the signal. Theses parameters are shown in figures 4.44, 4.45 and 4.46, respectively.

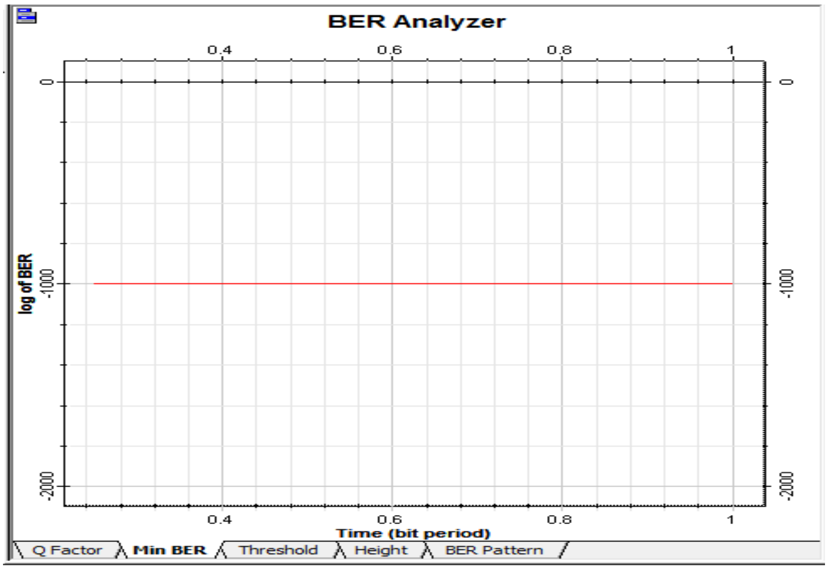
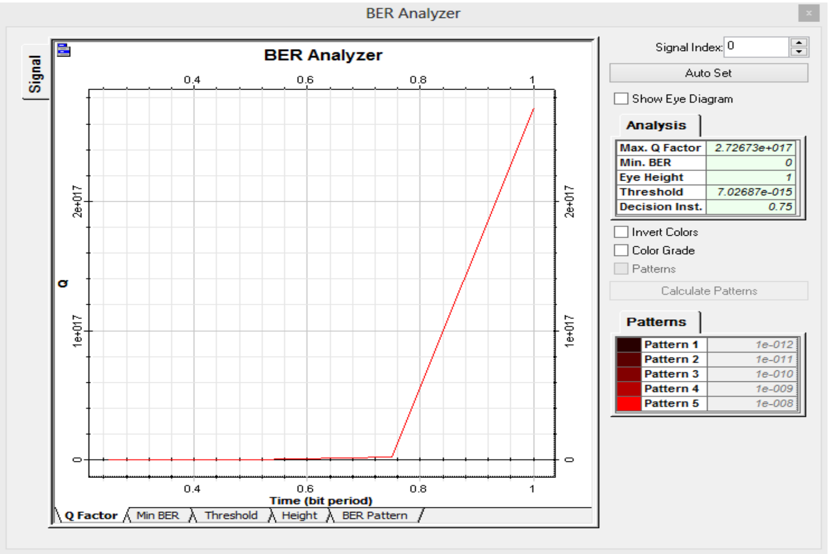


Figure 4.44 BER for Transmission Length of 120 km SMF-DCF Optical Link



Analysis	
Max. Q Factor	2.72673e+017
Min. BER	0
Eye Height	1
Threshold	7.02687e-015
Decision Inst.	0.75

Patterns	
Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Figure 4.45 Q Factor

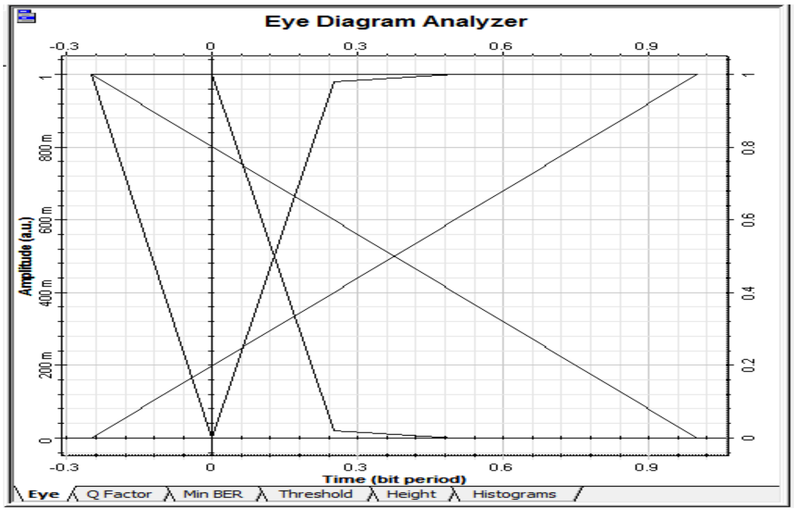


Figure 4.46 Eye Diagram for a Transmission Length of 120km SMF-DCF Optical Link

Table 4.8 gives the signal details at the Receiver for 100Gbits/s WDM CO-OFDM system.

Table 4.7 Signal Details at the Receiver for 100Gbits/s

Max.Q Factor	2.7363×10^{17}
Min. BER	0
Eye Height	1
Threshold	7.02799×10^{-15}
Decision Inst	0.75

Chapter 5 Conclusions and Future Work

5.1 Conclusions

In this thesis three different systems were modeled for different data rates using direct and coherent OFDM detection. The first project was DD-OFDM; 7.5GHz frequency carrier is used in this system. The data rate was 10Gbits/s with modulation type of 16-QAM, 256 subcarrier and 512 FFT points, this system investigate different transmission links. In this system, it has been found that as the transmission length increases the Q-factor decreases with a lower value of BER. The best value of BER was zero.

The second project was CO-OFDM system with SMF, the data rate was 40Gbits/s with 16-QAM modulation type, 512 subcarrier and 1024 FFT points. The length of the transmission link was 150km. This system was designed and simulated to achieve the best value of BER which was zero.

The final project was WDM CO-OFDM with 120km SMF-DCF transmission link. In WDM system, 4 channels of 25Gbits/s 4-QAM OFDM signals were transmitted, the carrier wave frequencies were set from 193.05THz to 193.2THz with 50GHz channel spacing, 512 subcarrier and 1024 FFT points. This system was designed and simulated to achieve the best value of BER which was zero.

In DD-OFDM, a photo-diode is used to perform the optical to electrical conversion, while in CO-OFDM detection, two identical pairs of balanced coherent detectors with a local oscillator (LO) is used to perform the I/Q optical to electrical conversion. Direct detection optical OFDM aims for simpler transmitter or receiver than CO-OFDM for lower costs. DD-OFDM has an advantage that it is more immune to impulse clipping noise.

However, it can be seen that Coherent Optical OFDM (CO-OFDM) is considered the next generation technology for the optical communications rather than the DD-OFDM, 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). Above all, integrating the coherent optical OFDM with Wavelength Division Multiplexing (WDM) systems 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.

Recently, it has been proved by many researchers that OFDM is better compared to the conventional single carrier modulation for long haul optical transmission.

5.2 Future Work

5.2.1 Optoelectronic Integrated Circuits for Optical OFDM

The notion that optoelectronic integrated circuits (OEICs) will enable the replacement of a large number of optical and electronic devices onto a single chip can be traced back approximately four decades [39]. However, in the past decade there has been a dramatic resurgence of interest in OEICs from both industry and academia [40-44].

The fundamental reasons for the of OEICs are twofold [44, 45]:

- Supporting software-defined photonics: Through incorporation of the electronic signal processing, the photonic chip can be reconfigured for multiple functionalities in a number of aspects of transmission, reception, and filtering.
- Performance enhancement: The speed and noise performance of optoelectronic devices can be significantly improved by integration due to the reduction of parasitic reactance, an almost perfect matching condition for balanced devices and mechanical stability.

5.2.2 Optical OFDM-Based Access Networks

OFDM is an excellent candidate to be used for indoor optical wireless applications [47, 50] and passive optical networks (PONs)[49]. Currently, PON is being deployed to replace conventional cable based access networks. With optical fiber used as the transmission medium, PONs offer much higher bandwidth while supporting various communication services. For future PON applications, different PON technologies have been studied, including WDM-PON, SCM-PON and OCDM-PON. OFDMA-PON has been advocated by Xu et al [46].

5.2.3 Wavelet Packet Transform (WPT) based CO-OFDM

Recently, the CO-OFDM systems based on WPTs have been proposed [51, 52]. Wavelets used as the basis functions in these advanced systems have finite length in the time domain. For this reason, WPT-OFDM systems do not need CP which results in a higher SE [51, 52]. The WPT-OFDM can mitigate a CD of 3380 ps/nm at 112 Gb/s rate without CP [51]. In WPT-OFDM communication systems the modulated signals are double-sideband [53].

It has been shown that the CD influence on WPT-OFDM is compensated automatically due to the phase symmetry of the both sidebands while the PMD does not possess the phase symmetry [53]. As a result, the two sidebands have two different dispersion, their addition does not reproduce the real wavelet basis, orthogonality condition is broken, and inter-packet-interference occurs [53].

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附录：详细摘要（中文）

在任何需要将信息从一个地方传输到另一个地方的场景，都可能需要应用到光纤传输。光纤提供的信道带宽比同轴电缆信道大几个数量级。在过去的 20 年中，具有较低信号衰减的光缆已经被研发出来，并且具有高可靠性的光子器件已经被应用于信号的检测。伴随着技术的迅猛发展，光纤信道的应用也更加广阔，已不仅仅只应用于国内通信系统中，也应用于跨大西洋和跨太平洋的通信中。由于光纤信道具有很高的传输带宽，因此有可能使电话公司为用户提供一个宽系列电话业务，包括语音、数据、传真和视频等。

作为数据传输技术的一种，光纤通道具有防干扰性能好、衰减小、带宽高等优点，因此被广泛应用于长途干线网上，成为现代通信的基础。然而，在企业、地铁和长途运输市场等对数据需求量大的领域，迫切需要将传输速率提升至 100Gbit/s 甚至更高。上一代的传输系统已经无法适应高速传输的要求，如果继续使用，现有的光传输设施将会超负荷运行，因此建立下一代高速传输系统已经势在必行。

在通信系统中，信道所能提供的带宽通常比传送一路信号所需的带宽要宽得多。如果一个信道只传送一路信号是非常浪费的，为了能够充分利用信道的带宽，就可以采用频分复用的方法。在现代通信系统领域，正交频分复用(Orthogonal Frequency Division Multiplexing，简称 OFDM)是通信系统中一个已经被广泛采用的技术，OFDM 技术实际上是多载波调制(Multi Carrier Modulation，简称 MCM)技术的一种。OFDM 技术由 MCM 技术发展而来，是多载波传输方案的实现方式之一，它的调制和解调是分别基于 IFFT 和 FFT 来实现的，是目前实现复杂度最低、应用最广的一种多载波传输方案。

OFDM 技术的主要思想是将信道分成若干正交子信道，将高速数据信号转换成并行的低速子数据流，并调制到每个子信道上进行传输。正交信号可以通过在接收端采用相关技术来分开，这样可以减少子信道之间的相互干扰(Inter channel Interference，简称 ICI)。每个子信道上的信号带宽小于信道的相关带宽，因此每个子信道上可以看成平坦性衰落，从而可以消除码间串扰，而且由于每个子信道的带宽仅仅是原信道带宽的一小部分，信道均衡变得相对容易。

OFDM 的应用领域非常广泛，例如在使用了金属铜的数字用户线(DSL)，数字视频广播电视(DVB-TV)和陆地广播等众多通信系统；在无线局域网络光纤传输系统中使用的光纤射频传输技术，充分结合了 OFDM 与高频无线电波传输的优点；新一代移动通信系统 LTE 中同样采用 OFDM 作为其无线网络演进的唯一标准。之所

以在无线通信中广泛采用 OFDM，因为它可以补偿无线环境障碍，因为多径传播会产生频率选择性衰减、影子衰减和其他用户的干扰。例如，将 OFDM 用于 ADSL、比特加载算法可以通过更好的传输信道来分配更多的比特。

最新研究表明，正交频分复用对于满足带宽需求、增加宽带服务是一种行之有效的技术。特别是在提出了相干检测和直接检测等具有很大吸引力的长距离传输格式之后，正交频分复用技术在光通信领域引起了更多更广的关注。OFDM 有能力克服许多光纤限制，例如色散(CD)和偏振模色散(PMD)。使用 FFT 进行调制使得副载波具有正交性，这样每个解调器就只会接收各自子信道的频率。此外，将相干光 OFDM 与波分复用(WDM)系统进行集成能够为传输系统提供更高的带宽，更高的数据传播速率和更高的频谱效率。

对于利用不同波长的激光载波而言，在单模光纤(SMF)中对光信号进行多路复用是非常复杂的，面对不断提高的带宽要求，WDM 技术提供了有效的解决方案。WDM 是利用多个激光器在单条光纤上同时发送多束不同波长激光的技术。每个信号经过数据（文本、语音、视频等）调制后都在它独有的波长内传输。WDM 能使电话公司和其他运营商的现有光纤基础设施容量大增。可以支持 150 多束不同波长的光波同时传输，每束光波最高达到 10Gb/s 的数据传输率。这种系统能在一条比头发丝还细的光缆上提供超过 1Tb/s 的数据传输率

本研究着重于系统的实现和对高数据率传输性能的分析，以及 OFDM 在长距离传输中的应用。本研究从单个用户进行分析，并逐步扩展为能够实现 100 Gbit/s 传输的 OFDM-WDM 系统。本文采用了 Optisystem 仿真工具来用于设计和实现该系统。该系统使用的范围从 10Gbit/s 的直接检测到 100Gbit/s 的 OFDM-WDM，采用 QAM 作为对 OFDM 信号的调制类型，采用 I/Q 调制作为发射机，直接和相干检测作为接收机。为了对系统的性能和信号的质量进行分析，需要测试三个参数，分别是 Q 因子、误码率和眼图。

为了对不同数据传输速率进行直接和相干 OFDM 检测，本文在各不同的系统中进行了建模。对数据速率的直接检测在 16 QAM-OFDM 系统中实现，为了使最终的误码率为零，采用了 256 个子载波。OFDM 相干检测在 WDM 系统和 CO-OFDM 系统的集成系统中实现，为了得到最优误码率，采用了 512 个子载波。

第一个系统是 DD-OFDM，该系统使用 7.5GHz 的频率载波。当调制类型为 16-QAM，采用 256 副载波和 512 点 FFT 变换时，数据传输速率为 10Gbits/s。研究发现，随着传输长度的增加，品质因数会下降，但误码率基本不变，最优的误码率的值是零。系统中同时对不同色散值下的传输速率进行了研究，研究表明增加光纤

色散，品质因素会有所降低。

第二个系统是结合 SMF 的 CO-OFDM 系统。相干光 OFDM(CO-OFDM)系统具有灵敏度高，频谱效率高，能有效降低偏振色散，提升鲁棒性等优点，但该系统的收发器的设计复杂。将该系统用于传输 16-QAM 调制类型，512 个副载波，1024 点 FFT 下 40 Gbits/s 速率的信号。传输线的长度是 150 公里，对接收到的光信号的检测是通过两个相同的双平衡相干检测器实现，这两个双平衡相干检测器具有一个本地振荡器(LO)，通过该检测器可以实现 I/Q 光信号到电信号的转换并达到消除噪声作用。每个探测器包括两个耦合器和两个 PIN 光检测器。每个 PIN 光检测器使用的暗电流为 10nA，响应率为 1A/W，热噪声为 1×10^{-24}W/Hz，中心频率为 193.1THz。这个系统设计和仿真的目标在于使最佳误码率为零。

最后一个系统是使用了 SMF-DCF 传输线的 WDM CO-OFDM 系统，该传输线的长度为 120km。在 WDM 系统中，WDM 将光谱分成了几个更小的通道，用来进行同时传输和接收数据。为了对 100Gbits/s 的传输速率提供支持，需要四个 OFDM 信号，这就意味着四个 OFDM 接收机都需要有相同的设计和参数。唯一的例外是含有激光频率的从 193.05THz 到 193.2THz 之间的频率范围内的光载波，频率间隔为 50GHz。WDM 系统需要四个信道来支持四个 OFDM 频带，且都要保证在 50GHz 的信道空间内。每个 OFDM 信号都需要有 25Gbps 的比特率以提供一个整体 100Gbit/s 的数据速率。这个系统设计和仿真的结果实现了最佳误码率为零。

在 DD-OFDM 系统中，一个光电二极管被用来执行光子到电子的转换，而在 CO-OFDM 检测中，两个使用了本地振荡器(LO)的相同的双平衡相干检测器被用于实现 I/Q 光子到电子的转换。直接 OFDM 光检测的目标是简化发射机或接收机，使它们相对于 CO-OFDM 能降低更多的成本。DD-OFDM 有一个优势就是它能抑制脉冲削波噪声。

然而，相干光 OFDM(CO-OFDM)被认为是下一代光学通信技术，因为它集成了相干系统和 OFDM 系统两者的优势。它有能力克服许多光纤限制，如色散等(CD)和偏振模色散(PMD)等。最重要的是，将相干光 OFDM 与波分复用(WDM)系统进行集成提供了传输系统高带宽，高数据传输速率以及在不增加成本和系统的复杂性下的高频谱效率。在日益提高的高宽带要求和数据传输速率的要求下，集成 CO-OFDM 和 WDM 的系统是一个非常有效的方案。最近，经许多研究人员研究证明，相比于传统的单载波调制在长距离中的光传输，使用 OFDM 的效果更好。

仿真软件使用的是 OptiSystem 系统，因为该仿真工具能够规划和实现一整套的光网络，本文中需要大量的光信号和无线组件也是该软件所能提供的。

光通信系统正在变得日益复杂。这些系统通常包含多个信号通道、不同的拓扑结构、非线性器件和非高斯噪声源，对它们的设计和分析是相当复杂的。OptiSystem是一款创新的光通信系统模拟软件包，它集设计、测试和优化各种类型宽带光网络物理层的虚拟光连接等功能于一身。它是一个基于实际光纤通信系统模型的系统级模拟器，OptiSystem具有强大的模拟环境和真实的器件和系统的分级定义，该软件内同时包含了大量的有源和无源器件库。它的性能可以通过附加的用户器件库和完整的界面进行扩展，而成为一系列广泛使用的工具。