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INTEGRATION OF OOFDM WITH RoF FOR HIGH DATA RATES LONG-HAUL  
OPTICAL COMMUNICATIONS

A Thesis

Presented to

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

University of Denver

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science

---

by

Fahad Almasoudi

November 2013

Advisor: Dr. Mohammad Matin

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Author: Fahad Almasoudi

Title: INTEGRATION OF OOFDM WITH RoF FOR HIGH DATA RATES LONG-HAUL OPTICAL FIBER COMMUNICATIONS

Advisor: Dr. Mohammad Matin

Degree Date: November 2013

### **Abstract**

One of the advanced technologies in optical fiber communication systems that support efficient convergence of wireless and optical access network structure is Radio over Fiber (RoF). In RoF, light is modulated by using a radio signal and sent over an optical fiber link to simplify wireless access. The demand for high-speed wireless communications is increasing rapidly. To increase the capacity and bandwidth of the optical fiber communication system a Wavelength-Division Multiplexing (WDM) is used. In WDM, multiple optical carrier signals are multiplexed and transmitted over one optical fiber.

Optical Orthogonal Frequency Division Multiplexing (OOFDM) technology commits to be a fundamental technique for accomplishing high data when is integrated with RoF. OOFDM is an effective method to overcome different restrictions of optical fiber transmission systems such as chromatic dispersion, polarization mode dispersion, and modal dispersion. Therefore, the combination of OOFDM and RoF will enhance the system flexibility and help to cover a very large area without increasing the system complexity and cost very much.

This thesis investigates the integration of OOFDM with RoF for achieving high data rates and the transmission of the signal over long haul optical fiber. Results from the OptiSystem model shows the performance of OOFDM signals through the WDM RoF is studied by using a simulation tool called OptiSystem version 12.

## **Acknowledgment**

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## Abbreviations

AM “Amplitude Modulation”  
BER “Bit Error Rate”  
BS “Base Station”  
CATV “Community Access Television”  
CFBG “Compensating Fiber and Chirped Fiber Bragg Grating”  
CO-OFDM “Coherent Optical OFDM”  
CP “Cyclic Prefix”  
CS “Central Station”  
CS “Cyclic Suffix”  
CW “Continuous Wave”  
DAC “Digital to Analogue Converters”  
DCF “Dispersion Compensating Fiber”  
DCM “Dispersion Compensating Module”  
DFT “Discrete Fourier Transform”  
DGD “Different Group Delay”  
DWDM “Dense Wavelength Division Multiplexing”  
EDFA “Europium Doped Fiber Amplifier”  
E/O “Electrical to Optical”  
FBG “Fiber Bragg Grating”  
FFT “Fast Fourier Transform”  
FSK “Frequency Shift Keying”  
FTTH “Fiber To The Home”  
FWM “Four-Wave Mixing”  
GSM “Global System for Mobile”  
IFFT “Inverse Fast Fourier Transform”  
IMDD “Intensity Modulated Direct Detection”  
IM-DD-OOFDM “Intensity Modulation Direct Detected Optical OFDM”  
ISI “Inter-Symbol Interference”

LiNbO<sub>3</sub> “Lithium Niobate”  
LPF “Low Pass Filter”  
LTE “Long Term Evolution”  
MBS “Mobile Broadband System”  
MFD “Mode-Field Diameter”  
MMF “Multimode Fiber”  
MVDS “Multipoint Video Distribution Services”  
MZM “Mach-Zehnder Modulator”  
NA “Numerical Aperture”  
O/E “Optical to Electrical”  
OFDM “Orthogonal Frequency Division Multiplexing”  
OOFDM “Optical Orthogonal Frequency Division Multiplexing”  
OSNR “Optical Signal to Noise Ratio”  
PAPR “Peak to Average Power Ratio”  
PD “Photodiode”  
PMD “Polarization-Mode Dispersion”  
PON “Passive Optical Network”  
PSK “Phase Shift Keying”  
QAM “Quadrature Amplitude Modulation”  
QPSK “Quadrature Phase Shift Keying”  
RAUs “Remote Antenna Units”  
RF “Radio Frequency”  
ROF “Radio Over Fiber”  
SBS “Stimulated Brillouin Scattering”  
SIO<sub>2</sub> “Hydrogen Oxide Entrenched in the Silica”  
SMF “Single Mode Fiber”  
SNR “Signal to Noise Ratio”  
SPM “Self-Phase Modulation”  
SRS “Stimulated Raman Scattering”  
TDM “Time Division Multiplexing”

UMTS “Universal Mobile Telecommunication System”

VSF “Vestigial Side Band”

WDM “Wavelength-Division Multiplexing”

XPM “Cross-Phase Modulation”

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## **Chapter 1**

### **Introduction**

#### **1.1 Project Background**

Much research has been conducted in relation to Radio over Fiber (RoF), Optical Orthogonal Frequency Division Multiplexing (OOFDM), and efWavelength Division Multiplexing (WDM) networking to get the advantages of improving the system efficiency, increasing the data rates, supporting the long-haul transmission, and reducing the system cost. All the studies needed to face great challenges to design a system that is applicable to the above advantages. As a result, the need for understanding each component in the access network such as RoF, OOFDM and WDM is in great demand.

The development of digital receivers for optical fiber communication systems gives the ability to employ more advanced modulations formats like orthogonal frequency division multiplexing (OFDM). OFDM is a modulation technique of encoding a data stream on many subcarriers and then transmitting it continuously on a common path [1]. For example, the operation of the OFDM technique in the mobile communication systems is based on dividing a radio spectrum into many sub-channels placed at the base station (BS). Currently, OFDM is very attractive technique for both wire and wireless wideband digital communication. OFDM has been used in many applications such as digital television, DSL broadband internet access, wireless networks, audio broadcasting, and 4G and LTE (long term evolution) mobile communications.

The Wavelength Division Multiplexing (WDM) is a very effective technique in optical fiber communication. It is used to multiplex a multiple number of optical carrier signals and transmit them over one optical fiber by using various wavelengths of laser light to send different signals. This technique helps to increase the capacity and reduce the cost in optical fiber communication systems.

The need for large bandwidths and high data rates has introduced a new technology called Radio over Fiber (RoF). This is a combination of an optical fiber network and a wireless network. In this technology, light is mixed with a radio signal and transmitted over optical fiber. The use of RoF has brought many advantages to the system. For instance, it provides high data rates, reduces power consumption, and immunizes against electromagnetic interference. Furthermore, it offers large bandwidth that is suitable for maintenance and makes installation easy with operational flexibility [2-6].

OFDM is a promising technique that could provide very high spectrum efficiency and is robust against dispersion. Therefore, the use of OFDM in optical fiber communication systems helps to improve the capability and the transmission distance of the system. Recently, OFDM has been used in many applications in RoF. For example, it is used in passive optical networks (PON) to support high data rates and increase the transmission distance.

Because of the increasing demand of high data rates and large bandwidth, OOFDM offers a great solution to boost the data rate for greater than Tbps when it is integrated with RoF. This thesis research is based on designing and investigating the performance of the OOFDM structure combined with Radio over Fiber to transmit high



data rates over a long-haul optical fiber transmission link. The design of this thesis was simulated by using commercial software called OptiSystem version 12.

## **1.2 Problem Statement**

The need for broadband services has motivated research on millimeter wave frequency for wireless access network in relation to speed, spectrum availability, efficiency, and a condensed size of devices that are used in radio frequency. However, the millimeter wave signal is limited to the transmission distance due to atmospheric attenuation. To overcome the losses in the transmission distance, researchers introduced a very effective medium that has the advantages of low attenuation while being electromagnetic interference free. In this thesis, the combination of Radio over Fiber (RoF) and Optical Orthogonal Frequency Division Multiplexing (OOFDM) is used to support high data rates in long haul optical fiber transmission distance. Also, a wavelength division multiplexing technique is used to maximize the use of bandwidth to get high data rates greater than 1Tbps.

## **1.3 Thesis Objectives**

The first objective of this thesis is to investigate the design of OOFDM for a RoF access network. The second objective is to design and simulate the OOFDM scheme for RoF by using commercial software, Optisystem version 12.0 from Optiwave. The third objective is to study the practicability performance of OOFDM in WDM RoF in terms of optical signal to noise ratio (OSNR), signal to noise ratio (SNR), bit error rate (BER) and publish the results of this thesis research in significant journals and in international conferences.

## **1.4 Scope of Thesis**

The scopes of this thesis are:

1. Understanding the essential principle by reading literature studies of OOFDM modulation technique, WDM, and RoF.
2. Designing and simulating the integration of OOFDM signals and a RoF network by using commercial software: Optisystem version 12.0 from Optiwave.
3. Study the performance of the design system in relation to optical signal to noise ratio (OSNR), signal to noise ratio (SNR), and bit error rate (BER).

## **1.5 Methodology**

The methodology of this thesis is explained in the next flow chart in Figure 1.1. The first step is to read the literature studies, and understand and review the latest development of the OOFDM modulation technique and RoF system.

The second step is to understand and analyze the system design of OOFDM modulation technique for a RoF network. The main goal of this thesis is to study the fundamental concept of the RoF system, OOFDM modulation technique, and the combination of OOFDM with a WDM RoF access network.

After that, the system will be formed and designed to perform the connection between the OOFDM transmitter and OOFDM receiver through optical fiber. Then an effective simulation software tool, Optisystem version 12.0, is used to simulate the system design. The next step is to study the result and the system performance of the simulated design. While studying the results, the system design is being optimized to get a good performance and better simulation results. Finally, a comparison is made between the simulation results and the previous works.

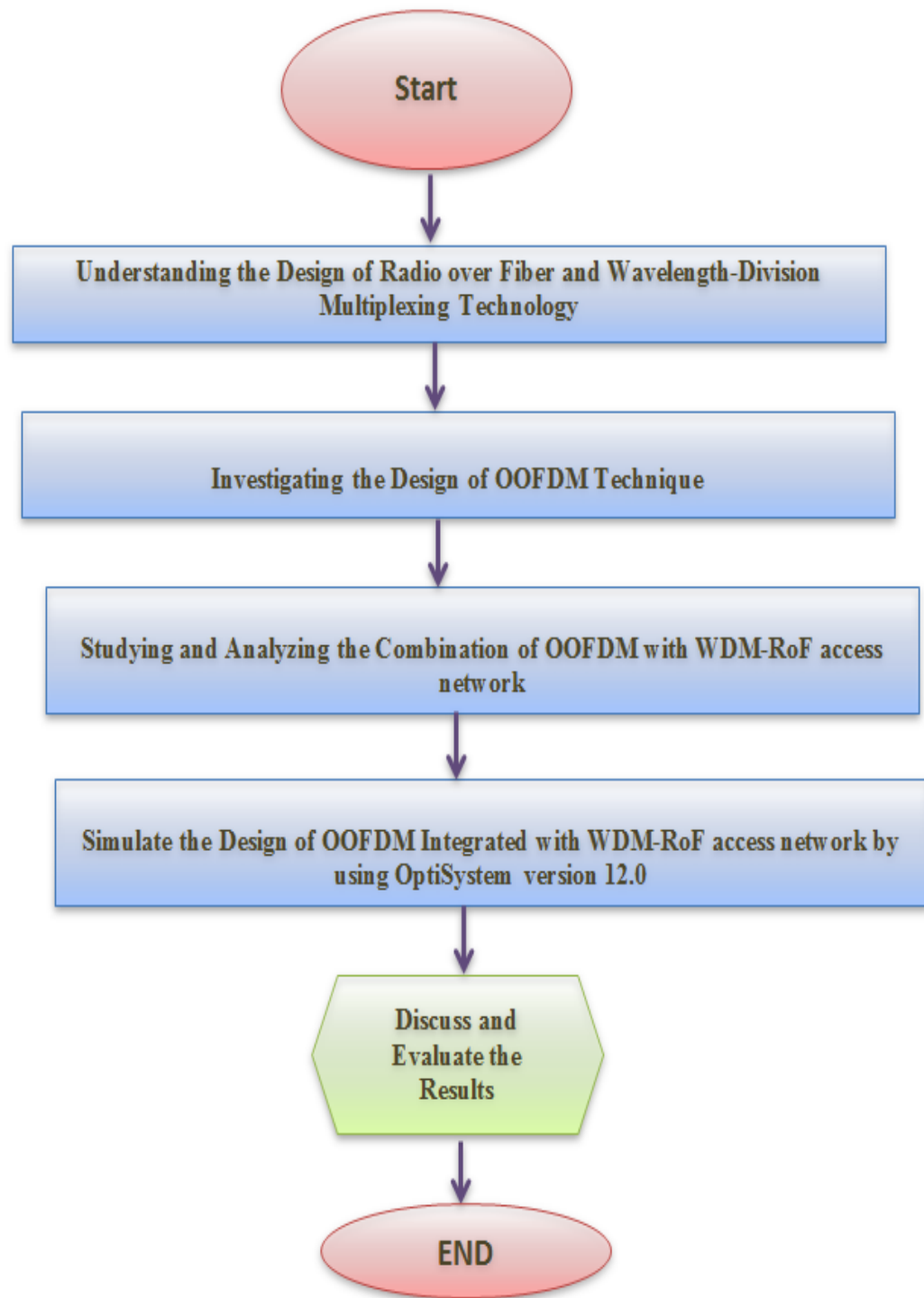


Figure 1.1: Flow Chart of the Main Steps of the Thesis

## **1.6 Thesis Outline**

This thesis consists of five chapters and is arranged as follows:

Chapter 2 reviews the state of art for the fiber optic technology and explains the basic components of the optical fiber network. Also, it describes the Radio over Fiber technology with respect to its design, advantages, and applications. Chapter 3 presents the basic concept of the OFDM technique and explains its transceiver. Moreover, it introduces the OOFDM technique and presents its two major types and their block diagram. In chapter 4, the simulation results and the system performance are illustrated and discussed. Chapter 5 states conclusions, reviews the important contributions of this thesis, and finally presents the future works for improving the system model.

## **Chapter 2**

### **Basic Concept of Fiber Optic Technology**

#### **2.1 Introduction**

This chapter handles the theory of fiber optic, the transmissions issues via fiber, the technology of Radio over Fiber and the fiber component parts related to this research thesis. The first generation of optical fiber began in the 1980s as a method to send data in communication systems, working at a wavelength of 0.8nm and a data rate of 45 Mb/s. Costs of installation and maintenance were reduced when fiber optic was used compared to coax cable because the spacing between repeaters was 10km as opposed to 2km of coax cable.

Presently, researchers concentrate on optical fiber transmission of 100Gbps for each wavelength channel and beyond. The transmission of high data rates in the optical fiber communication system can be done by using advanced modulation techniques, DSP, polarization-multiplexing, and coherent detection [7].

The capacity of narrowband wireless systems is limited because of their low frequencies carrier that is only able to provide small bandwidth. For example, Global System for Mobile communications (GSM) operates at frequencies 900 or 1800 MHz and has an allocated frequency spectrum of 200 kHz; Universal Mobile Telecommunication System (UMTS) operates at frequencies of about 2 GHz and has an allocated bandwidth

of 4 MHz. The wireless system supports high mobility because it works with large cells. However, the spectrum efficiency is poor and the power consumption is high.

Radio over Fiber has become the accepted solution for increasing the capacity and efficiency of wireless communication systems. RoF is applied for operation inside buildings because of the high signal losses usually caused by the walls when large cells are used by a system.

## **2.2 Basic Principle of Propagation of Light**

The basis of optical fiber communication systems is the principle that light, in a medium of glass, is capable of carrying a high amount of data and is able to transmit it over a long distance. Currently, the purity of optical fiber glass supports the transmission of digitized light signals when the signals are transmitted for hundreds of kilometers without using amplifiers. The fiber optic can be seen as a perfect transmission medium because of low transmission loss, low interference, and large bandwidth capacity.

The operating function of fiber optic works as follows: the waves of light are directed through the fiber optic core. The light is then reflected inside the core until it reaches the end of the fiber. The capability of reflecting the light inside the core is determined by the structure of the cladding proportional to the core glass. The reflection inside the core can occur when the refractive index of the core is higher than the surrounding cladding and this will produce the waveguide. Another way to produce the waveguide is to reduce the cladding refractive index by the application of various doping agents [8-9]. When the light is totally reflected, the attenuation in the fiber optic will be reduced. The light can permit the transfer of any transparent material with a speed lower than the speed of light in a vacuum.

**2.2.1 Light Waves Refraction**

The direction of light is changed when a light wave transports from one medium to another medium. The Dutch astronomer W. Snellius (1580–1626) recreated the law of refraction 600 years ago. The refraction of waves that is transmitted from one medium into another transparent medium with a different phase speed is described by Snell’s law. This law is appropriate for all waves. Figure 2.1 displays the refraction of light, after passing from a thin optical medium (n1) into a dense optical medium (n2).

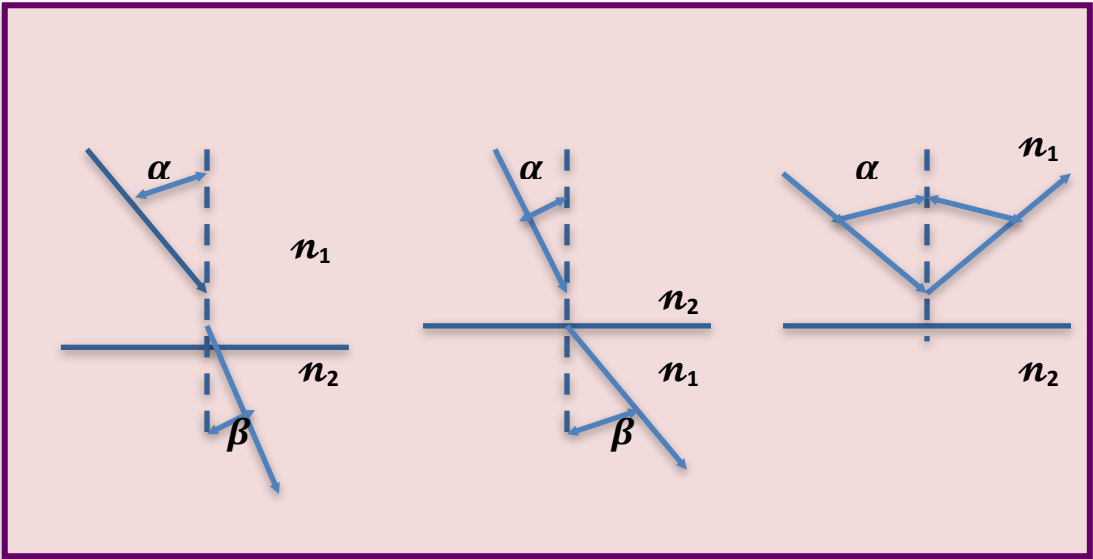


Figure 2.1: The Refraction of Light

The light refracts in a perpendicular direction and the refraction angle ( $\beta$ ) is smaller than the incidence angle ( $\alpha$ ). In this situation the refraction angle is bigger than the incidence angle. If the incidence angle increases, as can be seen in Figure 2.1, the beam of light will be totally reflected and will not access the second medium [9].

$$\frac{\sin \alpha}{\sin \beta} = \frac{n_2}{n_1} \tag{2.1}$$

Equation 2.1 defines the refraction between two different materials of light transmitting [9].

$$\alpha = \sin^{-1}\left(\frac{n_2}{n_1}\right) \quad 2.2$$

$$n_2 = n_1 \sin \alpha \quad 2.3$$

Equations 2.2 and 2.3 define the entire reflection of the beam light. Light transports over a dielectric transparent material at a speed that relies upon the dielectric constant of the material and its wavelength. The following equation illustrates the generation of a monochromatic plane wave over a dielectric medium in the z direction:

$$E(t, z) = Ae^{[j(\omega t - \beta z)]} \quad 2.4$$

where A represents the field amplitude  $\omega = 2\pi f$  and  $\beta$  denotes the propagation constant.

The medium's dielectric constant is a frequency function. Hence, different optical frequencies travel at different velocities over the medium. The optical signal, composed of a frequencies band, and each frequency enters the medium at a small difference of velocity and phase. Consequently, group velocity, which is noted as  $v_g$ , can be considered as the envelope velocity of the frequencies of the optical signal. Furthermore, it can be explained as the signal pulse speed [10].

$$v_g = \frac{L}{\tau_g} = \frac{c}{n_g} = \left(\frac{\partial \beta}{\partial \omega}\right)^{-1} = -\frac{2\pi c}{\lambda^2} \left(\frac{\partial \beta}{\partial \lambda}\right)^{-1} \quad 2.5$$

where L is fiber length in km, c is the speed of light in vacuum in m/s,  $\beta$  is the parameter of phase propagation in rad/m, and  $\omega$  is angular frequency. Where  $\omega = 2\pi c/\lambda$  in rad/s,  $v_g$  is the signal group velocity in m/s.  $n_g$  is fiber's effective refractive index at  $\lambda$  or  $\omega$ .



### 2.2.2 Equation of Nonlinear Schrödinger (NLS)

The first person to describe a wave equation was Erwin Schrödinger, the Austrian physicist. He proposed that light is an electromagnetic ray which carries energy (E) and the photon momentum (p). Both parts of his equation display the probability of a photon travelling during a medium. In the optical fiber communication, nonlinear effects and dispersion are taking into account the modified equation. The nonlinear effects are referred to on the right side of the equation. Chromatic dispersion and attenuation are referred to on the left side of the equation [9-11].

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{j\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3}{\partial t^3} + \frac{\alpha}{2} A = j\gamma |A|^2 A - j\gamma_R A \frac{\partial(|A|^2)}{\partial t} - \gamma_s \frac{\partial(|A|^2 A)}{\partial t} \quad 2.6$$

The expressions of these terms are explained below:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$$

$$\beta_1 \frac{\partial A}{\partial t} \quad \text{represents the group velocity;}$$

$$\frac{j\beta_2}{2} \frac{\partial^2 A}{\partial t^2} \quad \text{denotes the effect of the chromatic dispersion;}$$

$$-\frac{\beta_3}{6} \frac{\partial^3}{\partial t^3} \quad \text{indicates to the slope of the chromatic dispersion;}$$

$$\frac{\alpha}{2} A \quad \text{is the fiber attenuation;}$$

$$j\gamma |A|^2 A \quad \text{represents the nonlinear Kerr effect;}$$

$$j\gamma_R A \frac{\partial(|A|^2)}{\partial t} \quad \text{denotes the Raman scattering;}$$

$$\gamma_s \frac{\partial(|A|^2 A)}{\partial t} \quad \text{is the self-steepening;}$$

$$A \quad \text{is the electric field modulating signal and its unit is } V/m;$$

- $|A|^2$  represents the optical intensity and its unit is  $Wm^2$ ;
- $\gamma$  is the nonlinear coefficient and its unit is  $(Wm)^{-1}$ ;
- $\gamma_R$  is the nonlinear coefficient of the stimulated Raman scattering and its unit is  $(Wm)^{-1}$ ;
- $\gamma_S$  is the nonlinear coefficient of the self-steepening and its unit is  $(Wm)^{-1}$ ;
- $n_2$  denotes to the refractive index and its unit is  $m^2/W$ ;
- $\alpha$  is the attenuation coefficient;

### 2.3 Major types of Optical Fiber

In optical fiber communication systems, a silica-based fiber optic is the preferred medium for large capacity and long distance. The low-loss feature is the major characteristic of optical fiber to achieve a loss of 0.2 dB/km at  $\lambda=1.55\mu m$  wavelength. This denotes that the light intensity of the original signal will be reduced by half after it is transmitted for 20km over the fiber optic [12]. There are two common types of optical fibers: single mode fiber (SMF), and multimode fiber (MMF). As presented in Figure 2.2, the difference between those two kinds of fiber is that the diameter core of a MMF is approximately six times bigger than the diameter core of a SMF.

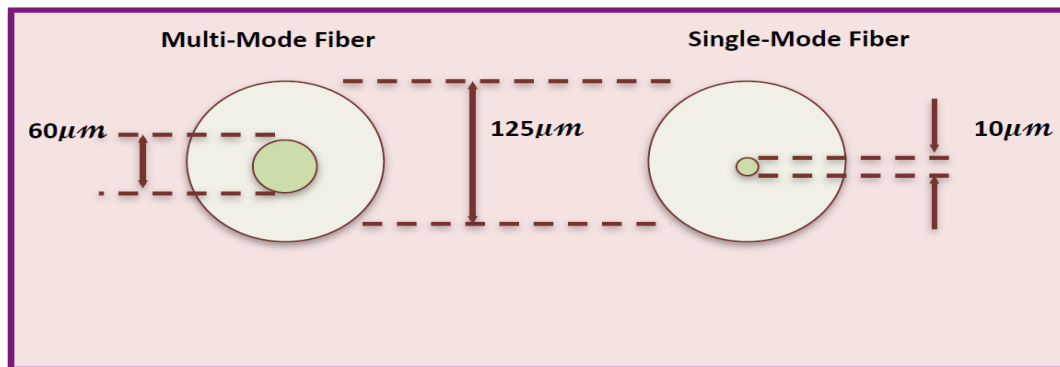


Figure 2.2: The Core Diameter of SMF and MMF

The core diameter of MMFs is larger than the core diameter of SMFs, ranging between 50 to 100  $\mu\text{m}$ . In MMFs, the waves of light are propagated into multiple paths when travelling over the core of the optical fiber. Usually, two different wavelength frequencies are used in MMF- 850 or 1300nm. The major problem of MMF is that it has more than one path of light. This will generate signal distortion, especially when the length of the optical fiber is greater than 900m. Therefore, the quality of the signal will be affected.

Nevertheless, MMF provides a large bandwidth at a high data rate of 100Mbit/s for a transmission distance up to 2km, 1Gbps for a transmission distance ranging between 220 to 550m, and 10Gbps for a transmission distance of 300m. In addition, it is the preferred optical fiber as a low-cost application for short distance because of its low cost installation. For example, MMF can be used on campus or in buildings. The implementation of MMF is easier than SMF because it is significantly larger, which helps to reduce the difficulty of the installation of splices and connectors. Furthermore, the connection of MMF to transceiver modules is easier than SMF, which provides the advantage of being more cost-effective than SMF.

The core diameter of SMF is small and is ranging from a 1 to 16  $\mu\text{m}$  optical fiber. SMF is used widely in transmission and access networks for long-haul optical fiber transmission. SMF has specific advantages over MMF, such as low attenuation, high bandwidths, and a large area of wavelength. On the other hand, MMF is appropriate for the short link fiber to the home (FTTH) and indoor cabling because it has high installation costs and large bending loss. Through the SMF, light rays travel through only one mode or one physical path. The refractive index of the core is greater than the

refractive index of the cladding and the difference between them is a round 0.6%. Because of this, SMF has a narrow numerical aperture (NA) and usually a laser source in this type of fiber [13]. The maximum angle needed for the core of the fiber to take in light is measured by the numerical aperture as shown in Figure 2.3. This is also known as the acceptance angle of a fiber optic. NA can be calculated as follows [14]:

$$NA = \sqrt{n_1^2 - n_2^2} \quad 2.7$$

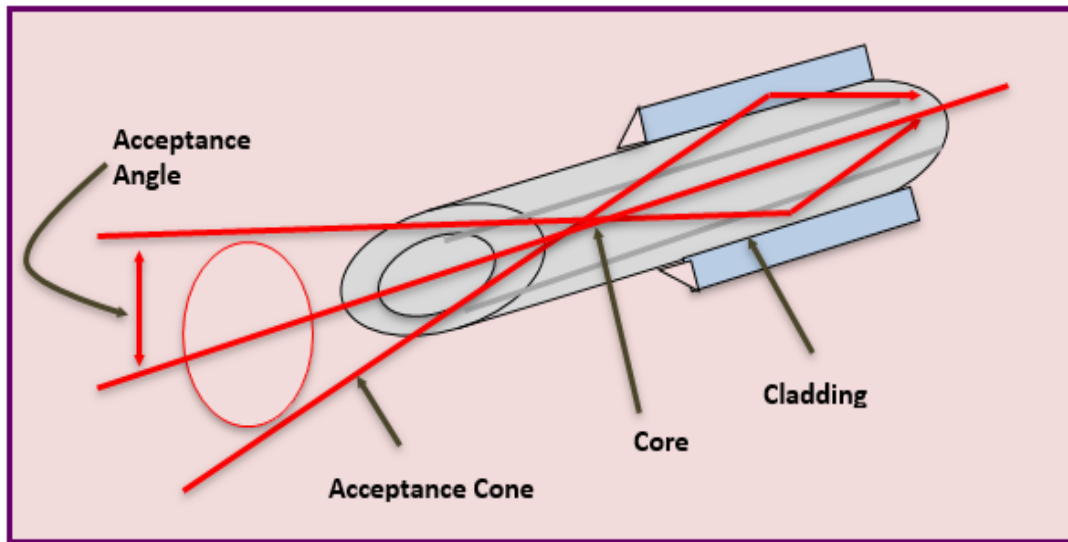


Figure 2.3: Fiber's Acceptance Angle

Generally, SMF is used in different modulation technique such as Quadrature amplitude modulation (QAM) or amplitude modulation (AM). Moreover, it is used in a vestigial side band (VSB) and community access television (CATV). Compared to MMF, SMF has low loss and has the advantage of eliminating intermodal dispersion because it has only one mode. Therefore, SMF is the preferred optical fiber used in high data rates and in long haul optical fiber transmission. For high data rates greater than 2.5Gbps, SMF has a major problem of group velocity dispersion or chromatic dispersion.

## 2.4 Attenuation in a Fiber

Attenuation is defined as the degradation of the power of light or signal strength through the length of the fiber optic cable length and is calculated in decibels per kilometer (dB/km). In optical fiber communications, the expressions fiber loss, fiber attenuation or power attenuation are used equally. Power loss inside the fiber generally is a result of scattering and absorption. Absorption causes loss to the photons and their energy is converted into heat. Scattering occurs because of the small defects in the optical fiber that redirect parts of light into rays that are no longer carried by the optical fiber [9][15]. Optical signal's attenuation alternates. As a function of wavelength, that means the attenuation constant is not identical for all frequencies. The power attenuation of an optical fiber at a length L is described as follows [16].

$$P(L) = P(0)10^{-\frac{\alpha(\lambda)L}{10}} \quad 2.8$$

$\alpha(\lambda)$  is representing the attenuation constant of the optical power. The maximum optical fiber length is described by [15]:

$$L_{max} = \left[ \frac{10}{\alpha(\lambda)} \right] \log_{10} \left[ \frac{P(0)}{P_r} \right] \quad 2.9$$

The attenuation constant ( $\alpha$ ) of the optical power is non-linear is illustrated in [17]:

$$\alpha = \frac{C_1}{\lambda^4} + C_2 + A(\lambda) \quad 2.10$$

$C_2$  is a constant because of Rayleigh scattering.  $C_2$  denotes to optical fiber imperfections and also is a constant.  $A(\lambda)$  is a function representing the optical fiber impurity and it is a function of wavelength.

The attenuation at a wavelength of 1550 nm is measured at 0.2 dB/km. Because of this low attenuation, the optical signal can travel through the optical fiber for a distance of 100 km without using amplifiers or regenerators. Recently optical fiber has been the preferred medium because of it offers low attenuation and large bandwidth. The signal reliability and the cost of a system can be reduced when fiber optic is used because it requires fewer amplifiers and regenerators.

### 2.4.1 Area of Low Water Peak

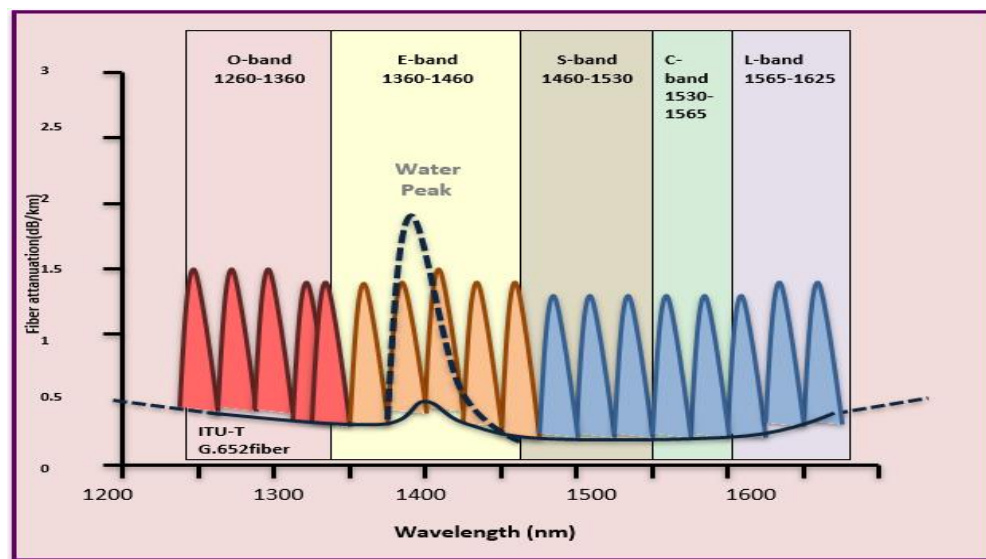


Figure 2.4: The Area of Water Peak between 1271 nm to 1611 nm

Attenuation can come from many sources, such as splices, connectors, and light leakage [9][18]. The scattering of light, created by imperfections in the core structure at a molecular level, implies the typical form of the graph of attenuation. Another cause for attenuation are remaining materials, such as water ions or metals, inside cladding and inside the core of the fiber that absorb photons. The hydrogen oxide entrenched in the silica ( $\text{SiO}_2$ ) makes the optical fiber cable generate the “water peak” area and it is located around 1383 nm on the curve of attenuation, as shown in Figure 2.4. The expanding

effect of the “water peak” area causes attenuation for adjacent wavelengths. Hence, manufacturers of optical fiber now offer a good type of single mode fiber that has a low water peak. This kind of fiber will provide larger bandwidth than standard SMF.

#### **2.4.2 Rayleigh Scattering**

Generally the loss in high quality SMF comes from the scattering of light over the fiber length that is named “Rayleigh scattering” [9] [16] [17]. The Rayleigh scattering occurs due to the collisions between fiber molecules and the light wave. Because of this, light will escape from the fiber waveguide or travel in the opposite direction to the source.

Shorter wavelengths of light are more scattered than longer wavelengths. Because of the wavelength sensitivity, light of a shorter wavelength will scatter more than light of a longer wavelength. This will guide us to the fact that the relationship between the Rayleigh scattering and the wavelength is inversely proportional the wavelength of power four. Consequently, the scattering loss in fiber optic can be decreased by extending the transmission wavelength. Generally, the wavelength of 1550nm is used instead of 1310nm for a long distance transmission. To reduce the impurities in material and light loss that occurs from scattering, manufacturers cool the optical fibers very slowly [19].

### **2.5 Dispersion**

Dispersion occurs because the pulses of the signal are broadening or spreading as they move over the length of the fiber. Because of the broadening of pulses, the adjacent pulses interfere with each other and this causes Inter-Symbol Interference (ISI). There are three major kinds of dispersion:

- I. Intermodal delay (modal delay)
- II. Intramodal dispersion (chromatic dispersion)
  - a. Material dispersion
  - b. Waveguide dispersion
- III. Polarization-mode dispersion

### **2.5.1 Intermodal Delay (Modal Delay)**

Intermodal delay happens because each mode of the optical signal travels a different transmission distance over the same period of time. This indicates that each mode travels at a different group velocity along the fiber. Therefore, the broadening of optical pulses occurs because modes of light enter the optical fiber at the same time and leave the optical fiber at different time. Broadening of the optical pulses causes distortion to the optical signal. It is obvious that as the optical fiber length increases, the intermodal delay increases.

Intermodal delay is the major dispersion in MMFs because it has more than one mode. Also, the intermodal delay cannot happen in SMFs because it has just one mode [17].

### **2.5.2 Intramodal Dispersion (Chromatic Dispersion)**

Intramodal dispersion is also called chromatic dispersion and it is generated because of the broadening of the optical signal pulses. This broadening or spreading of pulses that cause intramodal dispersion and arises from the finite width of the spectral emission of an optical source [20]. The broadening of pulses occurs at each kilometer during travel over the optical fiber length. Hence, as the



optical fiber length increases, the pulses become broader and cause overlapping between the adjacent pulses. Because of this, the data will be corrupted and cannot be recovered [21-22]. As a result, the optical signal to noise ratio (OSNR) will be reduced and the bit error rate (BER) will increase. The intramodal dispersion is a linear effect and can be removed by adding the same amount of negative chromatic dispersion. The two types of chromatic dispersion are material dispersion and waveguide dispersion.

$$D_{chromatic} = -\frac{1}{L} \left( \frac{\partial t_g}{\partial \lambda} \right) \quad 2.11$$

where L represents the optical fiber length,  $t_g$  is the total time when a signal propagates over distance L, and the subscript g denotes group velocity. The group velocity can be calculated by the following equation:

$$v_g = \frac{\partial \omega}{\partial \beta} \quad 2.11$$

In general, the group velocity is the main parameter that determines the properties of the dispersion.

### 2.5.3 Material Dispersion

Material dispersion occurs because the variation of the material core makes the refractive index a function of wavelength [9] [23] [24] [25]:

$$D_{material} = -\frac{\lambda}{c} \left( \frac{d^2 n_1}{d\lambda^2} \right) \quad 2.12$$

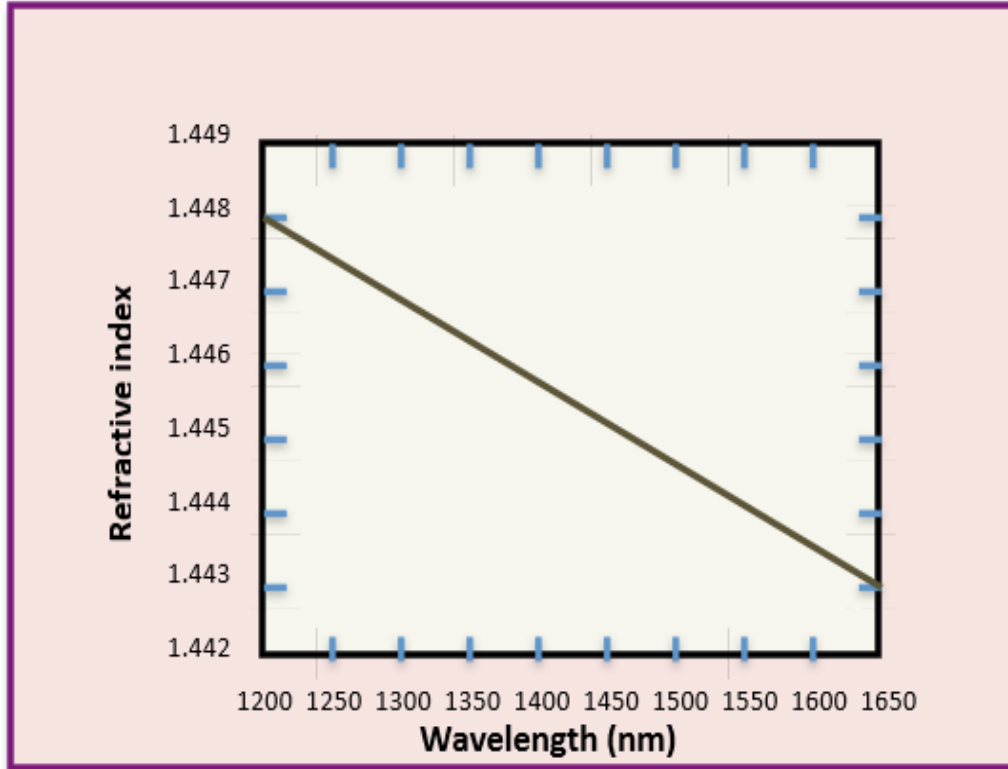


Figure 2.5: Variation of the Refractive Index for Different Wavelengths

Figure 2.5 shows that the optical fiber refractive index decreases when the wavelength increases. The propagation of the longer wavelength over the optical fiber is faster than the shorter wavelength. The amount of dispersion in standard SMF is equal to 16 ps/nm-km. Therefore, there is a 16 delay of picoseconds for each kilometer of optical fiber.

#### 2.5.4 Waveguide Dispersion

The other type of intramodal dispersion is waveguide dispersion. This kind of dispersion generates pulse broadening because only one portion of the optical power that transports along the optical fiber is enclosed in the core [9] [20].

Waveguide dispersion is based on the chemical composition of the optical fiber core. The wavelength is dependent on the mode-field diameter (MFD), which is defined

by measuring the width of the beam of light transmitting in a single mode fiber. Because of this, the waveguide dispersion is produced [9] [15].

Generally, only 80 percent of light is limited to the core in a standard single mode fiber. The remaining 20 percent is propagating at faster speed through the internal layer of the cladding because the refractive index of the cladding is smaller than the refractive index of the core. Therefore, different frequencies and wavelengths of signals are becoming dispersed and because of this the pulse cannot be differentiated.

One advantage of the waveguide dispersion is that it can be used to control the material dispersion by shifting the chromatic dispersion to zero at 1550 nm. The waveguide dispersion can be calculated by [9] [15] [24]:

$$D_{waveguide} = -\frac{\lambda}{c} n_1 \cdot \Delta \cdot \frac{d^2 b}{d\lambda^2} \quad 2.13$$

where  $\lambda$  is the wavelength,  $c$  is the speed of light in vacuum,  $n_1$  represents the refractive index of the core,  $\Delta$  denotes to the difference of the relative refractive index, and  $b$  stands for the propagation constant.

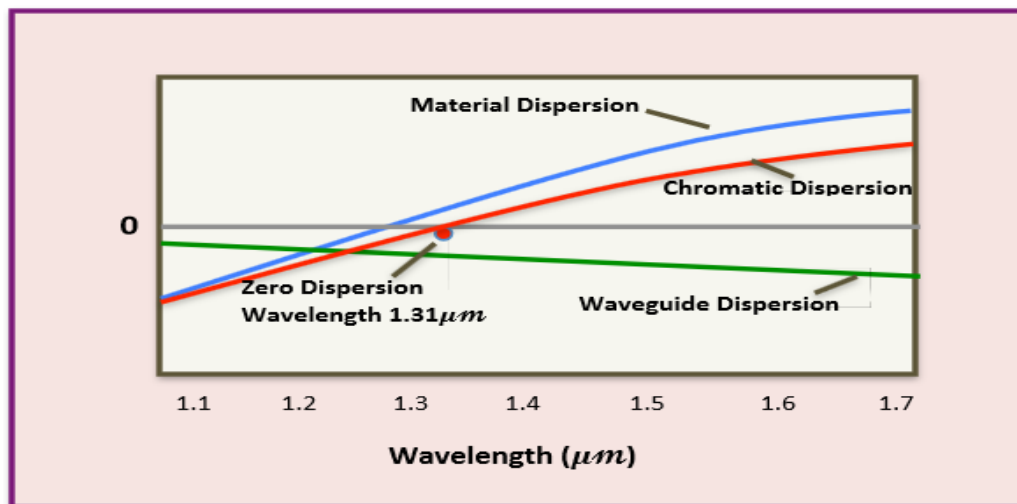


Figure 2.6: Different Kinds of Dispersion are Presented

As displayed in Figure 2.6, the chromatic dispersion can be measured by the sum of material dispersion and waveguide dispersion. The chromatic dispersion is equal to zero in SMF for a wavelength of 1310nm.

### 2.5.5 Polarization Mode Dispersion (PMD)

Polarization-Mode Dispersion (PMD) is produced by impurities in the optical fiber and it will cause pulse broadening. The imperfections in the optical fiber material can result from the installation process, the manufacturing process, and the changes in temperature [9] [15] [26] [27]. In polarization mode dispersion, two orthogonal polarizations of light are propagating at different velocities because the shape of the optical fiber core is not exactly circular. As illustrated in Figure 2.7 Different Group Delay (DGD) is generated when two orthogonal polarization states have various group velocities.

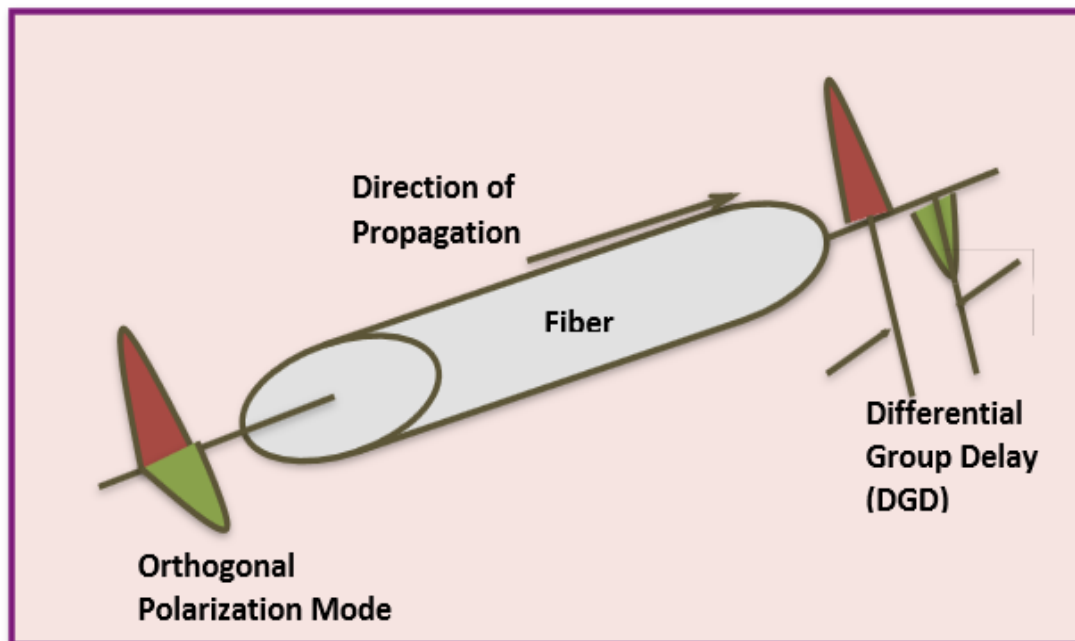


Figure 2.7: The Effect of the Polarization Mode Dispersion

## **2.6 Dispersion Compensating Modules (DCM)**

Commonly, the most major source of dispersion in SMF is the chromatic dispersion that is generated from pulse spreading. As mentioned previously, chromatic dispersion affects the quality of the signal and makes it difficult to recover the original shape of the signal. Because of this dispersion, a dispersion-compensating module (DCM) needs to be in place on the link of SMF to compensate the chromatic dispersion and recover the original signal. The dispersion compensation module can be adjusted physically before or after the installation. It is noted that a network of low bit rate can work for hundreds of kilometers without using a dispersion compensation module. On the other hand, a network of a high data rate greater than 40Gbps is limited to a transmission distance of 5 km when a dispersion compensation module is not used [28]. There are different types of dispersion compensation modules, such as Fiber Bragg Grating (FBG), Dispersion Compensating Fiber and Chirped Fiber Bragg Grating (CFBG). Those different techniques are used to adjust the chromatic dispersion and support networks for long distance transmission.

### **2.6.1 Dispersion Compensating Fiber (DCF)**

The demand for high data rates and long distance transmission has been increased due to the fast improvement in optical fiber communication networks. One of the most effective techniques to compensate for chromatic dispersion in a wavelength of large bandwidth is the Dispersion Compensating Fiber (DCF) method.

DCF is a highly effective technique that is used to compensate for the chromatic dispersion in a high speed system. The DCF method offers many advantages. For instance, it is a cost effective technique and has wide band characteristics of dispersion compensation [29]. The design of DCF is made to achieve a large negative value of dispersion up to -80 ps/nm. This allows the adjustment of a large amount of chromatic dispersion in the optical fiber. DCFs can be optimized to be used in different bands, but it has no effect when it is used in bands of lower frequencies, such as E band (1.360-1.460 $\mu$ m) [30]. The design of DCF requires higher attenuation than single mode fiber and this will produce more insertion loss. The high amount of the insertion loss can be overcome by increasing the power of the signal.

## 2.7 Fiber Nonlinearities

The power and phase of the transmitting optical signal are affected by the fiber dispersion, as mentioned before. In addition, there is the important factor of fiber nonlinearities that also affects the transmitting optical signal. There are two major types of the nonlinear effects. The first kind is known as the Kerr effect and is produced because of the dependency of the refractive index on the intensity of the transmitting signal [CO-OFDM]. This kind of nonlinear effect is described as follow:

$$n(\omega, |E|^2) = n(\omega) + n_2 |E|^2 \quad 2.14$$

where  $\omega$  represents the angular frequency and  $n_2$  denotes the nonlinear index coefficient.

Many types of nonlinear effects come under the category of the Kerr effect including XPM, SPM, and FWM [60]. The second major type of the nonlinear effect is

called Stimulated Raman Scattering (SRS). This kind of nonlinearity occurs because the optical field energy is transferred to a medium by a process called stimulated elastic scattering.

### 2.7.1 Self-Phase Modulation (SPM)

This kind of nonlinear effect depends on the refractive index. It can happen when an extremely short pulse is transmitted through a single mode fiber. This propagation of an extremely short pulse will cause a varying in the refractive index because of the Kerr effect. This variation in the refractive index will generate a phase shift. Therefore, a change will occur to the pulse of the frequency spectrum. The resulting nonlinear phase shift has a proportional relationship to optical intensity and can be describes as follow:

$$\phi_{NL}(l, T) = n_2 k_0 l |E(l, T)|^2 \quad 2.15$$

where  $n_2$  represents the nonlinear refractive coefficient,  $k_0 = 2\pi/\lambda_0$ ,  $\lambda_0$  is the wavelength of the signal,  $l$  denotes to the length of the fiber, and  $E(l, T)$  indicates the electrical field of a distance  $l$ . The optical pulse spectrum is extended by the effect of SPM with no change in the pulse shape. Consequently, this will cause a frequency chirp that generates more components of frequency to the optical pulse.

### 2.7.2 Cross-Phase Modulation (XPM)

The same behavior of SPM is exhibited in XPM. Nevertheless, XPM mainly arises when two or more optical pulses affect the intensity and phase of each other's. The nonlinear phase shift of two optical fields that are propagating through the fiber can be expressed in the following formula:

$$\phi_{NL}(l, T) = n_2 k_0 l (|E_1|^2 + |E_2|^2) \quad 2.16$$

where  $E_1$  and  $E_2$  represent the optical fields. XPM will cause a broadening of the signal as it travels over the optical fiber because of the chromatic dispersion.

### **2.7.3 Four-Wave Mixing (FWM)**

FWM is known as the third order nonlinearity of optical fibers and it is analogous to the intermodulation distortion in an electrical system [OFC book]. When channels of wavelength are placed close to the zero dispersion point, three optical frequencies ( $\nu_i, \nu_j, \nu_k$ ) will combine to generate a fourth optical frequency resulting from the intermodulation product  $\nu_{ijk}$ , which is given by:

$$\nu_{ijk} = \nu_i + \nu_j - \nu_k \quad 2.17$$

### **2.7.4 Stimulated Raman Scattering (SRS)**

When particles of light transport over a link of SMF, the molecules of light will excite and vibrate. Therefore, the particles of light will scatter during the transmission over the optical fiber, which can be known as SRS.

### **2.7.5 Stimulated Brillouin Scattering (SBS)**

SBS occurs when the input optical power is high [60]. The SBS causes a beam that travels only in the opposite direction of the information, which will affect the quality of the signal. Generally, the SBS has no effect when the input optical power is low.

## **2.8 Radio Over Fiber in Communication Networks**

Radio over Fiber (RoF) is a new technology used in communication networks. RoF is appropriate for high frequency especially for a broadband millimeter wave. RoF technology is an analogue fiber optic link that is used to carry the modulated radio frequency (RF) signals to allow wireless access. The majority of



the signal processing, such as the generation of RF, coding, modulation, and multiplexing takes place in the central station (CS). The expression RoF is generally assigned to the transmission of a wireless signal (RF) over fiber optic for wireless access. RF signals can be modulated by analogue or digital modulation. Some of the digital modulation techniques that can be used to modulate the RF signal are Quadrature Amplitude Modulation (QAM), Frequency Shift Keying (FSK) and Phase Shift Keying (PSK). The architecture design of RoF can be implemented for transmitting RF signals in both direction down link (from CS to base station (BS) and uplink (from BS to CS) [31-34].

The use of RoF provides many advantages in wireless communication networks. The main use of RoF around the world is in the distributed antenna systems because of the low maintenance and operation cost [35].

Additional benefits of using RoF networks are:

- The design of RoF can be used to cover the “dead zone” where wireless signals are not reachable. RoF can cover areas where it would not be possible to be covered by wireless signals, such as mountains, tunnels, and natural obstacles as shown in Figure 2.8.

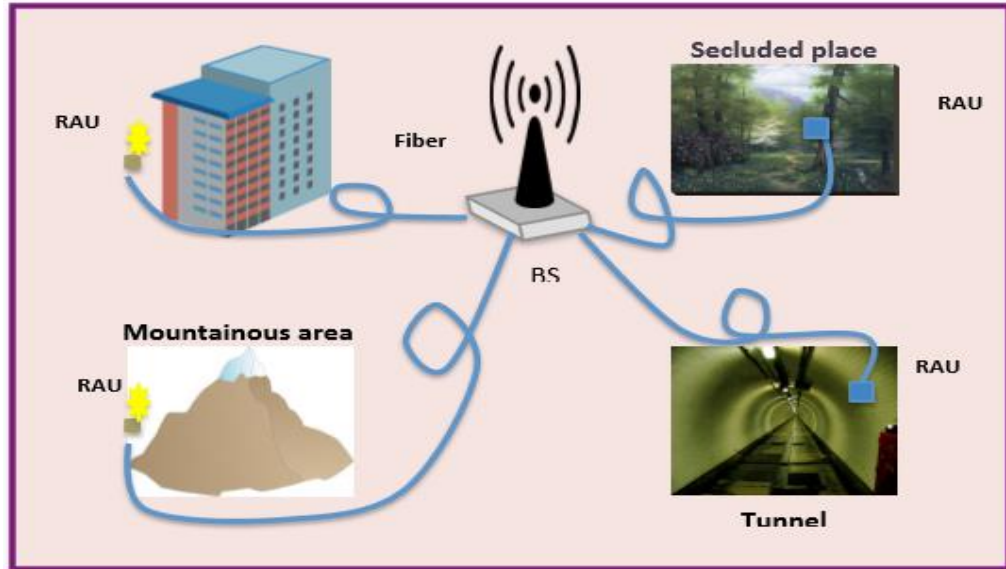


Figure 2.8: Coverage of RoF in Dead Zone

- The use of the low power of RF in remote antenna units (RAUs) can offer high spectrum efficiency and low interference [36-37].
- It is immune to electromagnetic interference.
- A RoF network provides large bandwidth and high data rates which can be the preferred technology for future high data rate networks.
- The optical fiber link can support different services, such as multimedia applications.
- The design of RoF is able to reduce the effects of a multipath [37].
- Optical fiber has low attenuation at 0.2dB/km compared to wireless media. Therefore, the transmission distance can be increased where a fewer number of amplifiers are needed.
- RoF network has good reliability against difficult weather conditions.

## 2.9 Direct Modulator

The most important feature in an optical fiber communication network that differentiates it from other networks is using light to transmit data. The data in the optical fiber link is carried over a continuous wave produced by a laser source. Mainly, two wavelengths are used in an optical fiber communication network, which are 1310nm and 1550nm with respect to their dispersion and attenuation.

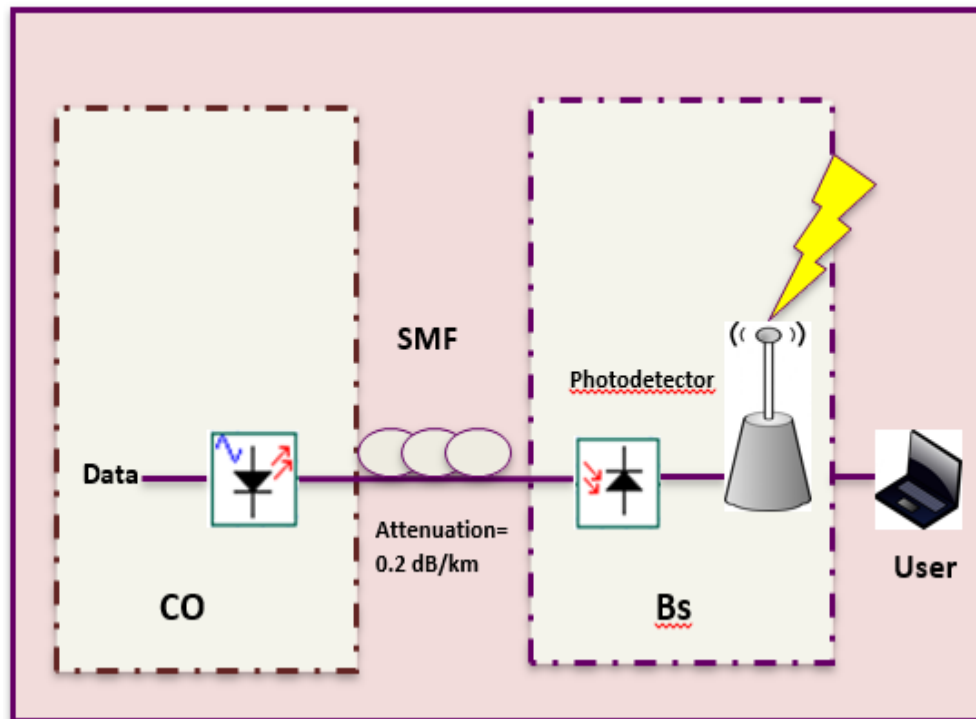


Figure 2.9: Direct Modulator Scheme

There are two different modulation techniques in an optical fiber communication network that are direct modulation and external modulation. Figure 2.9 shows the design of the direct modulation where the intensity of light is directly modulated by the RF signal. The received optical signal is converted to an RF signal by using a photodetector and then emitted by the antenna. The technical name of this modulation technique in optical fiber communication network is Intensity Modulated Direct Detection (IMDD).

Usually this method is used for transmission of a low data rate.

## 2.10 External Modulator

The second type of modulation technique in the optical fiber communication network is the external modulator. Figure 2.10 shows the design of the external modulation. A Mach-Zehnder Modulator (MZM) is used in the external modulator to modulate a light signal and a radio signal together.

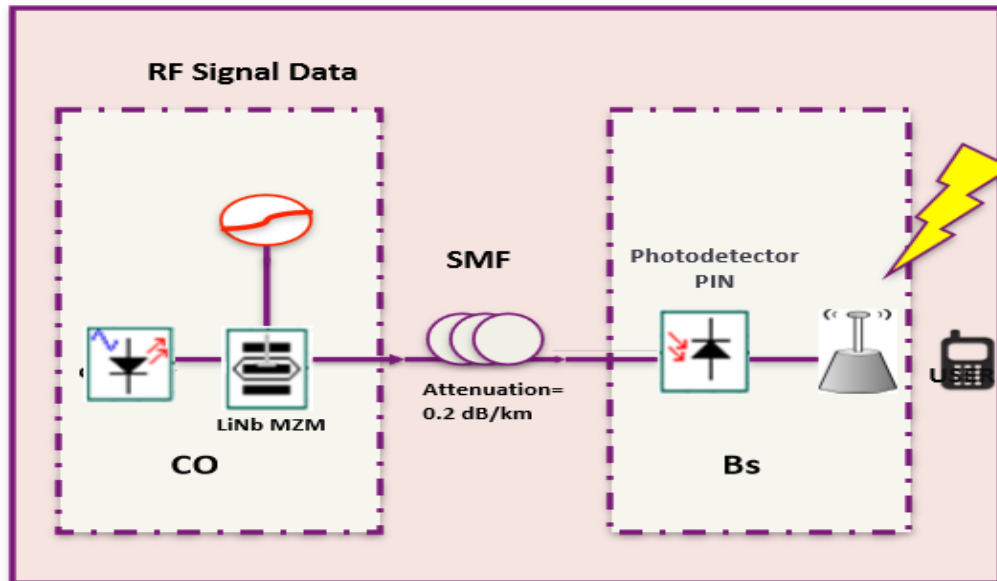


Figure 2.10: External Modulation Method

As mentioned before, the direct detection is limited to a small bandwidth and a low data rate. On the other hand, the external modulators support the system to achieve a large bandwidth at around 40GHz and a high data rate of about 10Gbps. Therefore, the use of an external modulator is preferred for long haul optical fiber communication networks. There is a disadvantage in using external modulators because it has a nonlinear design. Compensation needs to be made for these

nonlinearities and this will increase the complexity of the system [38-39].

### **2.11 Applications in RoF Networks**

RoF technology can be implemented in many applications, such as Mobile Broadband System (MBS), broadband wireless communication, and Multipoint Video Distribution Services (MVDS). The most important application of RoF technology is in mobile networks. RoF technology offers high data rates and large capacity. Therefore, RoF technology is the most effective technique to solve the increasing demand for broadband services and mobile users.

### **2.12 RoF Multiplexing Techniques**

A multiplexing technique is defined as more than one wavelength multiplexing and transmitting at the same time. The capacity of the optical fiber communication networks can be increased by using the multiplexing technique where each wavelength will have different frequency and carry data in parallel over one optical fiber.

#### **2.12.1 Wavelength Division Multiplexing (WDM) in RoF Systems**

WDM technique is a very efficient method that is used to integrate wavelengths of light signals over a single fiber. The WDM technique provides higher capacity for optical fiber communication networks compared with time division multiplexing (TDM).

Figure 2.11 illustrates the design of WDM where a WDM multiplexer is used to multiplex wavelengths of different frequencies and a WDM DE multiplexer is used to separate the multiplexing wavelengths. WDM supports the effective using of the optical fiber network's bandwidth for achieving a data rate of 1Tbps and above over one optical fiber. WDM can support a bit rate of 50Gbps for each channel. In addition, WDM can multiplex hundreds of channels by using small channel spacing, such as 25 GHz.

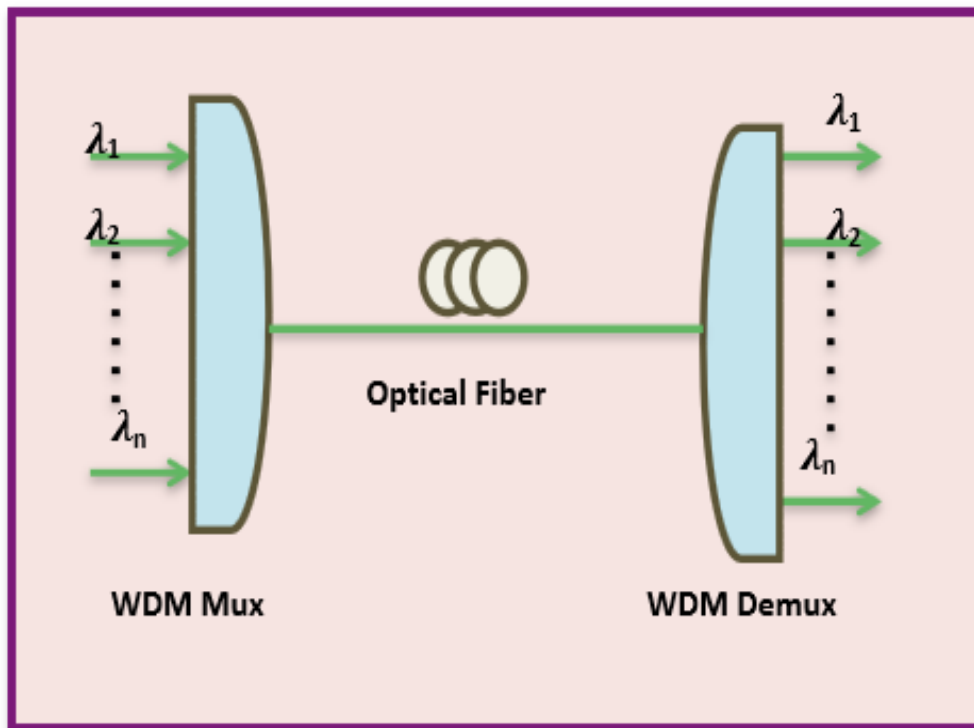


Figure 2.11: Wavelength Division Multiplexing (WDM) Technique

## **Chapter 3**

### **Orthogonal Frequency Division Multiplexing (OFDM)**

#### **3.1 Introduction**

OFDM is defined as a multicarrier modulation technique that can support the transmission of high data rates and provide higher performance than a single carrier modulation technique. OFDM has been widely examined and is used in wire and wireless communication [40-41]. In OFDM, the data is transported over many subcarriers of lower rate. OFDM has a good robustness to the channel dispersion. The guard intervals used in the OFDM to accomplish the orthogonality of the system provide large bandwidth and high data rates. On the other hand, the using of the guard intervals will affect the spectral efficiency of the system [42].

#### **3.2 OFDM Modulation**

Generally, there are many different ways of modulating and demodulating an OFDM transceiver [43]. Figure 3.1 demonstrates the block diagram of the OFDM transmitter and receiver. As shown in this diagram of the OFDM transmitter, the data is mapped by using multilevel modulation techniques such as quadrature amplitude modulation (QAM), frequency shift keying (FSK), phase shift keying (PSK). After that, the bit stream is converted from serial to parallel and followed by the Inverse Fast Fourier Transform (IFFT). A guard interval is placed after the IFFT box to make sure no overlapping occurs between the signals.

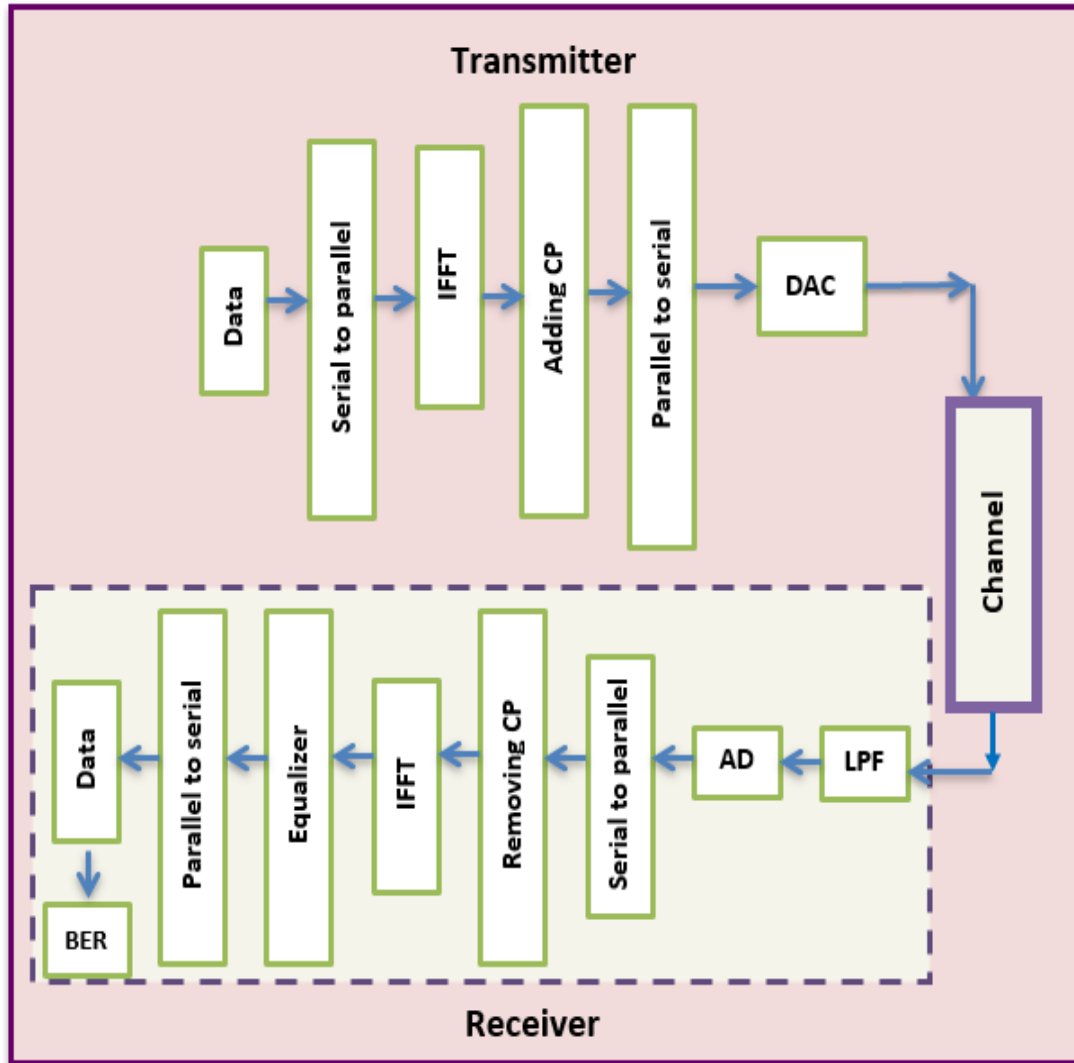


Figure 3.1: OFDM Transceiver Block Diagram

The last step in the OFDM transmitter is converting the bit stream from parallel to serial and then sending the data over a channel. In the OFDM receiver, the same process as the transmitter is performed, but with the opposite function. The first step in the OFDM receiver is that the data will be converted from serial. Then the guard interval (or cyclic prefix) will be removed from the data. After that, a Fast Fourier Transform (FFT) is performed, which will do the opposite function as the IFFT. Finally, the signal will be demodulated to get the original signal back.



### 3.2.1 Constellation

A data symbol is represented by a two dimensional constellation. The data symbol which indicates to the original information is shown as small points on the constellation diagram. The data symbol is interpreted as a complex number where the x-axis denotes the real part and the y-axis represents the imaginary part. The number of points that represents the data symbol depends on the type of the modulation method used in the system. For example, quadrature phase shift keying (QPSK) modulation method has 2 bits per symbol. Therefore, it has 4 signal points represented on the constellation diagram as shown in Figure 3.2. Other examples of modulation technique are shown in Figure 3.3 and Figure 3.4 for 16-PSK and 16-QAM, respectively.

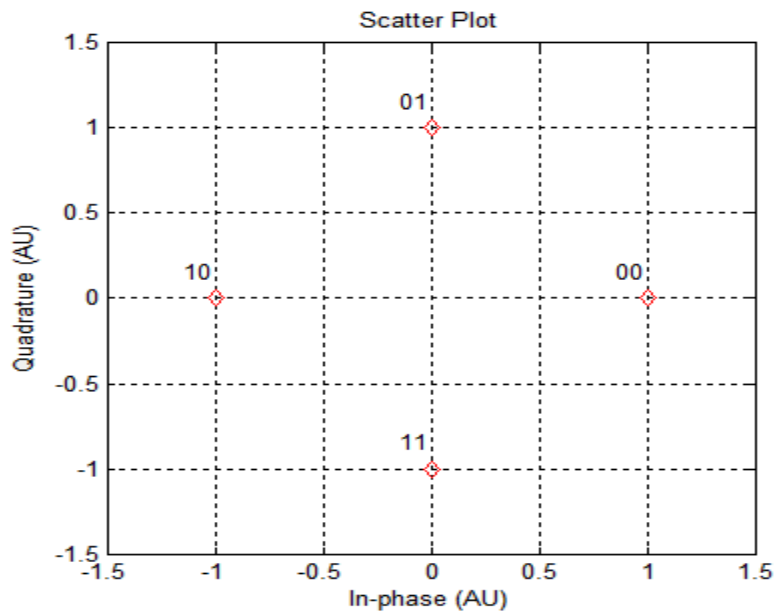


Figure 3.2: The Constellation Diagram of QPSK

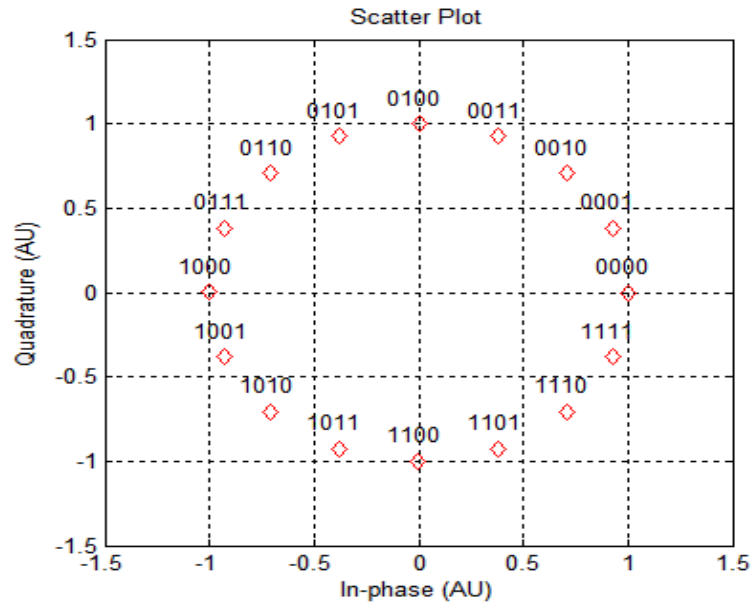


Figure 3.3: The Constellation Diagram of 16-PSK

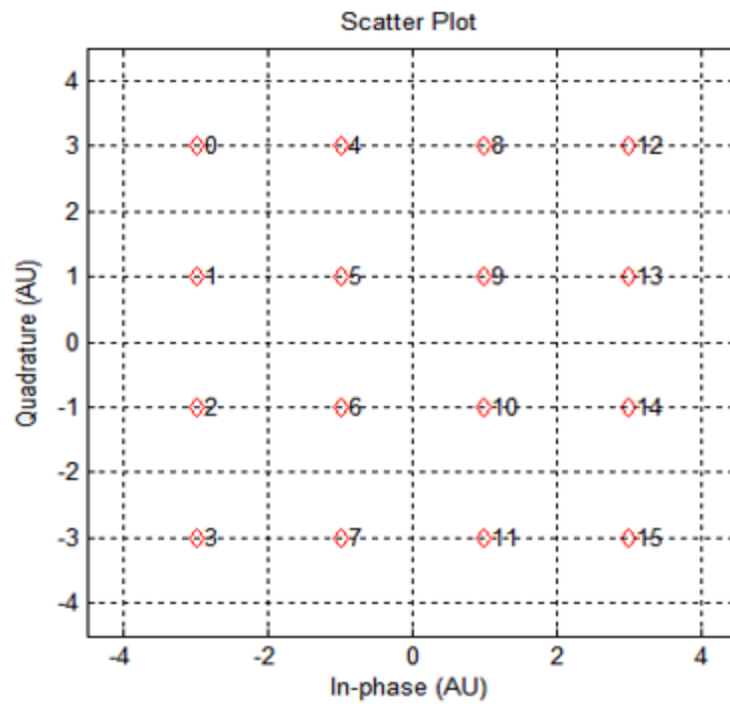


Figure 3.4: The Constellation Diagram of 16-QAM

### **3.2.2 Serial to Parallel Conversion**

After converting the data to complex value, the sequence of the data stream will be converted from serial to parallel. The resulting parallel data symbols are organized into a number of subsets. The number of data symbols that are transported by each subset can be determined by the number of subcarriers. To illustrate this operation let us assume that we have eight data symbols to be transmitted by four subcarriers. The number of data symbols for each subset can then be determined easily by dividing the number of data symbols by the number of subcarriers.

### **3.2.3 Inverse Fast Fourier Transform (IFFT)**

The symbols of the OFDM need to be generated quickly. As mentioned before, the OFDM is a multicarrier modulation technique. To generate the OFDM symbols, a unique radio frequency oscillator is needed for each carrier. Generating the OFDM symbols this way is very challenging due to the large number of subcarriers and the difficulty of maintaining the orthogonality between the signals. The OFDM is of great interest to researchers attempting to overcome these difficulties in generating OFDM symbols.

Researchers introduced the inverse Discrete Fourier Transform (DFT) as an approach to produce OFDM symbols and reduce the complexity of the OFDM transceiver. On the other hand, the DFT is not the preferred approach because of it needs long and complex calculations to operate. The most effective method for creating the OFDM symbols is called Fast Fourier Transform (FFT). The principle of this method was invented by Cooley and Tukey in 1965 [44]. The complexity of the OFDM transceiver is reduced by using the FFT and its inverse IFFT. The FFT algorithm can be used to ensure

no interference occurs between the adjacent signals by supporting the orthogonality of the system.

The IFFT is described by [45] as follow:

$$X(l) = \frac{1}{\sqrt{N}} X(k) e^{j2\pi k \frac{l}{N}}, \quad 3.1$$

$$X(k) = A_{k,n} e^{2j\theta_{k,n}}, \quad 3.2$$

where  $X(k)$  is the users data bit encoded with the N-th symbol and k-th subcarrier. The phase and amplitude of the points of signal constellation are represented by  $\theta_{k,n}$  and  $A_{k,n}$  respectively. The time domain of the k-th subcarrier within the n-th symbol duration can be defined as:

$$x_{k,n}(t) = X_{k,n} \Psi(t - nT_s) e^{j2\pi f_k(t)}, \quad k = 0, 1, 2, \dots, N_s, \quad 3.3$$

$$\Psi(t) = \begin{cases} 1, & t \in [0, T_s] \\ 0, & t \notin [0, T_s] \end{cases} \quad 3.4$$

where  $N_s$  denotes to the number of subcarriers,  $f_k$  represents the k-th subcarrier frequency,  $T_s$  is the symbol period of OFDM, and  $\Psi(t)$  has a unity magnitude over the duration time of  $T_s$  with a shape of rectangular pulse. As shown in Figure 3.5, each subcarrier will have a form of *sinc* spectrum. In the n-th symbol period, the relationship between any two subcarriers is specified by [46]:

$$\frac{1}{T_s} \int_{(n-1)T_s}^{nT_s} x_{k,n}(t) x_{l,n}^*(t) dt = e^{j2\pi(f_k - f_l)T_s} \frac{\sin(\pi(f_k - f_l)T_s)}{\pi(f_k - f_l)T_s}, \quad 3.5$$

Frequency spacing of subcarrier is defined as:

$$\Delta f = (f_k - f_{k-1}) = \frac{1}{T_s}, \quad k=1, 2, \dots, N_s - 1 \quad 3.6$$

### 3.2.3.1 Orthogonality

The most important advantage of the OFDM modulation technique is the orthogonality because it supports a system to achieve high spectral efficiency and large bandwidth. Moreover, if the orthogonality is satisfied in a system, it means that no degradation or interference occurs between the adjacent signals. The OFDM signal is represented as follow:

$$v(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi kt/T}, \quad 0 \leq t \leq T \quad 3.7$$

where the data symbols is represented by  $X_k$ ,  $N$  denotes to the subcarriers number, and  $T$  represents the OFDM symbol. The spacing of the subcarriers should be  $1/T$  to maintain the orthogonality. To verify that every two subcarriers are orthogonal, the orthogonality condition must be satisfied as shown below:

$$\frac{1}{T} \int_0^T (e^{j2\pi k_1 t/T}) * (e^{j2\pi k_2 t/T}) dt = \frac{1}{T} \int_0^T e^{j2\pi(k_2 - k_1)t/T} dt = \begin{cases} 1, & \text{for } k_1 = k_2 \\ 0, & \text{otherwise} \end{cases} \quad 3.8$$

If the dot product of the two signals equals to zero, the orthogonality condition will be satisfied and we can say that the two signals are orthogonal. Figure 3.5 illustrates the spectrum of OFDM signal.

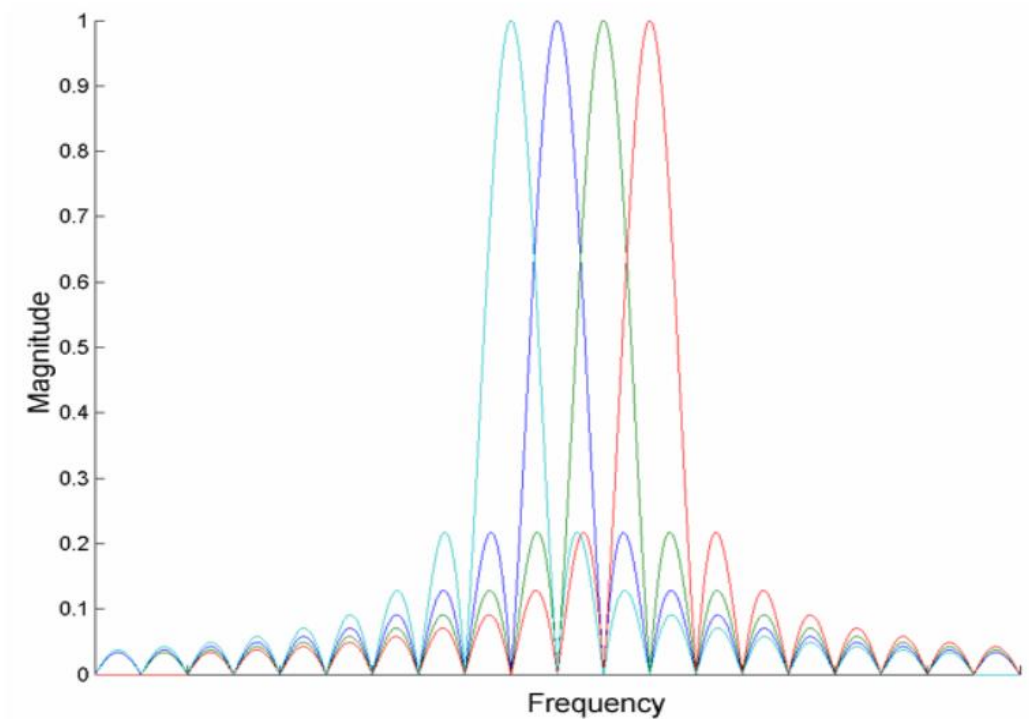


Figure 3.5: The Orthogonal Spectrum of the OFDM [47]

### 3.2.4 OFDM Guard Interval

To make sure that a system achieves orthogonality and no Intersymbol Interference (ISI) occurs, the guard interval must be inserted between the OFDM symbols. Interference between the OFDM symbols occurs because some of the OFDM symbols are delayed through transmission. Therefore, a guard interval is used to keep a space between the adjacent symbols preventing interference. There are two methods to make guard interval between the OFDM symbols: the cyclic prefix (CP); and cyclic suffix (CS). In the cyclic prefix method, the last part of the symbol is copied and inserted at the beginning of the symbol. Using the cyclic suffix method, the head of the OFDM symbol is copied and inserted at the end of the symbol.

### 3.2.4.1 Cyclic Prefix (CP)

One of the methods that can be used to eliminate ISI is to use CP. In this method, an extension from the last part of the symbol is added to the beginning of the symbol. The OFDM symbol time is equal to the subcarrier time plus the guard time.

$$T_{OFDM\ Sym} = T_{sub} + T_{Guard} \quad 3.9$$

Figure 3.6 illustrates how the cyclic prefix method work.

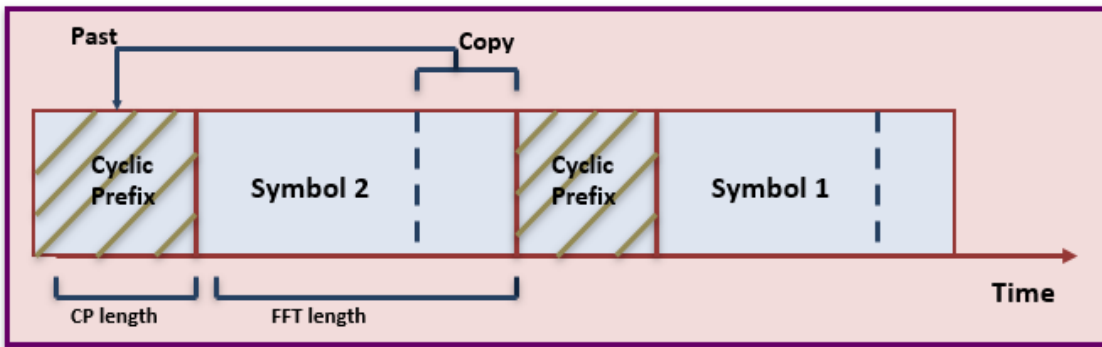


Figure 3.6: Cyclic Prefix method

The CP length should be longer than the length of the delay of the multipath channel to maintain the lowest effect of ISI. However, if the opposite happens, where the delay of the multipath channel is longer than the CP length, ISI will occur between the adjacent symbols.

### 3.2.5 Parallel to Serial Conversion

According to the OFDM block diagram, the parallel symbols are converted to serial after inserting the cyclic prefix. The OFDM signals will then be ready for the process of up-conversion. The OFDM symbol length can be calculated as follow:

$$X_{length} = M(T_{sub} + T_{Guard}) \quad 3.10$$

where  $X_{length}$  represents the length of the OFDM symbol, and  $M$  denotes to the number of symbols.

### **3.2.6 Digital to Analogue Converters (DAC)**

The OFDM signals have a major disadvantage which is a large peak to average power ratio (PAPR). The system capacity will be restricted in the presence of large PAPR because of the distortion. This distortion is generated from the nonlinear effect of fiber and any other component like a fiber amplifier. The resulting large PAPR increases the need for developing DACs that are more complex. This type of distortion will affect spectral spreading and will cause changes to the shape of the signals on the constellation diagram. This will increase the BER and affect the quality of the system. DAC is an important device that can limit the maximum capacity transmission of OFDM signals because of the quantization and clipping effects of the DAC signal [CO-OFDM]. There are many techniques that are used to reduce the effect of PAPR which will not be discussed in this thesis.

### **3.2.7 Up-Conversion**

The last step in the block diagram of the OFDM transmitter is the process of up-conversion. In this step, the OFDM complex baseband, which is the original form of the signal, is converted to the pass-band by using an RF signal of high frequency centered at  $f_c$ .

## **3.3 OFDM Demodulation**

In the OFDM demodulation, the same process is performed as in the OFDM modulation, but in an opposite function. The first step in the block diagram of the OFDM receiver is converting the signal from serial to parallel. Then the CP is removed from the OFDM symbols. After that, the Fast Fourier Transform (FFT) is applied to the signals and is followed by the channel estimator to convert the signal to the frequency domain



and gets the original signal. Before demodulating the signal by using any of the different types of multilevel demodulator, the signal is converted from parallel to serial.

### **3.3.1 Guard Period Removal**

As mentioned before, the guard interval is inserted to prevent ISI. In the OFDM receiver, the guard interval must be removed to get the original form of the OFDM symbol. Figure 3.6 illustrates how the length of the CP, which is noted as  $T_{Guard}$ , is removed to recover the OFDM symbol's length.

### **3.3.2 Fast Fourier Transform (FFT)**

The Fast Fourier Transform is applied to the symbols of the OFDM after taking out the CP. In this step, the real values will be converted to a frequency domain by using the FFT. To recover the original information, the subcarriers are removed by using the FFT. The use of FFT offers an efficient method to take out the subcarriers in only one step instead of using a large number of oscillators and filters. A signal sequence from 0 to  $N_{FFT}-1$  is formed with orthogonality after achieving time synchronization and removing CP successfully.

### **3.3.3 Converting from Parallel to Serial**

The operation of converting from a parallel symbol to serial is performed the same as in the OFDM transmitter block diagram. The aim of this step is to recover the original length of the duration because the parallel symbols have a shorter length of duration. By performing this process, recovery of the binary is easy after it is transmitted over the system.

### **3.3.4 Symbol Demodulation**

The final step in the block diagram of the OFDM receiver is the demodulation of the symbol. This step can be also called de-mapping, where the input of binary information is recovered. Depending on the amplitude and phase shift of symbols, the original binary information is mapped to signals of complex value.

The number of points, which represent complex values resulting from the conversion of the parallel symbols to serial, is dependent upon what type of modulation method is used in the transmitter. For instance, if a binary input is modulated by using the 16QAM modulation method, 16 points of complex signals are shown in the constellation diagram. The shape of these values will not be the same as shown on the constellation diagram of the transmitter side because of noise, attenuation and distortion.

## **3.4 Optical OFDM Principles**

Chapter 2 discussed the general idea of the OFDM technique and the transmitter and receiver block diagrams are explained. In this chapter, the optical OFDM (OOFDM) is investigated. A comparison between the RF domains of OFDM and the OOFDM is invalid because the OOFDM signals are converted to higher optical frequencies by using electro-optic converters in the process of up conversion. The OOFDM signals suffer from nonlinear effects when they are transmitted over an optical fiber channel because the electro-optic converters are nonlinear.

### **3.4.1 The OOFDM-RoF System Design**

The impairments of fiber linearity and non-linearity with the OFDM method were discussed in the last section. The first use of the OFDM technique in the optical fiber communication was in 2005. The most important advantages of applying the OFDM

technique to optical fiber networks is high spectral efficiency, removal of symbol interference and sub-channel, and employing the FFT method for modulation and demodulation which supports the system against dispersion [47].

### **3.4.2 Detection Techniques**

There are two major techniques of OOFDM that have been established and categorized according to the type of the detection structure. The first type of the OOFDM is called intensity modulation direct detected optical OFDM (IM-DD-OOFDM) [48] and the second type is known as coherent optical OFDM (CO-OOFDM) [49].

#### **3.4.2.1 IM-DD OOFDM**

The block diagram of the IM-DD-OOFDM is illustrated in Figure 3.6. As shown in this figure, the OFDM electrical signals are generated by the OFDM transmitter. The signal is then up converted to the optical field by using a device called an electrical to optical (E/O) up converter. The signals are then transmitted over the optical channel.

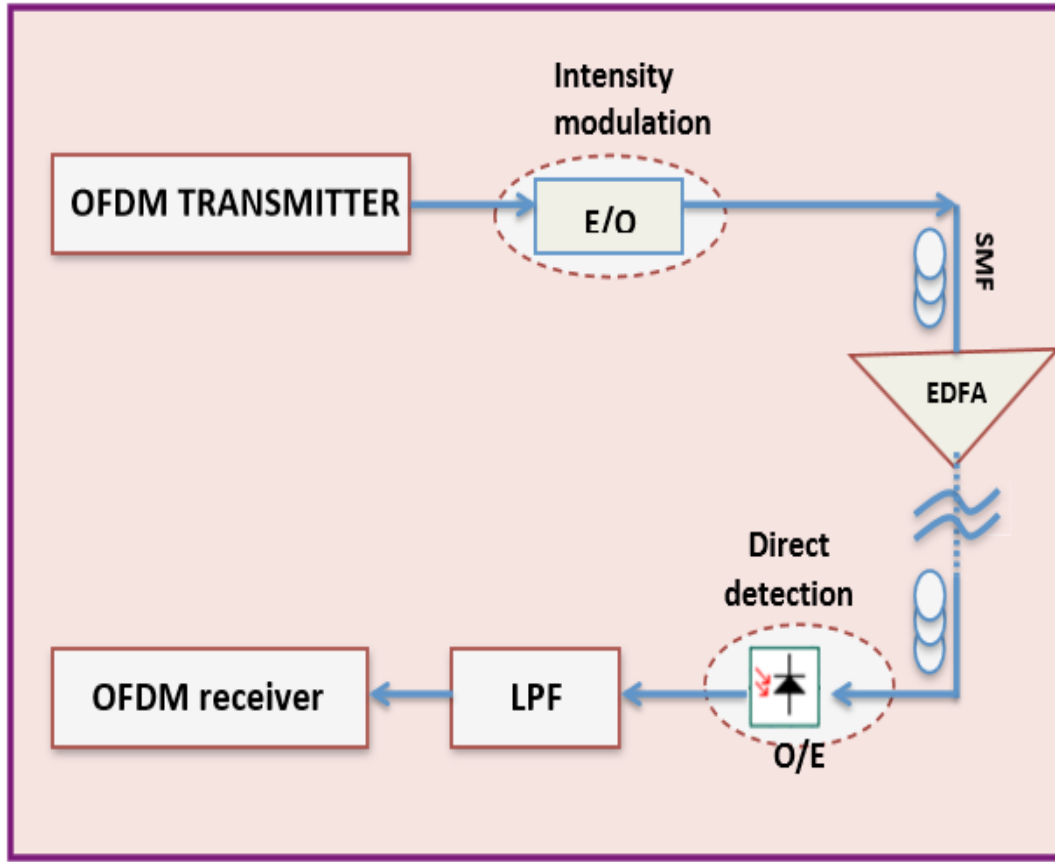


Figure 3.7: DD-OOFDM Scheme

At the end of the optical channel, the signals are converted to the electrical domain by using an optical to electrical (O/E) down converter and then processed by OFDM receiver.

The values of the OFDM signals need to be real for the process of the E/O converter to operate the laser source. According to the IM-DD scheme design, the real OFDM values are converted from parallel to serial after adding CP to the symbols. The OFDM symbols are then converted from digital to analog by ADC. Finally, the analog OOFDM signals are converted from electrical to optical by the E/O up converter and the signals are launched into the fiber optic [50].

The optical signals will be converted to electrical by using an O/E down converter at the receiver. The electrical OFDM signal is recovered by using a square law photodiode. The received electrical signal can be expressed as:

$$A_e(t) = |A_o(t)|^2 \otimes h_e(t) + w(t) \quad 3.11$$

where  $A_e(t)$  notes to the received electrical signal,  $A_o(t)$  represents the OOFDM signal,  $h_e(t)$  is the electrical impulse response, and  $w(t)$  is the noise of the system.

The signals being down converted from optical to electrical enter a low pass filter (LPF) and then pass through ADC. As mentioned before, the sampled signals are coded in the transmitter. But in the receiver, the sampled signal is decoded after ADC to extract the original information. The difference between the IM-DD-OOFDM and CO-OOFDM is that there is no local oscillator in the IM-DD-OOFDM receiver. Therefore, it is clear that the IM-DD-OOFDM method is less complex than the CO-OOFDM method.

#### **3.4.2.2 Coherent Optical OFDM (CO-OOFDM)**

In this section, the second method of the OOFDM known as CO-OOFDM will be discussed briefly. Figure 3.8 shows the block diagram for the CO-OOFDM. A local oscillator is used in the CO-OOFDM method to produce optical signals at a specific wavelength [51]. In the transmitter, two Mach Zehnder modulators (MZM) up converters are used to convert the complex OFDM electrical signals to optical. At the receiver, the CO-OOFDM uses two pairs of parallel photodiodes and an optical oscillator to perform the detection of the optical I/Q. The signals are then down converted to form the baseband and recover the original data [52].

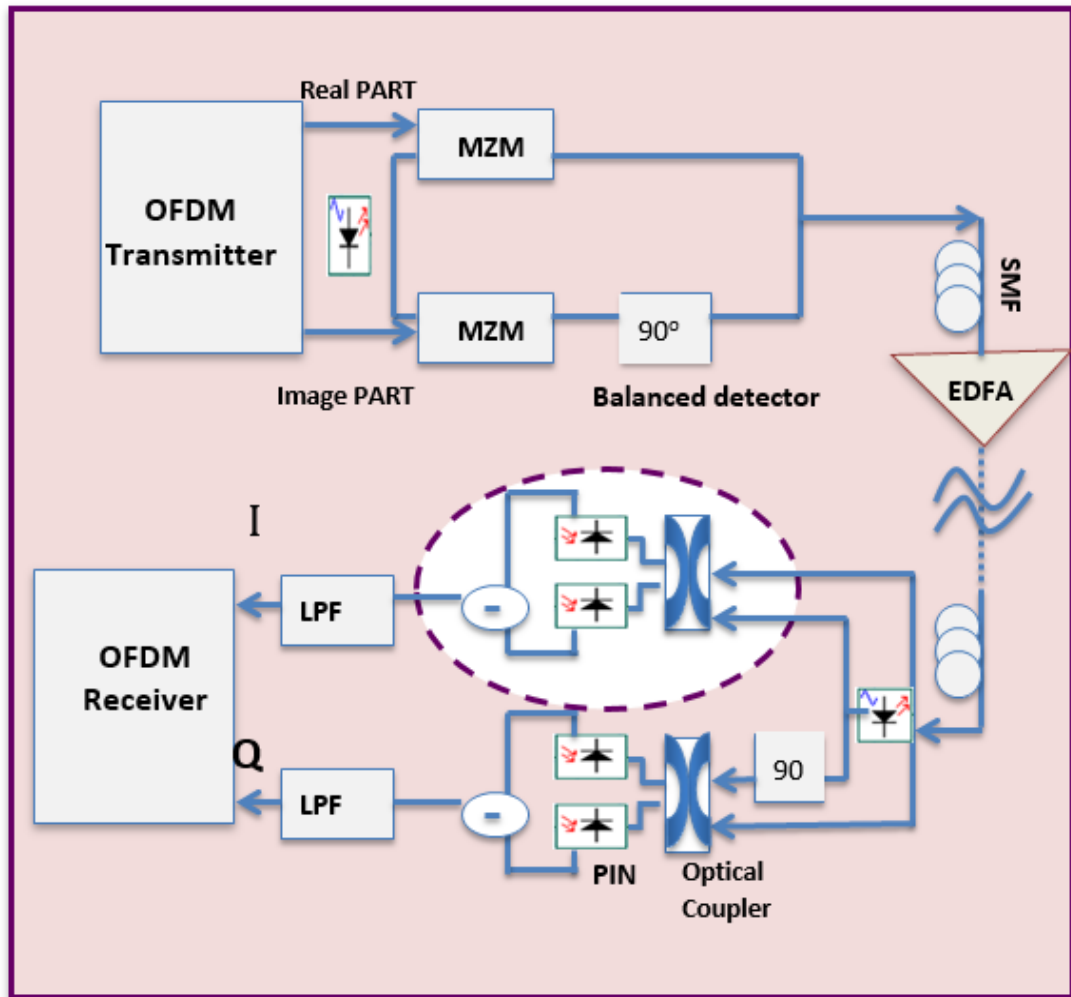


Figure 3.8: The Block Diagram of CO-OFDM

## Chapter 4

### System Design and Simulation

#### 4.1 Introduction:

The demand for high speed and large bandwidth for mobile wireless communications has rapidly increased in recent years. Optical orthogonal frequency division multiplexing (OOFDM), which is an advanced modulation technique, has recently been considered as a viable option to satisfy the increasing demand for high data rates and large capacity. OOFDM is being introduced as a promising scheme for supporting large capacity and high spectral efficiency for the advanced optical fiber communication networks.

In this thesis, the design and simulation of OOFDM, combined with RoF, is studied and investigated. First, the design of a single user 4-QAM-OOFDM integrated with RoF with data rate of 10Gbps and a transmission distance of 100 km SMF is simulated. The system performance is investigated by measuring the signal to noise ratio (SNR), the optical signal to noise ratio (OSNR), and by studying the constellation diagram. To support the system design in long-haul transmissions, a DCF is used as shown in the second design. Third, a dense wavelength division multiplexing (DWDM) is used to achieve high data rates where more than one OOFDM user can be integrated and transmitted at the same time.

## **4.2 Methodology**

Many different methods can be used to research the area of optical fiber communication systems, such as performing experiments and using simulation programs. In practice, it is expensive and time consuming to design a system mode. Moreover, the fiber optic measurement equipment needed to measure the performance of the system is very expensive.

### **4.2.1 OptiSystem Simulation Software**

Cost and time can be reduced when a system model design is done by using simulation software. Also, designers can extend their investigation by using simulation software. In this thesis, all the system models and simulations are performed by using simulation software called OptiSystem to study the performance of different system models. This software offers a broad range of wireless and optical parameters, which help researchers design a complete optical fiber network. Because of this, it is used by different telecommunication companies, such as Alcatel, Huawei and Fujitsu.

#### **4.2.1.1 Applications**

OptiSystem allows users to design, simulate and test the performance of different optical parameters and networks:

- Design of SONET/SDH ring;
- Design of transmitter, receiver and amplifier;
- Design of next generation of optical networks;

#### **4.2.1.2 Analysis Tools**

- Spectrum analyzer, BER analyzer, Eye diagrams, Q-Factor measurement;
- Constellation diagrams;



- Power meter, WDM analyzer, SNR, OSNR;
- Optical spectrum analyzer, WDM analyzer;

### 4.3 Simulation and Setup of One User OOFDM Combined with RoF

Figure 4.1 shows the setup configuration of the OOFDM-RoF system for a 100 km SMF length and a dispersion of 16ps/nm/km. The OOFDM-RoF transmitter is constructed for 4-QAM (2 bit-per-symbol) at a data rate of 10Gbps.

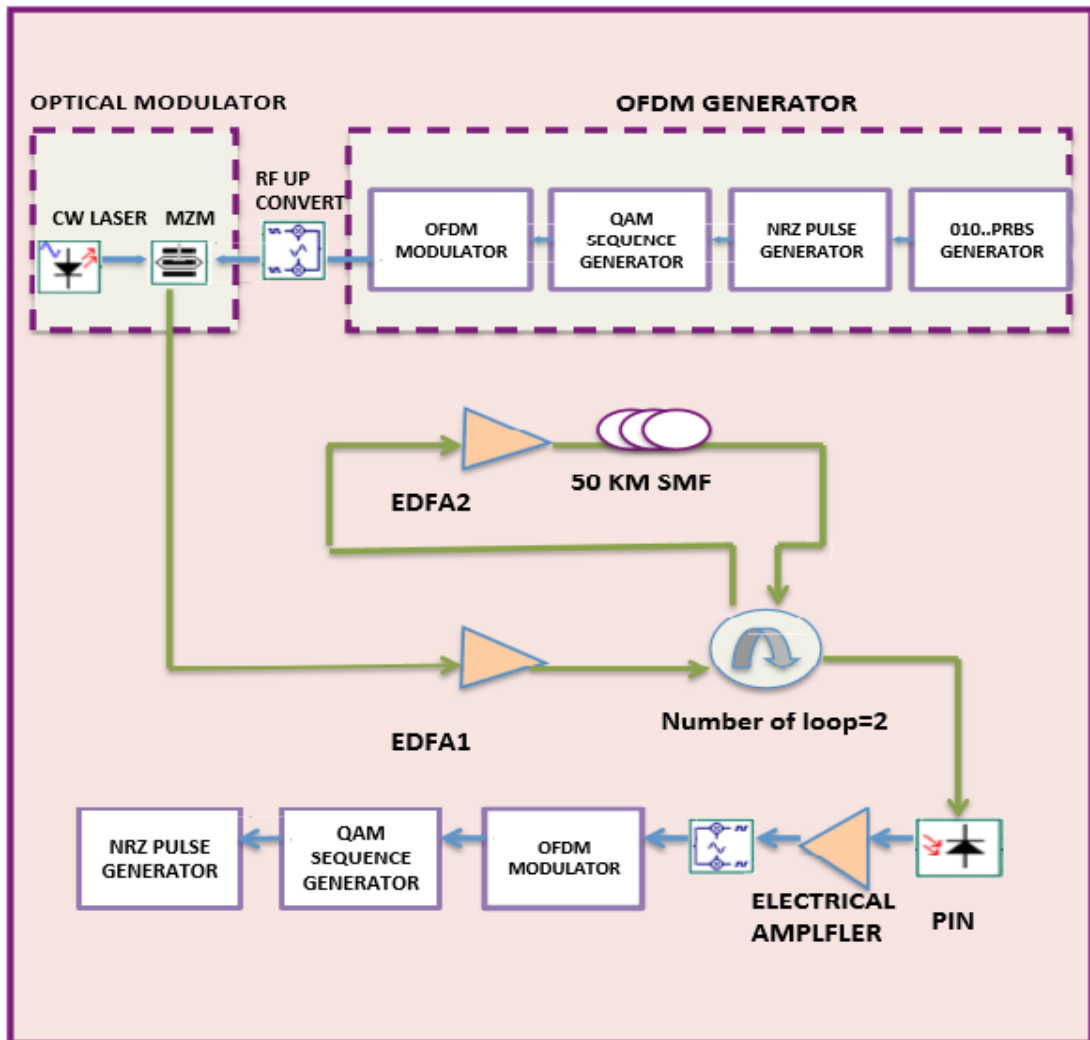


Figure 4.1: The Block Diagram of OOFDM-RoF System for 100 km SMF

Table 4.1 provides the OFDM transmission parameters, which consist of 256 subcarriers with FFT value of 1024. The output of the OFDM is modulated by using a Quadrature modulator as stated in (4.1) [53].

$$V_{out}(t) = G[I(t) \cos(2\pi f_c t + \phi_c) - Q(t) \sin(2\pi f_c t + \phi_c)] + b \quad 4.1$$

where G represents the gain, I and Q are the electrical input signals, b is the bias,  $f_c$  stands for the carrier frequency, and  $\phi_c$  is the carrier phase.

<b>Number of subcarriers</b>	<b>512</b>
<b>Number of FFT points</b>	<b>1024</b>
<b>Cyclic prefix</b>	<b>5/6</b>

Table 4.1: OFDM Modulator Parameters

An  $\text{LiNbO}_3$  external modulator is used in this design.  $\text{LiNbO}_3$  is a crystalline material that is used in several electro-optic modulators. Lithium niobate ( $\text{LiNbO}_3$ ) external modulators support both large bandwidth and can also minimize the dispersion effects in optical fiber. Because of this it is used in long-haul optical fiber transmission applications.

The lithium niobate (LiNb) Mach-Zehnder Modulator is used to modulate the OOFDM-RoF-transmitter (Tx) with a 7.5 GHz radio frequency (RF) carrier to the optical carrier by using a continuous wave (CW) laser diode signal of 193.1THz. The power of the CW laser diode is set at -5dBm. The optical signal is then transferred over the SMF with dispersion of 16 ps/nm/km, signal attenuation of 0.2dBm/km, and a dispersion slop of 0.075 ps/nm<sup>2</sup>/km. To amplify the optical power signal, a europium doped fiber amplifier (EDFA) is placed on the e SMF link to amplify the power of the optical signal.

At the receiver, a Photodiode (PD) is used to detect the coming optical signal and then convert it to an RF electrical signal. The parameters of the PD are as follow: responsivity of 1A/W, 10 nA dark current, a center frequency of 193.1THz, and a thermal noise of  $100e-24$ W/Hz. The electrical RF signal is then demodulated by using a Quadrature demodulator that performs an analogue demodulator. The Quadrature demodulator is used to convert the RF signal to a baseband signal and then transmit it to the OFDM block demodulator. Finally, a QAM decoder is used to decode the signal in order to get binary signal. As shown in Table 4.2, the OFDM demodulator has the following parameters: a number of 1024 FFT, 256-subcarrier, and the bit rate is divided by 2.

Bit rate	Bit rate/2
Number of subcarriers	512
Number of FFT points	1024

Table 4.2: OFDM Demodulator Parameters

### 4.3.1 Simulation Results and Discussion

In this part, the simulation results of the 4-QAM OFDM signal implemented for RF 7.5GHz through RoF are discussed and described for different lengths of SMF.

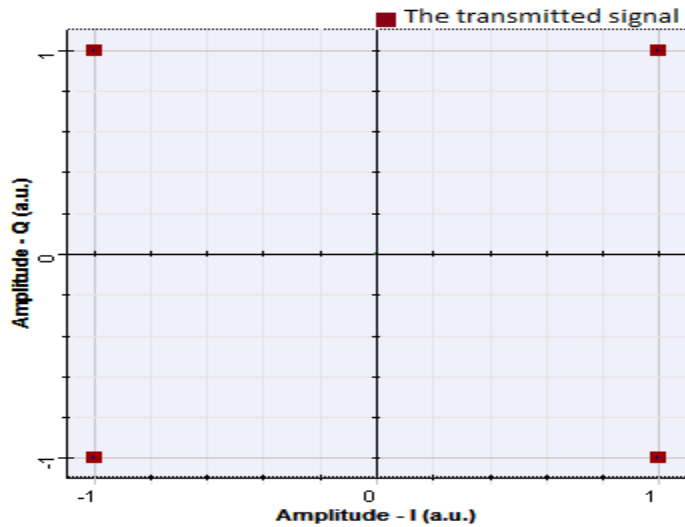


Figure 4.2: Constellation for OFDM-RoF Signal Transmission at Transmitter

Figure 4.2 displays the constellation diagram of the original transmission signal for 4-QAM digital modulator at the transmitter. A constellation diagram is used to display the modulated signal in two dimensional scatter diagrams. The distortion interference in a signal can be recognized by the shape of the signal that is shown in the constellation diagram. The SNR at transmitter is measured at 90.11 dB.

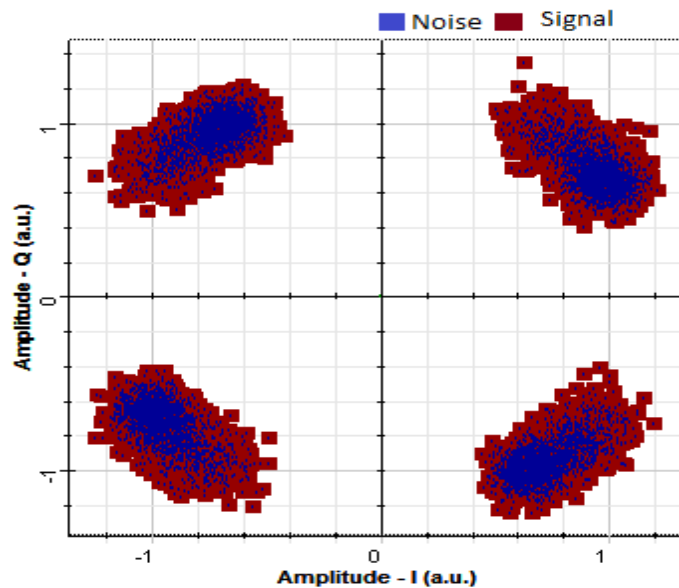


Figure 4.3: The Constellation Diagram for OFDM-RoF Signal Transmission at Receiver for a Length of 100 km SMF

Figure 4.3 shows the constellation diagram of the 4-QAM OFDM-RoF signal at the receiver after 100km SMF. The shape of the constellation diagram of the signal at the receiver is changed when compared with the transmitter due to chromatic dispersion, power attenuation, noise, and Rayleigh scattering. Because of this, the SNR is decreased and is measured at 48.71dB. As shown in Figure 4.3, the red points represent the signal and the blue points show the noise that is generated from the laser diode.

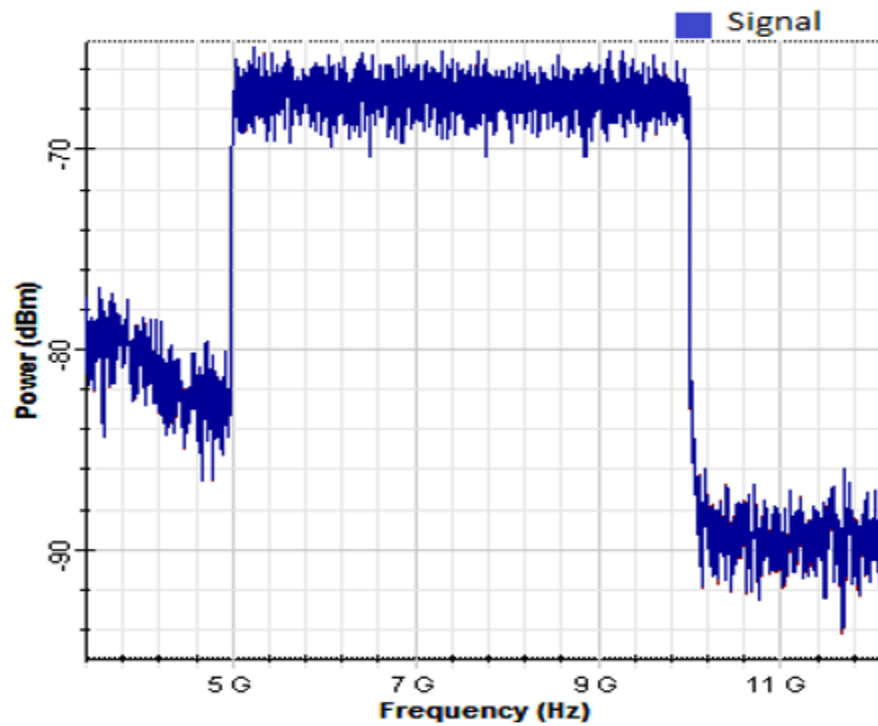


Figure 4.4: RF Spectrum for OFDM-RoF for 100km SMF

Figure 4.4 represents the RF spectrum of 4-QAM OFDM-RoF at the receiver for a carrier frequency of 7.5GHz and a bandwidth of 5GHz. At the receiver, the optical signal is converted to an electrical signal by using the photodiode (PD). The power of the RF is measured at -66dBm. The signal is represented by the blue color. The transmission distance is increased to 150km SMF and the constellation diagram is shown below.

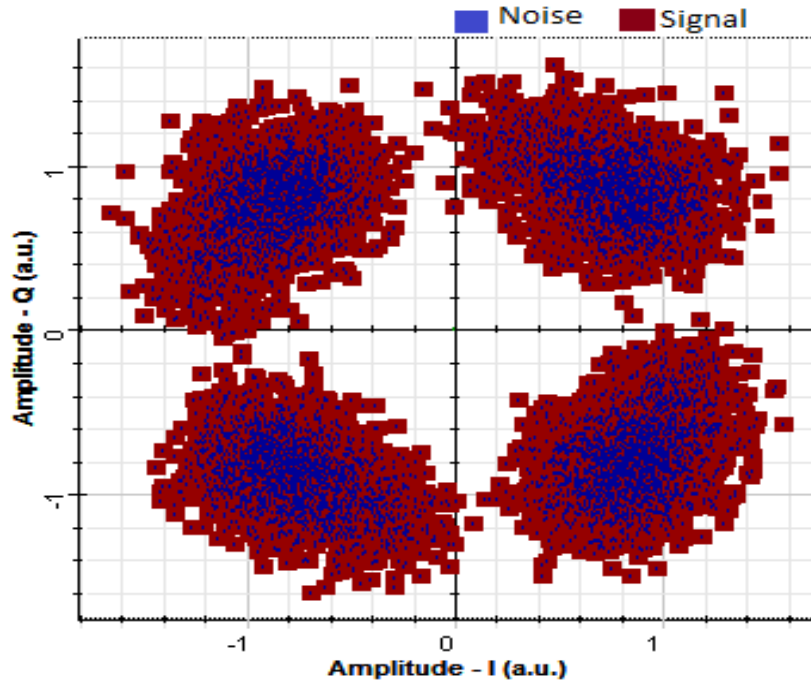


Figure 4.5: Constellation Diagram at the OFDM-RoF Receiver after 150km SMF

Figure 4.5 illustrates the constellation diagram of 4-QAM OFDM-RoF-Rx for 7.5GHz and 5GHz bandwidth after 150km SMF. It is clear that the distortions are increased in the signal after the transmission is increased because of noise, attenuation and, chromatic dispersion. The amount of the positive dispersion is increased as the transmission distance is increased, which causes a broadening in the pulses. As a result, the pulses will overlap with each other. It then becomes difficult to recover the data due to the huge amount of dispersion. Consequently, it is very important to adjust the amount of the positive dispersion employing a dispersion compensation fiber.

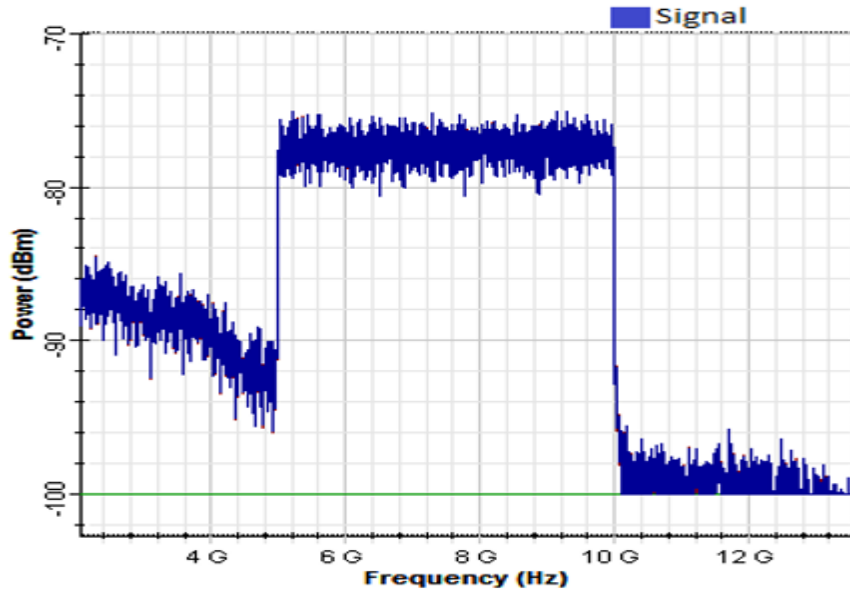


Figure 4.6: RF Spectrum of OFDM-RoF-Rx after 150km SMF

Figure 4.6 displays the RF spectrum at the 4-QAM OFDM-RoF receiver. The power of the RF is measured at -76dBm. It is clear that the RF power is reduced from -66 dBm to -76 dBm when the transmission distance is increased to 150km. This means that the quality of the signal is decreased because more attenuation is added to the fiber. The transmission is then increased from 150km to 180km SMF. The system constellation diagram for this is shown below.

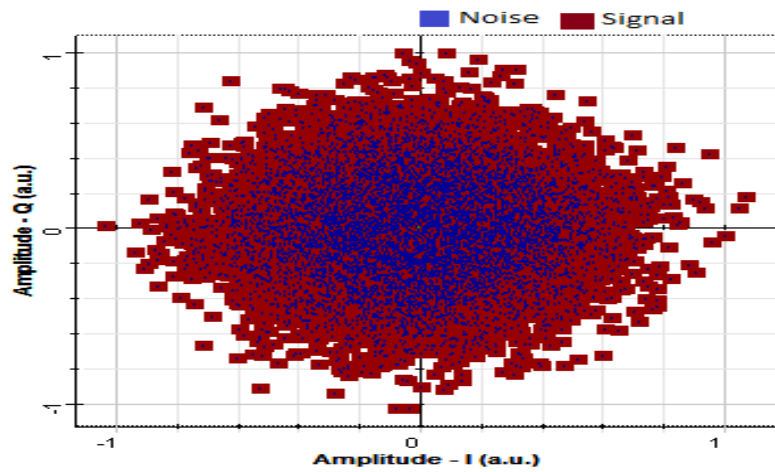


Figure 4.7: Constellation Diagram after 180km SMF with EDFAs Power of 25dB

Figure 4.7 represents the constellation diagram after 180km. It is clear that the signal is destroyed. The chromatic dispersion and power attenuation in SMF are increased when the signal is transmitted over a long distance due to scattering and absorption, which will affect the quality of the signal.

The first method to recover the corrupted signal is by increasing the EDFAs power. The power of the EDFA is increased to 37dB to amplify the transmitted signal in the fiber and reduce the high amount of attenuation.

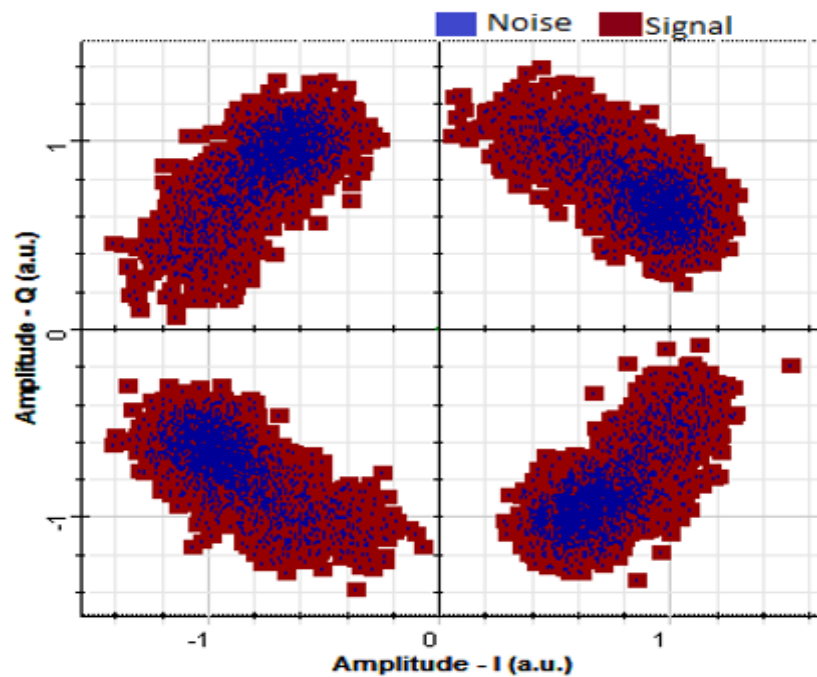


Figure 4.8: Constellation Diagram at OFDM-RoF-Rx after 180 km SMF with EDFAs Power 37dB

Figure 4.8 shows the constellation diagram after increasing the EDFAs power to 37dB. It is clear that the quality of the signal is much improved when the EDFAs power is increased. The value of the SNR is measured at 44.14dB and OSNR at 35.2dB.



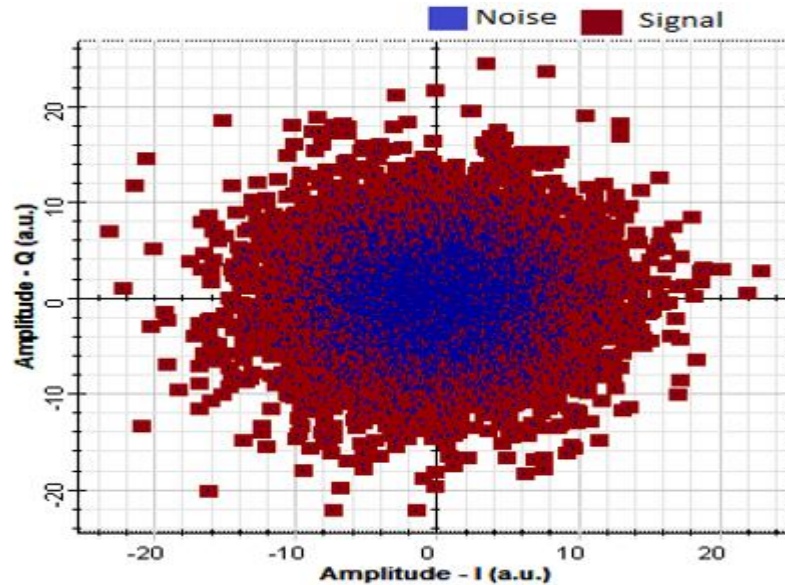


Figure 4.9: Constellation Diagram after 200km SMF with EDFAs Power of 37dB

Consequently, the transmission distance of the signal is increased to 200km SMF and the power of the EDFAs is increased to a value greater than 37dB. Still the damaged signal is not changed, as shown in Figure 4.9. Therefore, the power amplifier cannot improve the quality of the signal when the signal is transmitted over 200km SMF because it cannot compensate for the huge amount of power loss.

To improve the transmitted signal in the fiber for transmission distances over 200km without increasing the EDFA power, a dispersion compensation model is proposed. In the following section, a dispersion compensation fiber (DCF) is placed on the optical fiber link to compensate for the huge amount of positive dispersion, increase the transmission distance, and improve the quality of the signal.

#### 4.4 OFDM-RoF (SMF-DCF)

Figure 4.10 explains the configuration setup of the OOFDM-RoF system for the design of SMF-DCF. The SMF has a positive dispersion value of 16ps/nm/km and DCF

has a negative dispersion value of  $-80\text{ps/nm/km}$ . The OOFDM transmitter is designed for 4-QAM (2 bits-per-symbol) for a data rate of 10Gbps. The LiNb Mach-Zehnder Modulator is used to modulate the OOFDM transmitter with a 7.5 GHz carrier frequency to the optical carrier and a continuous wave (CW) laser diode signal of 193.1THz

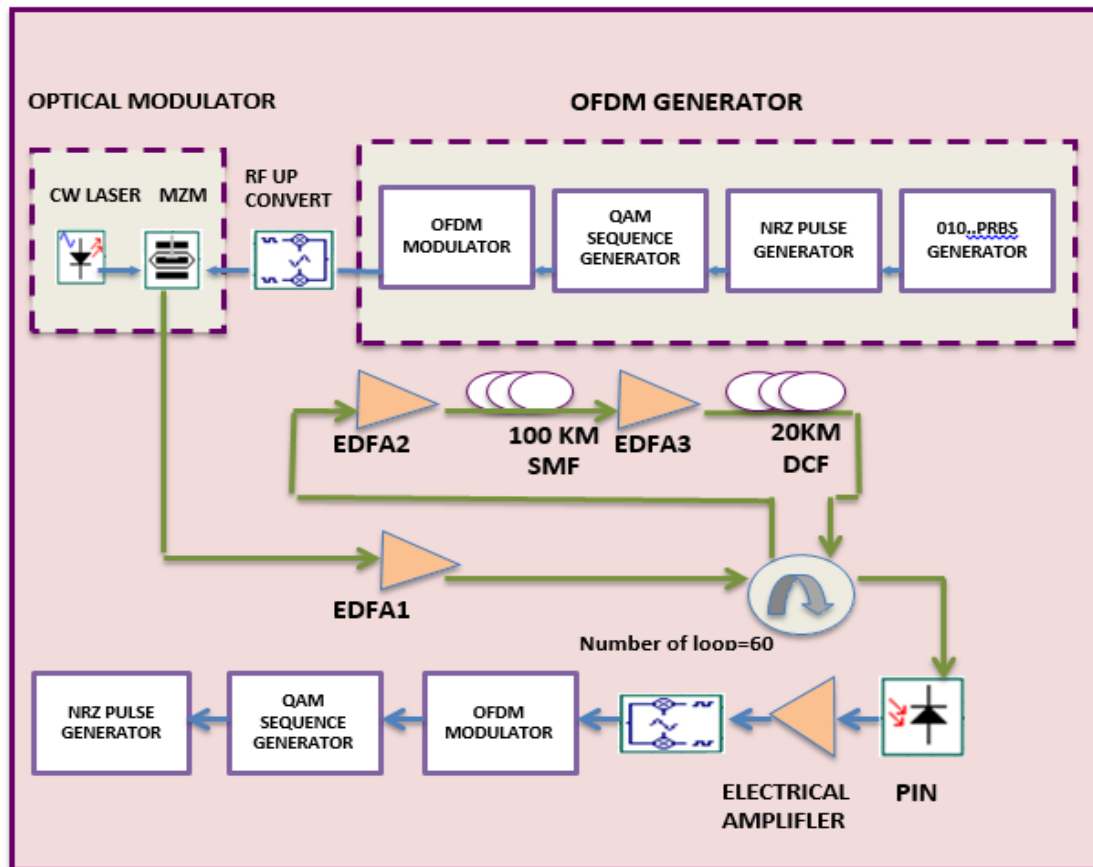


Figure 4.10: The Block Diagram of OOFDM-RoF System for the Design of SMF-DCF

The optical signal is transferred over the optical link that is composed of SMF-DCF. The SMF has power attenuation at  $0.3\text{dB/km}$  and the DCF has power attenuation at  $0.2\text{dB/km}$ . The dispersion slope of the SMF and the DCF are  $0.08$  and  $-0.45\text{ps/nm}^2/\text{km}$ , respectively. At the end of the optical fiber link, the optical signal is received by the photodetector and then converts it the signal from optical to electrical and

sends it to the OFDM-RoF receiver. The parameters of the photodetector are 1A/W, 10nA dark current, and center frequency 193.1 THz.

The power of the optical signal is amplified by applying an EDFA at the beginning of the SMF link. The fiber optic transmission distance can be extended by using post-dispersion compensation fiber with SMF. A SMF of 100km length is used with a dispersion value of 16 ps/nm/km. Therefore, the total amount of dispersion in 100km SMF is equal to  $16 \times 100 = 1600$  ps/nm. The large amount of positive dispersion can be compensated by using 20km of DCF with a dispersion value of -80ps/nm/km. The total amount of the negative dispersion is equal to  $20 \times (-80) = -1600$  ps/nm. Therefore, the negative amount of dispersion will cancel the positive dispersion. Hence, the signal can be transmitted over long distance. In this system design, the transmission distance is extended to 7200km by using 60 loops.

#### 4.4.1 Simulation Results and Discussion

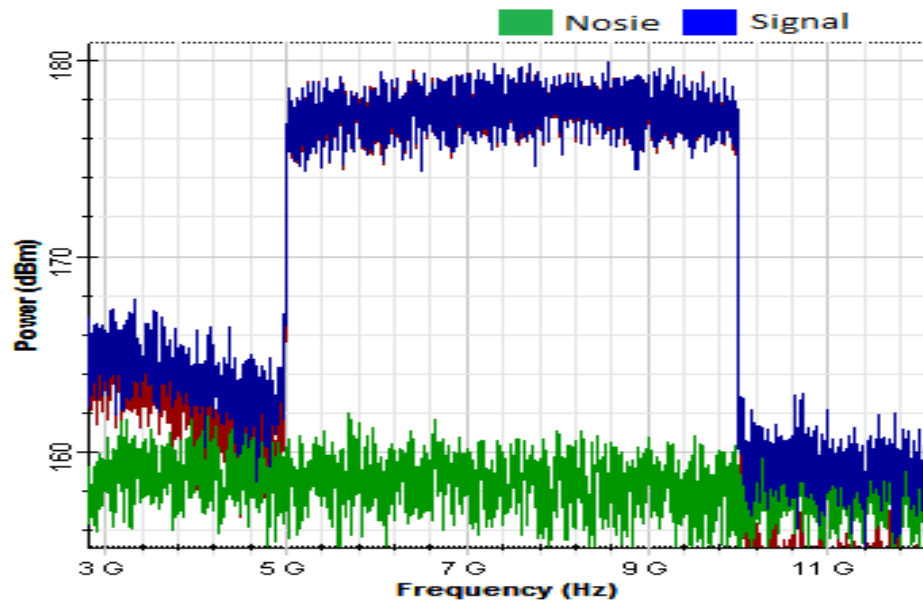


Figure 4.11: RF Spectrum of OFDM-RoF Receiver for SMF-DCF Length of 7200km

Figure 4.11 shows the RF spectrum of a 4-QAM OFDM-RoF receiver for 7.5GHz radio frequency and 5GHz bandwidth. The signal is transmitted over 7200km SMF-DCF. The power of RF is measured at 179dBm, the SNR at 19.23dB, and OSNR is measured at 26.14dB.

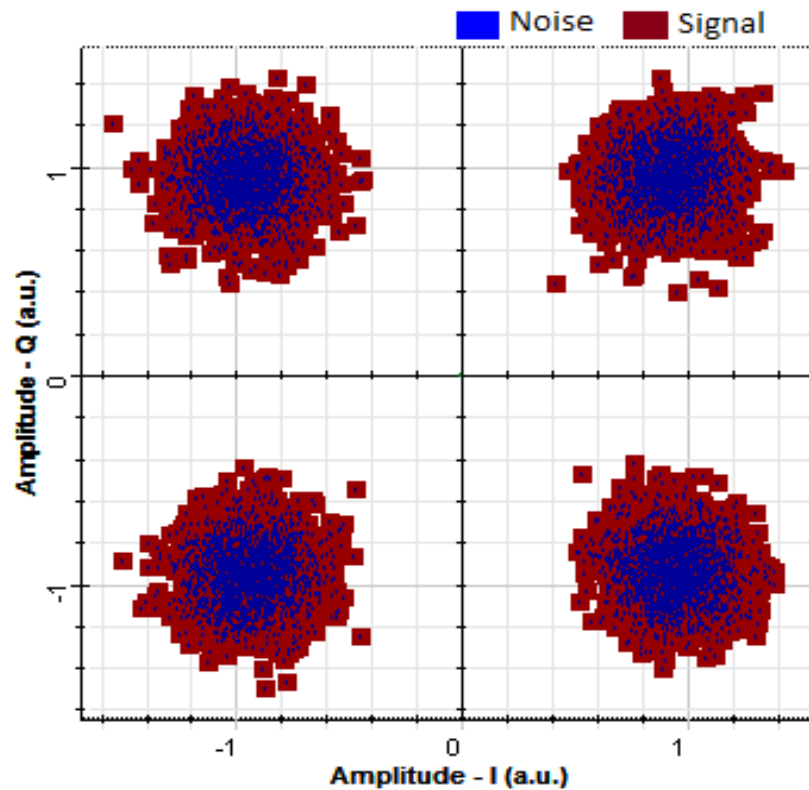


Figure 4.12: The Constellation Diagram of OFDM-RoF at Receiver for 7200km SMF-DCF

Figure 4.12 illustrates the constellation diagram of 4-QAM OFDM-RoF-Rx after a fiber length of 7200km SMF-DCF. The 4-QAM bit clearly displays noise at the OFDM-RoF-Rx. The system has successfully transmitted over 7200km SMF-DCF with some noise by using the method of the DCF.

## 4.5 OOFDM-RoF for High Data Rates

In the previous section, the result and simulation of the 4-QAM OFDM-RoF with a data rate of 10Gbps were presented and discussed. In this section, the design of a network that can support a high data rate is discussed. One of the most efficient methods to extend the capacity of a transmission link is to increase the order number of the digital modulation scheme [54]. For instance, each symbol in a 4-QAM signal is 2 data bits, whereas for 64-QAM and 256-QAM signals it is 6 and 8 data bits. In this section, the data rate is increased by using higher order modulation, 16-QAM.

### 4.5.1 System result and simulation

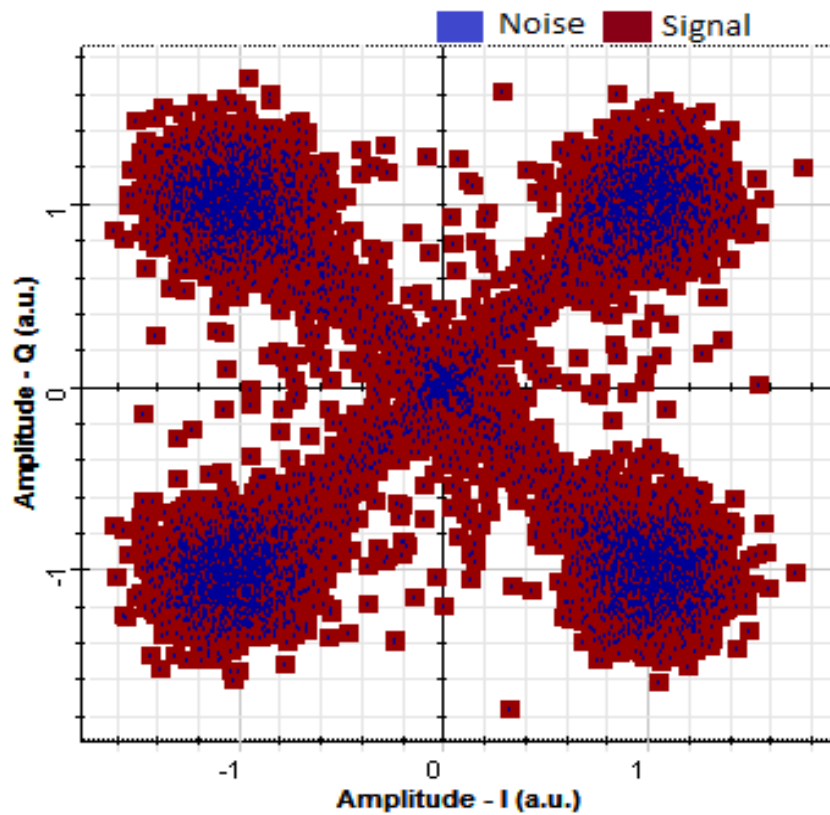


Figure 4.13: The Constellation Diagram of 4-QAM-OFDM RoF for 35Gbps over 3600km SMF-DCF

Figure 4.13 presents the constellation diagram of a 4-QAM-OFDM RoF for 35Gbps and it is clear that the signal is distorted and cannot be recovered by the receiver. Therefore, a larger capacity is needed to support the high data rate of 35Gbps by using a higher order modulation of QAM. Instead of using 4-QAM (2 bits/symbol), 16-QAM (4 bits/symbol) is used to double the transmission link capacity.

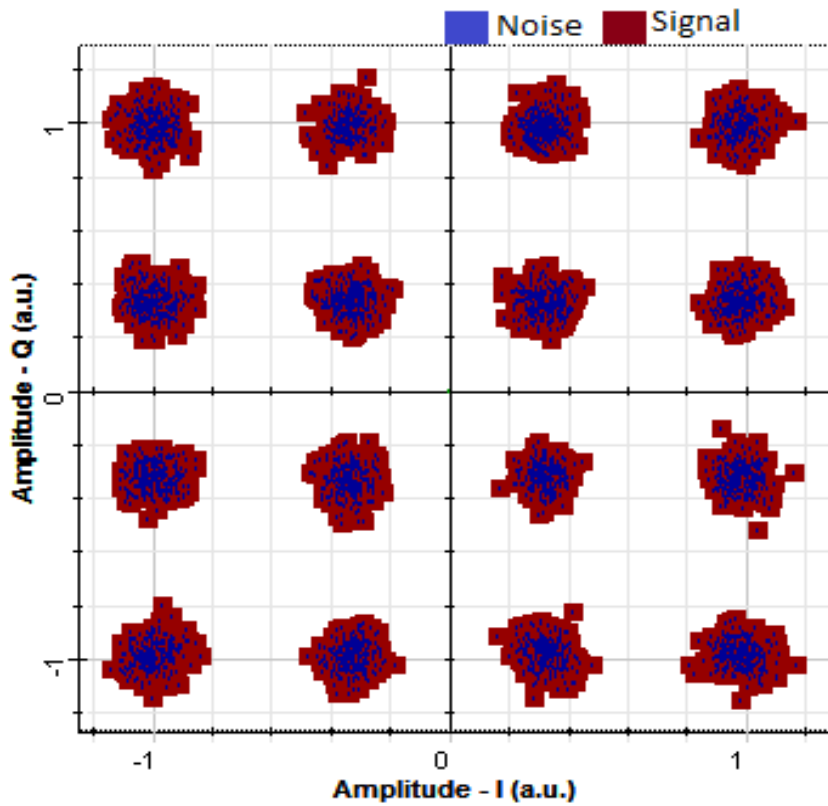


Figure 4.14: The Constellation Diagram of 16-QAM-OFDM RoF for 35Gbps over 6000km SMF-DCF

Figure 4.14 illustrates the constellation diagram of a 16-QAM-OFDM RoF at 35Gbps for a length of 6000km SMF-DCF. It is clear that the constellation diagram is much improved compared with Figure 4.12 where 16-QAM is used. The signal has some noise due to attenuation and the noise of the laser diode.

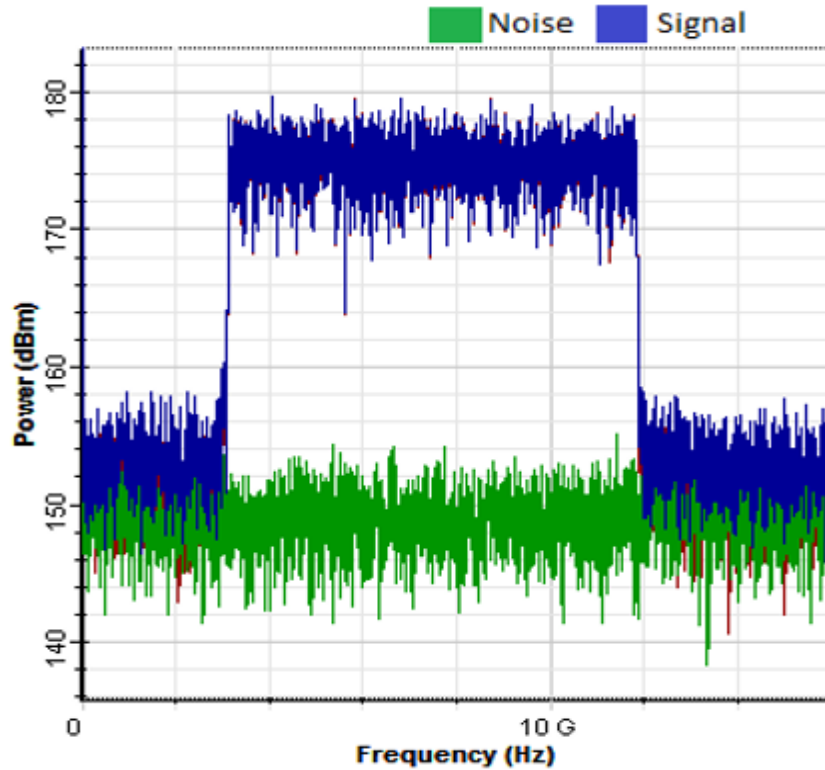


Figure 4.15: The RF Spectrum of 16-QAM-OFDM RoF at Receiver for 6000 km SMF-DCF

Figure 4.15 presents the RF spectrum of a 16-QAM-OFDM RoF receiver for the 7.5GHz carrier frequency over a transmission length of 6000 km SMF-DCF. The power of RF is measured at 178dBm. The SNR and OSNR power are measured at 37 and 45.62dB, respectively. Now the data rate is increased to 50Gbps and the constellation diagram is shown below.

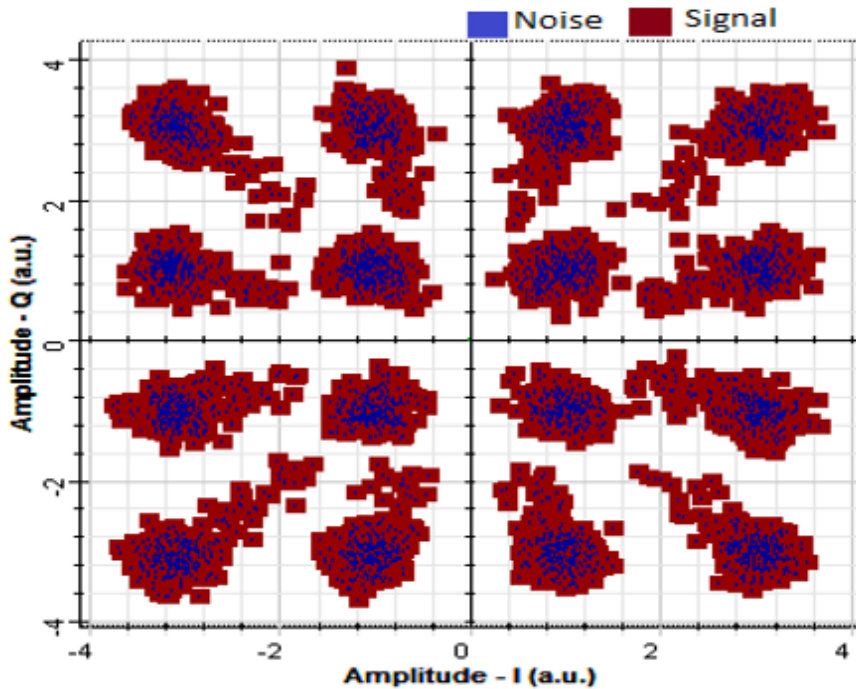


Figure 4.16: The Constellation Diagram of 16-QAM-OFDM RoF for 50Gbps over 6000km SMF-DCF

Figure 4.16 shows the constellation diagram of a 16-QAM-OFDM RoF for 50Gbps. It is clear that the signal is distorted due to the high data rate and even if the EDFAs power is increased, the result will be the same. Also, it is not desirable to go with a higher order of digital modulation format because it will add more complexity on the receiver side. To solve this problem and increase the data rate for more than 100Gbps without the need of using higher order modulation formats, a wavelength division multiplexing (WDM) is introduced in the next section.

#### 4.6 OOFDM-RoF Integrated with WDM for High Data Rates beyond 1Tb/s

The first objective of this thesis was to show a system model for the transmission of an OOFDM signal via RoF for a long-haul transmission distance with a capability of reaching 6000km SMF-DCF at data rate of 35Gbps. The second objective of this thesis was to demonstrate a system model capable of transmitting the OOFDM signal via RoF



for high data rates. One of the efficient methods to increase the data rate without adding complexity to the system is to integrate more than one OOFDM signal by using WDM and transmit them over one optical fiber link as shown in Figure 4.17.

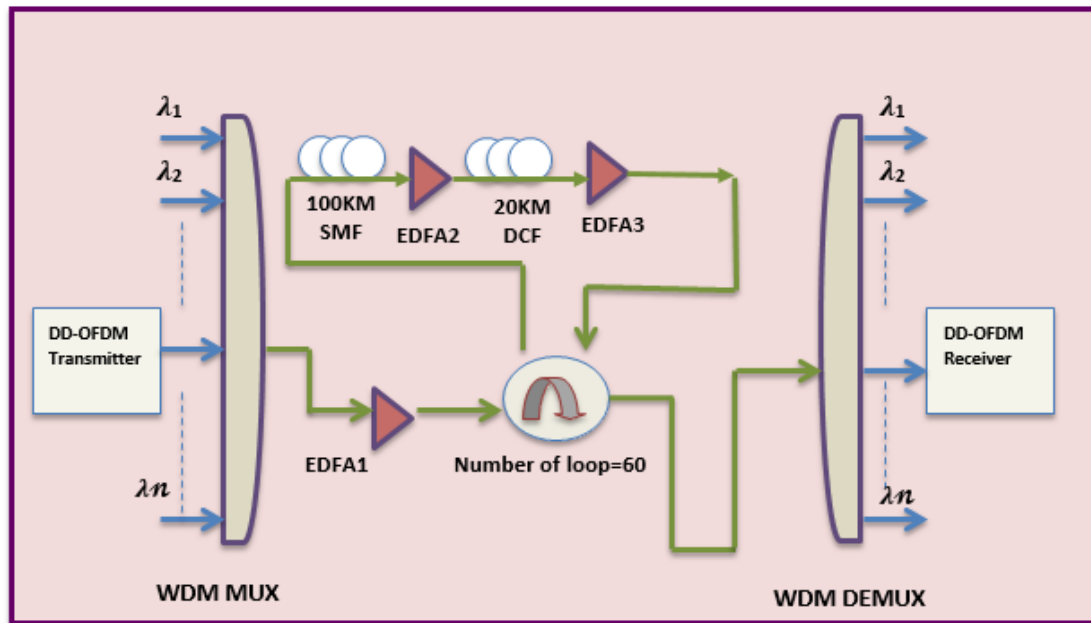


Figure 4.17: The Block Diagram of OFDM Integrated with WDM [55]

WDM is an attractive technology that supports high data rates when it transmitted over a single optical fiber by using several wavelengths, where each wavelength carries a separate channel. Hence, the telecommunication network's capacity can be extended without the need for installing more optical fiber cables. WDM accomplishes this by separating the spectrum of the light into a number of smaller channels and allows data to be the transmitted and received at the same time. Due to current high-speed electronics, the WDM can support a data rate of 40Gbps for each channel [56-58].

#### 4.6.1 System Result and simulation

To achieve high data rate, 40 OOFDM signals are integrated with WDM and transmitted via RoF for a total data rate of 1.4Tbps and over 6600km SMF-DCF. Two different types of modulation format, 16-PSK and 16-QAM, are used.

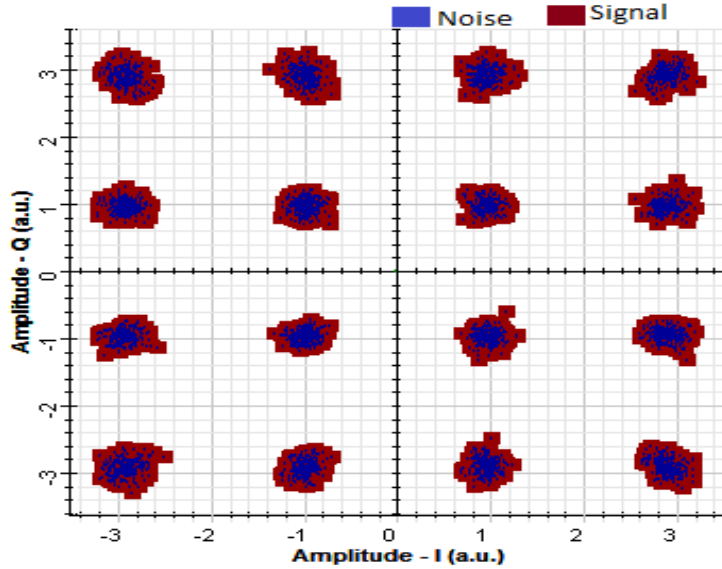


Figure 4.18: The Constellation Diagram of 16-QAM

Figure 4.18 presents the constellation diagram of the 16-QAM OFDM-RoF signal at the receiver after 6600km SMF-DCF. It is obvious that the constellation diagram is clear and the system has succeeded in achieving a high data rate of 1.4Tbps by using DWDM over only one optical fiber. The SNR and OSNR are measured at 31.07 and 45.62 dB, respectively.

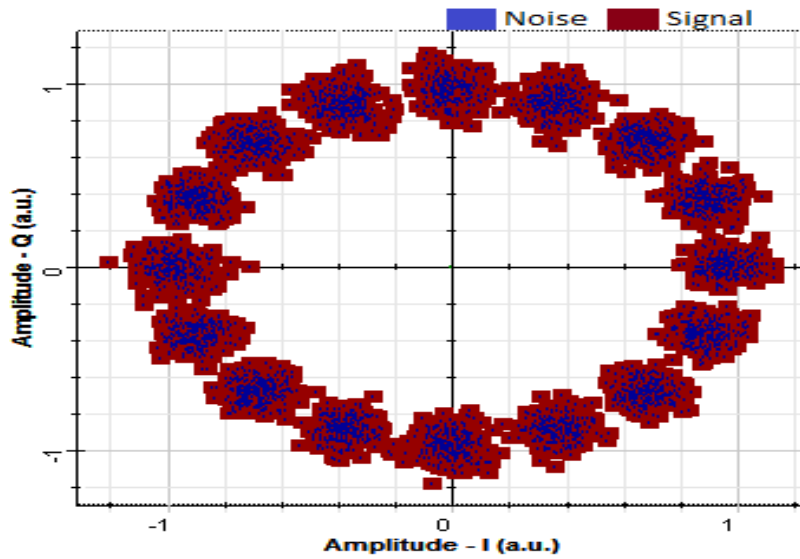


Figure 4.19: The Constellation Diagram of 16-PSK

Figure 4.19 illustrates the constellation diagram of the 16-PSK OFDM-RoF signal at the receiver after 7200km SMF-DCF. It is clear that 16-QAM modulation has better quality and high performance when compared with 16-PSK because the amount of noise and distortion are increased when 16-PSK is used.

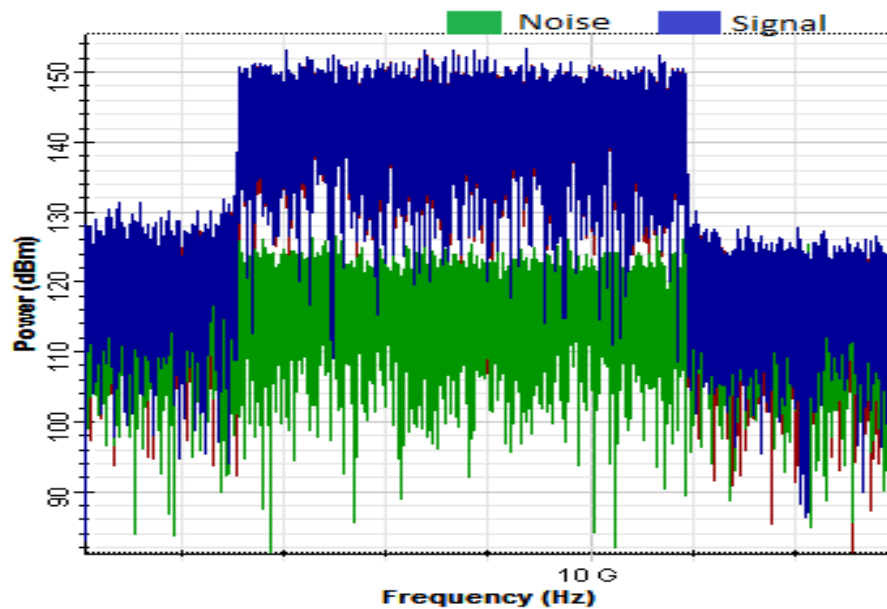


Figure 4.20: The RF Spectrum of 16-QAM-OFDM RoF at Receiver for a Data Rate of 1.4Tbps and Over 6600km SMF-DCF

Figure 4.19 illustrates the RF spectrum of 16-QAM OFDM-RoF at the receiver for a carrier frequency of 7.5GHz and a signal bandwidth of 5GHz. At the receiver, the optical signal is converted to an electrical signal by using the photodiode (PD). The power of the RF is measured at 150dBm. The signal is represented by the blue color.

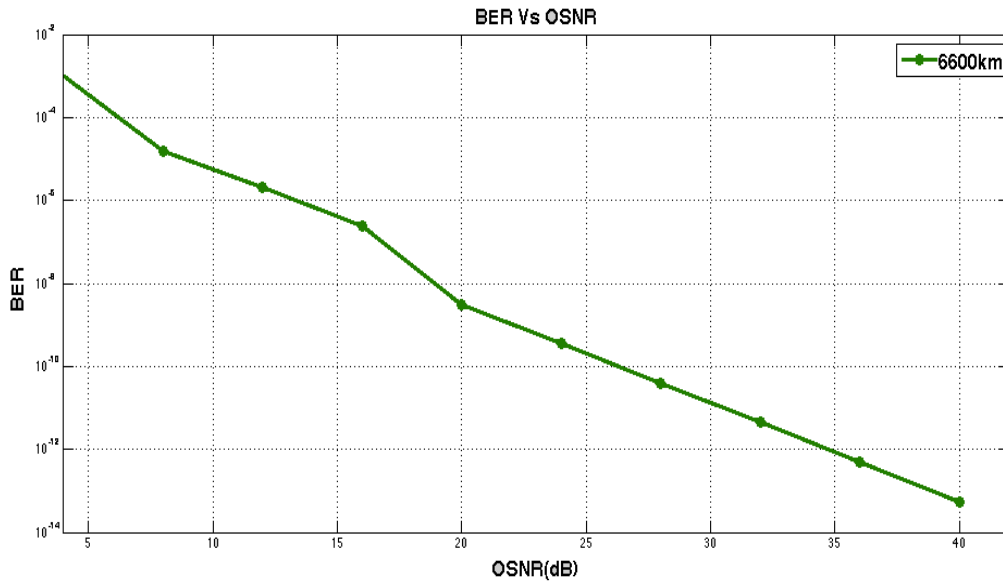


Figure 4.21: BER versus OSNR for an Optical Fiber Length of 6600km SMF

The relationship between BER and OSNR is explained in Figure 4.21. It is clear that as the OSNR increases, the BER decreases because the OSNR is defined as the value of the ratio between signal power and noise power in the optical channel. Therefore, the value of the OSNR must be large to ensure a good quality of the signal. As shown in Figure 4.20, the value of OSNR should be greater than 40dB for a BER less than 10<sup>-14</sup>.

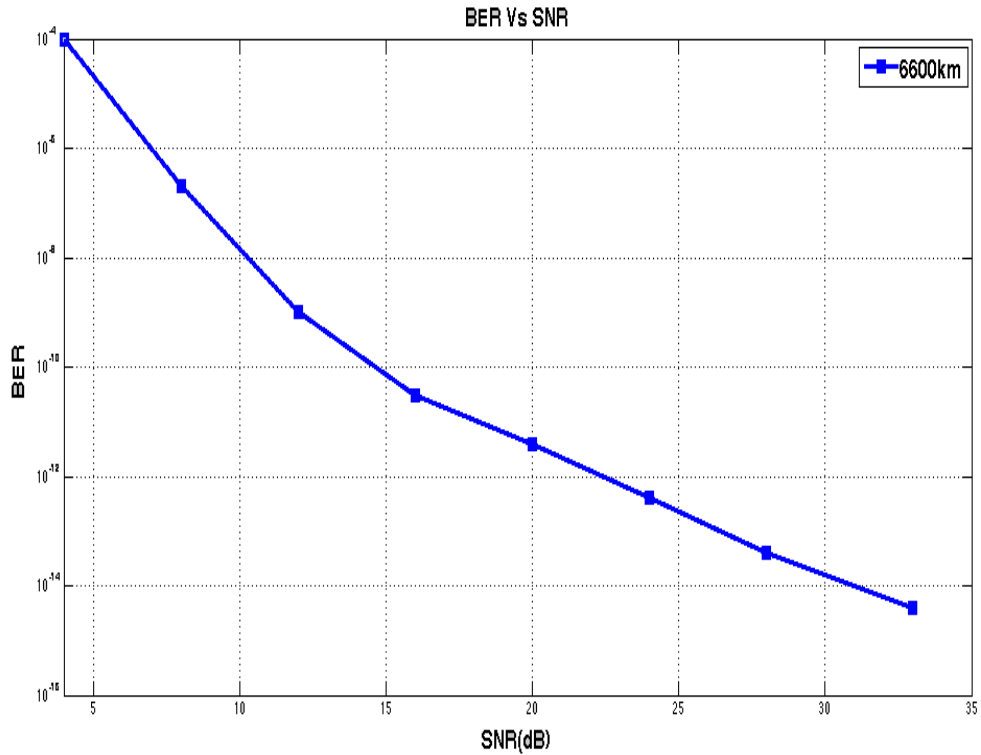


Figure 4.22: BER versus SNR for an Optical Fiber Length of 6600km SMF

Figure 4.22 illustrates the relationship between the BER and SNR over a transmission distance of 6600km. It is obvious that the higher value of SNR the lower value of BER because the SNR is measured as the power ratio of signal and noise. As shown in Figure 4.22, for a BER less than  $10^{-16}$ , the value of the SNR must be greater than 35dB.

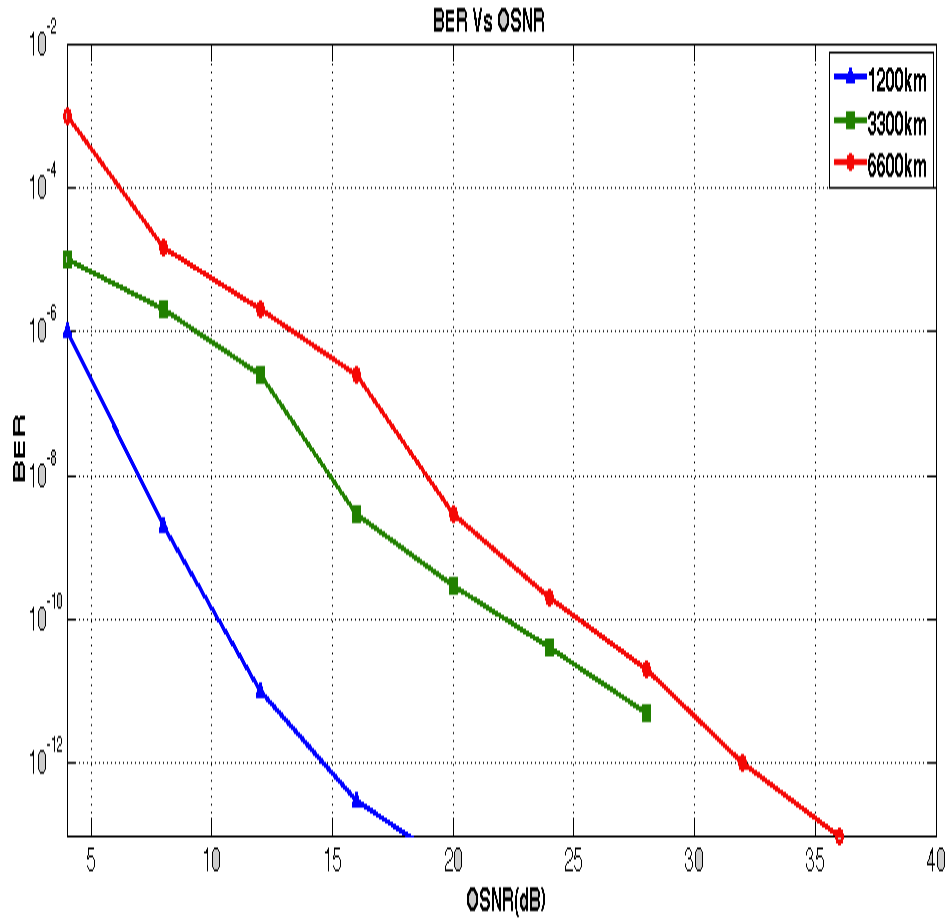


Figure 4.23: BER versus OSNR for Different Length of Optical Fiber

Figure 4.23 presents the relationship between BER and OSNR for an optical fiber of different lengths. It is clear that the value of the OSNR increased when the transmission distance increased to maintain a low BER.

## **Chapter 5**

### **Conclusion and Future Work**

#### **5.1 Conclusion**

The research work of this thesis is summarized in this chapter and completed with the accomplishment of the research goals. Consequently, the future work is suggested and discussed.

The main goal of this thesis is to provide effective solutions for the increasing demand of large bandwidth and high data rates by employing Radio over Fiber (RoF) technology. The research work of this thesis went through three steps to achieve high data rates in long-haul transmissions.

First, the performance of one-user OOFDM signals transmitted via RoF for different optical fiber lengths was shown by applying the post-dispersion compensator technique to compensate for the positive chromatic dispersion that limits the transmission distance. The transmission distance is increased from 180km to 7200km by using the post-dispersion compensation fiber. The value of the OSNR was 26.14dB, and the SNR 19.23dB for a bit rate of 10Gbps.

Second, the data rate of the system is increased from 10Gbps to 35Gbps by applying higher order modulation. As shown in the results, 4-QAM cannot support a high data rate of 35Gbps. The problem is solved by doubling the capacity of the system by using 16-QAM.

Third, the data rate of the system is increased beyond 1Tbps by applying the DWDM method. According to the results, it is clear that a single user cannot reach 50Gbps. Therefore, a DWDM is used to increase the capacity of the system for more than 1Tbps where multiple users can transmit at the same time over one single mode fiber. In this thesis, 35 OFDM users transmitted at the same time by using DWDM to achieve data rate of 1.4Tbps over 6600km SMF. The results display a good performance in the SNR, OSNR and BER values. Finally, the resulting data verified the efficiency of the OOFDM-WDM-RoF system in providing significantly higher data rates.

## **5.2 Future Work**

After successfully simulating the OFDM via RoF for a high data rate, the future work will focus on implementing the OOFDM in real time by using optical FPGAs. FPGA stands for field programmable gate array and it is an integrated circuit that can be designed by a designer.

Moreover, the quality of the system can be improved by applying a coded OFDM technique that uses a series of error correcting codes. Examples of coded modulation are Block Coded Modulation (BCM) and Trellis Coded Modulation (TCM).



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## Appendix A: List of Publications

*Optics and Photonics Journal (OPJ)*

DOI: [10.4236/opj.2013.32035](https://doi.org/10.4236/opj.2013.32035),

Volume 3, Issue 2 (June 2013), PP 217-224

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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

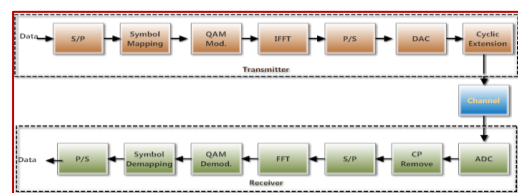
#### 1. Introduction

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**

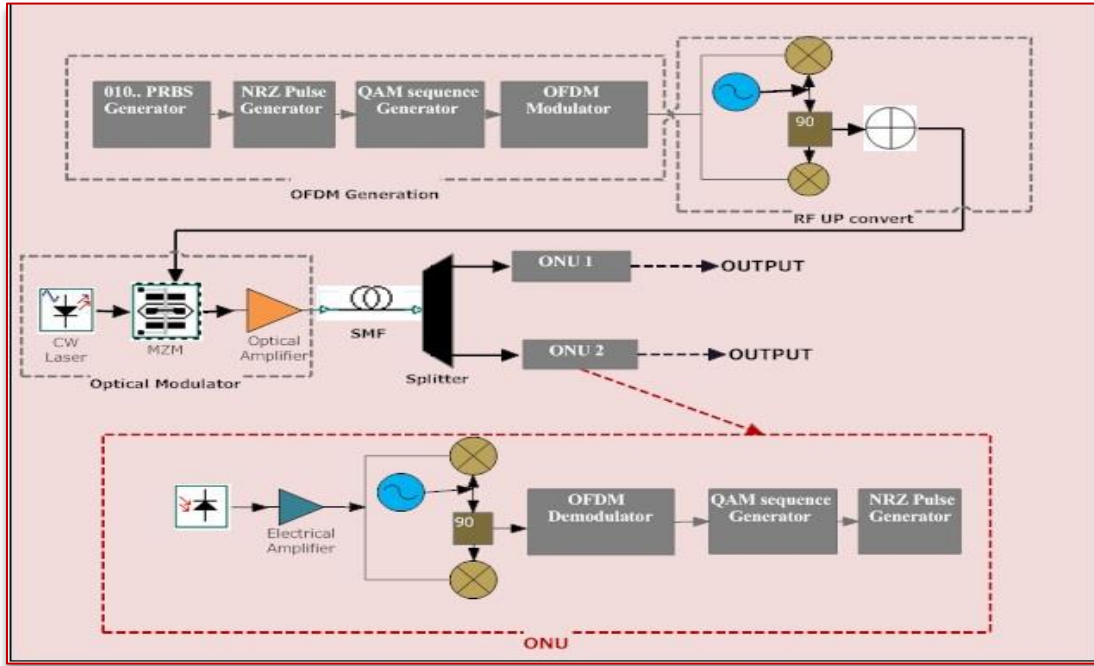


Figure 2: RoF OFDM-PON system design

## 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	<b>65536</b>

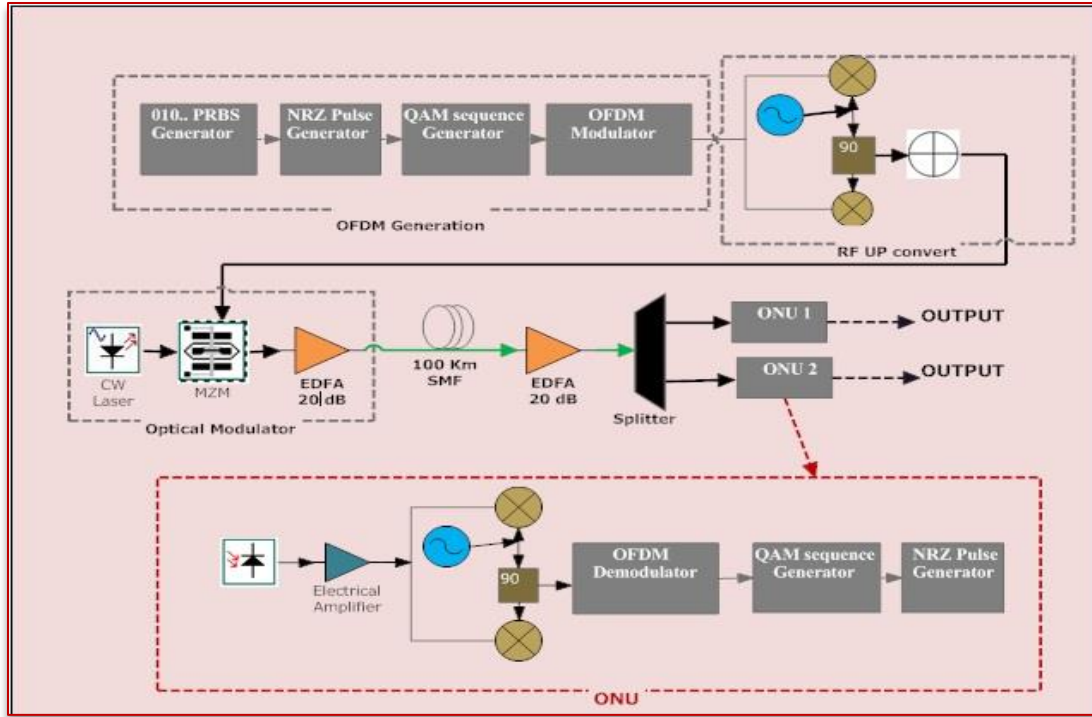


Figure 3: ROF-OFDM-PON-100 Km SMF system Design

## 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 LiNbO<sub>3</sub> 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 LiNbO<sub>3</sub> 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.



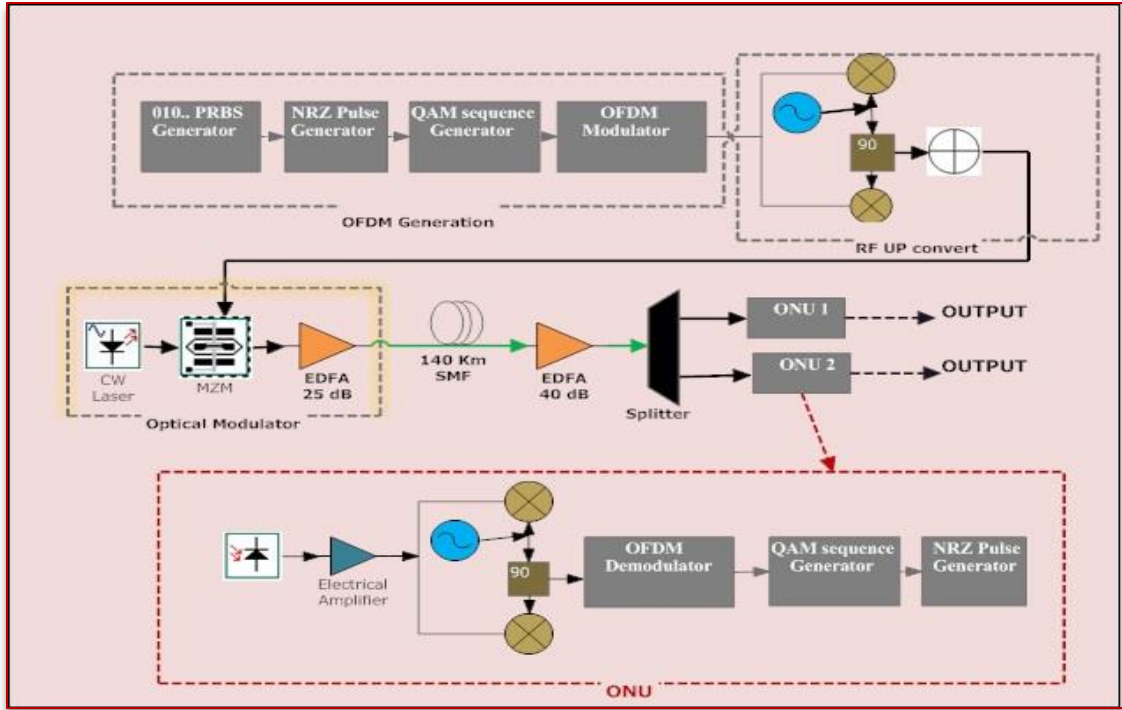


Figure 4: ROF-OFDM-PON-140 Km SMF system Design

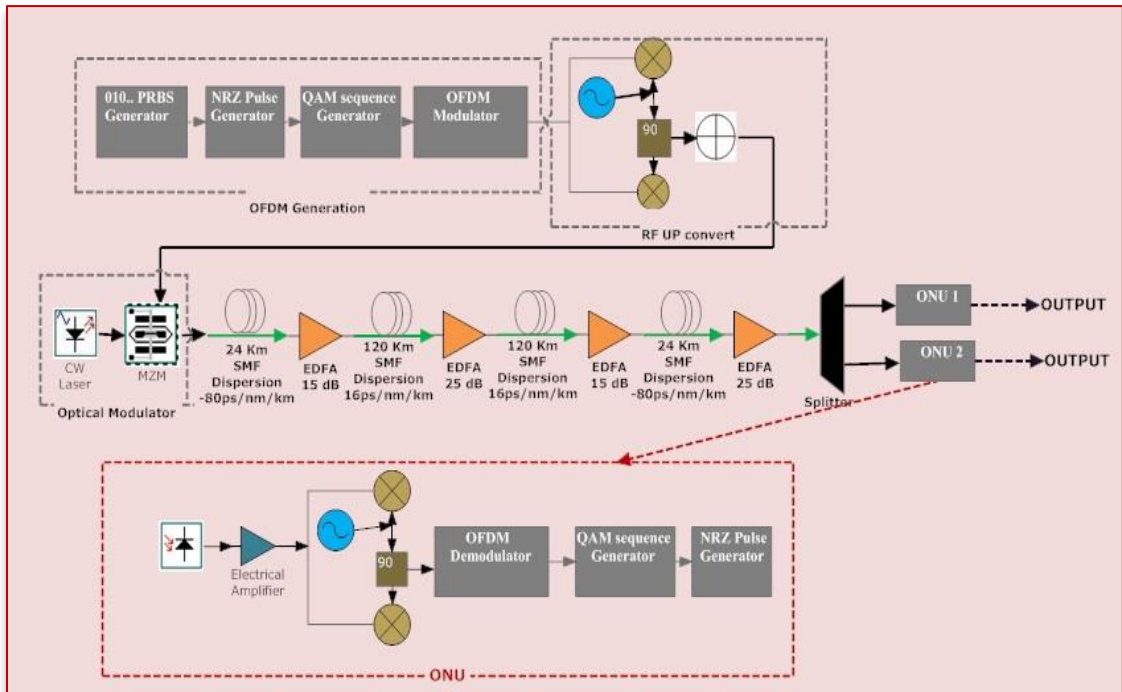


Figure 5: ROF-OFDM-PON-288 Km SMF with DCF system Design



### 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 the noise that comes from the laser diode and the red points represent the signal.

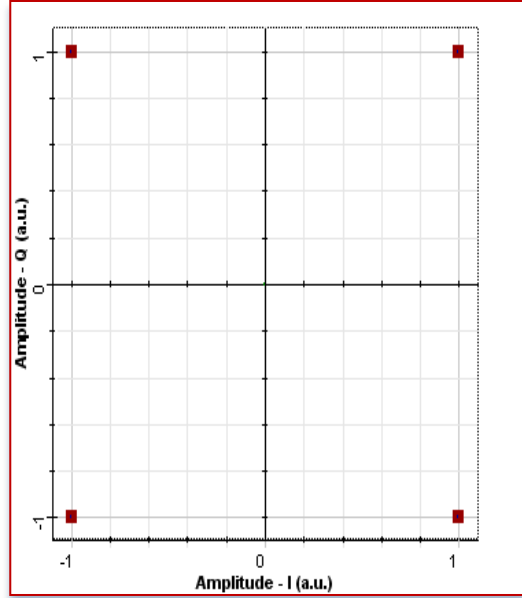


Figure 6: Constellation diagram for 7.5 GHz signal transmissions at transmitter.

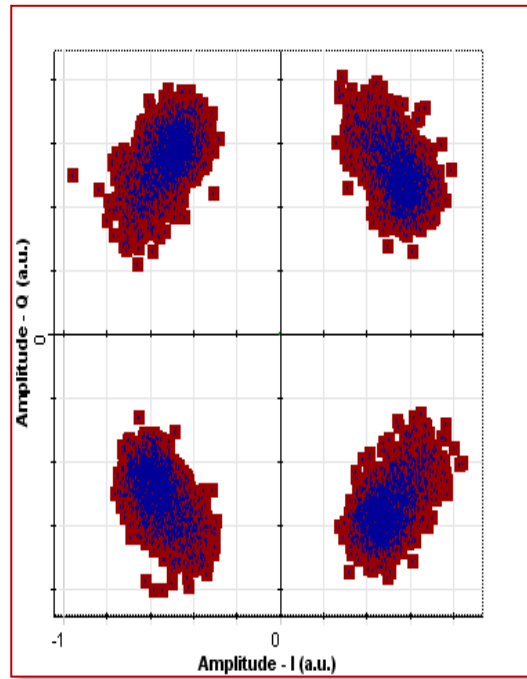
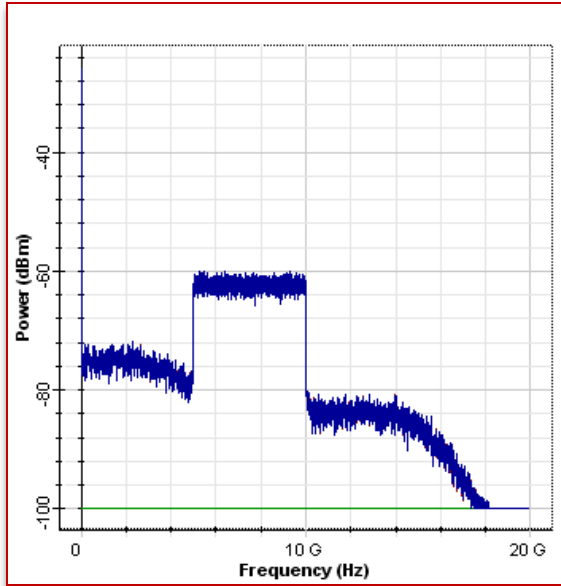
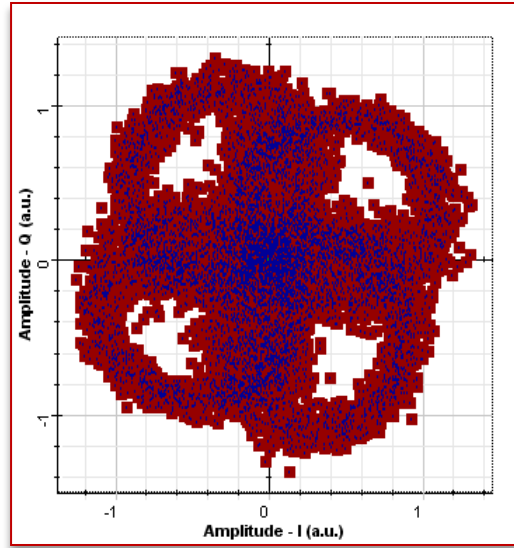


Figure 7: the Constellation diagram for SMF of 100km length.



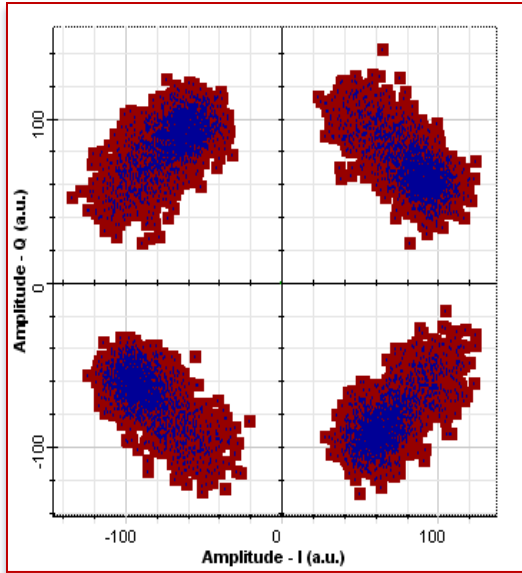
**Figure 8: RF spectrum for 100km SMF**

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.



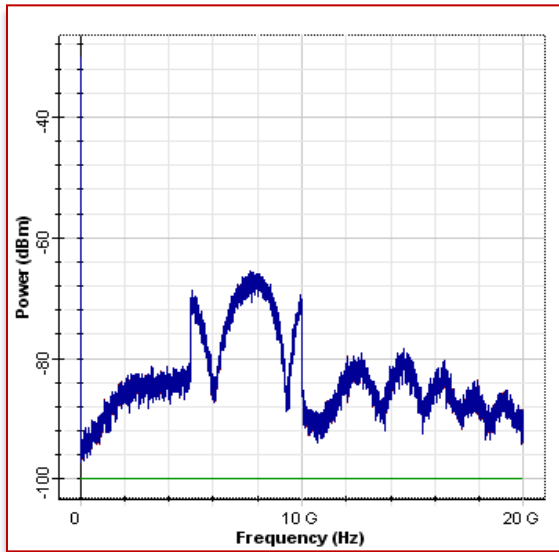
**Figure 9: Signal constellation of 140km SMF length**

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.



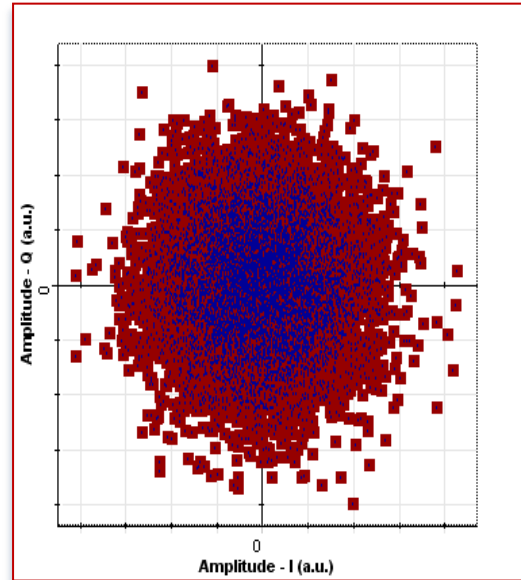
**Figure 10: Constellation diagram of 140 km SMF for EDFAs power of 25 and 40dB, respectively.**

**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**.



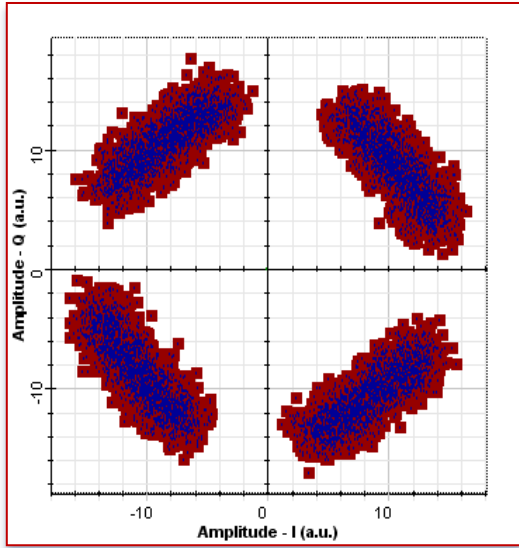
**Figure 11: RF spectrum for 140km SMF**

**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-OOFDM) 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.

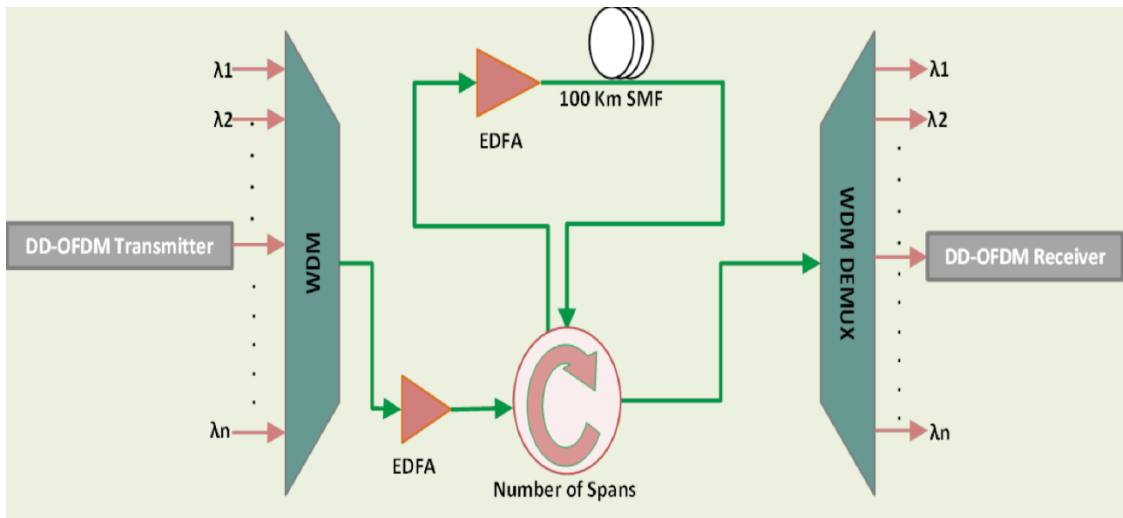


Figure 1: DD-OOFDM-WDM System design

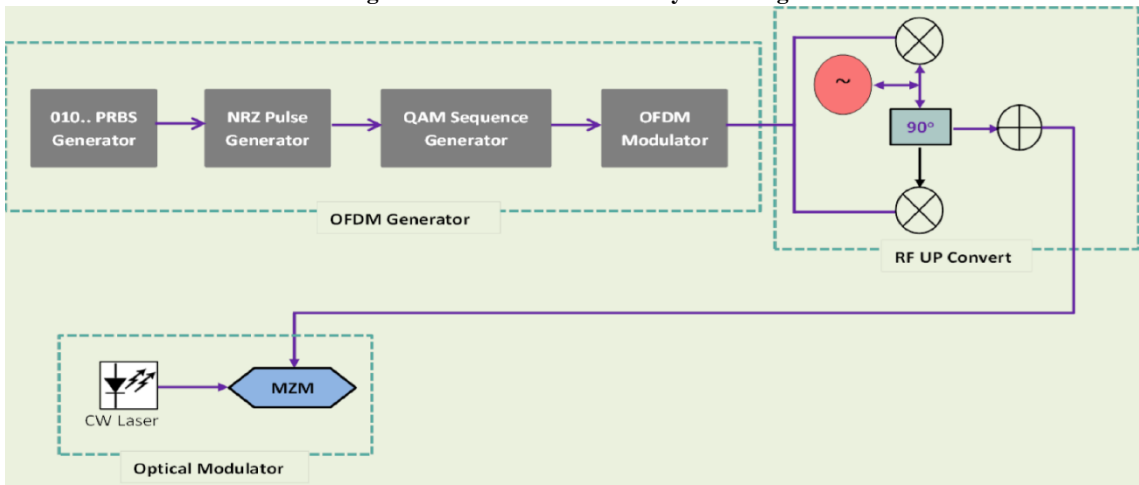


Figure 2: DD-OOFDM transmitter block diagram



## 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  $\varphi_c$  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**.



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**.

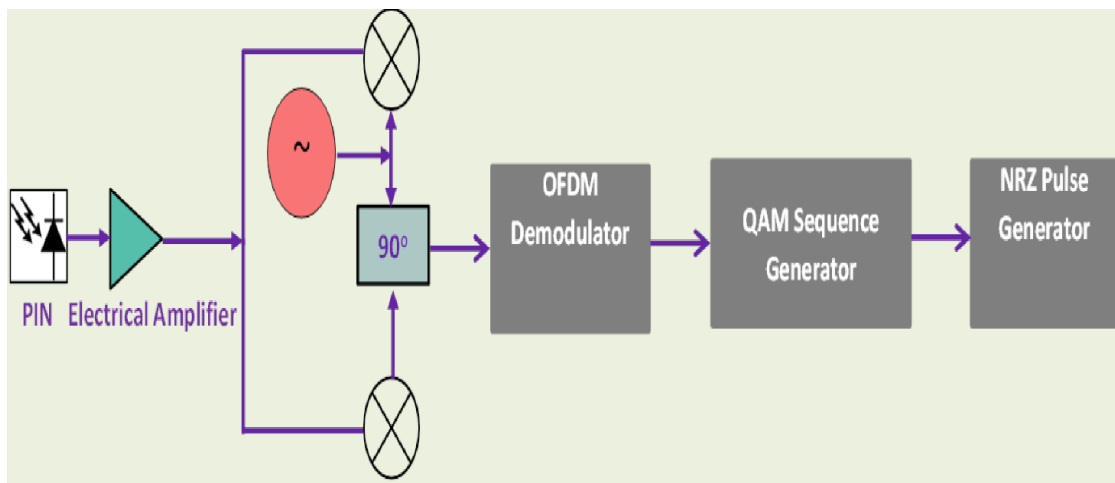


Figure 3: DD-OOFDM receiver block diagram

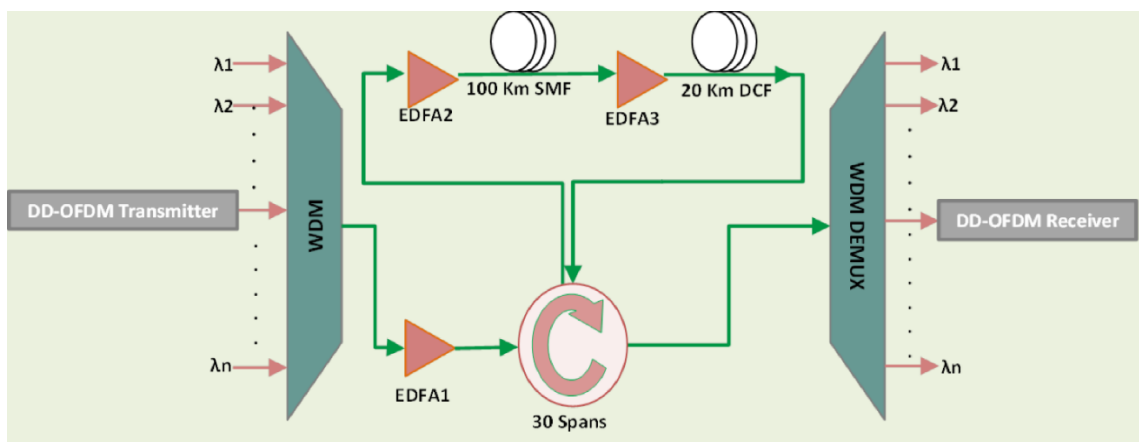
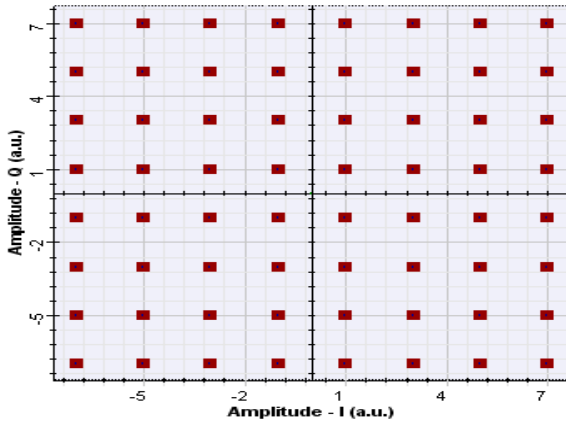


Figure 4: Post compensation fiber design.

## 4. Results and Discussion

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

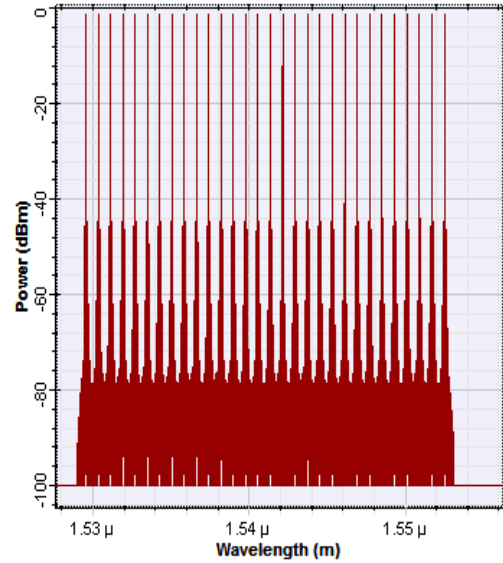
The constellation shows a two-dimensional scatter diagram of the signal. **Figure 5** demonstrates a signal modulated 64-QAM. As can be seen from the graph, all samples are free of interferences and noise.



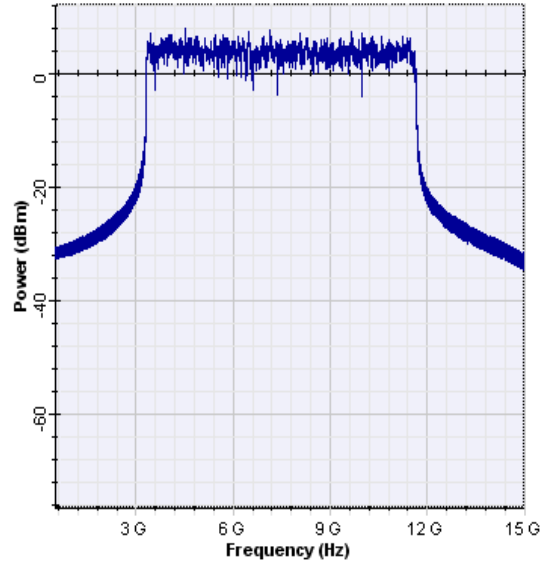
**Figure 5: Constellation diagram of 64-QAM OOFDM at transmitter**

**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.

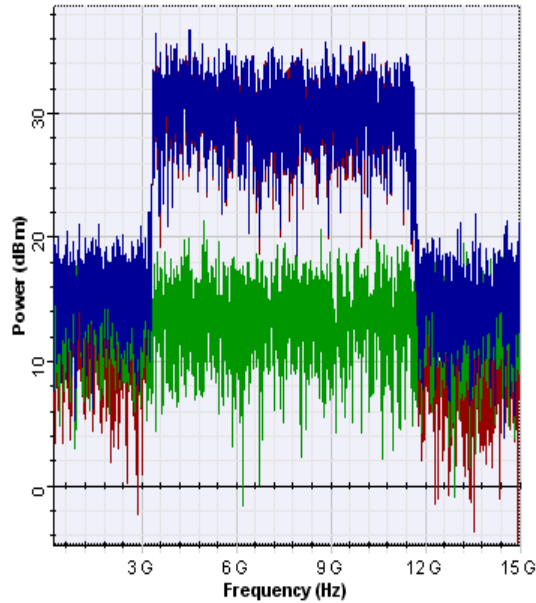


**Figure 6: The Spectrum of the signals after WDM**



**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**

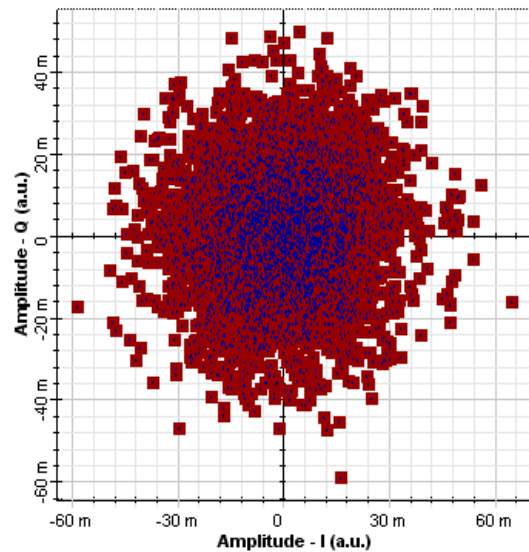
Fiber length (km)	100
Attenuation (dB/km)	0.2
Dispersion (ps/nm/km)	16
Slope (ps/nm <sup>2</sup> /k)	0.08
Effective area ( $\mu\text{ m}^2$ )	80
Nonlinear refractive index $n_2$ ( $\text{m}^2/\text{w}$ )	$2.6 \times 10^{-20}$

**Table 5: DCF Parameters**

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

**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.

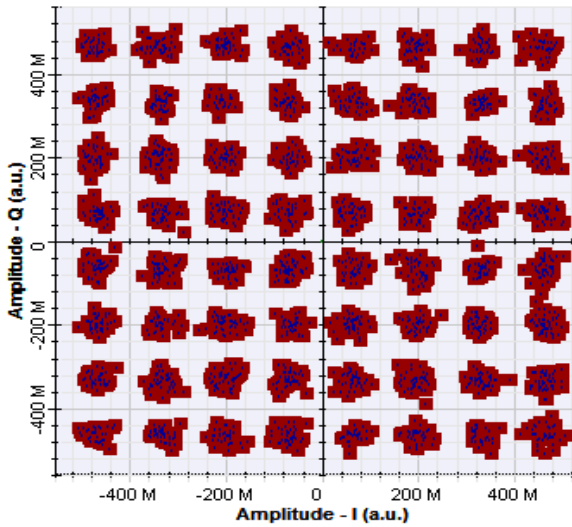


Figure 10: Shows the constellation diagram of the 64-QAM OOFDM signal after the DCF

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.

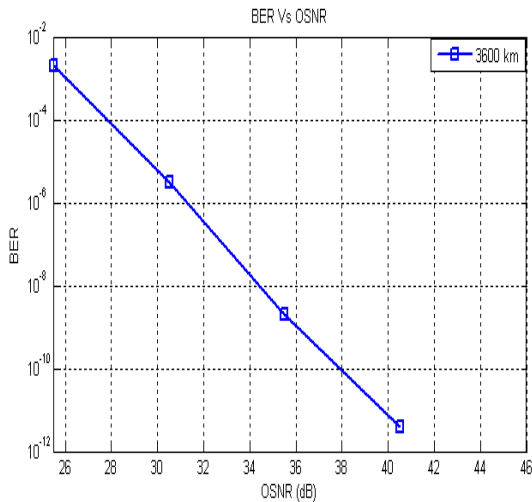


Figure 11: Shows the relationship between BER and OSNR for a transmission length of 3600 km SMF

In Figure 12 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  $10^{-12}$ .

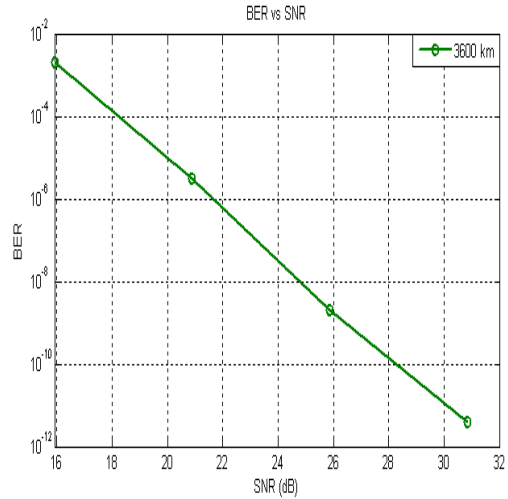


Figure 12: Shows the relationship between BER and SNR for a transmission length of 3600 km SMF

## 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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# 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

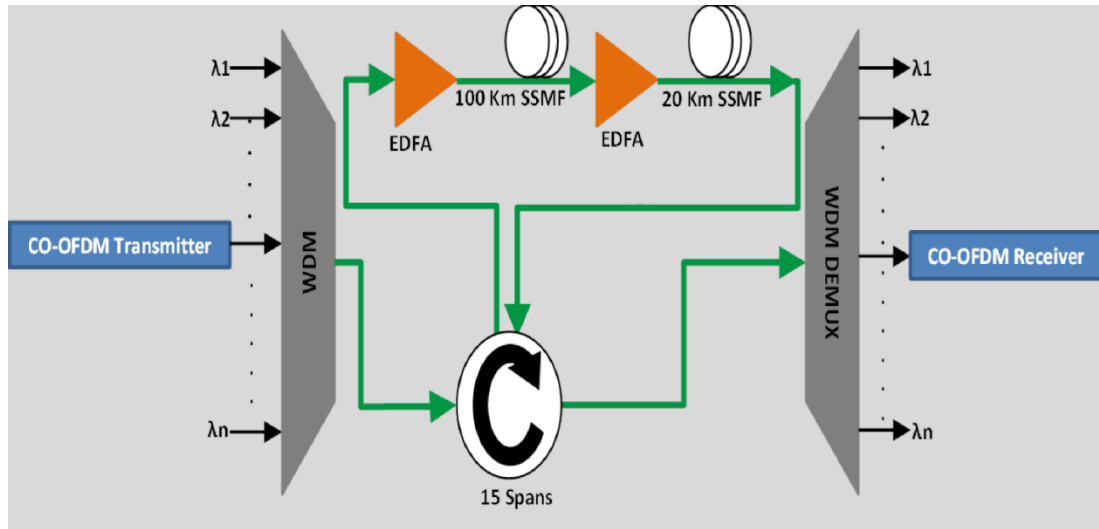


Figure 1: WDM CO-OFDM System design

## 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  $2.6 \times 10^{-20}$ ; 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 <sup>2</sup> /km
PMD Coefficient	0.2 ps/km
Effective area	80 $\mu\text{m}^2$
Nonlinearity Coefficient	$2.6 \times 10^{-20}$
Attenuation	0.2 dB/km

Table 4: DCF Parameters

DCF	
Dispersion	-80 ps/nm/km
Dispersion Slope	-0.45 ps/nm <sup>2</sup> /km
PMD Coefficient	0.2 ps/km
Effective area	30 $\mu\text{m}^2$
Nonlinearity Coefficient	$2.6 \times 10^{-20}$
Attenuation	0.4 dB/km

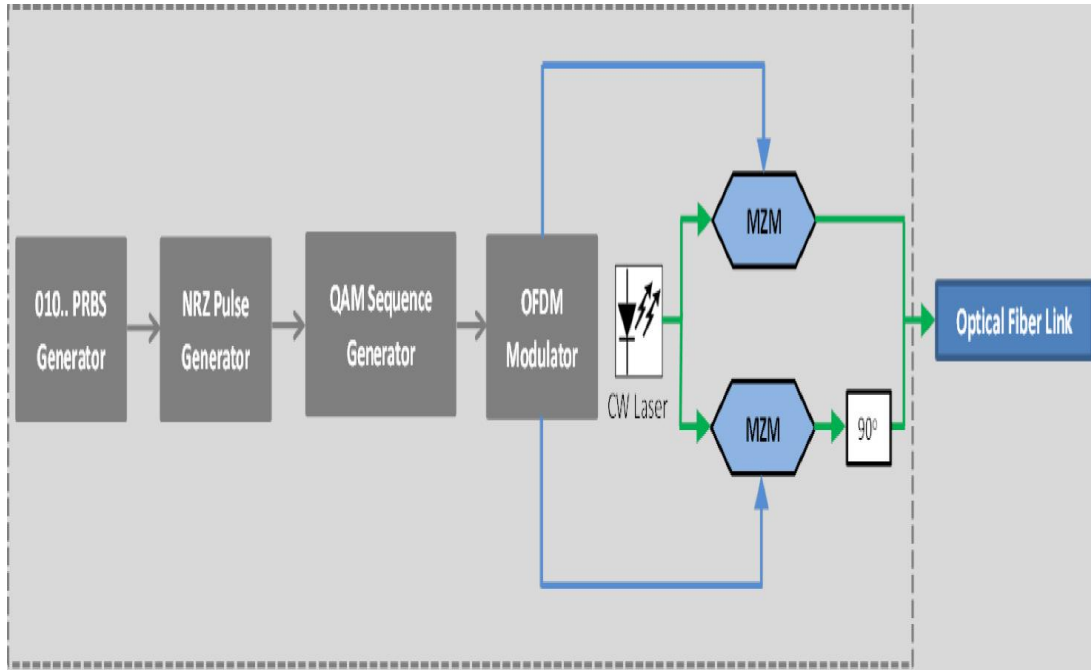


Figure 2: CO-OFDM Transmitter Design

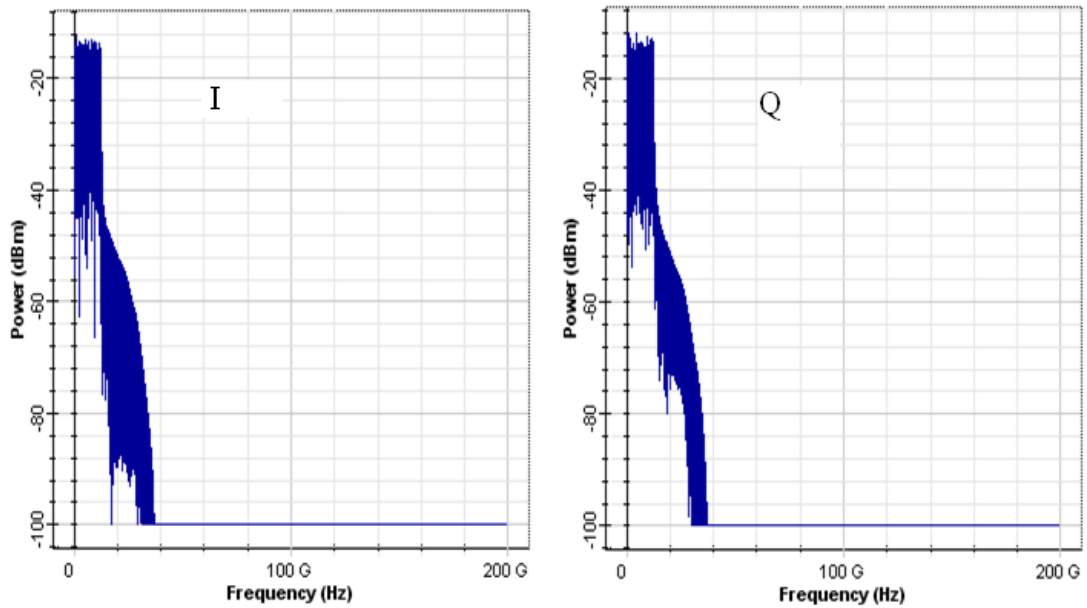


Figure 3: OFDM I/Q Spectrum



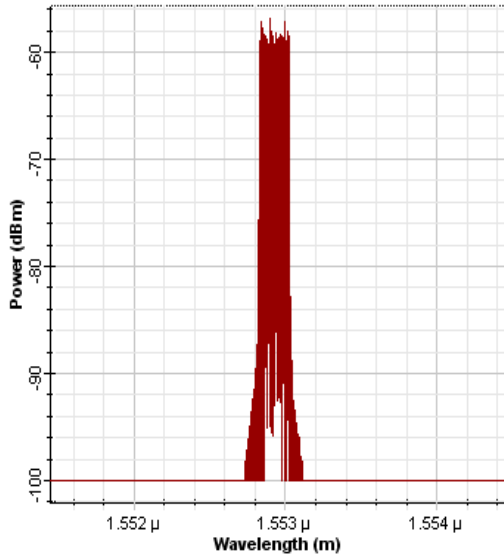


Figure 4: OFDM Signal after the two MZMs

### 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].

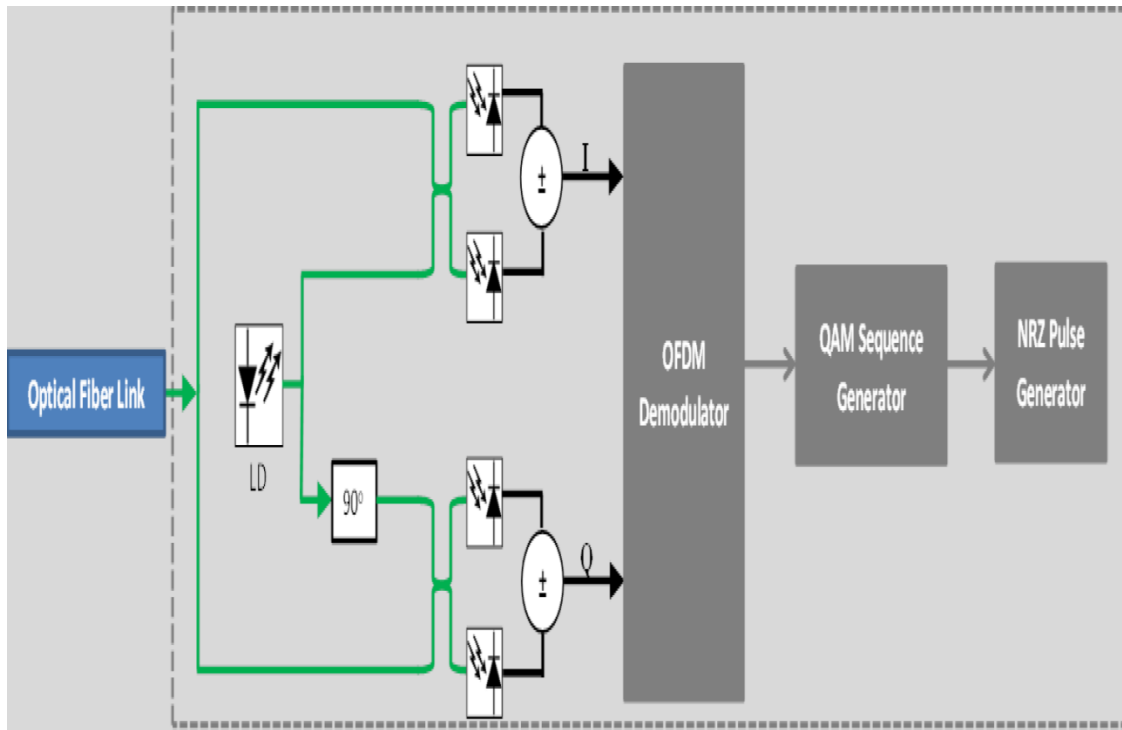
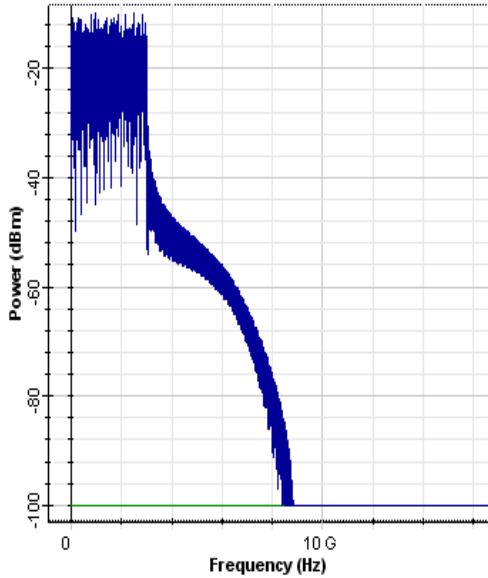


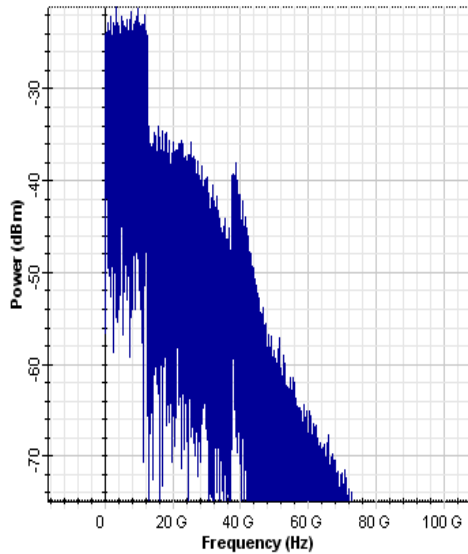
Figure 5: CO-OFDM Receiver Design

### 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.



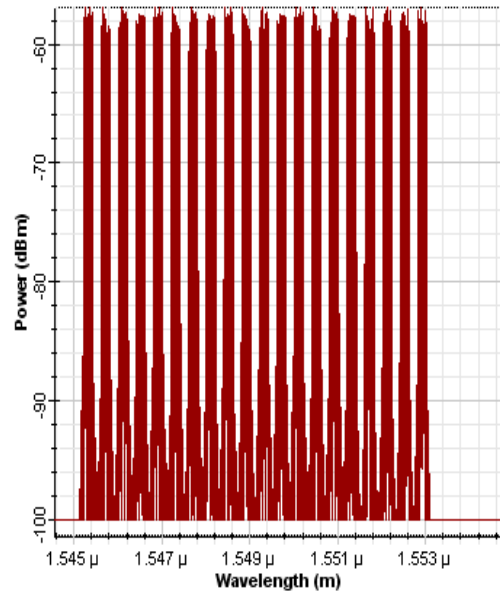
**Figure 6:** RF spectrum of the signal at the transmitter side



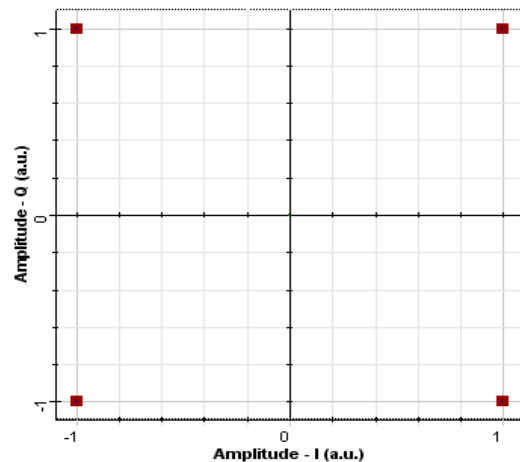
**Figure 7:** RF spectrum of the signal at the receiver side

**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.



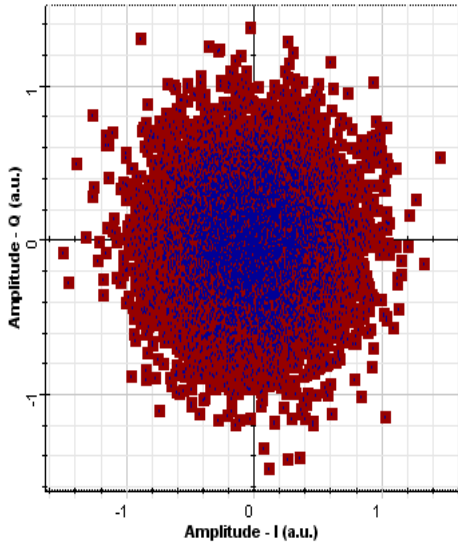
**Figure 8:** 20 WDM CO-OFDM Channels



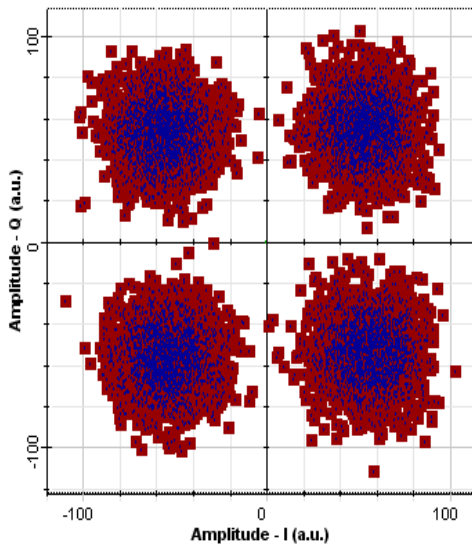
**Figure 9:** 4-QAM constellation diagram at the transmitter side

**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.



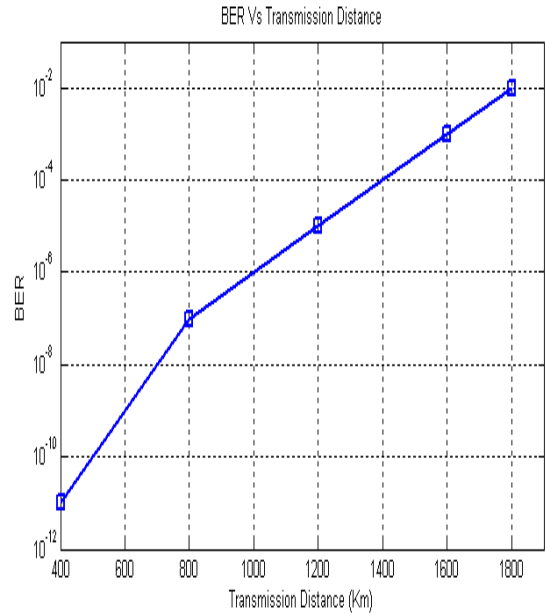
**Figure 10:** Constellation diagram after 1800 Km before using the DCF



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

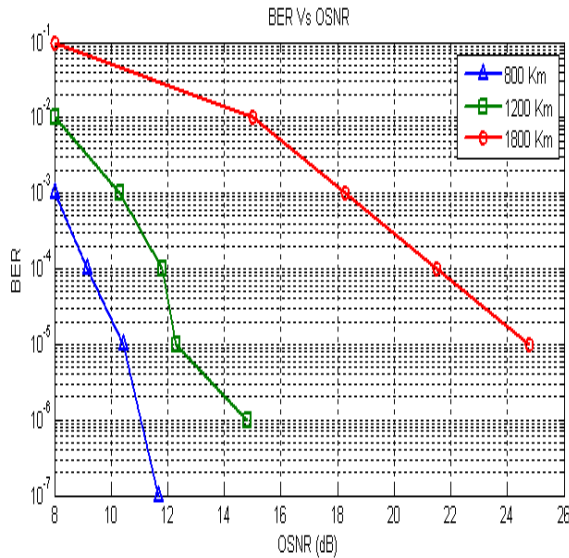
To study the performance of the system for the high data rate, the relationship of the BER and the OSNR with regard to the transmission distance is

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]:

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

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

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

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	<b>16384 Bits</b>
Samples per bit	<b>8</b>
Number of samples	<b>131072</b>

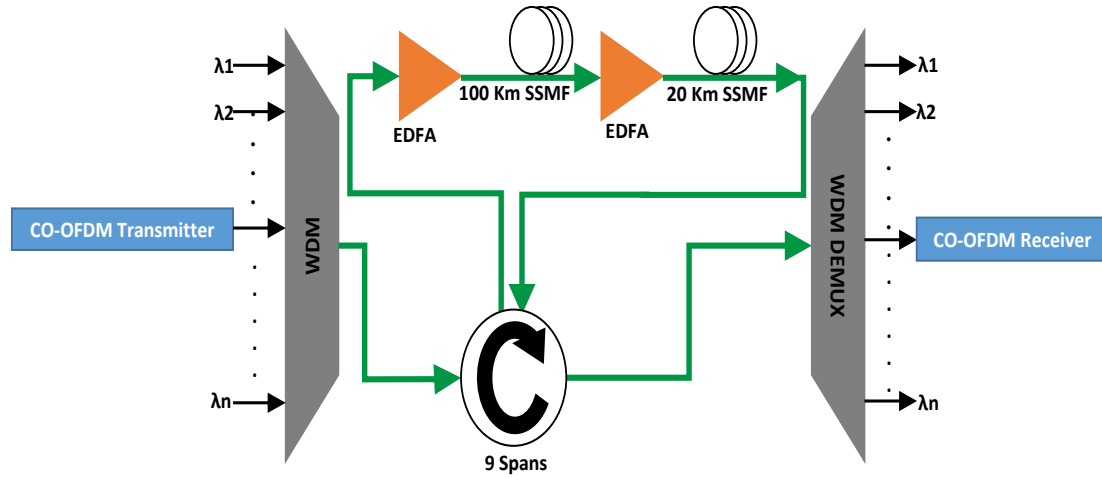


Figure 1: the conceptual system design of the system

## 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].

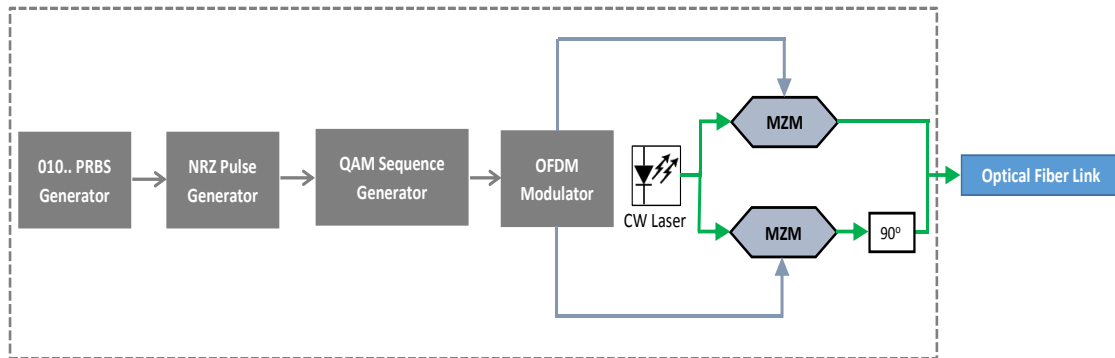


Figure 2: CO-COFDM transmitter.

## 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 <sup>2</sup> /km
PMD Coefficient	0.2 ps/km
Effective area	80 $\mu\text{m}^2$
Nonlinearity Coefficient	$2.6 \times 10^{-20}$
Attenuation	0.2 dB/km

Table 3: Compensation Parameters

DCF	
Dispersion	-80 ps/nm/km
Dispersion Slope	-0.45 ps/nm <sup>2</sup> /km
PMD Coefficient	0.2 ps/km
Effective area	30 $\mu\text{m}^2$
Nonlinearity Coefficient	$2.6 \times 10^{-20}$
Attenuation	0.4 dB/km

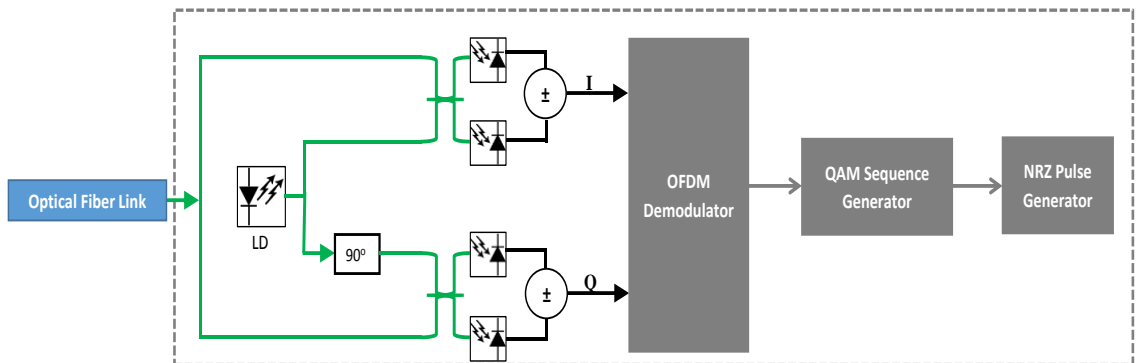


Figure 3: CO-OFDM Receiver.



### 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.

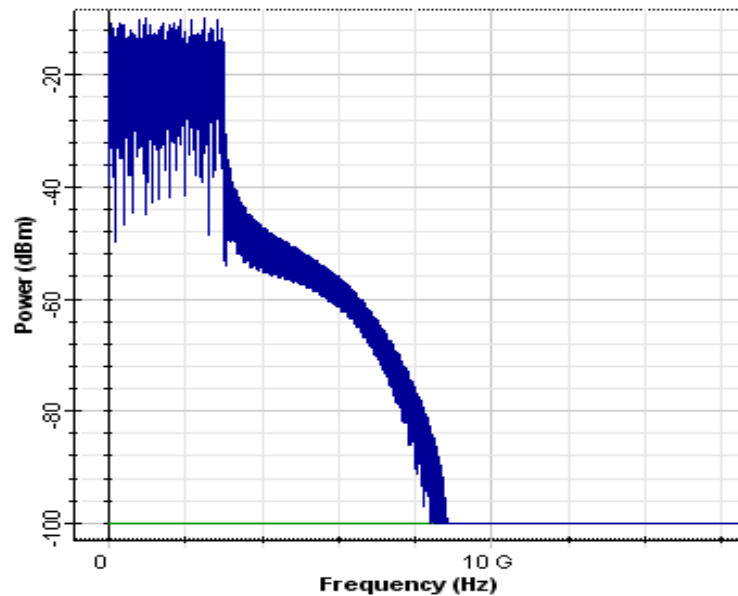


Figure 4: RF spectrum for CO-OFDM at the transmitter.

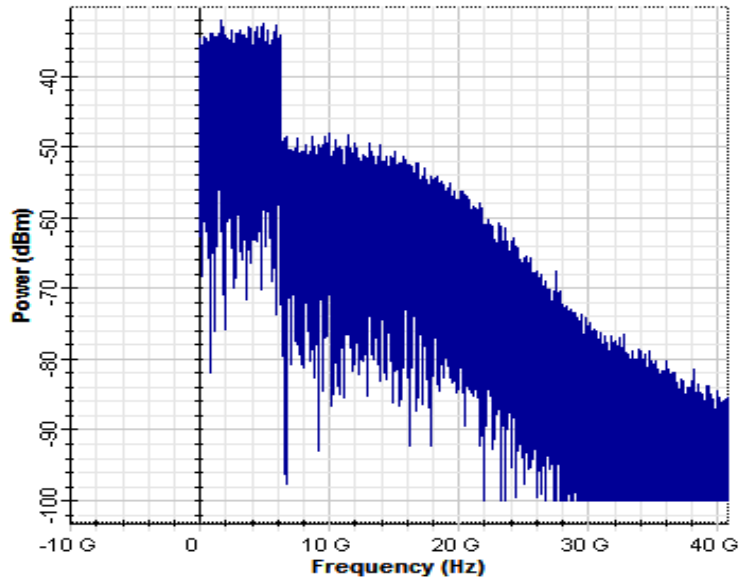


Figure 5: RF spectrum for CO-OFDM at the receiver.

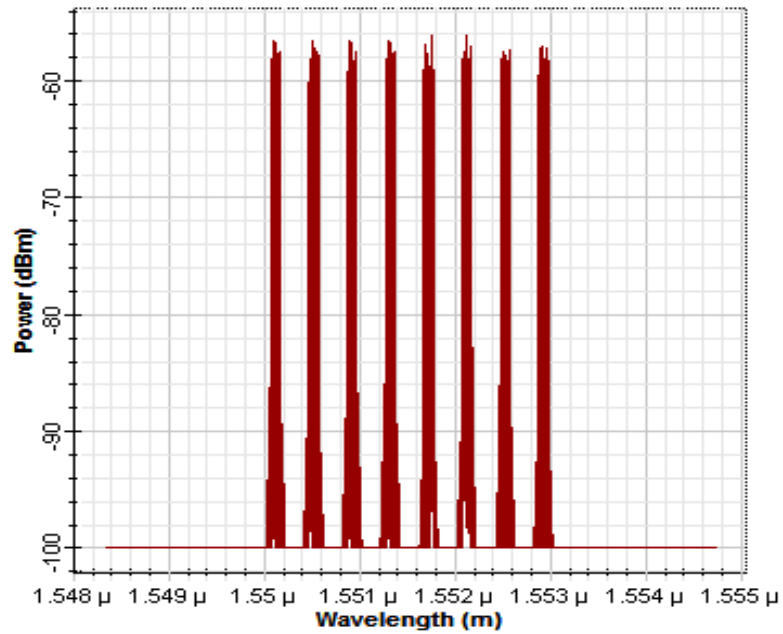


Figure 6: the spectrum of the 8 CO-OFDM signals after the WDM multiplexer.

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.

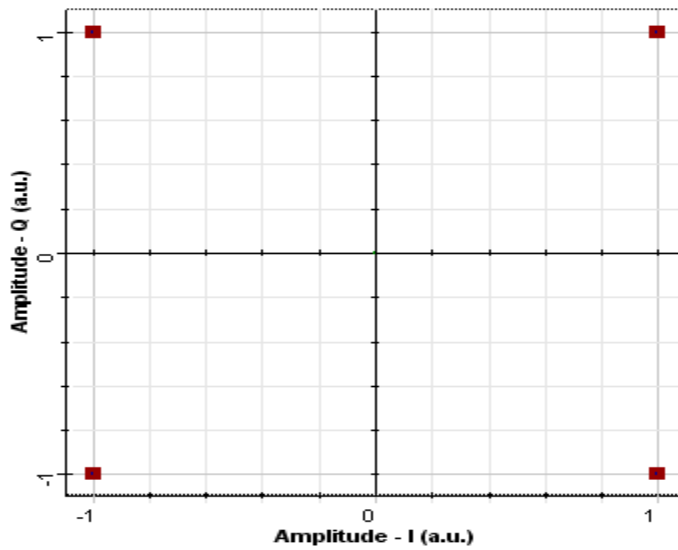


Figure 7: the constellation diagram at CO-OFDM transmitter

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.

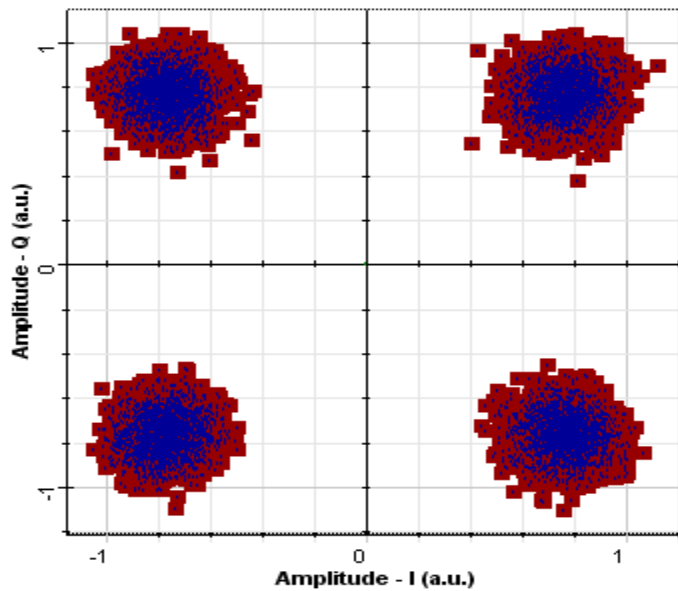


Figure 8: the constellation diagram of B2B CO-OFDM at receiver

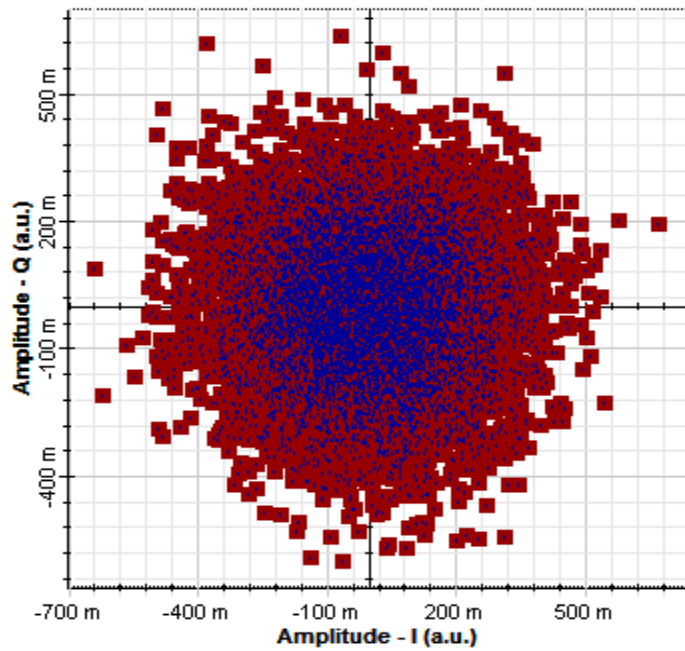


Figure 9: the constellation diagram of CO-OFDM at receiver after 1000 Km and before using DCF.

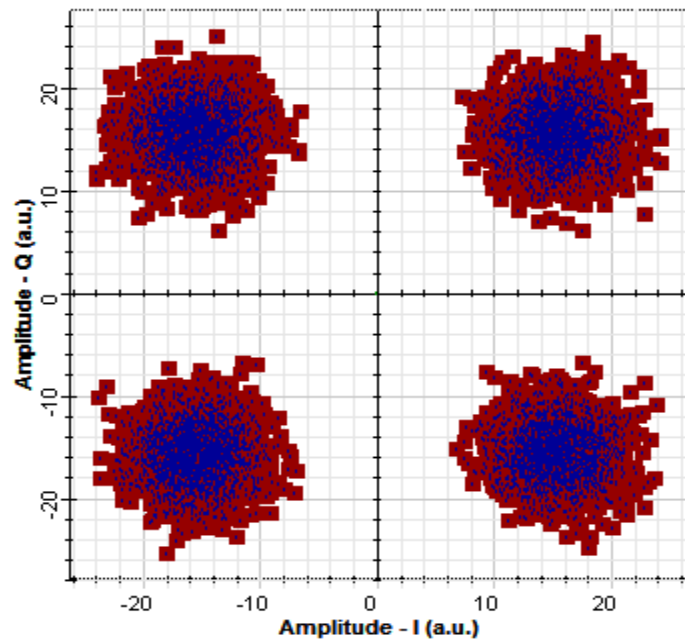


Figure 10: The constellation diagram of CO-OFDM at receiver after using DCF.

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.

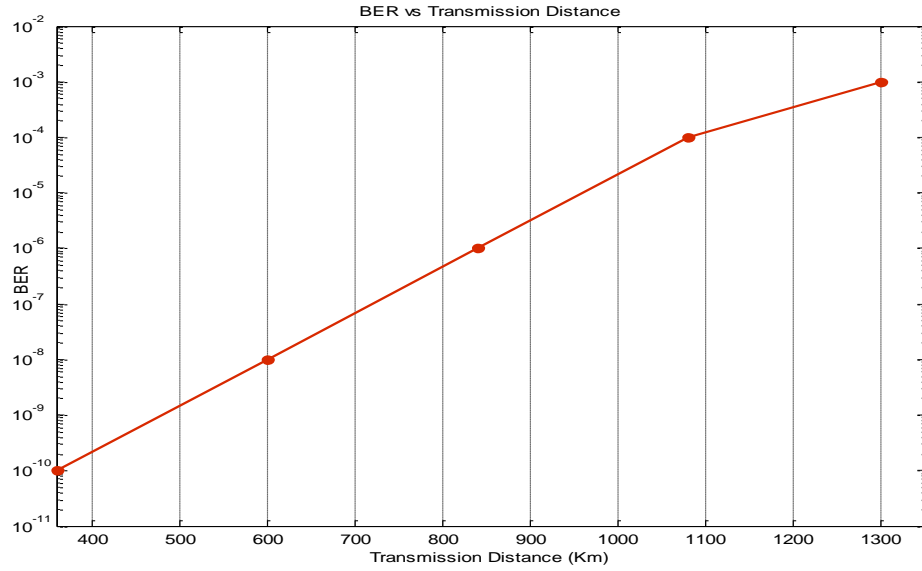


Figure 11: the relationship of BER and transmission distance

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.

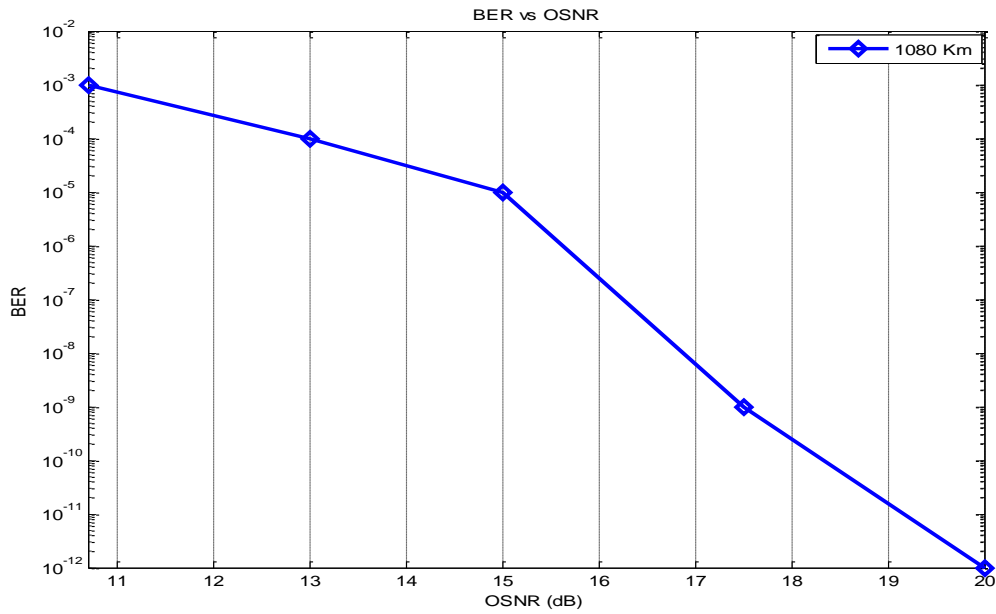


Figure 12: The relationship of BER and OSNR for 1080 Km

## 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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## **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].



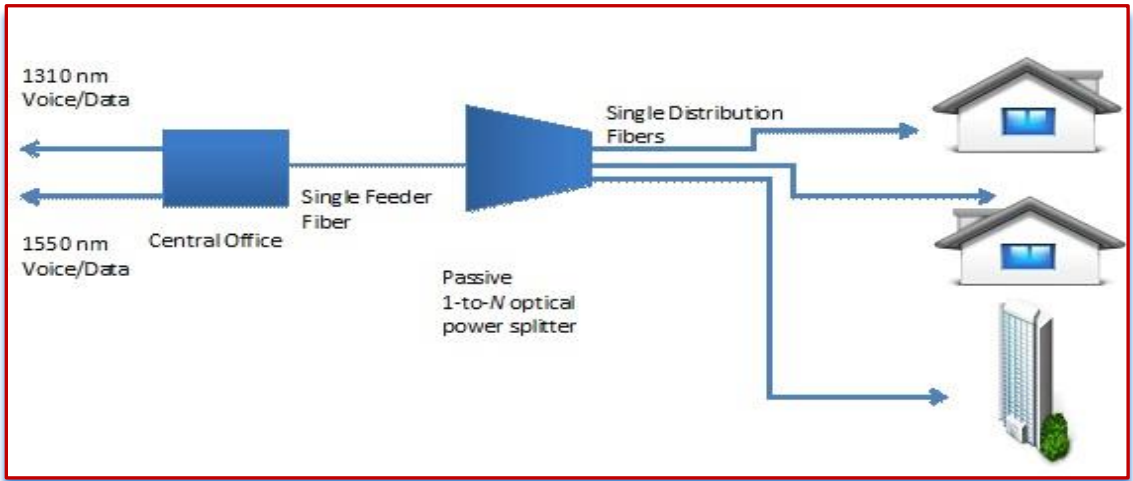


Figure 1: Basic Architecture of WDM-PON network

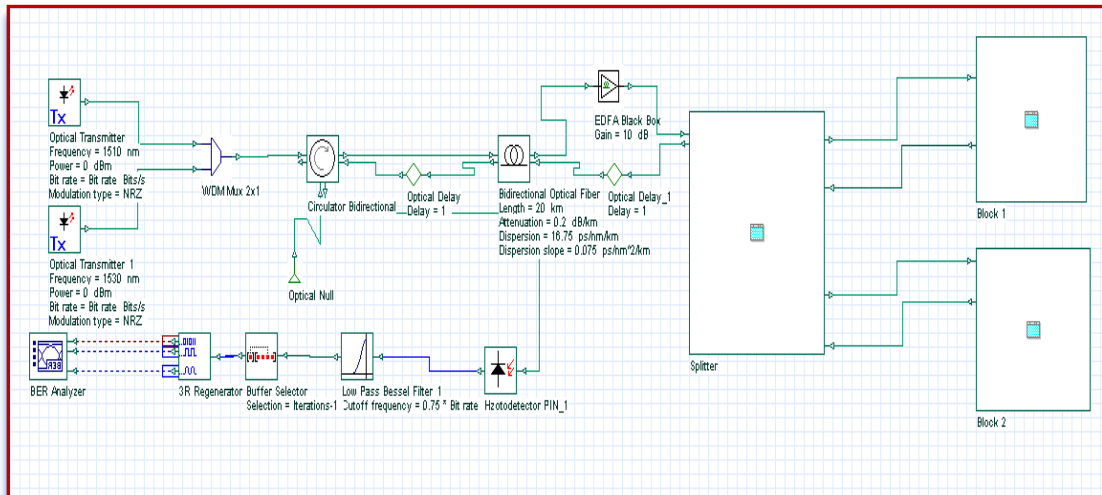


Figure 2: System Model

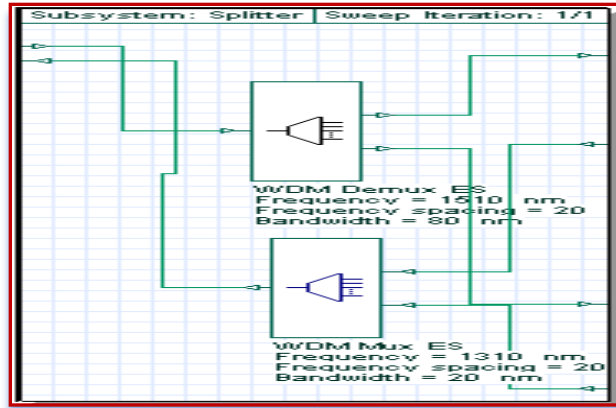


Figure 3: Splitter Circuit with WDM Mux and Dmux

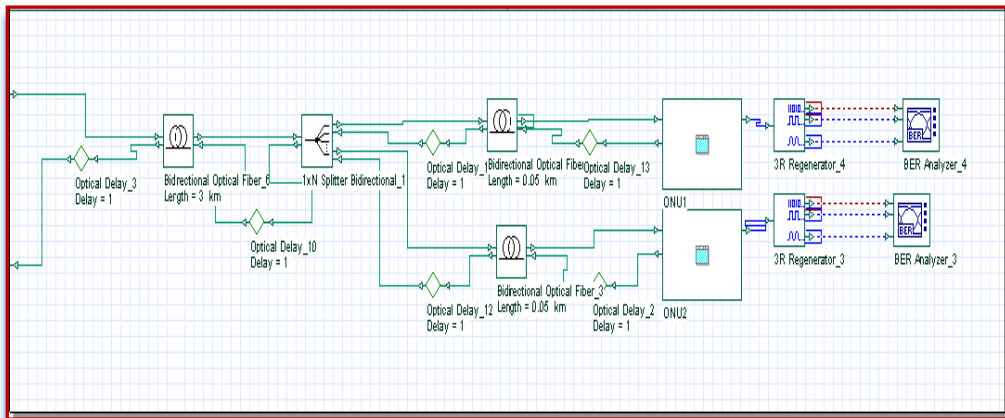


Figure 4: Passive Optical Network for one Block

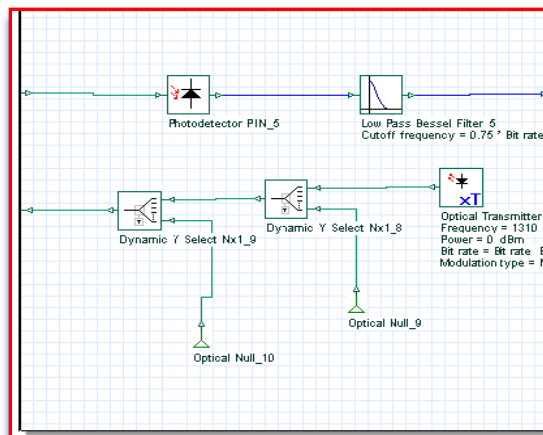


Figure 5: Optical network unit (ONU)

## 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**

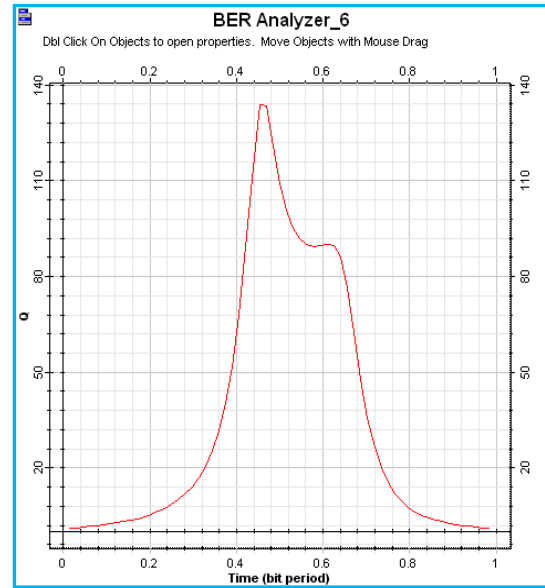
	Without 40-GHz mm-wave	With 40-GHz mm-wave
Max. Q Factor	133.819	67.909
Min. BER	0	0
Eye Height	0.008254238	0.00765657
Threshold	0.00200062	0.00347784
Decision Inst	0.5	0.5

## 3. Results

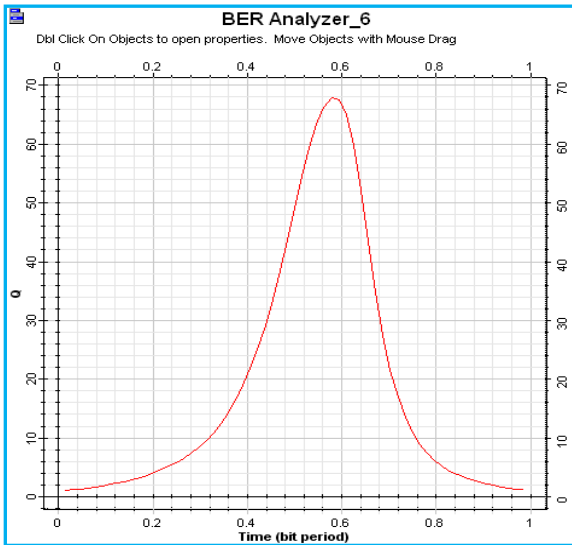
After designing this PON, a number of parameters have to be considered such as bit rate, sequence length, samples per bit and the total samples, as given in Figure 7. In the case we have studied this system is at 2.5 G/s as a bit rate, the sequence length is 128 bits, samples per bit are 64 and the total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

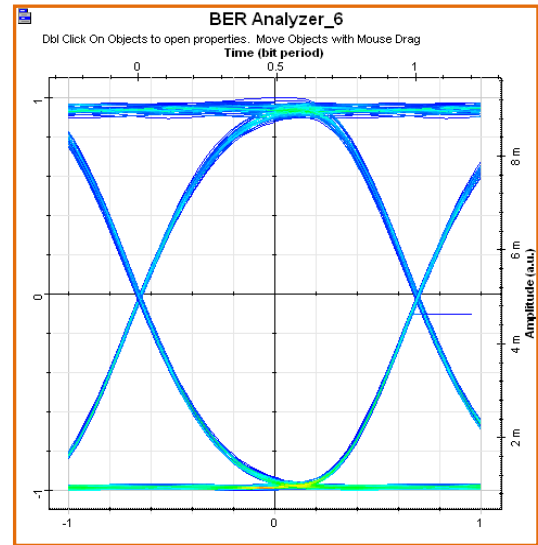


(a)



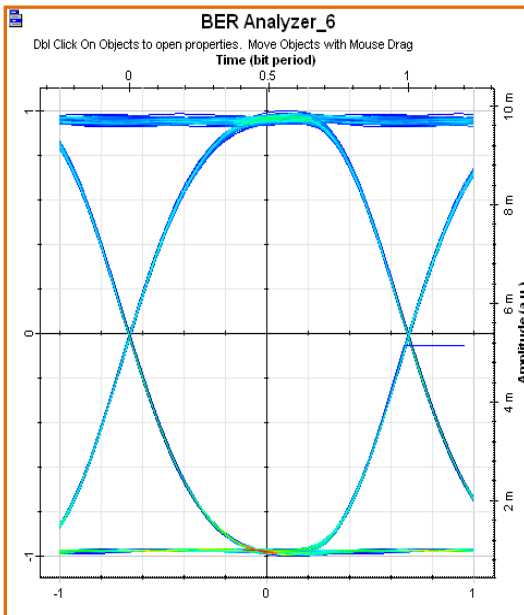
(b)

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.

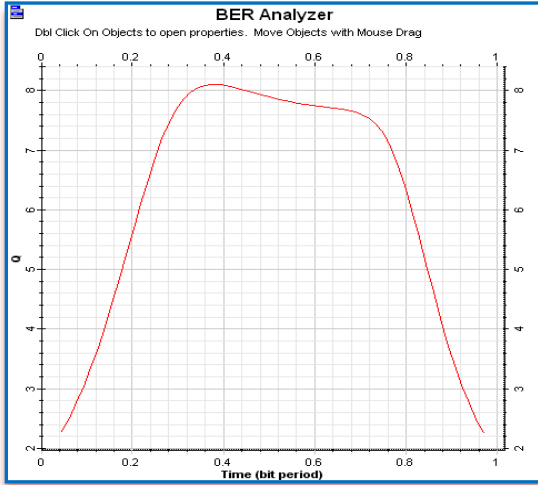
	Without RF Generator	With RF Generator
Max. Q Factor	8.09842	3.90774
Min. BER	1.6922e-016	1.50805e-005
Eye Height	0.000345197	5.84756e-005
Threshold	0.000318945	0.000103043
Decision Inst	0.375	0.359375

### 3.2 Upstream Design Analysis.

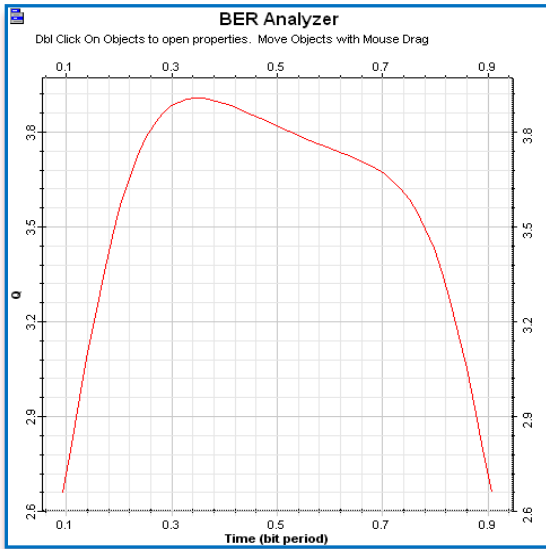
Before running the upstream design, seven iterations have to be set in order to operate the design. Seven iterations are needed because each upstream signal from any individual user will go through seven time delays before reaching the upstream receiver. Table-2 shows the most important details of the 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.

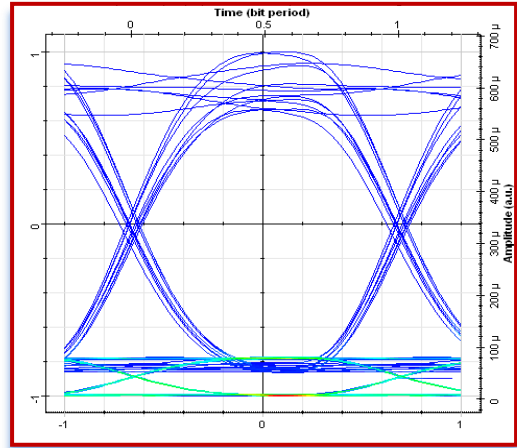


(a)

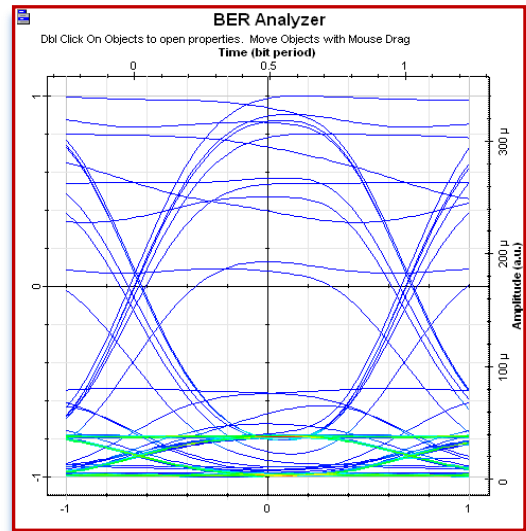


(b)

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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