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Coherent OFDM for Optical Communication systems

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Dedications

I dedicate my dissertation work to my family, a special feeling of gratitude to my loving parents, their words of encouragement and push for tenacity ring in my ears.

I also dedicate this dissertation to my wife and my daughter leen. Thank you for believing in me, for allowing me to further my studies. Please do not ever doubt my dedication and love for both of you.

Finally, I would like to express my appreciation to my friends, for their encouragements to complete this work.

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ABSTRACT

Orthogonal frequency division multiplexing (OFDM) has quickly gained its attraction in optical communications that are evolving towards software-enhanced optical transmissions. Coherent optical OFDM (CO-OFDM) takes advantage of software capabilities of electronic digital signal processing (DSP) to perform sophisticated operations and has demonstrated its easiness of realizing high spectral efficiency and combating various distortions at the same time.

Coherent optical OFDM (CO-OFDM) has attracted lots of interest due to its high spectral efficiency (SE) and robustness to fiber dispersion and is considered as a promising candidate for long haul optical fiber transmission systems.

In the beginning of this study, we will focus in (OFDM) theoretically with basic initial concepts, then a theoretical study of (CO-OFDM) and Direct detection (DD-OFDM) systems in deep with comparing between them, and identifying the advantages and disadvantages for both systems.

Next, a practical study for the previous systems, by using (Optisystem), a special simulation program to simulate and analyze the system. This simulation we will simulate (CO-OFDM) for long-haul transmissions with its analysis such as optical signal to noise ratio (OSNR), RF spectrum, and constellation diagrams .In addition, we will simulate (DD-OFDM) with the same previous parameters and compare between the two systems .Then, we will compare (CO-OFDM) with dispersion compensating fiber (DCF) as a treatment to increase the transmission distance.

Finally, we will integrate the wavelength division multiplexing system (WDM) with (CO-OFDM) system, to increase the system performance and achieve high data rates.

ملخص الرسالة

إن نظام تقسيم الترددات المتعامد (OFDM) يحظي بجانب قوي من الإهتمام في أنظمة الإتصالات الضوئية التي تتطور بصوره دائمة في مجال البرمجيات البصرية , تمتاز الأنظمة المتسقة في تقسيم الترددات المتعامدة في أنظمة الاتصالات الضوئية (CO-OFDM) بميزات خاصة في معالجة الإشارة الرقمية و تنفيذ عمليات متطورة , ولقد أظهرت سهولة استخدامة في تحقيق الكفاءة الطيفية العالية ومكافحة العديد من التشوهات في نفس الوقت .

لقد جذبت تقنية (CO-OFDM) الكثير من الإهتمام وذلك لأهميتها في تحقيق الكفاءة الطيفية العالية وكذلك مناعتها ضد التشتت الذي يحصل في كوابل الألياف الضوئيه وأيضا تعتبر من التقنيات الواعده في أنظمة الإتصالات الضوئية لمسافات طويلة .

سنقوم في هذه الأطروحة دراسة نظام (OFDM) بصوره عامة مع المفاهيم الأساسية, ومن ثم دراسة نظام (CO-OFDM) ونظام (DD-OFDM) تحت دراسة معمقة مع المقارنة بين النظامين وعمل مقارنة بين النظامين للتعرف على المزايا والمساوئ لكل نظام .

بعد ذلك سيتم دراسة الموضوع من ناحية عملية , حيث سيتم استخدام برنامج محاكاه خاص لأنظمة الإتصالات الضوئية يسمى (Optisystem) , وعن طريق هذا البرنامج سيتم أولا دراسة نظام (CO-OFDM) للمسافات البعيده, وذلك للحصول على أقصى مسافة للنظام وكيفية كشف الإشارة ومعايير اخرى مثل مقياس نسبة الإشارة الضوئيه الى معدل الضوضاء (OSNR) ومعيار طيف الترددات الراديوي (RF spectrum), بعد ذلك ننتقل الى دراسة نظام (DD-OFDM) بنفس المحددات السابقة, ثم سننتقل الى عمل مقارنة بين نظام (CO-OFDM) العادي ونظام (CO-OFDM) باستخدام تقنية تعويض التشتت في الألياف الضوئية (DCF) , حيث ان تقنية تعويض التشتت تعتبر حل مناسب لزيادة مسافة الإرسال في الألياف الضوئية.

أخيرا , سنقوم بتسليط الضوء على استخدام نظام (CO-OFDM) مع أنظمة الإرسال المتعدد للأطوال الموجية (WDM) , الهدف من ذلك هو الحصول على زيادة في معدلات البيانات التي تنتقل على كيبل الألياف الضوئية , أيضا دراسة مسافة الأرسال المناسبة التي لا تؤدي الى تشتت الإشارة الضوئية .

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LIST OF ABBREVIATIONS

(ADC)	**Analogue to Digital Converters**
(ADSL)	**Asymmetric Digital Subscriber Line**
(AWGN)	**Additive White Gaussian Noise**
(BER)	**Bit Error Rate**
(BPSK)	**Binary Phase Shift Keying**
(CATV)	**Cable Television**
(CD)	**Chromatic Dispersion**
(CFBG)	**Chirped Fiber Bragg Grating**
(CMOS)	**Complementary Metal-Oxide Semiconductor**
(CO-OFDM)	**Coherent Optical Orthogonal Frequency Division Multiplexer**
(CP)	**Cyclic Prefix**
(CWDM)	**Coarse Wave length Division Multiplexing**
(DAB)	**Digital Audio Broadcasting**
(DAC)	**Digital to Analogue Converters**
(DCF)	**Dispersion Compensation Fiber**
(DD-OFDM)	**Direct Detection Orthogonal Frequency Division Multiplexer**
(DSP)	**Digital Signal Processing**
(DVB)	**Digital Video Broadcasting**
(DWDM)	**Dense Wave length Division Multiplexing**
(E/O)	**Electrical to Optical Converter**
(EDFA)	**Erbium Doped Fiber Amplifier**
(FBG)	**Fiber Bragg Grating**
(FDM)	**Frequency Division Multiplexing**
(FFT)	**Fast Fourier Transform**
(FWM)	**Four Wave Mixing**
(ICI)	**Inter Carrier Interference**

(IF)	**Intermediate Frequency**
(IFFT)	**Inverse Fast Fourier Transform**
(ISI)	**Inter-Symbol Interference**
(LED)	**Light Emitting Diode**
(LO)	**Local Oscillator**
(LPF)	**Low Pass Filter**
(LTE)	**Long-Term Evolution**
(MCM)	**Multi Carrier Modulation**
(MMF)	**Multi Mode Fiber**
(MZM)	**Mach Zehender Modulators**
(O/E)	**Optical to Electrical Converter**
(OFDM)	**Orthogonal Frequency Division Multiplexer**
(OSNR)	**Optical Signal to Noise Ratio**
(PAPR)	**Peak to Average Power Ratio**
(PIN)	**Positive Interstice Negative**
(PMD)	**Polarization Mode Dispersion**
(PRBS)	**Pseudo Random Binary Sequence**
(PSK)	**Phase Shift Keying**
(QAM)	**Quadrature Amplitude Modulation**
(QPSK)	**Quadrature Phase Shift Keying**
(RTO)	**RF to Optical up Converter**
(SBS)	**Stimulated Brilouin Scattering**
(SMF)	**Single Mode Fiber**
(SNR)	**Signal to Noise Ratio**
(SPM)	**Self-Phase Modulation**
(SRS)	**Stimulated Raman Scattering**
(TDM)	**Time Division Multiplexing**
(VLSI)	**Very Large-Scale Integration**
(WDM)	**Wave length Division Multiplexing**

(WIMAX)	**Wireless Metropolitan Area Networks**
(WLAN)	**Wireless Local Area Networks**
(XPM)	**Cross-Phase Modulation**

Chapter 1: Introduction

1.1 Overview

The increasing in internet traffic which includes data, voice and video services, has led the increased demand in high data rates, this increasing due to explosion in online videos. According to Cisco Visual Networking index, the internet traffic from 2009 to 2014 will quadruple. Figure 1.1 shows as a 2014 projection of video services as a percentage of internet traffic [1] . Moreover, there are wide ranges of online applications under development and there is huge demand of distance learning. All of this will increase the bandwidth in the future .

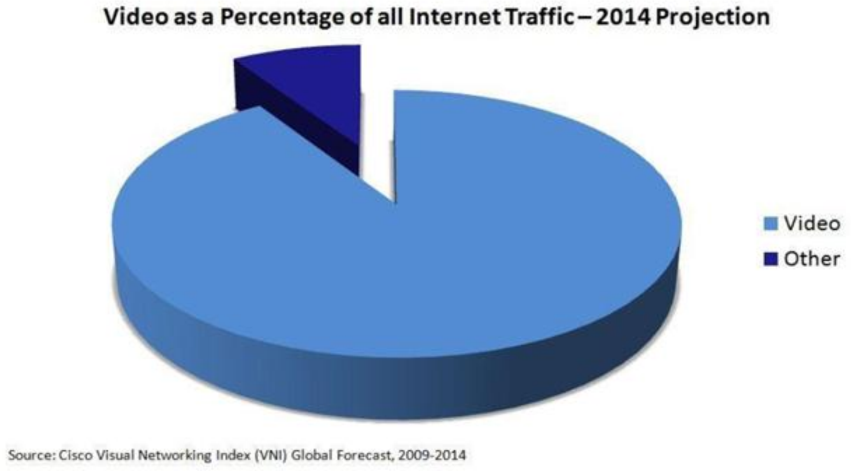

Figure 1.1: projection of video services percentage of Internet Traffic [1]

Many researches and experimental efforts are being conducted to meet the requirements in high capacity demand. The two main issues need to be identified to increase the data rate to 100Gb/s per wavelength are [2] :

1-Bandwidth expansion

One of the solutions to increase the capacity of the system is to increase the transmission bandwidth per wavelength either optically or electronically. In optical communication there are two techniques used for increasing the transmitting capacity [2] . The first technique is to extend the bandwidth by adding several optical carriers, this technique called Wave length Division

Multiplexing (WDM). WDM can be useful by adding multiple transceivers for existing optical fiber links without the need of changing the optical link [2]. The second technique is to extend the electronic bandwidth per wavelength by using CMOS technology. The current digital to analogue converters (DAC) / (ADC) can only support 6 GHz bandwidth. It is a challenge to realize 100 Gb/s transmission in a cost effective manner [3, 4]. But, recently achieved more than 30Gb/s with more than 20 GHz analogue bandwidth this can support 100Gb/s transmission [5].

2- Enhancing the spectral efficiency

The most important merit in optical communications is the spectral efficiency, optical networks uses the intensity modulation and direct detection for transmission and binary modulation in order to reduce the complexity of the transceiver. But with binary modulation the spectral efficiency will not exceed 1 bits/s/Hz [6] . Recently, many advanced modulation formats in phase, signal amplitude, and polarization have been studied to increase capacity of the system. By comparing the modulation techniques with coherent detection technique the result is easily to reach of several bits/s/Hz [7]. One of these advanced modulation techniques is the orthogonal frequency division multiplexer (OFDM). OFDM gained a huge attraction after it was proposed as modulation techniques for long-haul transmission in both direct and coherent detection. This integration between the two modulation techniques Coherent and OFDM bring two main advantages for communication systems [8] . The coherent system brings linearity to the OFDM in both RF to optical up/down converter [9]. The OFDM provides the coherent system with high spectral efficiency and simple channel and phase estimation.

Coherent optical OFDM (CO-OFDM) is the next generation technology for optical communications as it integrates the advantages of both coherent and OFDM systems. CO-OFDM can employ a high bandwidth and high spectral efficiency [10].The CO-OFDM system has the ability to overcome many optical fiber obstacles such as chromatic dispersion (CD) and polarization mode dispersion (PMD) [10, 11], and the resistance against inter-symbol interference (ISI).

1.2 Problem Statement

Indeed, the huge demand on internet traffic has driven the increase for bandwidth and high data rates. OFDM and CO-OFDM techniques can provide high spectral efficiency and enhancement to the receiver sensitivity respectively. CO-OFDM is the solution for long-haul transmission for its tolerance to the CD and PMD problems, In addition, WDM technique is proposed as solution to maximize bandwidth, avoid any cross-talking in single mode fiber (SMF), and increase the data rate of the system.

1.3 Thesis Objectives

The first objective of this research is to study the OFDM and CO-OFDM integration .The second objective is to simulate the CO-OFDM for long-haul transmission by using OptiSystem simulation tool v.13 .The third objective is to make comparison between DD-OFDM and CO-OFDM by comparing constellation diagrams with different modulation schemes .Also, evaluate CO-OFDM with WDM for long-haul by studying the constellation diagram of the system with different modulation schemes. Finally, analyze the effect of the transmission distance on the DD-OFDM and CO-OFDM and WDM.

1.4 Methodology

The research will be conducted according to the following steps:

- Studying the basics of mitigation interference technology, theory, architectures and related subjects.
- Revising the existing work in the literature which is related to the (CO-OFDM).
- Compare the existing schemes and classify them into main categories depending on their performance with respect to optimization techniques.
- Propose an algorithm that aim to increase the efficiency of (CO-OFDM).
- Testing of the proposed algorithm in a simulated system.
- Compare this work with other related work to get the final deduction.

1.5 Thesis Outline

This section gives a brief description all the chapters constructing this thesis:

Chapter 1 provides a brief introduction of the research overview, problem statement, objectives, scopes of the thesis, methodology, and finally, the thesis structure.

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

Chapter 3 presents the literature review of OFDM system for better understanding of CO-OFDM, an explanation of optical OFDM including direct and coherent detection, and a comparison between direct and coherent optical OFDM.

Chapter 4 discusses the methodology of this thesis in terms of integrating OFDM with an optical coherent for long-haul transmission. Also the DD-OFDM is discussed and compared with CO-OFDM .The integration between WDM and CO-OFDM has been studied to reach high data rates with long distance. The Optisystem simulation tool v.13 is used to simulate and analyze the system. In addition, this chapter discusses the simulation results for the proposed system.

Chapter 5 provides the conclusion of the thesis and the future work required to develop and improve the system transmission distance and the data rates.

Chapter 2: Fiber-Optic Communication

Like any other communication system, optical fiber consists of three main stages which are a transmitter, a receiver, and communication channel. The difference between the fiber-optic communication system and other communication systems is the communication channel is an optical fiber and the optical transmitter and the receiver are designed to meet the requirements of this communication channel Figure 2.1 [12]. The communication system can be classified as a long-haul more than 100 km and a short-haul less than 50 km system. However, the fiber-optic communication technology is driven by long-haul applications because of its benefits in high data rates.

The most important advantage of using optical-fiber communications channel is to transmit the signal without distortion and with small loss. The light wave can be transmitted with loss (attenuation) equal to 0.2 dB/Km. But, for long haul applications the attenuation increases every 100 km by 1% .As a result, when we design the optical fiber the attenuation loss must be considered to determine the space between amplifiers or repeater of the system

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

One of the optical fiber problems and considered as a drawback is the fiber dispersion. This leads the light pulse expanding while it travels along the fiber and make it overlap with the closer pulses. In some times, this problem is hard to recover the original signal accurately [12].The dispersion can occur in multimode fiber more than single mode fiber , which makes the single mode fiber is the best choice for long haul applications [13].

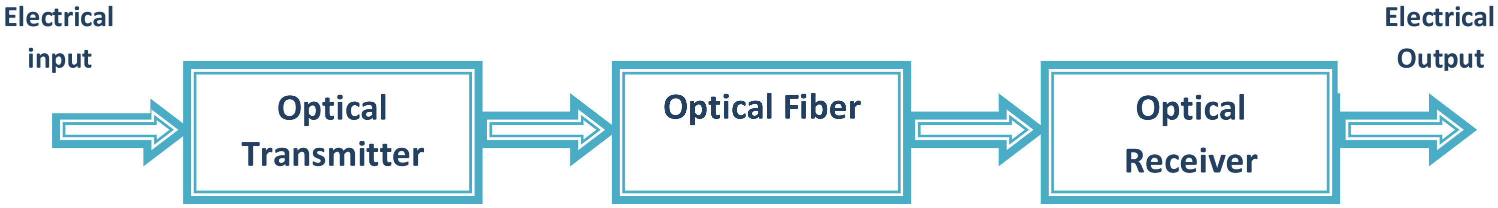

Figure 2.1: Optical communication system [14]

The optical transmitter will convert the electrical signal to an optical signal and lunch the resulting signal into the optical fiber. The optical transmitter consists of an optical source and an optical modulator as shown in Figure 2.2. The optical source can be a laser or light-emitting diode (LED) and the optical modulator can be direct or external modulator. An example of external modulator is a Mach Zehnder modulator [13].

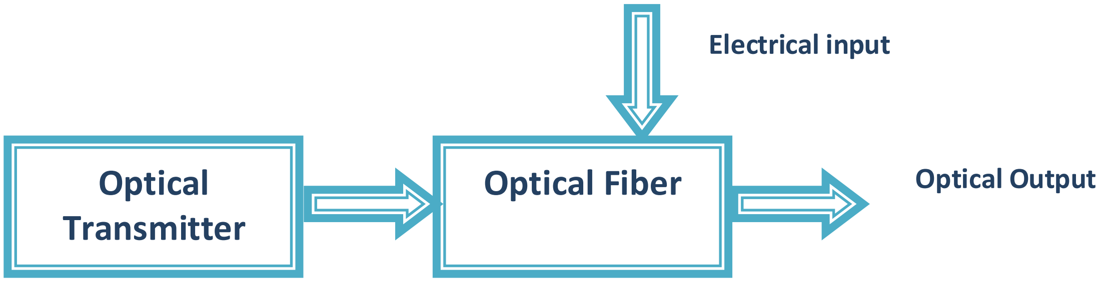

Figure 2.2: Optical transmitter [14]

In the receiver part, the receiver will detect the optical signal and convert it to electrical signal. The optical receiver consists of a photodiode, which converts the optical signal to electrical, and an electrical demodulator, which extracts the original electrical signal that was sent, as shown in Figure 2.3 [13].

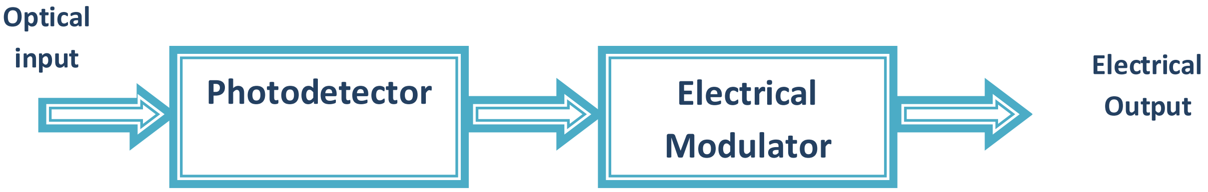

Figure 2.3: Optical receiver [14]

2.1 Fiber Attenuation

Attenuation, also known as fiber loss, transmission loss, and power loss, means the reduction of the intensity of the light or the light power as it travels along the fiber. The attenuation unit is dB/km, the scattering and absorption is the main cause of attenuation in optical fiber. Attenuation can be expressed as the ratio of input optical power and output optical power after L length of optical fiber This ratio is a function of wavelength and can be expressed as [13] :

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

2.1.1 Absorption

As mentioned above, the main cause of attenuation is scattering and absorption. The main absorption reason in fiber is the presence of impurities in the fiber material such as OH ions (water). These ions enter the fiber either during the chemical manufacturing process or from the environmental humidity[12].

2.1.2 Rayleigh-Scattering

Scattering losses occurs from material density microscopically variations, compositional fluctuations, and from defects during fiber producing process [12, 15]. The collision between the light wave and the molecules of the fiber will result in the escape of the light from the fiber waveguide or in it reflecting back to the source. This is known as scattering [12, 15] . Rayleigh-scattering in glass is the same principle as the Rayleigh scattering of sunlight in the atmosphere which causes the sky to appear blue. It is hard to have accurate calculations for attenuation caused by the scattering because of the random molecular nature of glass. But it can be approximated using equation 2.2 for a specific wavelength (λ) [12] :

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

Where n is the refractive index, k_B is the Boltzmann's constant, p is the photo elastic coefficient, T_f is the fictive temperature, and β_t isothermal compressibility.

2.2 Fiber Dispersion

Dispersion in optical fiber is the expansion of the light pulse while it travel along the fiber .A pulse overlap with the closer pulses will be as a result of fiber dispersion and the signal will hard to recover from the original signal accurately [12]. There are different types of signal dispersion that can occur during the transmission of a signal such as Intermodal dispersion, Chromatic Dispersion (Intramodal Dispersion), and polarization-mode dispersion[13].

2.2.1 Intermodal Dispersion

It also known as modal delay and it appears because each mode of the signal at a single frequency has a different group velocity value as the signal travels through the fiber [12]. This difference in group velocities is the reason to make the signal broaden and will lead eventually to signal distortion [13]. As the length of the fiber increases the intermodal dispersion increases and it appears only in multimode fibers because the single-mode fiber has only one mode.

2.2.2 Chromatic Dispersion (Intramodal Dispersion)

Chromatic dispersion is the pulse broadening that happens in a single mode fiber. The main cause for this broadening in the pulse is the finite spectral width of the optical source. Chromatic dispersion depends on the wavelength and therefore increases with the spectral width of the optical source. There are two causes for chromatic dispersion: material dispersion and waveguide dispersion [12, 13].

2.2.2.1 Material Dispersion

Because of the variation of refractive index of the core material of the fiber with the change of the optical wavelength the material dispersion arise. The main cause of material dispersion is that the index of refraction is a function of the wavelength[12, 15].

2.2.2.2 Waveguide Dispersion

Another type of chromatic dispersion is the waveguide dispersion. Waveguide dispersion depends on the fiber core diameter and it causes signals of different wavelengths to travel at different velocities which will spread the pulse and make it overlap with neighboring pulses, the material dispersion will cause the spreading of the signal[12, 13].

2.2.3 Polarization-Mode Dispersion (PMD)

Polarization mode dispersion is caused by a fiber birefringence which affects the polarization state of the optical signal and causes a pulse broadening[12]. Birefringence can caused from many factors such as the bending or twisting of the fiber , imperfections from the manufacturing process , or weather conditions[12, 15].

2.3 Fiber Nonlinear Impairments

Dispersion in optical fiber is a main factor that can affect the transmission and degrade the optical signal. But, there are other factors .The optical signal can be subject to fiber nonlinearity which can affect the transmission. There are two types of fiber nonlinear impairments the Kerr nonlinearity and the stimulated elastic scattering process. The Kerr nonlinearity caused from the refractive index in fiber which is dependent on the intensity of the propagated signal[16].The kerr nonlinearity is Consists of three important nonlinear effects: Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM) [16]. The second type of fiber nonlinear impairments, the stimulated elastic scattering, helps the energy transfer from the optical field to the medium. It includes two types: Stimulated Raman Scattering (SRS), and Stimulated Brillouin Scattering (SBS)[16].

2.3.1 Self-Phase Modulation (SPM)

During the propagation of an ultra-short pulse through the single mode fiber the (SPM) happens. This will cause a variation in refractive index. Due to this variation, phase shift on the pulse will occur. After that , a change in the pulse’s frequency spectrum will be as a result[17]. The shape of optical signal will not change because of (SPM), but broadens the optical pulse spectrum. This broadening will generate a frequency chirp which will add a new frequency to the pulse[17].

2.3.2 Cross-Phase Modulation (XPM)

XPM is similar in behavior to SPM, but it occurs when two or more optical pulses affect the phase and intensity of each other while broadening[18].

2.3.3 Four-Wave Mixing (FWM)

FWM occur when three wavelengths interfere with each other producing refractive index gratings. The gratings will interact with the signals and result in new frequencies, producing the fourth wavelength[17].

2.3.4 Stimulated Raman Scattering (SRS)

SRS occurs when the molecules vibrate and get excited by the light particles travelling through a single mode fiber. As a result, the light particles will be scattered, which is known as SRS. This can happen in both forward and backward directions[18].

2.3.5 Stimulated Brillouin Scattering (SBS)

When the input power in the optical fiber is high the SBS happens. A beam of light will generated and propagated in the backward direction , the SBS effect is negligible when the input power is low [18].

2.4 Dispersion Compensation

The attenuation in the fiber can be solved by using optical amplifiers but it makes the fiber dispersion worse. On the other hand , dispersion in optical fiber can be compensated by other techniques such as : Dispersion Compensation Fiber (DCF), Fiber Bragg Grating (FBG), and Chirped FBG [13, 15, 19]. These techniques can control the dispersion and extend the transmission distance. The following sections describe these techniques.

2.4.1 Dispersion Compensation Fiber (DCF)

The optical fiber communication is the best solution of high data rates and long transmission distances. As a result, the compensation of the chromatic dispersion in optical fiber is required. (DCF) is considered as a good solution to overcome the fiber dispersion because of its cost effective and temperature stability [13, 15]. (DCF) can be designed to compensate for the dispersion of an optical fiber. By using negative dispersion coefficients up to -80 ps/nm , to make cancellation of the positive dispersion in the fiber.

It is not an effective way to use (DCF) with the single bands which are S-band (1460-1530 nm), C-band (1530-1565 nm), and L-band (1565-1625nm) because the (DCF) will balance the dispersion. But, for lower bands such as the E-band (1360-1460nm) the improvements in the transmission distance becomes effective. The disadvantage of the (DCF) that it has a higher attenuation than the single mode fiber (SMF) which will create high insertion loss to the system [19]. To overcome this disadvantage is to increase the signal power. However, by increasing the signal power the nonlinearity impairments of the system will result to signal distortion. Therefore , the power increasing can be done in acceptable standards in limited way [12].

2.4.2 Fiber Bragg Grating

The high insertion loss and nonlinear impairments are some of DCF drawbacks. This issues can be solved by using Bragg Grating (FBG) for dispersion compensation [13, 20]. By using FBG in optical fiber, the refractive index of the core will change periodically. As a result , specific wavelengths will be transmitted and the others will be reflected [20]. Any light with wavelength that satisfies the Bragg condition will be reflected. So, FBG can be considered an optical filter. As an optical filter , it has many advantages such as : low loss , sensitivity to the polarization of the light , and cost effectiveness [20] . FBGs are used widely in the WDM systems and also can be used as tunable filters. Moreover, FBGs can be used for remote monitoring and as laser diode filters [15].

2.4.3 Chirped Fiber Bragg Grating (CFBG)

Because of CFBG low insertion loss, low nonlinear effects, and its low cost; it is widely used to compensate the chromatic dispersion of the optical fiber and for power loss reduction. CFBG is similar to the FBG in the structure but it takes different forms and different periods over the length of the grating. CFBG can be symmetrical, linear chirp or quadratic chirp [21]. In CFBG, different wavelengths can be reflected by different parts of the grating along the fiber and, therefore, can have a different time delay. Thus, the input signal can be affected by this delay to compensate the dispersion that occurred along the fiber [21, 22] .

2.5 Optical Modulation

The first consideration when designing an optical fiber communication system is how to convert the electrical signal to an optical signal. An optical modulator is needed which can be a direct or an external modulator.

2.5.1 Direct Modulation

Direct modulation occurs when the electrical information stream varies the laser current directly to produce a different optical power as shown in Figure 2.4. Therefore, it will lead the laser to turn on and off and create 1 and 0 bits [12, 15]. Direct modulation is suitable for data rates of 2.5 Gbits or less.

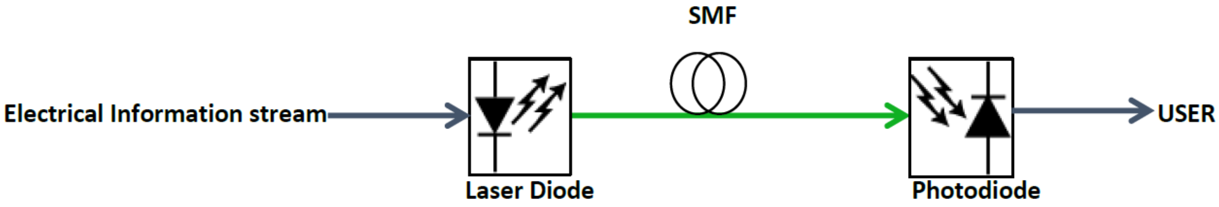

Figure 2.4: Direct Modulation [14]

One of the drawbacks of direct modulation is the broadening in the line width of the laser because the laser on-off process, these results from the electrical signal that drives the laser source .The broadening in width is called chirp, and it will lead to degradation in the system performance. For that reason , direct modulation is not suitable for data rates greater than 2.5 Gbits [12, 13].

2.5.2 External Modulation

In external modulation, the laser source emits a constant amplitude signal that enters the external modulator such as a Mach-Zehnder modulator (MZM) as shown in Figure 2.5 [12, 15]. The electrical signal then enters the external modulator to change the optical power level that the external modulator will transmit, but not change the amplitude of the light that comes originally from the laser to produce optical signal with time variance [12]. The constant amplitude signal from the laser source will help to avoid the chirp of the pulses which will reduce the dispersion and make this process more effective for systems with high data rates of 10 Gbits/s and greater, and for the long-haul communication systems [12, 15].

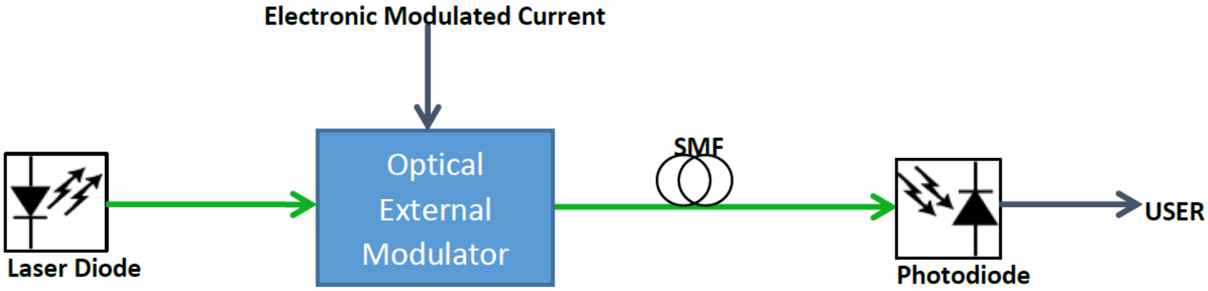

Figure 2.5: External Modulation [14]

2.6 Wavelength Division Multiplexing (WDM)

The wavelength –division multiplexing (WDM) is a technology which multiplexes a number of optical carrier signals into a single optical fiber by using different wavelengths of laser light. this technique enables bidirectional communications over one stand of fiber, as well as multiplication of capacity[23], Where each wavelength carries a separate channel. WDM divides the optical spectrum to smaller channels, which are used to transmit and receive data simultaneously [24]

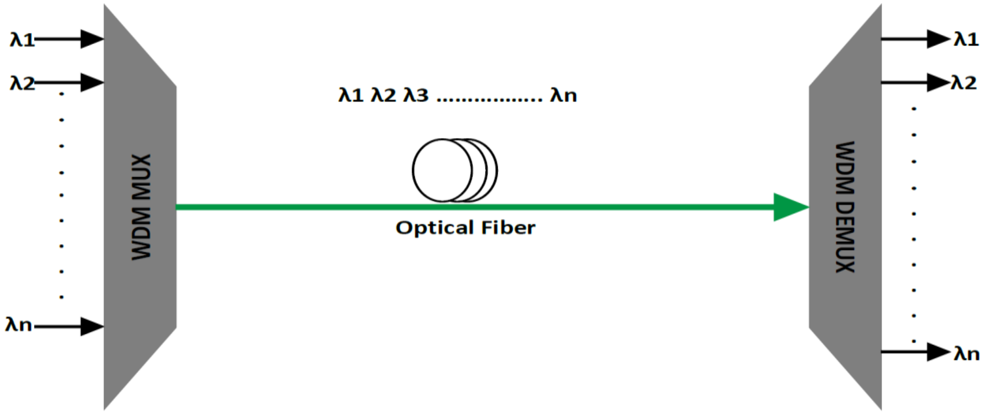

Figure 2.6: Wavelength Division multiplexing [14]

Figure 2.6 illustrates the optical WDM networks, where wavelength substitutes frequency and each transmitter transmits separated wavelength λ_i , where i= 1, 2, 3,……N. WDM systems include two types, Dense Wavelength Division Multiplexing (DWDM) and Coarse Wavelength Division Multiplexing (CWDM).

2.6.1 Dense Wavelength Division Multiplexing (DWDM)

The DWDM is the solution for huge demand in data in communications networks. Currently, Time division multiplexing (TDM) is used to provide internet service to users via cable which restricts the available bandwidth for each user. DWDM connects the users' devices directly to the router which provides greater bandwidth [25]. By using DWDM, the transmission capacity and distance will increase by minimizing wavelength spacing. It can reach wavelength spacing of 200-50 GHz (0.4-1.6 nm) in the 1500-1600 nm wavelength area which makes it facilitates 32 to 128 channels per single fiber [26]. The disadvantage of using DWDM , when the temperature rising , the system efficiency will decreased [26]. As a result, it will need cooling system which consumes a lot of energy and this will lead to increase in cost.

2.6.2 Coarse Wavelength Division Multiplexing (CWDM)

Another type of WDM is CWDM which is cost effective because it does not require temperature control. CWDM typically Consists of 18 wavelengths with spacing of (20-40 nm) in the (1260 1670 nm) band [27]. CWDM is used for short transmission distances of less than 50 km because it is more cost efficient than the DWDM system [28].

Chapter 3: Orthogonal Frequency Division Multiplexing (OFDM)

3.1 Introduction

Orthogonal frequency-division multiplexing (OFDM) is classified as multicarrier modulation (MCM) in which the data information is carried over many lower rate subcarriers. The main two advantages of OFDM are its robustness against channel dispersion and its ease of phase and channel estimation in a time-varying environment. In addition, advantage of silicon Digital signal processing (DSP) technology. OFDM also has disadvantages , such as high peak-to-average power ratio (PAPR) and its phase noise and sensitivity to frequency [11]. Therefore, a good understanding of OFDM basics and its applications is essential for our study.

In this chapter, we present a historical perspective of OFDM, and then we provide the fundamentals of OFDM and its applications in optical communications. Finally, a study of CO-OFDM as it is our main research field is presented.

3.2 Historical Perspective of OFDM

The perception of OFDM was first introduced by Chang in [29, 30].OFDM gained the most development part in military applications , because the lack of broad band applications for OFDM and powerful integrated electronic circuits to support the complex computation required by OFDM. However, the development in broadband digital applications and the Very Large-Scale Integration (VLSI) CMOS chips in the 1990 brought OFDM in to the spotlight. In 1995, OFDM was the first Digital Audio Broadcasting (DAB) standard, and then OFDM became the most important modulation technique in many standards such as Digital Video Broadcasting (DVB) ,Wireless Local Area Networks (WLAN) (Wi-Fi; IEEE 802.11a/g), wireless metropolitan area networks (WiMAX; 802.16e) , asymmetric digital subscriber line (ADSL; ITU G.992.1), and long-term evolution (LTE) which is the fourth-generation mobile communications technology.

The OFDM optical applications are occurred unexpectedly and in late relatively with RF applications. While the same contraction of OFDM has long been used as standard for “optical frequency division multiplexing ” in the optical communication field [31, 32].However, the advantage of OFDM , to be exact is its robustness against optical channel dispersion , was not unknown in optical communications until 200 , when Dixon proposed the use of OFDM to solve the modal dispersion dilemma in multimode fiber (MMF)[33]. So it's not a chance that the early work in optical OFDM focused in MMF fiber applications [33, 34]. The main interests in optical OFDM are in three fields : OFDM for long-haul transmission ,direct-detection optical OFDM (DDO-OFDM) [35, 36] and coherent optical OFDM (CO-OFDM) [37].

3.3 OFDM Basics

OFDM is considered as a modified version of Frequency Division Multiplexing (FDM). In FDM technique , different information for different users is transmitted at the same time over different frequency carriers as shown in Figure 3.1[33] .At the transmitter part , each subcarrier is set with a wide guard band after it is modulated by the user's data to prevent it from overlapping with the adjacent subcarriers. However, this guard band will reduce the spectral efficiency of the system. The received signals at the receiver are then demodulated by oscillator banks [18].

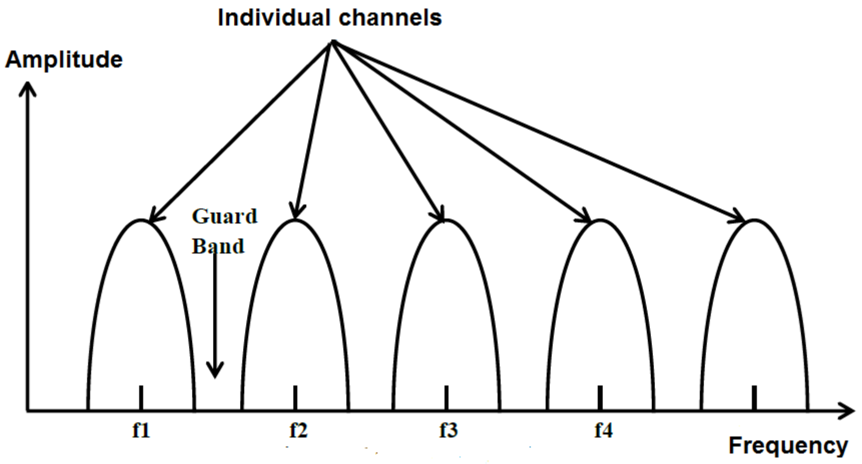

Figure 3.1 : FDM spectral [14]

In OFDM, as a special case of FDM ,OFDM uses many carriers per a given spectrum that are very close to each other, however in an exact distance one from another so they remain orthogonal to each other. The use of the Fast Fourier Transform (FFT) and Inverse FFT help to demodulate and construct the original signal even if there is overlapping between the subcarriers as shown in Figure 3.2 [18, 38, 39].

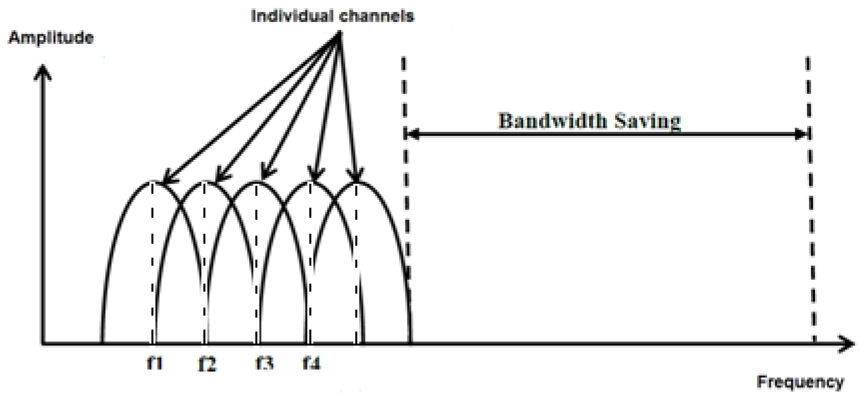

Figure 3.2 : OFDM Spectral[14]

3.4 OFDM Modulation Scheme

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

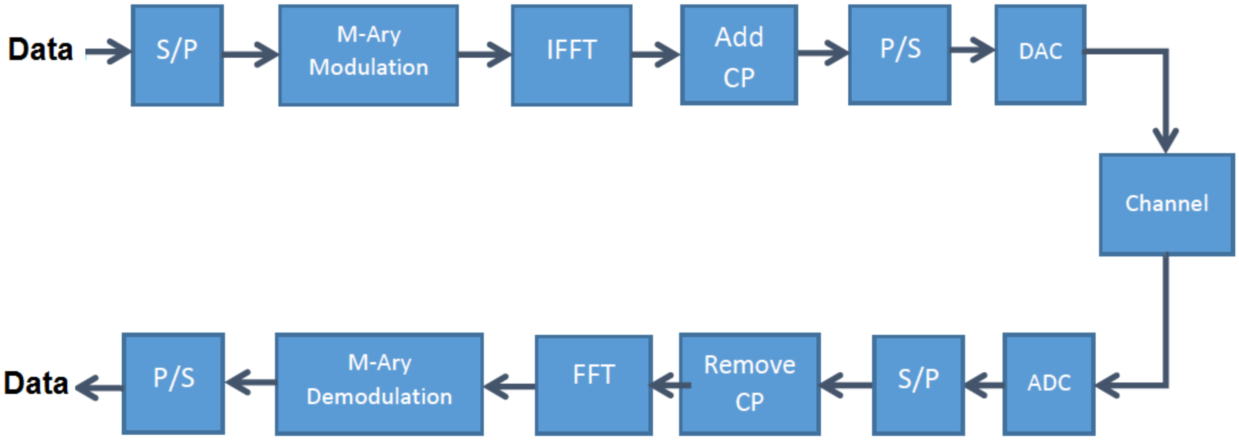

Figure 3.3: OFDM Block diagram[14]

In the transmitter part, the data in serial sequence are converted to parallel and mapped by an M-ary Modulator which could be Quadrature Amplitude modulation (QAM) or phase shift-keying (PSK) modulations. After that the signal is processed by Inverse Fast Fourier Transform (IFFT) and guard interval is added to prevent overlapping between subcarriers .Then the signal sent to the channel after performing a parallel to serial conversion [40].

In the receiver part , the received signal now in serial sequence , so its converted to parallel and the guard interval is removed .The signal now passes throw the Fast Fourier Transform (FFT) stage , and is demodulated using M-ary demodulator which could be either QAM or PSK .Lastly, the data in parallel sequence are converted to serial to get the original data [41].

3.4.1 Constellation Diagram

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

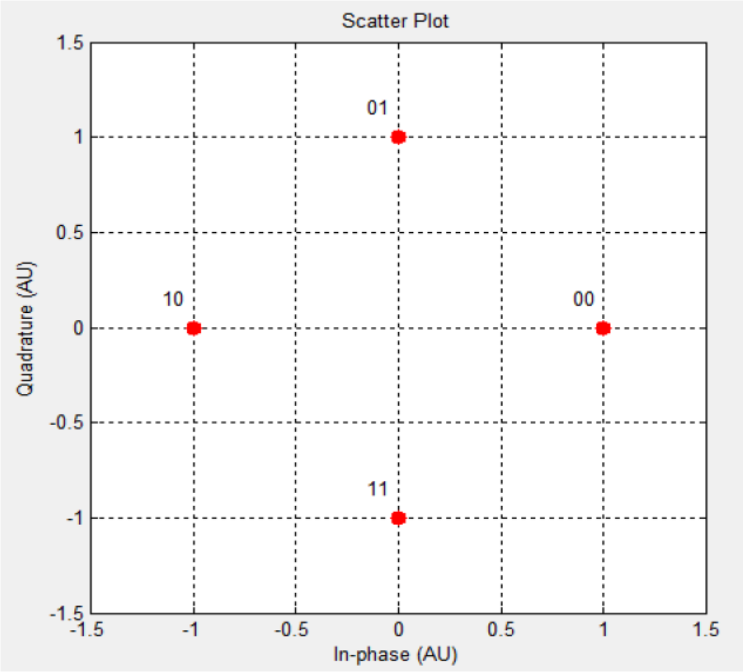

Figure 3.4: QPSK constellation diagram[14]

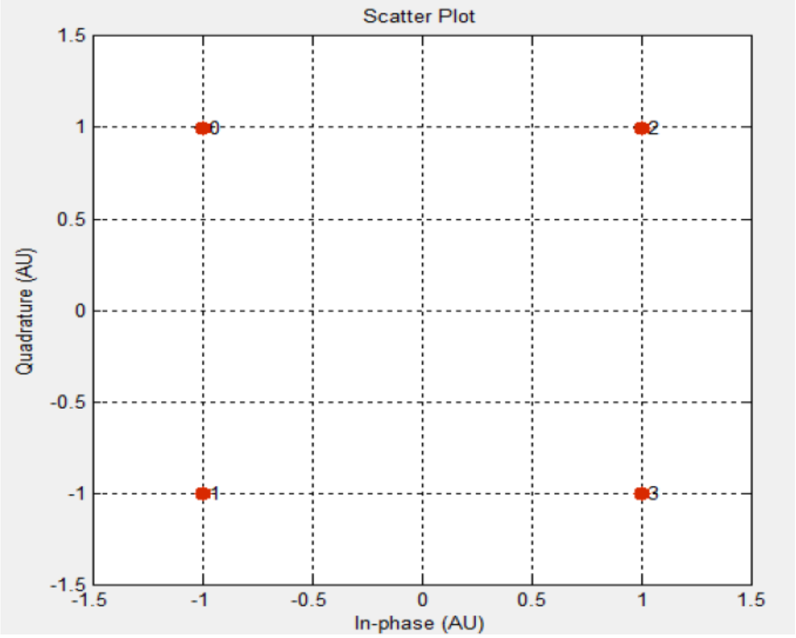

Figure 3.5 : 4-QAM constellation diagram[14]

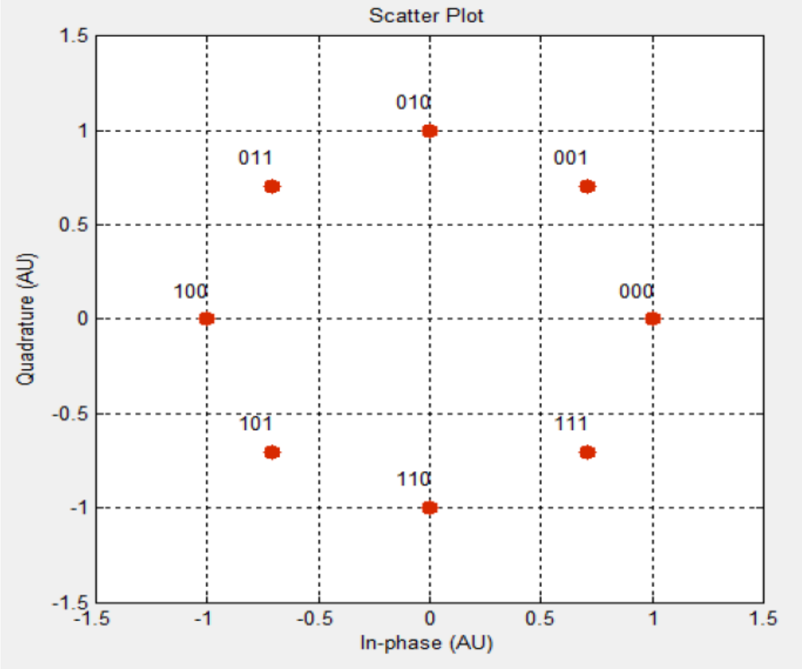

Figure 3.6 :8-PSK constellation diagram[14]

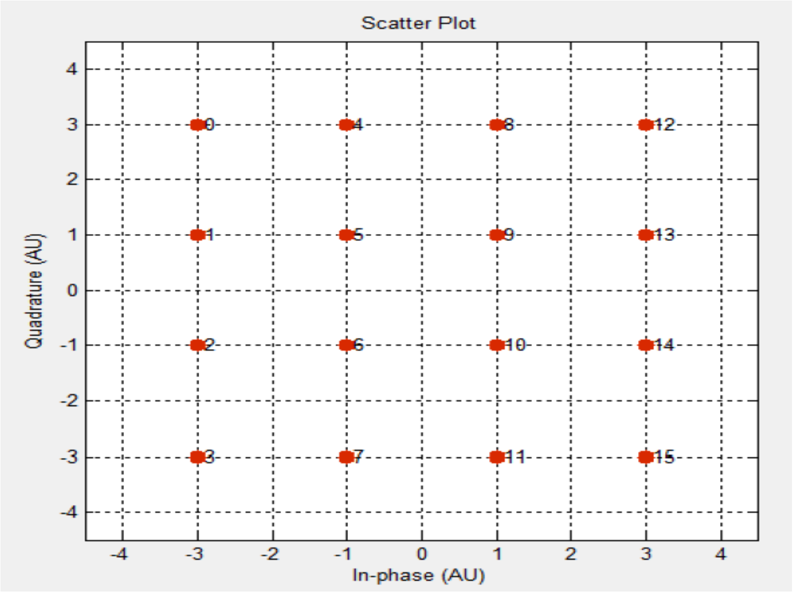

Figure 3.7 : 16-QAM constellation diagram[14]

3.4.2 Symbol Mapping

The basic function in OFDM usually sinusoidal signal:

$$\phi_n(t) = A(t) \exp\ (j\ 2\pi\ f_n\ t) \tag{3.1}$$

Where f_n is the frequency of the signal, n subcarrier numbers, and A is the amplitude

We can rewrite equation 3.1 to be:

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

Where I (t) is the in-phase component and Q(t) is the Quadrature component .

By using equation 3.2 the input data are presented by in-phase and Quadrature form .To demonstrate the idea of I/Q component. Take both of Binary phase shift keying (BPSK) and Quadrature phase shift keying (QPSK) as an illustrative example .In case of BPSK one binary value only is used each time, and the value will be 0 or 1. The values of the I and Q components are presented in Figure 3.8:

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

(a)

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

(b)

Figure 3.8: (a) I/Q Components for BPSK (b) I/Q Components for QPSK[42]

3.4.3 Serial to Parallel Conversion

In this stage after converting binary values to complex values, the data signal must pass through serial to parallel converter to convert the complex values to parallel symbols .These symbols are arranged into sets and each set will carry the number of symbols which is determined by the number of subcarriers.

3.4.4 Inverse Fast Fourier Transform (IFFT)

By using Inverse Fast Fourier Transform (IFFT) this has the ability to perform the frequency up converting and multiplexing of the complex subcarriers in accurate and efficient way. In addition, at the receiver side, the Fast Fourier Transform (FFT) is used for demodulating and de-multiplexing .So, the core component of the OFDM transceiver is the IFFT/FFT digital process.

The structure of a complex multiplier (IQ modulator/demodulator), which is commonly used in MCM systems, is also shown in the Figure 3.9. The MCM transmitted signal $S(t)$ is represented as [43]:

$$S(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{sc}} c_{ki} s_k (t - iT_s) \tag{3.3}$$

$$S_k(t) = \prod(t)\, e^{j 2\pi f_k t} \tag{3.4}$$

$$\prod(t) = \begin{cases} 1\,,\ (0 < t \le T_s) \\ 0\,,\ (t \le 0\,,\ t > T_s) \end{cases} \tag{3.5}$$

Where c_{ki} is the ith information symbol at the kth subcarrier, s_k is the waveform for the kth subcarrier, N_{sc} is the number of subcarriers, f_k is the frequency of the subcarrier, T_s is the symbol period, and $\prod(t)$ is the pulse shaping function.

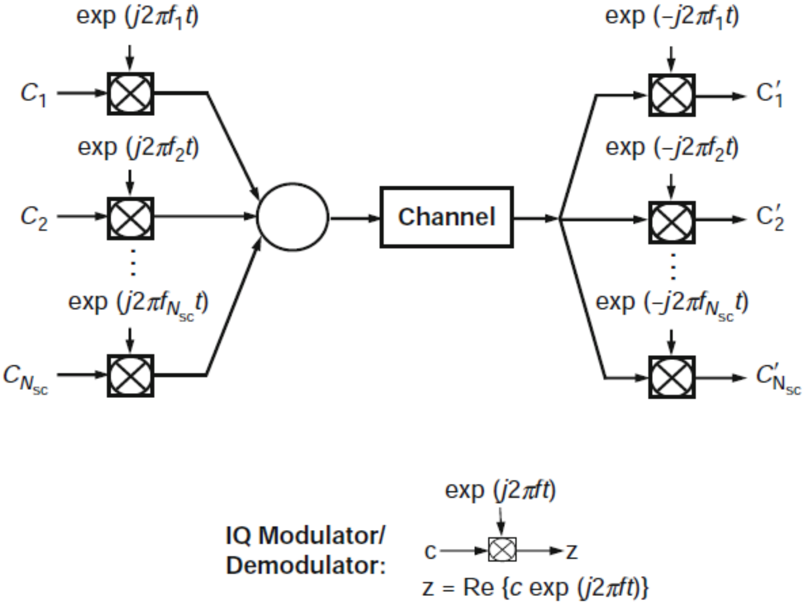

Figure 3.9 : Conceptual diagram for a generic multicarrier modulation system[43]

The optimum detector for each subcarrier could use a filter that matches the subcarrier waveform or a correlator matched to the subcarrier as shown in Figure 3.9 .Therefore, the detected information symbol c'_{ik} at the output of the correlator is given by:

$$c'_{ik} = \frac{1}{T_s}\int_0^{T_s} r\,(t - iT_s)\, s^*{}_k\, dt = \frac{1}{T_s}\int_0^{T_s} r(t - iT_s)\, e^{-j2\pi f_k t}\, dt \tag{3.6}$$

Where $r(t)$ is the received time domain signal. The classical MCM uses nonoverlapped bandlimited signals and can be implemented with a bank of large numbers of oscillators and filters at both transmit and receive ends.

The major disadvantage of MCM is that it requires excessive bandwidth. This is because to design the filters and oscillators cost-effectively, the channel spacing has to be a multiple of the symbol rate, greatly reducing the spectral efficiency.

The FFT algorithms will guarantee the orthogonality of the subcarriers in the OFDM transceivers and will be help to avoid any interference .The most important thing for maintaining the orthognality between subcarriers is to make sure that the subcarriers center frequency are not overlapping with other subcarriers while the subcarrier spectrum overlaps .This will give us overlapped but orthogonal signal sets [44].This orthognality occurs from direct correlation between any two subcarriers is given by [43, 45]:

$$\delta_{kl} = \frac{1}{T_s}\int_0^{T_s} s_k s^* l \, dt = \frac{1}{T_s}\int_0^{Ts} \exp\,(j2\pi(f_k - f_l)t)\,dt = \exp\,((j2\pi(f_k - f_l)T_s)\frac{\sin(\pi(f_k - f_l)T_s)}{\pi(f_k - f_l)T_s} \qquad (3.7)$$

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

$$f_k - f_l = m\frac{1}{T_s} \qquad (3.8)$$

is satisfied ,and the two subcarriers are orthogonal to each other .This orthognality condition will help to improve the signal without Intercarrier Interference (ICI) ,regardless of the strong overlapping of the signal spectral . Figure 3.10 illustrates power signals where their spectrums are overlapping but their centers are spaced equally.

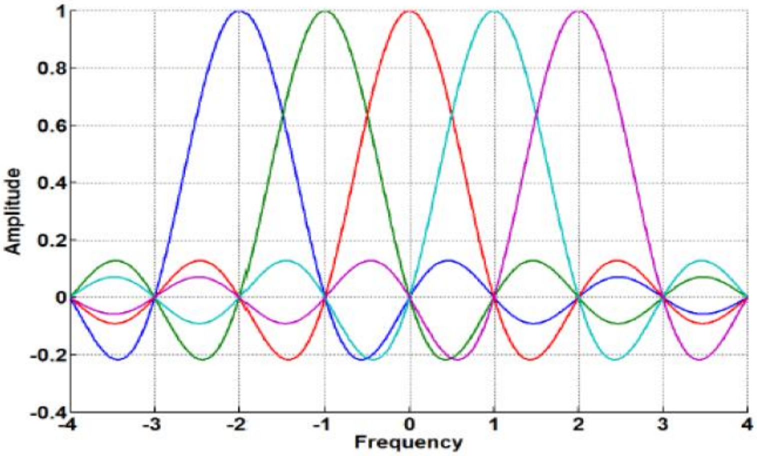

Figure 3.10 : OFDM Power Spectrum[18]

3.4.5 Guard Interval

The Guard Interval is essential to prevent the Inter-Symbol Interference (ISI), and to maintain orthogonality. When there is a delay in the transmitted OFDM symbol then the ISI occur. Which will cause this symbol to interfere with the next OFDM symbol? The Guard intervals provide a period of protection to make sure that the transmitted OFDM symbol apart from the next OFDM symbol .A guard interval could be zero padding, cyclic prefix, or cyclic suffix.

3.4.6 Cyclic Prefix (CP)

CP is used to reduce the effect of the ISI and to improve the multipath propagation problem robustness. This technique involves copying the last fraction of each OFDM symbol and adding it to the front of the symbol. Figure 3.11 illustrate the concept of CP.

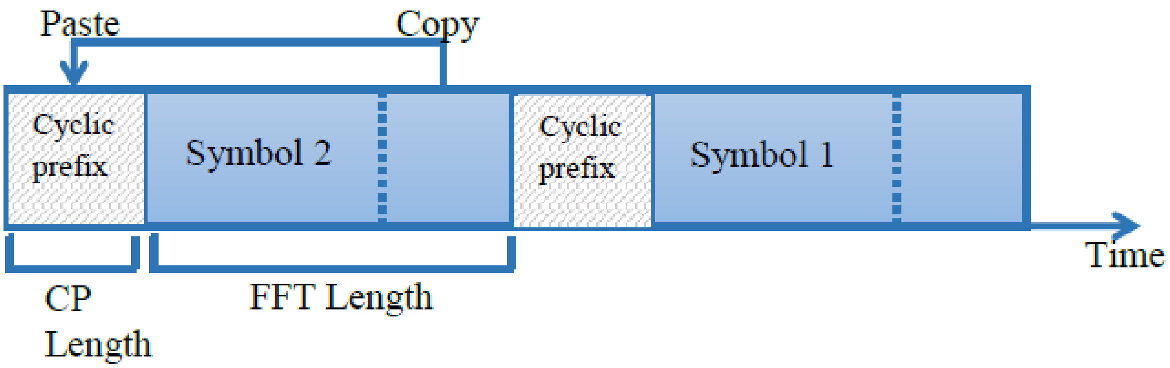

Figure 3.11: OFDM Cyclic Prefix[14]

The CP operator is defined by:

$$\eta = \frac{T_p}{T_s - T_p} \qquad (3.9)$$

Where the length of CP is T_p , T_s is the symbol length after adding the CP, and $T_s - T_p$ Is the FFT length [18] .

The CP length should be selected carefully to maintain the minimum ISI effect. The CP length should be longer or in the same length as the multipath channel delay .If the CP length is selected shorter than the multipath channel delay ,then the OFDM symbol will be affected by next OFDM symbol which will cause ISI [46].

After adding the CP , the OFDM signal will pass through parallel to serial converter to convert the parallel OFDM symbols to serial symbols .After this operation , the OFDM signals are ready now for up conversion process .

3.5 OFDM Demodulation

In this operation, assume that a perfect estimation for the receiver is done, then the guard interval will be removed .To get the original OFDM signal .Also, the cyclic prefix CP which was added to the transmitter side should be removed, CP removal is an easy process as shown in Figure 3.12, where the CP length of Tp should be removed to get the original OFDM symbol.

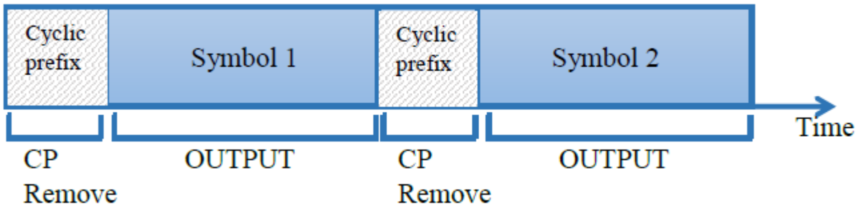

Figure 3.12: OFDM Cyclic Prefix Removal[14]

3.5.1 Fast Fourier Transform (FFT)

By removing the guard intervals, the OFDM symbols are now ready to enter the next stage which is the FFT, this can be done by converting the real values to the frequency domain. So FFT can recover the subcarriers in one step without needing the large numbers of oscillators and filters. After down converting the signal, the digital signal can be represented by:

$$r(k) = \exp\left(j\frac{2\pi kv}{N_{FFT}}\right)\sum_{p=0}^{k-1} h_p s(k-\eta) + n(k) \qquad (3.10)$$

where v is the carrier spacing offset, N_{FFT} number of bytes ,and complex gain is represented by h_p , the path time delay is represented by η, and $n(k)$ is the Additive white Gaussian noise AWGN.

3.5.2 Symbol Demapping

Now, the input binary information is recovered as mentioned previously, the original binary input was mapped to complex-valued signals. This depend on the modulation type of the transmitter, the same input information can be recovered using the same modulation type at the receiver. As an example, if the binary input is modulated by using 4-QAM, then there are four complex valued signals on the constellation diagram. Therefore, before the demapping stage, the received signal will have four complex valued signals. But the received signal will have some noise and will not look exactly as the same in the transmitted signal, due to equalization errors and phase shift.

3.6 Optical OFDM

OFDM was introduced to optical domain in 2005,the main two techniques were studied and investigated according to the detection scheme [43].The first technique is the direct detection optical OFDM (DD-OFDM) , and the second technique is the coherent optical OFDM (CO-OFDM).

3.6.1 DD-OFDM

Figure 3.13 shows the block diagram of the DD-OFDM system which consists of a DD-OFDM transmitter, optical fiber link, and DD-OFDM receiver.

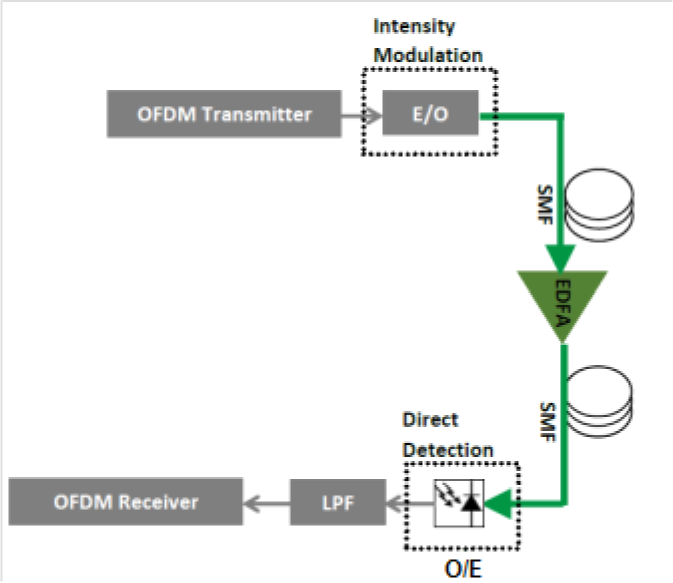

Figure 3.13 : DD-OFDM Block Diagram[14]

At the transmitter side , the OFDM transmitter produces the electrical OFDM signal which already up converted in to optical domain by electrical to optical (E/O) up converter which does the intensity modulation . The generated optical signal is transmitted through optical fiber link and an Erbium Doped Fiber Amplifier (EDFA) is used to compensate for the loss in the fiber.

At the receiver side ,the incoming optical signal is converted to electrical domain by an optical to electrical (O/E)converter , which is in this case a photodiode [47].The received electrical signal is given by:

$$A_e(t) = |A_0(t)|^2 \otimes h_e(t) + w(t) \tag{3.11}$$

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

3.6.2 Coherent Optical OFDM (CO-OFDM)

Figure 3.14 shows the block diagram of CO-OFDM system. The CO-OFDM system is similar to the DD-OFDM system except for the real/imaginary (I/Q) modulator and local oscillator. The optical local oscillator is used in optical coherent systems to generate specific wavelengths. According to the frequency of the local oscillator, the optical coherent detection can be classified

Into two categories, heterodyne detection and homodyne detection.

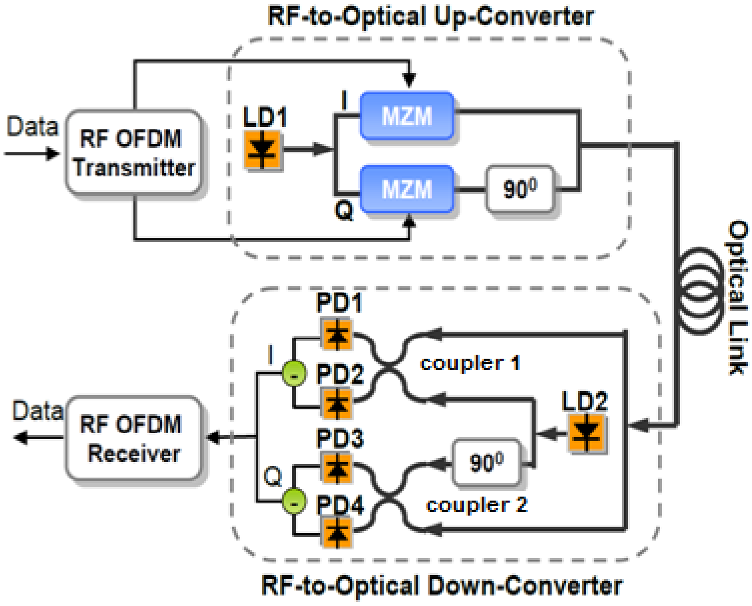

Figure 3.14 : CO-OFDM Block Diagram[11]

In Heterodyne detection scheme, the local oscillator frequency does not match the received signal frequency. So , in the photodiode detector when the two signals are mixed a new frequency is generated , the difference between these two signals is called the intermediate frequency (IF) and IF considered as new frequency [48]. This technique will reduce the thermal noise and the shot noise, and to override this problem we have to improve the SNR performance. However, the optical source frequency tends to drift over time. As a result, the IF has to be regularly monitored, and the local oscillator must be changed correspondingly to maintain the IF constant.

In Homodyne detection scheme, which we will use in this research, the local oscillator frequency is the same as the incoming signal.

The other additional component in the optical coherent system is the I/Q modulator. Where "I" is the "in-phase" component of the waveform, and "Q" represents the Quadrature component. In its various forms, IQ modulation is an efficient way to transfer information, and it also works well with digital formats. An IQ modulator can actually create AM, FM and PM [42].The I/Q components of the digital signal are converted to an analogue signal by using two digital to analogue converters (DAC) at the OFDM transmitter side . The I/Q modulator consists of two

Mach-zehender modulators (MZM) , up converter to convert the complex OFDM signal (I/Q component) to the optical domain , As a result, the modulated signal can be written as:

$$E(t) = x(t)\exp(j\omega_{LD1}t + \phi_{LD1}) \tag{3.12}$$

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

$$E_{r(t)} = E(t) \otimes h(t) + w(t) \tag{3.13}$$

Where h(t) is the channel impulse response and w(t) is the channel noise.

The incoming signal is detected by two identical pairs of balanced coherent detectors and an optical 90^0 hybrid to perform the I/Q optical to electrical conversion. Each detector consists of two couplers and two PIN photodiodes. The output of the four 90^0 optical hybrid ports is given by [49] :

$$E_1 = \frac{1}{\sqrt{2}}[E_r + E_{LD2}] \tag{3.14}$$

$$E_2 = \frac{1}{\sqrt{2}}[E_r - E_{LD2}] \tag{3.15}$$

$$E_3 = \frac{1}{\sqrt{2}}[E_r - jE_{LD2}] \tag{3.16}$$

$$E_4 = \frac{1}{\sqrt{2}}[E_r + jE_{LD2}] \tag{3.17}$$

Where E_{LD2} is the electrical signal from the local oscillator at the receiver. In addition, as can be seen from Figure 3.14, two photodiodes (PD1 and PD2) are used to recover the I component which can be represented by:

$$I_1 = |E_1|^2 = \frac{1}{2}[|E_r|^2 + |E_{LD2}|^2 + 2\operatorname{Re}(E_r E_{LD2})^*] \tag{3.18}$$

$$I_2 = |E_2|^2 = \frac{1}{2}[|E_r|^2 + |E_{LD2}|^2 - 2\operatorname{Re}(E_r E_{LD2})^*] \tag{3.19}$$

Where the real component is represented by Re. The photocurrent of the real components can be represented by [45]:

$$I_1(t) = I_1 - I_2 = 2\mathrm{Re}(E_r E_{LD2})^* \qquad (3.20)$$

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

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

$$I_Q(t) = I_3 - I_4 = 2I\mathrm{m}(E_r E_{LD2})^* \qquad (3.21)$$

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

$$I(t) = I_I + jI_Q = E_r E_{LD2} * \qquad (3.22)$$

Therefore, the detected OFDM signal is:

$$y(t) = I(t) = x(t)\exp(j\Delta\omega t + \Delta\phi) \otimes h(t) + w(t) \qquad (3.23)$$

where $\Delta\omega$ is the angular frequency difference between the laser diode at the transmitter and the local oscillator, and the $\Delta\emptyset$ is the phase difference between them which can be expressed as [50] :

$$\Delta\omega = \omega_{LD1} - \omega_{LD2}' \qquad (3.24)$$

$$\Delta\phi = \phi_{LD1} - \phi_{LD2}' \qquad (3.25)$$

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

3.6.3 Comparison between DD-OFDM and CO-OFDM

By comparing CO-OFDM with DD-OFDM, we will find that the CO-OFDM provides the best robustness against chromatic dispersion CD, and polarization mode dispersion PMD .This is because of the linear effect in coherent detection technique which improves the receiver sensitivity. Therefore, theoretically, the dispersion tolerance in CO-OFDM is unlimited. On the contrary, the dispersion tolerance in DD-OFDM is limited because of the nonlinear direct detection [51-53].

On the other hand, CO-OFDM needs frequency offset compensation because the use of the local oscillator which make problems in the receiver part when compared to the DD-OFDM. In addition, CO-OFDM is mostly used in long-haul applications due to the expensive and complex equipment used in the E/O and O/E conversion. In contrast , DD-OFDM is cost effective solution for cost sensitive applications such as Local Area Networks LANs and Metropolitan Area Networks MANs[51-53].

Chapter 4: System Design and Analysis

CO-OFDM system is designed and investigated with 4-QAM for long-haul transmission. The CO-OFDM system is fully designed and simulated by using OptiSystem simulation software V.13

OptiSystem is a comprehensive software design suite that enables users to plan, test, and simulate optical links in the transmission layer of modern optical networks, also it can be used by telecommunications companies around the world for planning and implementing a full optical network, which is a low cost and time saving approach, and the researchers can use it to work in highly effective manner.[54]

4.1 CO-OFDM System with SMF setup

The CO-OFDM system consists of the transmitter part, the optical fiber link, and the receiver .Figure 4.1 shows the system block diagram of a CO-OFDM system with single mode fiber (SMF) of 100 Km. The CO-OFDM transmitter is built with Pseudo Random Binary Sequence (PRBS) which generates a bit sequence that will approximate the random data characteristics, and a 4-QAM (2bit per symbol) works as encoder. The 4-Qam signal is linked to an OFDM modulator with 512 subcarriers and the number of FFT points is (1024). The resulting signal from the OFDM modulator will separate in two phases, the in-phase (I) and Quadrature (Q) to enter the RF to optical up converter (RTO) which consist of two Mach-Zehender modulators(MZM). The (MZM) will modulate the electrical signal from the OFDM modulator to the optical carrier with a laser source frequency (193.5) THz with power (-5 dBm).The resulting optical signal is then transmitted over SMF with an attenuation of 0.2 dB/km, a dispersion of (16 ps/nm/km), with a dispersion slope of (0.08 ps/nm^2/km) and a nonlinearity coefficient (2.6×10^{20}). An Erbium Doped Fiber Amplifier (EDFA) is used to amplify the optical signal and to compensate for the loss.

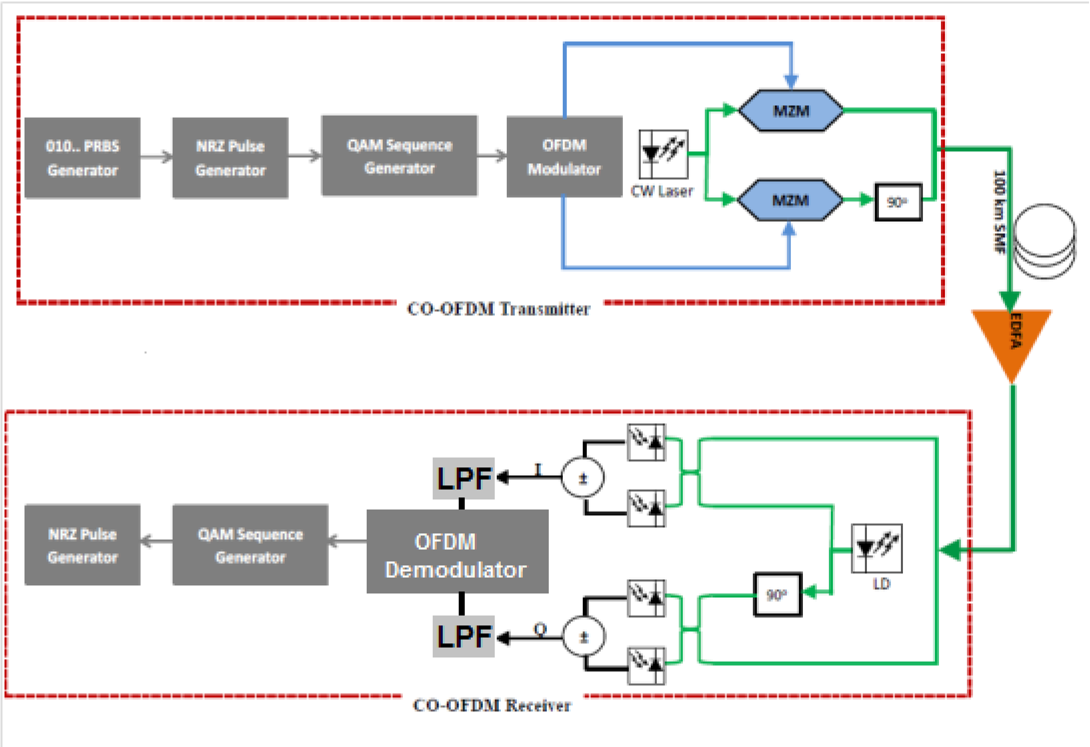

Figure 4.1 CO-OFDM Systems with 100 km SMF [14]

At the receiver side, the optical signal is detected by two identical pairs of balanced coherent detectors with a local oscillator (LO) to complete the I/Q optical to electrical conversion and also to cancel the noise. Every coherent detector consist of two PIN detectors and two couplers .The PIN photodetector has a dark current of 10 nA, a responsively of 1A/W, a thermal power density of (100x10^{-23} W/Hz), and a center frequency of 193. 5 THz. After this stage, the signal now is ready to enter the OFDM demodulator stage which is similar in parameters to the OFDM modulator and the guard interval is removed. Lastly, the resulting signal is fed into 4-QAM decoder to build the binary signal. The global parameters which used in the system are listed in table 4.1

Global parameters	
sequence length	16384 Bits
samples per bit	8
Number of samples	131072

Table 4.1: Simulation Global Parameters

4.1.1 Results and Discussion

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

Figure 4.2 demonstrate a clear constellation diagram of the 4-QAM modulator at the transmitter side. In QAM, the constellation points are usually arranged in a square grid with equal vertical and horizontal spacing , Since in digital telecommunications the data are usually binary, the number of points in the grid is usually a power of 2[55]. The OSNR value is (57.064 dB). The constellation diagram shows the modulated signal as a two dimensional scatter diagram which helps to study the distortion and the interference that will occur in the signal.

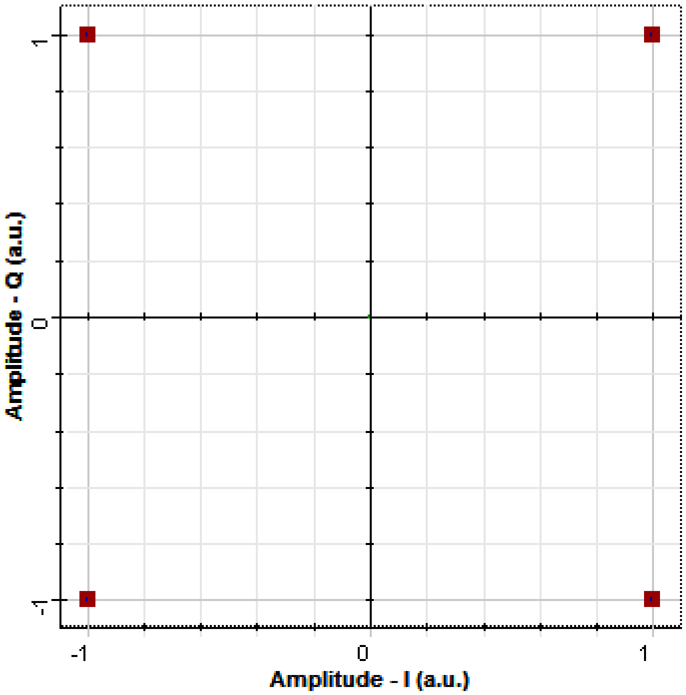

Figure 4.2: Constellation Diagram of 4-QAM at the CO-OFDM Transmitter

Figure 4.3 shows the RF spectrum for the I/Q component of the system at the CO-OFDM transmitter. The RF power is approximately (-7 dBm).

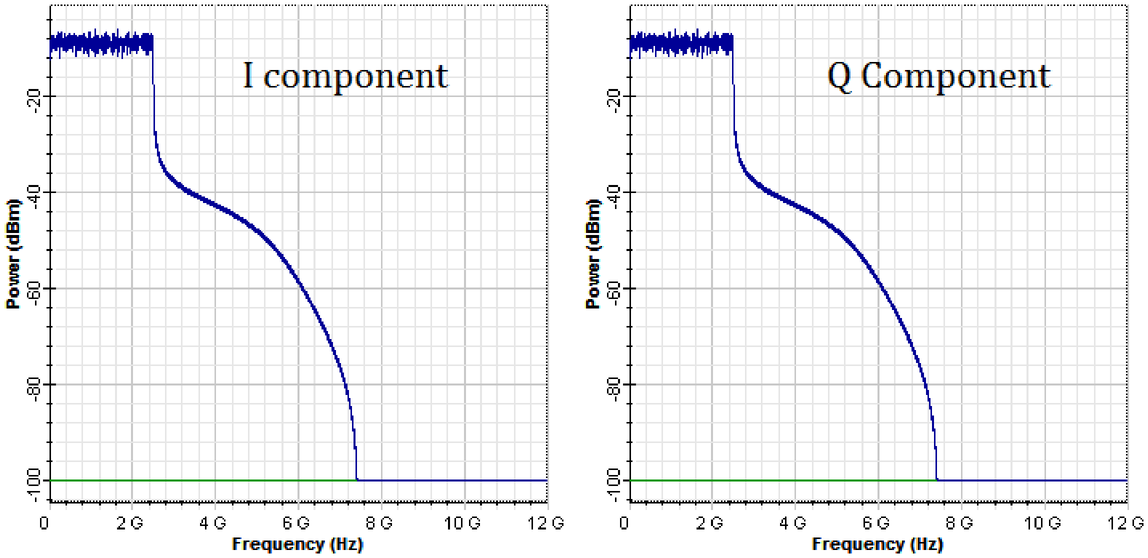

Figure 4.3: RF OFDM Spectrum I/Q Components

Figure 4.4 shows the optical signal spectrum, after modulating the electrical signal with the optical carrier using two MZMs.

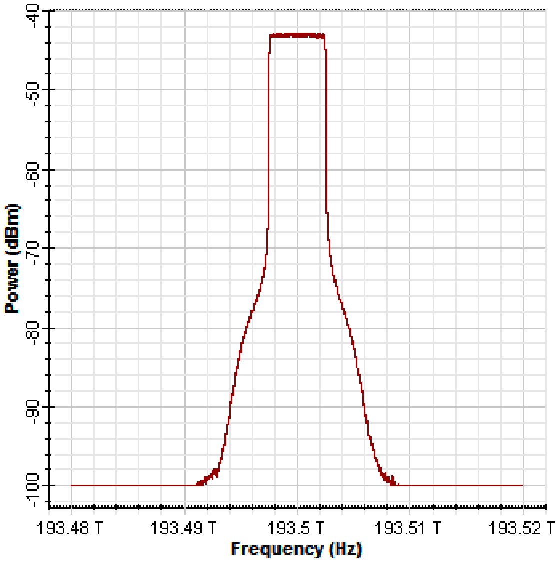

Figure 4.4: Optical OFDM Spectrum after the Two MZM Modulation

Figure 4.5 shows the constellation diagram of the system after 100 km SMF with EDFA amplifier of 25 dB at the receiver side. By comparing to Figure 4.2, the signal seems to be unclear and the OSNR degraded to (24.4 dB) because of the attenuation, chromatic dispersion and the noise, the blue dots represents the thermal and shot noise, the shot noise from the laser source, and the thermal noise from the photodetectors and the fiber dispersion.

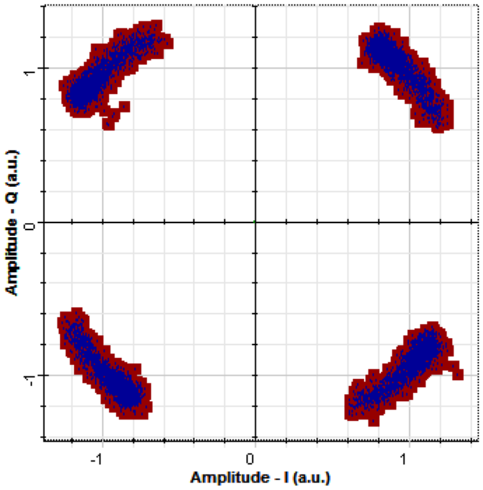

Figure 4.5: Constellation Diagram of CO-OFDM System at the Receiver Side after 100 km

Figure 4.6 shows the constellation diagram of the CO-OFDM system after 200 km SMF at the receiver side. Also it shows some distortion in the signal, by comparing with 100 Km SMF results in Figure 4.5. The distortion is increased and the OSNR degraded to (23.7dB)

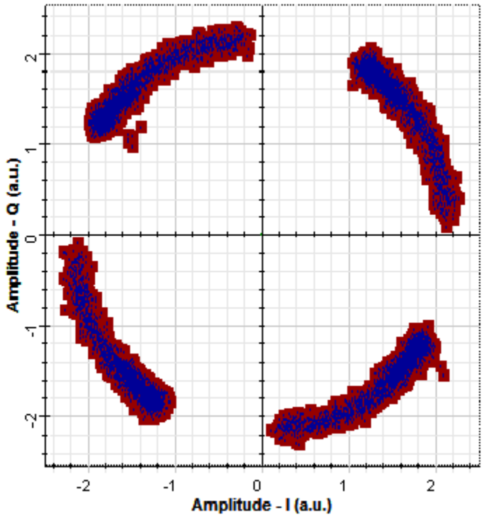

Figure 4.6: Constellation Diagram of the CO-OFDM System after 200 Km

Figure 4.7 shows the constellation diagram after 300 Km, it seems that the system will not easily detect the signal and the OSNR degraded to (23.4 dB).

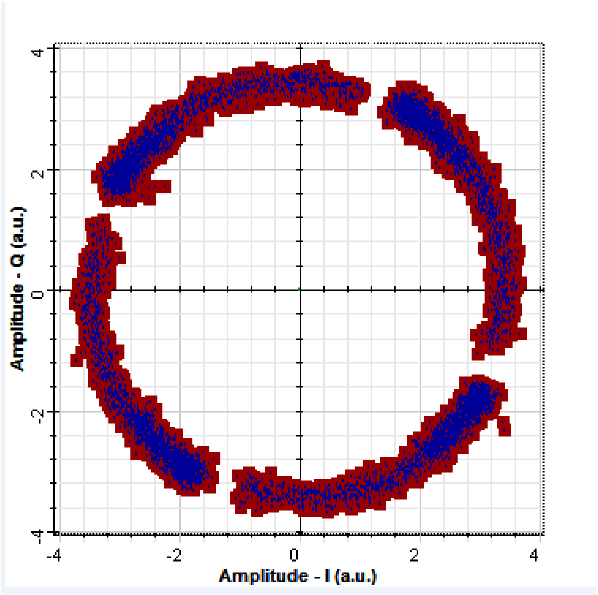

Figure 4.7: Constellation Diagram of the CO-OFDM System after 300 Km

Figure 4.8 shows the constellation diagram after 400 Km, It can be seen that the signal is distorted and totally corrupted. As mentioned before, Chromatic Dispersion causes the broadening of the signal after long distances and the attenuation increases.

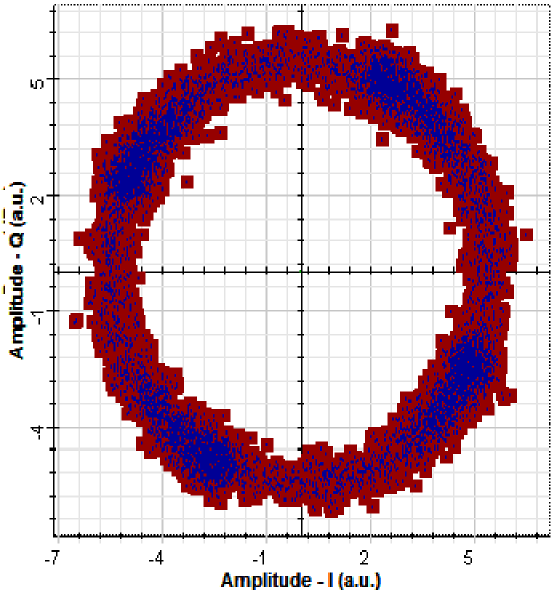

Figure 4.8: Constellation Diagram of the CO-OFDM System after 400 Km

Figure 4.9 shows the relationship between the OSNR values and distance values, it can be seen that the OSNR value at the receiver side is degraded regarding to the increasing of the distance.

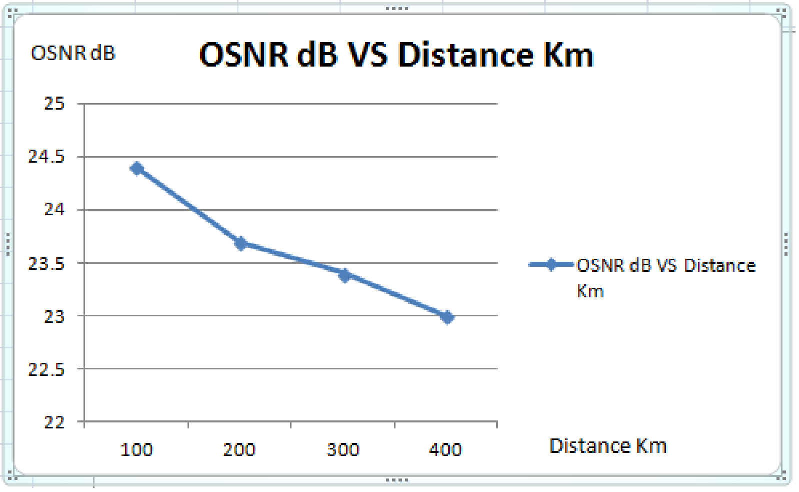

Figure 4.9: OSNR Vs Distance chart

From all previous constellations diagrams, the system cannot detect the signal at long distances. To solve this problem, we can increase the power of EDFA amplifier with limits, because the EDFA amplifier works effectively when the signal has low power loss. But, when the transmission length increases, the OSNR decreases and the signal is weak, even with increasing the power of EDFA the signal will not improve.

In the next section, a Dispersion Compensation Fiber (DCF) is proposed as a solution to help improve the quality of the signal and increase the transmission distance without the need of increasing the power of the EDFA.

4.2 CO-OFDM with Dispersion Compensation Fiber (DCF)

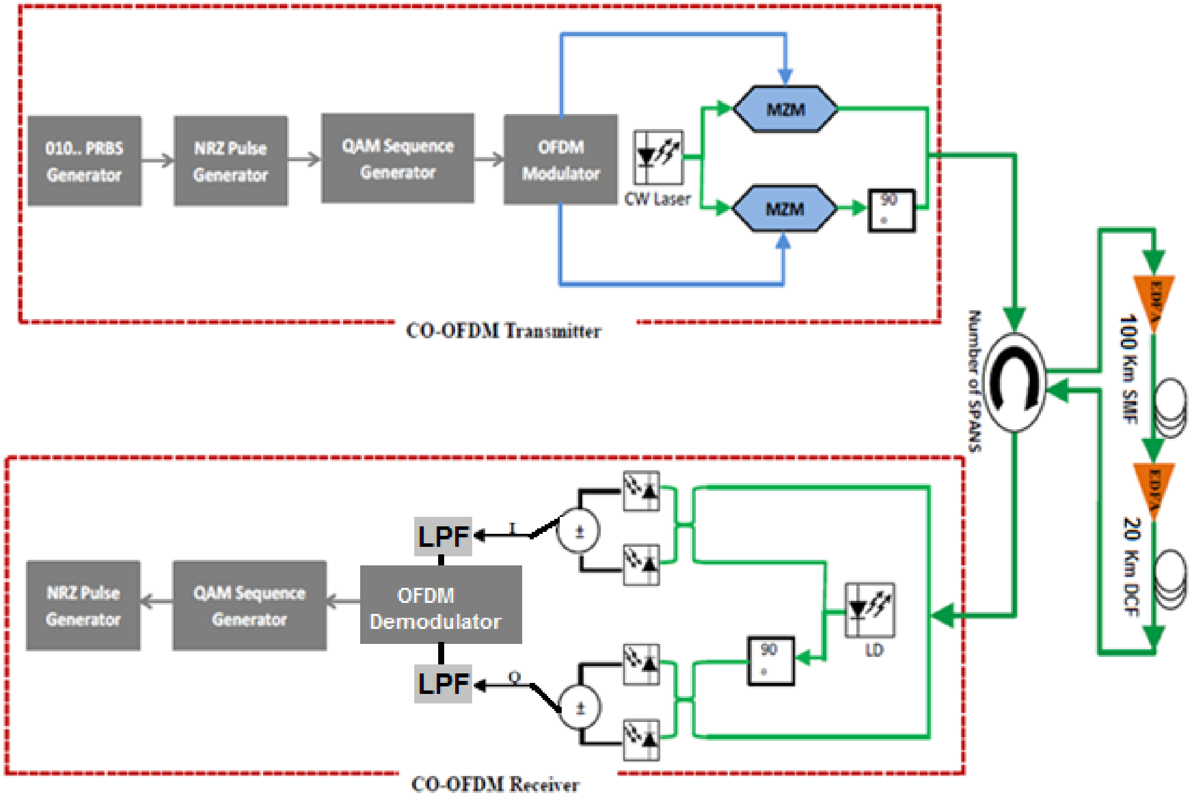

Figure 4.10: System Design of CO-OFDM with SMF-DCF [14]

Figure 4.10 shows the system design of the CO-OFDM system with a SMF-Dispersion Compensation Fiber. The DCF will compensate the dispersion of SMF and increase the transmission distance. The CO-OFDM transmitter is built with a Pseudo Random Binary Sequence (PRBS), to generate a bit sequence that will approximate the random data characteristics, and a 4-QAM (2 bit per symbol) encoder. The 4-QAM signal is connected to an OFDM modulator with a (512) subcarrier and (1024) FFT points. The in-phase (I) and Quadrature (Q) of the resulting signal from the OFDM modulator is transmitted to the direct I/Q optical modulator. The direct I/Q modulator consists of two lithium Niobate (LiNb) Mach-Zehnder modulators (MZM) and will modulate the electrical signal from the OFDM modulator to the optical carrier with a laser source of 193. 5 THz. a power of the laser source is (-5 dBm).

The resulting optical signal from the two LiNb MZMs is then transmitted through the SMF-DCF system. The SMF attenuation is (0.2 dB/km) and the DCF attenuation is (0.4 dB/km). The SMF dispersion is (16 ps/nm/km) for 100 km. The SMF will produce a dispersion of $16 \times 100 = 1600$ ps/nm. Therefore, to compensate the dispersion of the 100 km SMF, a 20 km long DCF is needed with dispersion of -80 ps/nm/km. This will produce a dispersion of $-80 \times 20 = -1600$ ps/nm, which will be negative to cancel the positive dispersion of the SMF. Two Erbium Doped Fiber Amplifiers (EDFA) are used, the first EDFA amplifier with (15 dB)gain to amplify the signal and to compensate for the loss with noise figure 2 dB , the second EDFA amplifier with(13 dB) gain and noise figure of 2 dB to amplify the signal which comes out of the DCF .

At the receiver side, the incoming optical signal is detected by two identical pairs of balanced coherent detectors with a local oscillator (LO) to perform the I/Q optical to electrical conversion and to cancel the noise. Each detector consists of two couplers and two PIN photodetectors. Each PIN photodetectors has a dark current of 10 nA, a responsivity of 1 A/W, a thermal noise of 100x10^{-23} W/Hz, and a center frequency of 193.5 THz. After detecting the signal by the balanced detectors, the signal is sent to the OFDM demodulator. The OFDM demodulator has similar parameters to the OFDM modulator and the guard interval is then removed. Finally, the resulting signal is fed into a 4-QAM decoder to create a binary signal.

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

Table 4.2: SMF Parameters

DCF Parameters	
Dispersion	**-80 ps/nm/km**
Dispersion Slope	**0.08 ps/nm^2 /Km**
PMD Coefficient	**0.5 ps/km**
Effective area	**22 um^2**
Nonlinearity Coefficient	**2.6×10^{-20}**
Attenuation	**0.5 dB/km**

Table 4.3: DCF Parameters

4.2.1 Results and Discussion

The simulation results of the long-haul CO-OFDM with DCF for different transmission lengths starting from 600 km to 6600 km are presented and discussed in this section.

Figure 4.11 shows the constellation diagram of the system at the CO-OFDM receiver side after 600 km of fiber length using five spans for both the SMF of 100 km and the DCF 20 km. The gains of the two EDFA's are in the same order parameters of 15 dB and 13 dB respectively, and the OSNR value degraded from (57.06 dB) to (15.97 dB).

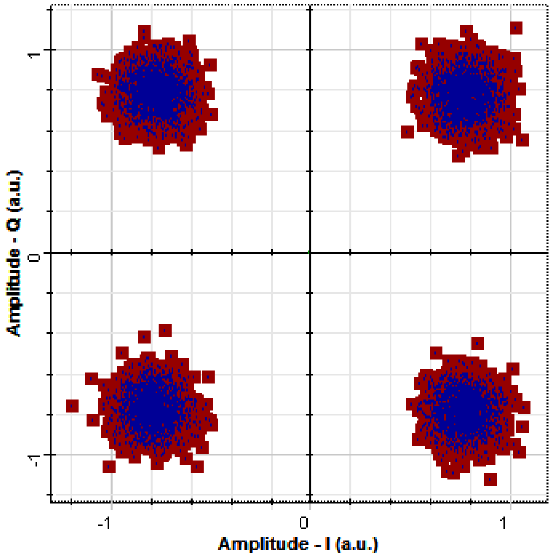

Figure 4.11: Constellation Diagram of the CO-OFDM System after 600 Km

Figure 4.12 shows the constellation diagram of the system at the CO-OFDM receiver side after 1800 km of fiber length using 15 spans for both the SMF of 100 km and the DCF 20 km. The powers of the two EDFA's are in the same order parameters of 15 dB and 13 dB. The signal is now suffer from little dispersion as the length increases the dispersion increases, and the OSNR degraded to (11.35 dB).

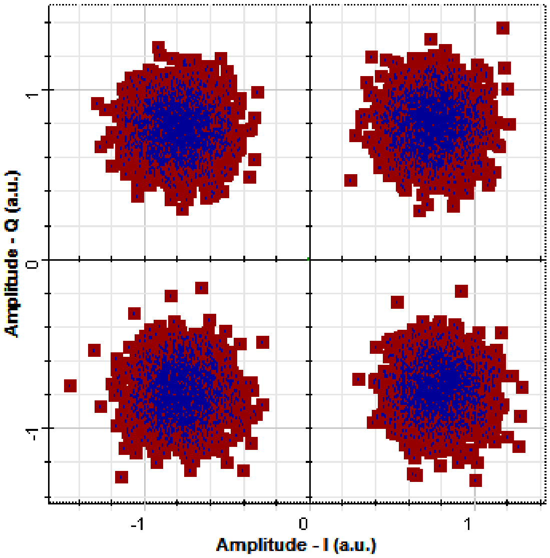

Figure 4.12: Constellation Diagram of the CO-OFDM System after 1800 Km

Figure 4.13 shows the constellation diagram of the system at the CO-OFDM receiver side after 3000 km using 25 spans for both the SMF of 100 km and the DCF 20 km. We can see that the signal still be detected and the dispersion is directly proportional with the length, and the OSNR degraded to (9.15 dB).

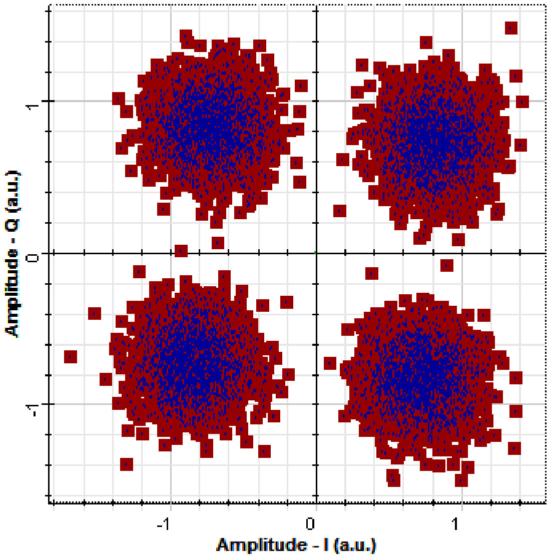

Figure 4.13: Constellation Diagram of the CO-OFDM System after 3000 Km

Figure 4.14 shows the constellation diagram of the system at the CO-OFDM receiver side after 4200 km using 35 spans for both the SMF of 100 km and the DCF 20 km. The signal still be detected although the dispersion still rising with the length, and the OSNR degraded to (7.69dB).

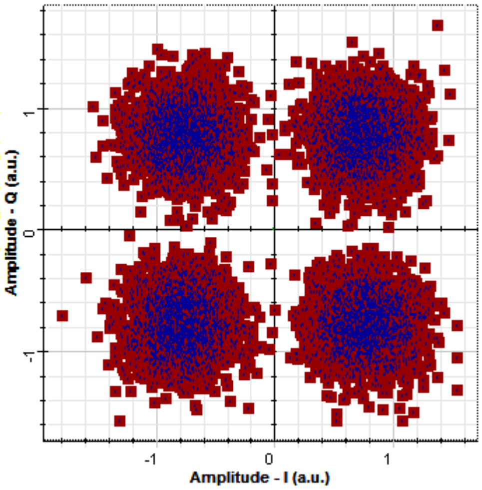

Figure 4.14: Constellation Diagram of the CO-OFDM System after 4200 Km

Figure 4.15 shows the constellation diagram of the system at the CO-OFDM receiver side after 5400 km using 45 spans for both the SMF of 100 km and the DCF 20 km. The signal suffers from too much distortion but still can be detected with the possibility of errors, and the OSNR degraded to (6.59 dB).

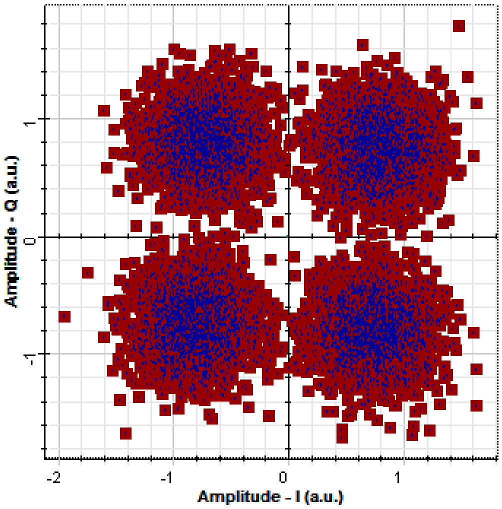

Figure 4.15: Constellation Diagram of the CO-OFDM System after 5400 Km

Figure 4.16 shows the constellation diagram of the system at the CO-OFDM receiver side after 6600 km using 55 spans for both the SMF of 100 km and the DCF 20 km. The signal suffers from too much distortion, and it is difficult to detect the signal with the same parameters due to the high amount of noise and attenuation caused by the long distance which weakens the signal, and the OSNR degraded to (5.75 dB).

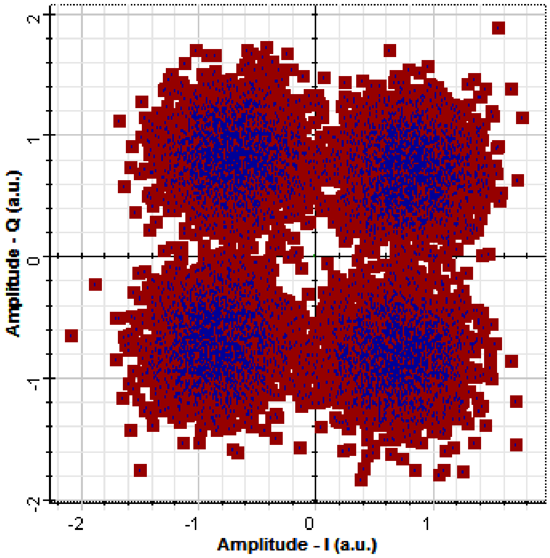

Figure 4.16: Constellation Diagram of the CO-OFDM System after 6600 Km

By applying the same simulation parameters with increasing of spans numbers, the signal is totally corrupted and cannot be recovered due to high amount of noise and attenuation caused by the long distance. Figure 4.17 shows the relationship between the OSNR values and distance values, it can be seen that the OSNR value at the receiver side is degraded regarding to the increasing of the distance.

One of the solutions to increase the transmission distance in this setup, is to increase the EDFA gain. As a result, if the EDFA power is increased, the signal will optimized for hundreds of kilometers and after that will be corrupted, because of the long transmission distance and the increase in the nonlinear effects due to the high increase in EDFA gain.

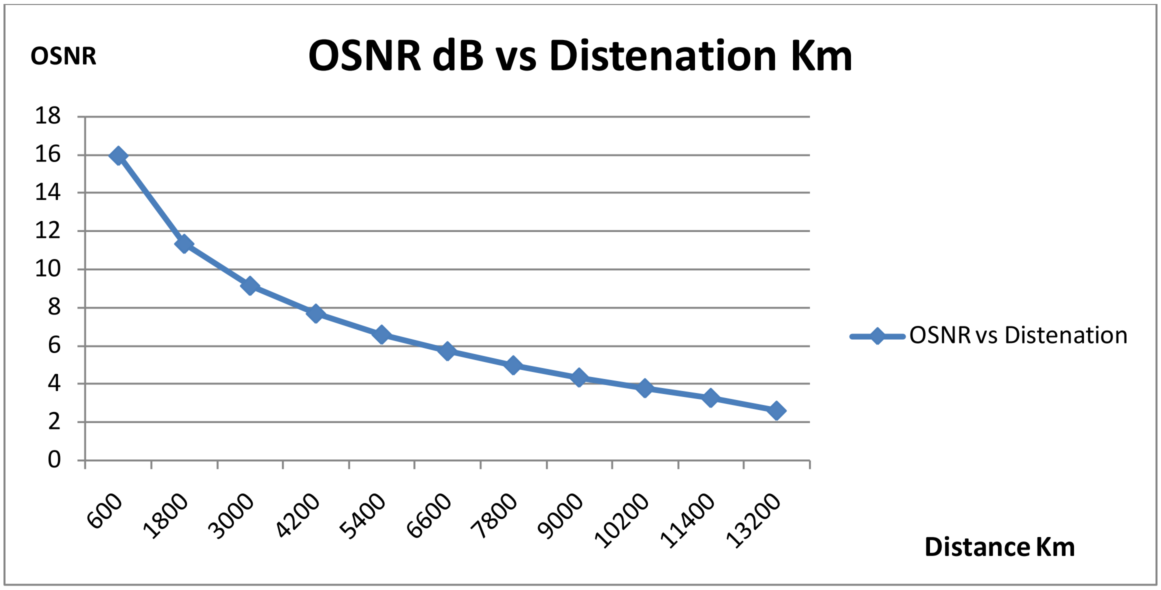

Figure 4.17: OSNR Vs Distance chart

4.3 DD-OFDM System with SMF setup

The DD-OFDM system consists of the transmitter part, the optical fiber link, and the receiver. Figure 4.18 shows the system block diagram of DD-OFDM system with single mode fiber (SMF) .The DD-OFDM transmitter is built with Pseudo Random Binary Sequence (PRBS) which generates a bit sequence that will approximate the random data characteristics, and a 4 -QAM (2bit per symbol) works as encoder. The 4-Qam signal is linked to an OFDM modulator with (512) subcarrier and the number of FFT points is (1024). The resulting signal from OFDM modulator will separate in two phases the in-phase (I) and Quadrature (Q) to enter the Lp cosine roll off filter to enter the Quadrature modulator with frequency of 7.5 GHz , after that the signal will enter the RF to optical up converter (RTO) which consists of one Mach-Zehender modulator (MZM).The (MZM) will modulate the electrical signal from OFDM modulator to the optical carrier with laser frequency (193.5) THz and power of -5 dBm.The resulting optical signal is then transmitted over SMF with attenuation (0.2 dB/Km),a dispersion of 16 ps/nm/km,a dispersion slope of 0.08 ps/nm^2/km and a nonlinearity coefficient of 2.6×10^{-20}. An Erbium Doped Fiber Amplifier (EDFA) is used to amplify the optical signal and to compensate for the loss.

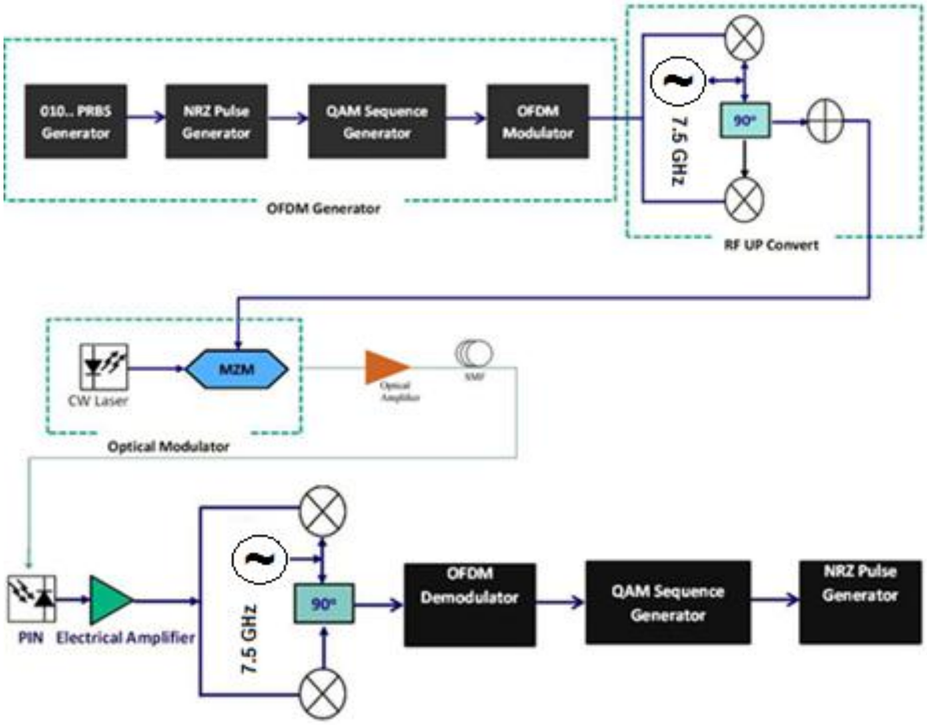

Figure 4.18: DD-OFDM system block diagram[56]

At the receiver part, the optical signal is detected by PIN detector and electrical amplifier .The PIN photodetector has a dark current of 10 nA, a responsively of 1A/W, a thermal power density ($15x10^{-23}$ W/Hz), and a center frequency of 193.5 THz. The electrical amplifier has a gain of 16 dB and noise power of -50 dBm, after this stage, the signal now is ready to enter the OFDM demodulator stage which is similar in parameters as the OFDM modulator and the guard interval is removed .Lastly, the resulting signal is fed in to 4-QAM decoder to build the binary signal.

Global parameters	
sequence length	16384 Bits
samples per bit	8
Number of samples	131072

Table 4.4: Global parameters

4.3.1 Results and Discussion

The simulation results of the long-haul DD-OFDM for different transmission Lengths starting from 100 km to 300 km are presented and discussed in this section.

Figure 4.19 shows a clear constellation diagram of the 4-QAM modulator at the transmitter side. The OSNR value is (40.54 dB). The constellation diagram shows the modulated signal as a two dimensional scatter diagram which helps to study the distortion and the interference that occurs in the signal.

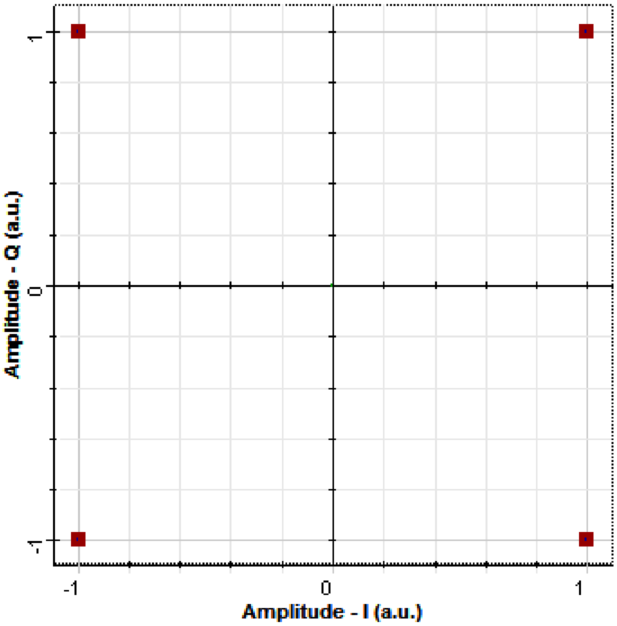

Figure 4.19: Constellation Diagram of 4-QAM at the DD-OFDM Transmitter

Figure 4.20 shows the RF spectrum for the I/Q component of the system at the DD-OFDM transmitter. The RF power is measured at almost (-8.5 dBm).

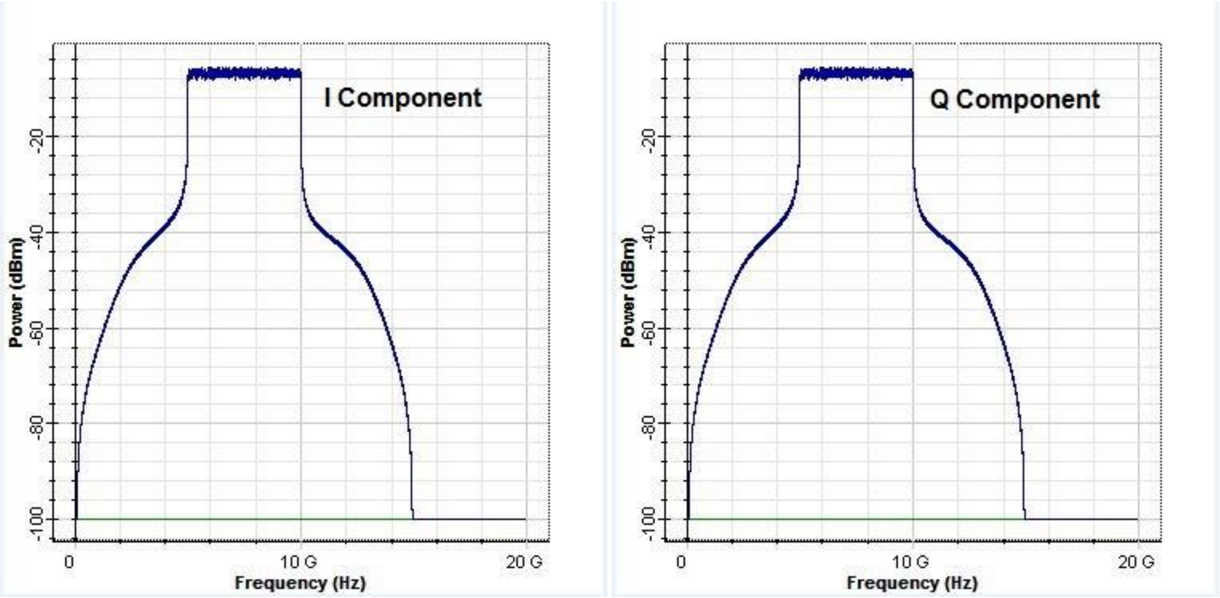

Figure 4.20: RF OFDM Spectrum I/Q Components

Figure 4.21 shows the Optical OFDM Spectrum after the MZM Modulator. The optical spectrum power is (2 dBm) measured after the optical amplifier.

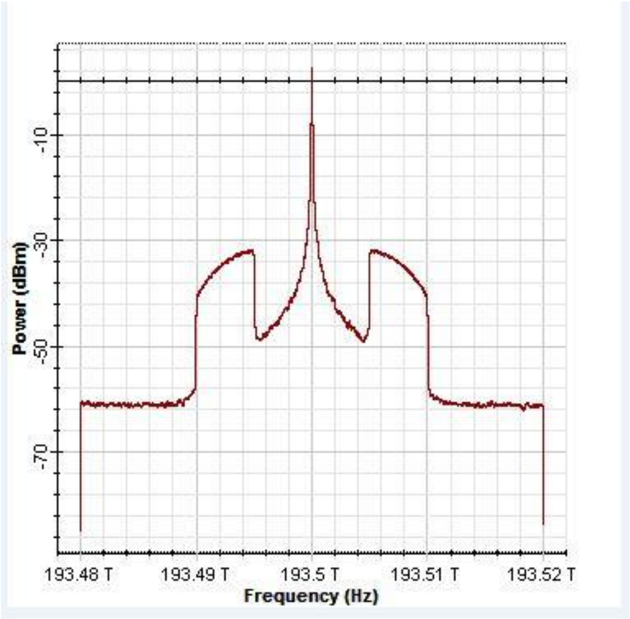

Figure 4.21: Optical OFDM Spectrum after the MZM Modulator

Figure 4.22 shows the optical OFDM spectrum in the receiver side, the optical spectrum power is (6 dBm), the power decreased because the fiber attenuation, noise, and chromatic dispersion.

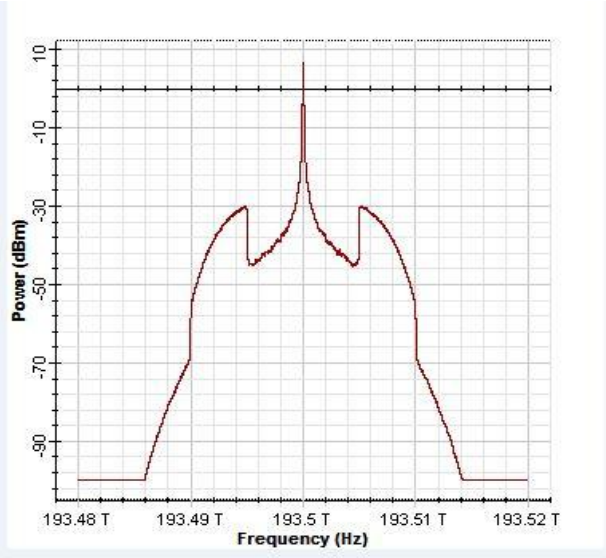

Figure 4.22: Optical OFDM Spectrum in the receiver side

Figure 4.23 shows the constellation diagram of the system after 100 km SMF with EDFA amplifier of 12 dB at the receiver side. By comparing with the transmitter constellation diagram in Figure 4.19, the signal seems to be unclear and the OSNR is (38.11 dB) because of the attenuation, chromatic dispersion and the noise, the blue dots represents the thermal and shot noise, the shot noise from the laser source, and the thermal noise from the photodetectors and the fiber dispersion .Also, by comparing the DD-OFDM constellation diagram with that of CO-OFDM with the same distance shows in Figure 4.5 , we can notice that the signal in DD-OFDM is distorted and seems to drift to the center.

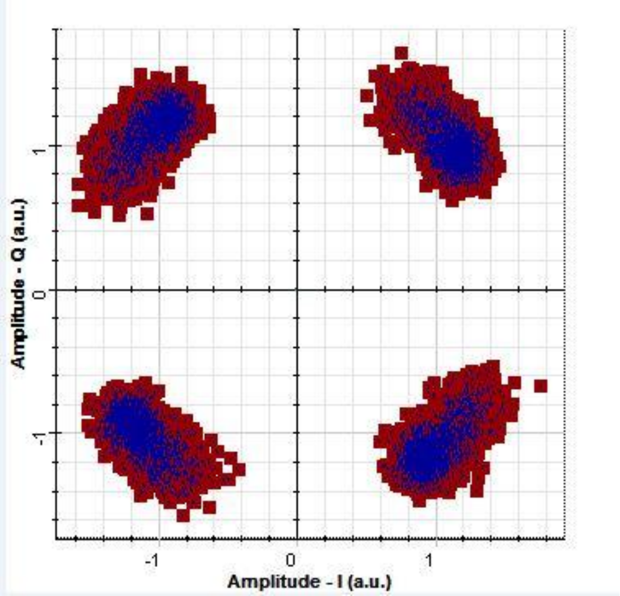

Figure 4.23: Constellation Diagram of DD-OFDM System at the Receiver Side after 100 km

Figure 4.24 shows the constellation diagram of the DD-OFDM system after 200 km SMF at the receiver side. Also it shows more distortion in the signal, by comparing with the Figure 4.23 of DD-OFDM system, the distortion is increased because of attenuation, chromatic dispersion from optical fiber length and noise. By comparing with Figure 4.6 in CO-OFDM system at the same length, we can notice the more complexity in the signal after the same length in CO-OFDM, and the OSNR degraded to (37.43 dB).

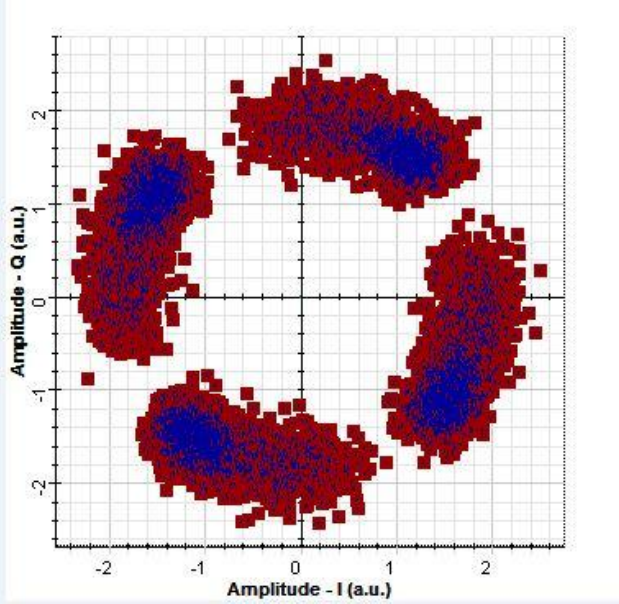

Figure 4.24: Constellation Diagram of DD-OFDM System at the Receiver Side after 200 km

Figure 4.25 shows the constellation diagram after 300 Km, it seems that the system will not detect the signal because of the distortion, chromatic dispersion and the noise, the OSNR degraded to (36.5 dB). By comparing with Figure 4.7 of CO-OFDM system, we can notice that the signal distorted in CO-OFDM after 400 Km, but in the DD-OFDM the signal is completely distorted after 250 Km, this indicated that the CO-OFDM system is working much better in the long-haul distances.

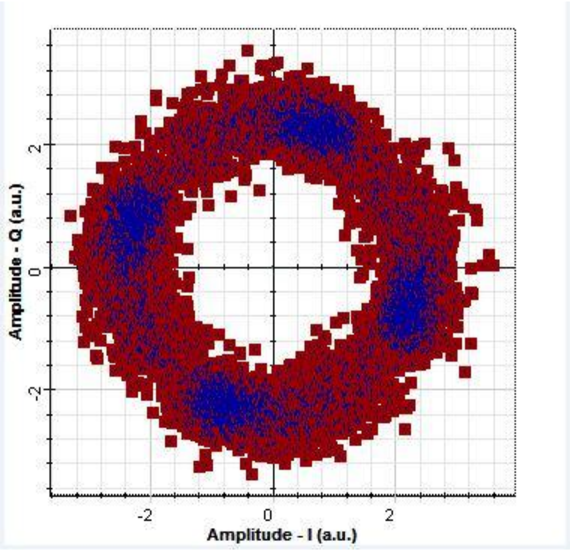

Figure 4.25: Constellation Diagram of DD-OFDM System at the Receiver Side after 300 km

In conclusion, The common feature for DD-OFDM is of course using the direct detection at the receiver side, DD-OFDM takes advantage of that the OFDM signal is more immune to the impulse clipping noise in the Cable Television (CATV) network [57],but we classified the DD-OFDM in chapter 3 into two categories according to how optical OFDM signal is being generated: (1) linearly mapped DD-OFDM (LM-DD-OFDM), where the optical OFDM spectrum is a replica of baseband OFDM, and (2) nonlinearly mapped DD-OFDM (NLM-DD-OFDM), where the optical OFDM spectrum does not display a replica of baseband OFDM.As a result ,the CO-OFDM system can support high bit rate and high spectral efficiency, with ultimate performance in receiver sensitivity, without any dispersion compensation compared with DD-OFDM system.

4.4 Integration of WDM with CO-OFDM:

WDM is an important feature in the development of optical communications. By using the WDM we can provide more flexibility to the system and to simplify the design of the network, it also enhances the capacity of network by using multiple wavelengths over single fiber, where each wavelength carries a separate channel. As a result, the data rate will increase.

Figure 4.26 shows the system design of WDM CO-OFDM system with a SMF of 200 km length. The CO-OFDM transmitter is built with a Pseudo Random Binary Sequence (PRBS) to generate a bit sequence that will approximate the random data characteristics. It is also built with a 4-QAM (2 bit per symbol) encoder. The 4- QAM signal is connected to an OFDM modulator with a (512) subcarrier and (1024 FFT) points. The in-phase (I) and quadrature (Q) of the resulting signal from the OFDM modulator is transmitted to the direct I/Q optical modulator. The I/Q optical modulator consists of two lithium Niobate (LiNb) Mach-Zehnder modulators (MZM) which will modulate the electrical signal from the OFDM modulator to the optical carrier. The optical carrier which has laser wavelengths starts from 193.05 THz to 193.2 THz.

The WDM system consists of four channels to support the four OFDM bands with channel spacing of 50GHz. Each OFDM signal has a 12 Gbps bit rate which will provide an overall data rate of 48 Gbps. The resulting signals from the OFDM transmitters are launched into the WDM MUX and filtered by a Gaussian optical filter. The four different wavelengths are merged to produce one signal to be launched on a single fiber.

The resulting optical signal of the WDM MUX is then transmitted through the SMF. The SMF attenuation is (0.2 dB/km) and the dispersion is (16 ps/nm/km) for 100 km. SMF will produce a dispersion of 16 × 100 = 1600 ps/nm. An Erbium Doped Fiber Amplifier (EDFA) is used with (20 dB) gain to amplify the signal and to compensate for the loss.

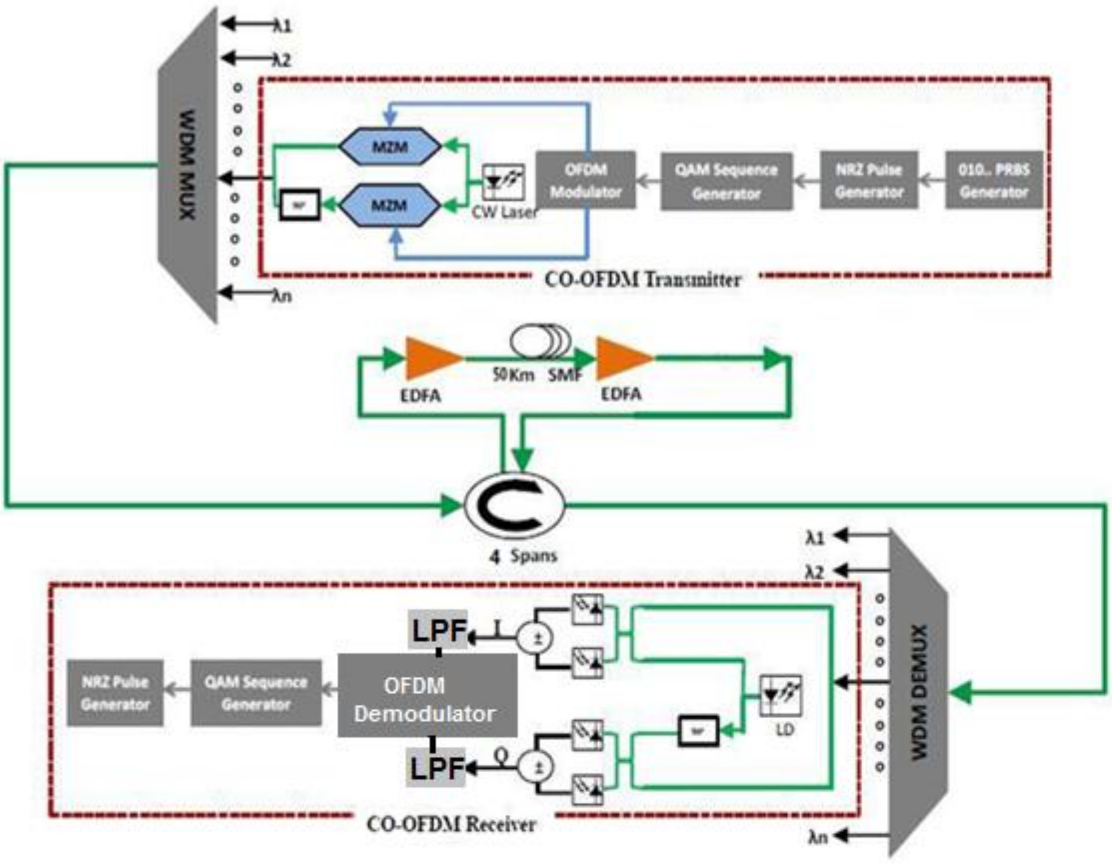

Figure 4.26: WDM CO-OFDM Block diagram of system with SMF [14]

The incoming optical signal from the optical fiber link is separated into four wavelengths by the WDM DEMUX and each wavelength is detected by its designed receiver. Four receivers are designed to have the same parameters except for the center frequency of the receiver and the local oscillator which will be identical to the wavelength of the laser transmitter.

Each receiver consists of two identical pairs of balanced coherent detectors with a local oscillator (LO) to perform the I/Q optical to electrical conversion and cancel the noise. Each detector consists of two couplers and two PIN photodetectors. Each PIN photodetector has a dark current of 10 nA, a responsivity of 1 A/W, and thermal noise of 100×10^{-23} W/Hz. After detecting the signal by the balanced detectors, the signal is sent to the OFDM demodulator which has similar parameters to the OFDM modulator. The guard interval is then removed. Finally, the resulting signal is fed into a 4-QAM decoder to create a binary signal.

4.4.1 Results and Discussion

Figure 4.27 shows the RF spectrum of I/Q component of the CO-OFDM WDM system for one user at the transmitter side .The RF power is measured about (-10 dBm).

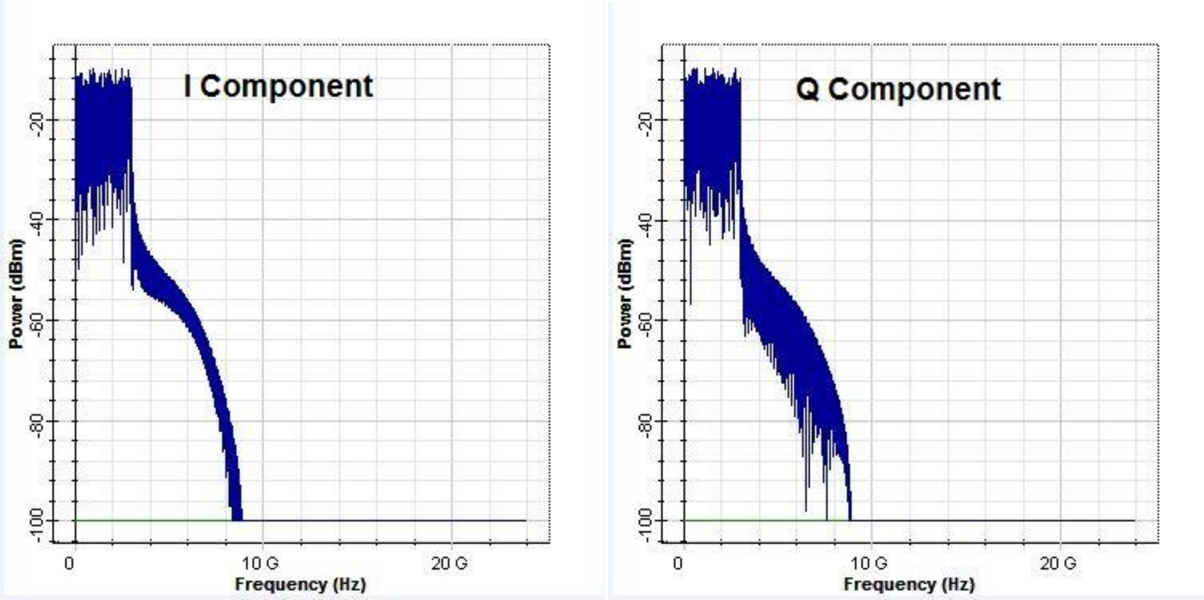

Figure 4.27: RF OFDM spectrum I/Q component at the CO-OFDM transmitter

Figure 4.28 shows the four OFDM spectrums after the WDM system. Four WDM channels starting from 193.05 THz to 193.2 THz with channel spacing of 50GHz,the power of the signals are about (-44 dBm).

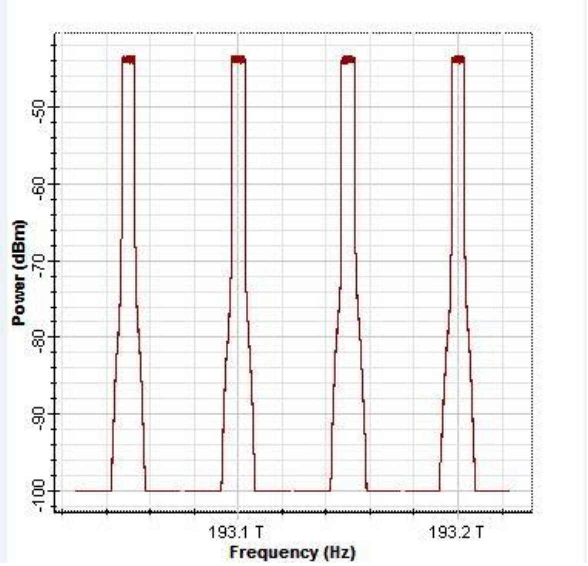

Figure 4.28: OFDM signal after WDM MUX with 4 channels at the transmitter side

Figure 4.29 shows the four OFDM signals after SMF with amplitude of -28 dBm.The amplitude decreased because the noise and the dispersions of the fiber link.

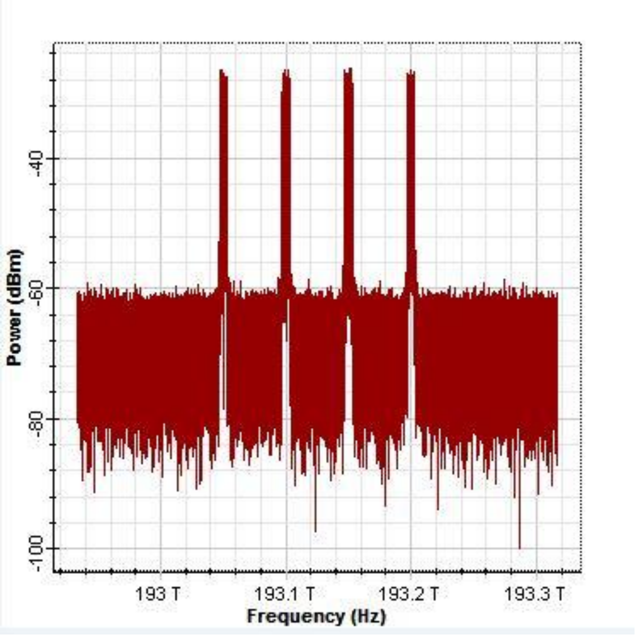

Figure 4.29: OFDM signal after SMF with 4 channels at the receiver side

Figure 4.30 shows the constellation diagram of the WDM CO-OFDM system after 200 Km. As can be seen from the figure, the transmission is successful and the signal is easy to detect.

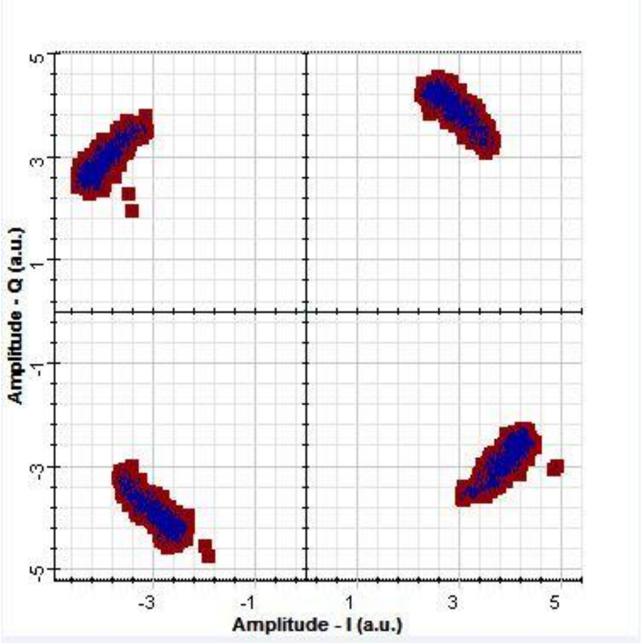

Figure 4.30: Constellation diagram of WDM CO-OFDM for one user at the receiver side after 200 Km

From all previous results , we can figure out that CO-OFDM system integration with WDM systems will give a better performance for the system, and it is easy to use the SMF with variant of wavelengths to increase the data rates capacity of the system .

Chapter 5: Conclusion and Future Work

CO-OFDM has been considered as a promising technique for future high-capacity optical networks, its practical application has been mainly determined by its tolerance to the optical fiber CD and susceptibility to the fiber nonlinearity particularly at high data rates and high Optical power levels. Therefore, addressing these technical challenges and increasing CO-OFDM system tolerance to CD and fiber non-linearity was the main focus of this thesis, for which, a comprehensive investigation (both theoretically and by means of simulation) have been undertaken in order to investigate the possibility of the CO-OFDM technique in coherent optical transmission systems.

The thesis has discussed the concept of CO-OFDM and DD-OFDM, which are widely considered as long-term solutions for long haul networks. CO-OFDM systems are susceptible to SMF CD and nonlinearities, therefore in this thesis; integrating the advantages of both coherent systems and OFDM systems and integrating the coherent optical OFDM with Wavelength Division Multiplexing have been studied.

In the beginning, the performance of a CO-OFDM and DD-OFDM system for short distance was Proposed, simulated, and analyzed. Then, DCF system proposed to increase the transmission distance up to 6600 Km, the DCF system is used to overcome the long-haul transmissions limits caused by the fiber dispersion with high data rates .The simulation results show that the system is reliable and can provide a good transmission for long-haul. By applying some modifications in EDFA amplifier and by adding another DCF, we can reach to a distance for more than 7000 Km.

Then, the performance of the integration of CO-OFDM system with WDM system for long-haul transmission of 200 km with high data rate of 48 Gbps was proposed, simulated, and analyzed. The WDM system consists of four channels to support the four OFDM bands with channel space of 50GHz. Each OFDM signal has a 12 Gbps bit rate which will provide 48 Gbps overall data rate. The results show that the system is reliable and can provide significant high data rates with four wavelengths in one SMF fiber. Also, the results show that the noise and CD increases as the transmission distance increases.

5.1 Future work

Although extensive research has been studied in this thesis, a number of issues related to CO-OFDM based long haul transmission may still be worth investigating in the future.

This research work is summarized as follow:

- Investigating of CO-OFDM, DD-OFDM and WDM transmission distances with the modifications in EDFA and DCF to increase the transmission distance.

- Applying more wavelengths to the WDM system to increase the performance of data rates for more than 1 Tbps.

- Investigating the CO-OFDM with WDM passive optical networks (PONs),where PONs are considered as a solution for the LAN and MAN networks, due to its cheap Electrical to optical E/O and Optical to Electrical O/E conversion. Although, the PONs was extensively researched, their deployment in coherent optical networks has not been investigated.

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