Addis Ababa University
Addis Ababa Institute of Technology
School of Electrical and Computer Engineering
Communication Engineering Graduate Program

PERFORMANCE ANALYSIS OF CO-OFDM INTEGRATED WITH WDM FOR LONG HAUL OPTICAL COMMUNICATION

by:

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A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master's Science in Communication Engineering

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ABSTRACT

The current internet demand requires high spectral efficiency. The integration of CO-OFDM with a WDM system has high spectral efficiency by dividing subcarriers orthogonally. To transmit within a single optical fiber, multiple data streams come together into one by a WDM system. This paper aims to investigate the effect of parametric value difference on the performance of the WDM system as well as CO-OFDM integrated with WDM. The power of the CW laser, the power of the EDFA, the length of DCF, and the EDF are the parameters used. The performance of the system is measured by BER, Q-factor, Eye Opening Height, and OSNR.

The system is designed and analyzed using the "Opti-System" simulation tool. The initial focus is to design WDM without a CO-OFDM system to study the parameters that influence the system's performance. CW laser power is accomplished better at 0 dBm instead of at 10 dBm because when the intensity of light increases, the nonlinearity effects are high. At 100mW, EDFA power dispatches better than if it were at 200mW. When the EDFA amplifies the signal power simultaneously, the noise power is amplified thus, the system's performance is minimized. DCF length is proportional to the length of single-mode fiber, resulting in improved performance. If the above parameter values are not within the normal range, the performance of the system becomes highly distracted.

The subsequent task involves understanding and analyzing which factors limit the transmission capacity and the reachability of CO-OFDM with WDM. The effect of the transmitted data and length on the system's performance is observed.

Key Words: **BER, CO-OFDM, DCF, EDFA, EDF, OSNR, Q-FACTOR, WDM**

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List of Abbreviations

BER	Bit error rate
CD	Chromatic dispersion
CH	channel
CMOS	complementary metal-oxide semiconductor
CO-OFDM	Coherent optical Orthogonal Frequency Division Multiplexing
CWDM	Coarse wave length division multiplexing
DWDM	Dense wave length division multiplexing
DCF	Dispersion Compensating Fiber
EDFA	Erbium Doped Fiber Amplifier
FDM	Frequency division multiplexer
FFT	Fast Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Inter symbol Interference
NRZ	Non Retern To Zero
OFDM	Orthogonal Frequency Division Multiplexing
OSA	Optical Spectrum Analyzer
OSNR	Optical signal noise ratio
PCF	partial carrier filling
PMD	Polarization Mode Dispersion
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RX	Receiver
RZ	Return to Zero
SMF	Single Mode Fiber
TX	Transmitter
WDM	Wavelength Division Multiplexing

Chapter 1: Introduction

1.1 Background of the Study

The demand for high data rates and capacity in the optical communications industry has encouraged us to explore the aspects contributing to integrated technology's performance [1]. The benefits of coherent detection and OFDM are combined in the modulation technology known as CO-OFDM. A local oscillator at the receiver is used in coherent detection to recover the broadcast signal. This makes identifying the optical signal's amplitude and phase possible, improving the system's spectrum efficiency and signal quality. Spectral efficiency is defined as the amount of information per unit of bandwidth [2].

Chromatic dispersion (CD) and polarization mode dispersion (PMD) are two optical fiber limitations that the CO-OFDM system can overcome. Because of the cyclic prefix code, the system is also immune to inter-symbol interference (ISI). Long-distance transmission support, flexible sub-carrier allocation, resilience against fiber impairments, and excellent spectral efficiency are some benefits of integrating OFDM with coherent optical communication [2].

A WDM system combines several data streams into one to transmit across a single optical cable. Expanding the transmission bandwidth per wavelength is necessary to boost a system's capacity. There are two popular methods for increasing the transmission capacity in optical communication. WDM can assist in increasing the bandwidth by adding more transceivers to the current optical fiber lines without building more fiber links. The second method uses complementary metal-oxide semiconductor (CMOS) technology to increase the electrical bandwidth per wavelength. However, in this document, the WDM technique is used to expand the bandwidth of the transmission medium [3]. The design comprises three main parts: CO-OFDM TX (transmitter), optical fiber link, and CO-OFDM Rx (receiver). In this paper, first we design the WDM system, followed by the CO-OFDM with the WDM system [1]. Then, perform an analysis to determine which limit each parameter is more suitable for based on its performance for long-haul optical communication and high data rates, aiming to enhance optical reliability and system performance.

1.2 Motivation of the study

Today's internet traffic in optical communication needs high spectral efficacy one of the techniques to maximize spectral efficacy is to apply CO-OFDM, and also, it is highly resistant to CD and PMD. WDM can help to multiplex multiple data streams to transmit in a single fiber Because of those existing benefits, we are heartily motivated to study the impact of each parametric value difference on the overall performance of WDM and CO-OFDM with the WDM system.

1.3 Statement of the Problem

This work aims to study parameter values that examine the performance of the systems. The performance of WDM and CO-OFDM with a WDM system mostly depends on the number of channels, the length of fiber, the amount of transmitted data, the modulation format, and the availability and unavailability of different parameters. Therefore, for further analysis, we need to investigate the effect of parametric value differences on the system's performance; this is essential to improving its reachability.

1.4 Related works

Various studies have been conducted to enhance the performance of the CO-OFDM integrated with the WDM communication network through different techniques. This section focuses on a review of several related papers that are relevant to this research topic. The paper in [4] describes a cost-effective, high-speed OFDM WDM-PON system utilizing a centralized light-wave source and direct detection that has been proposed and investigated. In this study, our considerations were limited to cost-effectiveness and transmission without a dispersion compensation component. However, to improve the transmission capacity, the CO-OFDM system can address the limitations of the DDO-OFDM system. It offers high receiver sensitivity to enable long-distance transmission. In the DDO-OFDM system, only the intensity information of the light can be detected, while the phase information cannot be detected.

The paper in [5] looks at the performance of the integration of a CO-OFDM system with a

WDM system for long-haul transmission of 200 km with a high data rate of 48 Gbps. The results show that the system is reliable and can provide significantly high data rates with four wavelengths in one SMF fiber. Also, the results show that the noise and CD increase as the transmission distance increases. It demonstrates a straightforward approach to using single-mode fiber (SMF) with different wavelengths to increase the overall data rate capacity of the system. Additionally, it's important to analyze the effects of the EDFAs' pump power and fiber length. The research goal is to investigate each parameter's appropriate value to improve optical reachability as well as data quality.

In the investigation [6] Modulation Mapping Influence in Coherent Optical OFDM System for Long Haul Transmission. This article has evaluated the performance of the M-QAM-modulated CO-OFDM system, including the effect of laser line width and changing the laser power. The system is significantly designed by using OFDM signals of 10 GB/s data rate transfer over standard SMF. The result indicates that for higher orders of modulation, higher OSNR is demanded to get the lowest BER. Rather than adjusting the modulation format, we deploy a WDM system to enhance the transmission capacity with existing fiber.

The paper in [7] studies a Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) as the main wired system for transmitting data at high rates. The simulation results showed that a fiber link length can be increased to 6600 kilometers, with the highest data rate up to 1.65 Tbps. This Journal paper considers improving the data rate and transmission distance by increasing the DCF negative dispersion value only, but also we give attention to EDFA pump power and CW laser power, which helps to demonstrate each parameter's appropriate value to evaluate the performance of the system when transmitting with a minimum BER.

The study focuses on paper [8] Performance Analysis of WDM Coherent Optical OFDM Systems. They examine the performance of integrated technology by studying the effect of several channels and the light intensity, and they show the relation of transmission distance with the Q-factor and BER values. This paper tries to show the factors that affect the peak average power ratio, which is the main factor in OFDM technology, to minimize the performance of the optical transmission. In addition to that, we examine the factors that affect the system's performance, like the pump power of EDFA, the amount of data rates to transmit,OSNR, and show the relation of its performance metrics scenarios within the transmitted data.

Finally the review in[9] Transmission simulation of coherent optical OFDM signals in WDM systems in this simulation, the results show at 10 Gb/s, the Q-factor value is over 13.0 dB for transmission up to 4800 km of standard-single-mode-fiber (SSMF) without dispersion compensation by the technique of partial carrier filling (PCF) for improving the nonlinearity of factors on OFDM transmission. To improve the performance of the system by partial carrier filling (PCF), but in systems with multiple channels, partial filling can lead to increased crosstalk and interference between channels and leads to overall signal power reduction. This can decrease optical signal-to-noise ratio (OSNR), potentially affecting signal quality, especially over long distances. Instead of PCF in this paper, consider an appropriate DCF value to address the above issues on the high data transmission.

1.5 Objective of the study

1.5.1 General Objective

- Study and analyze the parameter values to know the effect on performance of WDM, CO-OFDM integrated with WDM.

1.5.2 Specific Objective

- Explore a WDM system by adjusting various parameter values which are CW laser power, SMF length, DCF length, EDFA forward pump power and length of EDF.
- Examine the parametric values and analyze the system in terms Q-factor, BER, eye opening height and OSNR.
- Explore a CO-OFDM with WDM system by adjusting various parameters which are CW laser power, SMF length, DCF length, EDFA forward pump power and length of EDF.
- Examine the parametric values and analyze the system in terms Q-factor, BER, eye opening height and OSNR.
- Identify the best system and explore the relation of parameter values with the performance of the system.

1.6 Methodology

This section explains how these systems work and the methods used to test their performance.

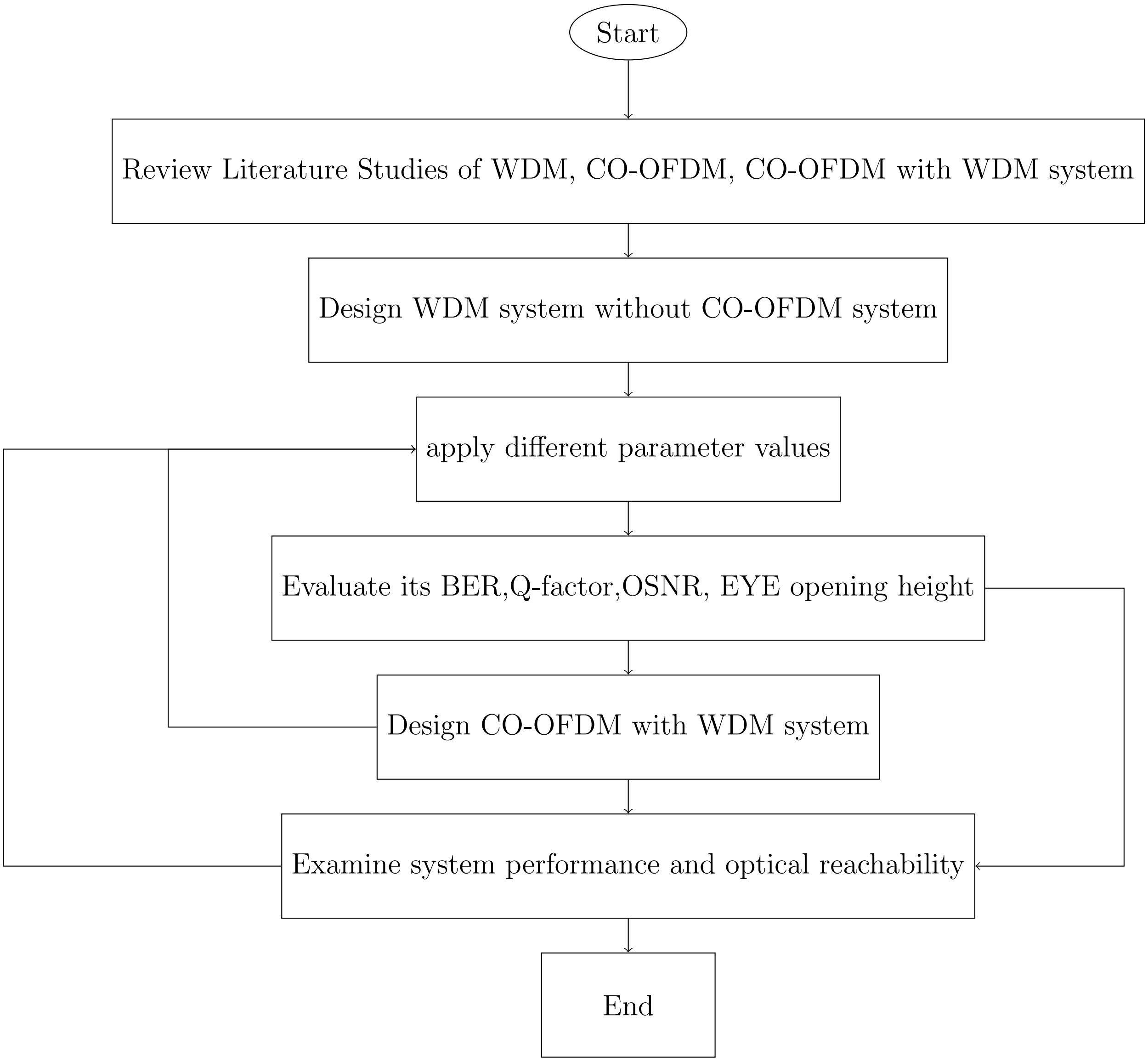


Figure 1.1: Methodology Flowchart

1.7 Scope and Limitation

1.7.1 Scope

- This research focuses on studying the parameters that affect the integration of CO-OFDM with WDM technologies specifically for long-haul optical communication. It aims to explore the benefits and challenges associated with combining these two techniques.

- This research aims to evaluate how the integration of CO-OFDM with WDM can extend the transmission distance and improve signal quality over the links.

- The paper determines the performance of WDM and CO-OFDM integrated with the WDM system by the key performance metrics such as minimum Bit-Error-Rate (BER), maximum Q-factor, Eye opening height and Optical-Signal-to-Noise Ratio (OSNR) by varying the parameter values.

1.7.2 Limitation

Several limitations need to be taken into account when interpreting the results.

- During the design of CO-OFDM with a WDM network, it needs an Optisystem simulation tool more than V-16. However, I can't access the cracked one easily, so it is much more complicated to do my paper.

- Limited number of channels, data rate and transmission distance: In this simulation, only four channels, data rate up to 1 Tbps, and transmission link length up to 1000 km were conducted, which means that the results may not fully represent the performance of CO-OFDM with WDM in a more complex system with a larger number of channels or higher data rates.

  Different channel configurations and data rates are frequently present in real-world circumstances, which can have an impact on quality factors and performance measures like BER.

- Simulation-based analysis: While simulations provided valuable data, the results may not fully reflect real-world conditions. Factors such as fiber imperfections and extreme environmental conditions can influence performance, requiring further validation through experimental testing. Testing in actual deployment scenarios would help confirm the effectiveness of the setup.

1.8 Thesis Contribution

As far as the knowledge of the author of this thesis is concerned, most of the researchers related to this work identify that instead of deploying WDM or CO-OFDM separately, it shall integrate those technologies to improve its performance. In addition, for further investigation we want to study and analyze the effect of each parametric value difference on the performance of WDM and CO-OFDM with WDM at a 1550nm reference wavelength to transmit a large amount of data for long haul with a minimum BER and within an acceptable maximum Q-factor in the system for efficient optical transmission of data. To know the impact of each parameter Value is more significant for companies like Ethio-telecom, Safari-com, and Ethiopian Electric Power, as well as other fiber optic communication user companies. One of the main advantages of analyzing the parameter values is that it reduces the negative impact of fiber optic communication dispersions.

1.9 Organization of the Paper

The study is divided into five chapters, each of which focuses on specific aspects related to the subject of the research.

- Chapter One: This chapter discusses the background of the study and its motivation, the statement of the problem, the related works studied before, the objectives of the study, the methodology, the scope and limitations of the study, and the specific contribution of the paper.
- Chapter Two: This chapter reviews the general overview of fiber-optic communication and its challenges. In addition, this chapter focuses more on the communication bands and their amplifiers.
- Chapter Three: Analysis and design of the integration of CO-OFDM with WDM communication systems and methods to improve its performance were discussed in detail.
- Chapter Four: This chapter includes all results, and their discussions were implemented on the simulation software OptiSystem.
- Chapter Five: Finally, this chapter presented the conclusion from the findings and recommendations for future work.

Chapter 2: Overview of Fiber-Optic Communication

2.1 Introduction to Fiber-optic Communication

Fiber-optic communication is a method that employs thin strands of glass or plastic known as optical fibers to convey information using light pulses. This technology allows for high-speed data transmission over long distances, making it a key component in modern optical communication. Which are lightweight, flexible, and can be grouped to increase capacity. The communication system is classified as a long-haul >100km or short-haul <50km [10]. Long-haul applications mainly drive fiber-optic communication. The optical fiber can transmit the light wave with a loss (attenuation) equal to 0.2 dB/km at 1550 nm. Optical fibers are not affected by electromagnetic interference since they are purely dielectric waveguides. The fiber loss in long-haul applications increases every 100 km by 1%. Thus, in the design of an optical fiber, the fiber loss must be considered [10]. The main purpose of the optical transmitter is to convert its electrical input signal into optical signals, which it transmits over the existing fiber. The optical receiver is to detect and convert the received signal from optical to electrical. [11]

2.2 Optical Communication Band

Fiber optic communication is mainly conducted in the wavelength region where optical fibers have small transmission loss. This low-loss wavelength region ranges from 1260 nm to 1625 nm and is divided into five wavelength bands referred to as the O, E, S, C, and L bands[12]

- O band (1260–1360 nm): utilized in data centers and local area networks (LANs) for short-range optical communication.
- E band(1360–1460) nm: In optical networks, the E-band is generally linked to applications requiring longer wavelengths.
- S band (1460-1530 nm): used in optical communications, particularly in single-mode fibers. It is often utilized for long-haul and metro networks.
- C band (1530-1565 nm): most commonly used band specifically for long-haul optical communication, so in this paper, we measure the system's performance according to the 1550nm reference wavelength to achieve minimum attenuation in optical communication.
- The second-lowest loss wavelength band, the L-band (1565–1625 nm), is frequently used when the C-band cannot adequately supply the required bandwidth

2.3 Challenges in fiber communication

2.3.1 Fiber Attenuation

Attenuation is an event where the optical power of a signal decreases as it travels through the optical fiber [13]. It is typically measured in decibels per kilometer (dB/km). The main causes of attenuation are scattering and absorption. Scattering occurs when light encounters impurities in the fiber material. Absorption is when the fiber material absorbs some of the light energy, converting it into heat [13].

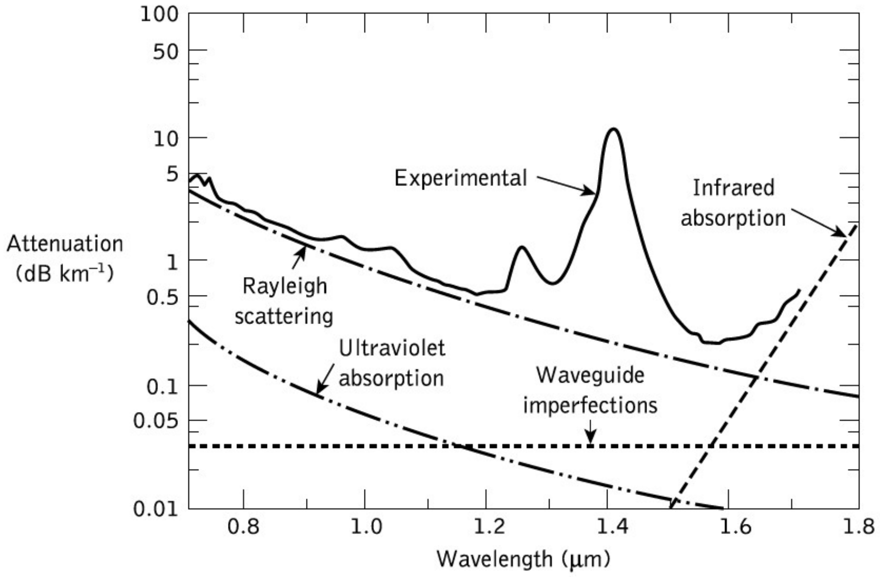


Figure 2.1: Attenuation spectrum for an ultra-low-loss single-mode fiber

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

Where:-α is the attenuation coefficient in decibels per unit length,L is the length of the fiber,P_{out} is the output power,P_{in} is the input power

2.3.2 Fiber Dispersion

Fiber dispersion is the optical pulses traveling through an optical fiber experience spreading or distortion. It is caused by various factors, like the fiber's material properties, waveguide structure, and polarization effects. Data rates and transmission distances are limited by dispersion. When optical pulses travel through the fiber, they consist of multiple colors of light. Since the refractive index varies, the pulse's wavelengths travel at slightly different speeds [10]. Various kinds of signal dispersion can happen when a signal is being transmitted, including:

- **Inter-modal Dispersion**: It is the spreading of an optical signal of different modes in multi-mode fibers, which causes variation in propagation time. The bandwidth and distance over which multi-mode fibers can effectively transmit data are limited by dispersion.
- **Intra-modal Dispersion (Chromatic Dispersion)**: It occurs in single-mode and multi-mode fibers.

2.3.3 Chromatic Dispersion (Intra-modal Dispersion)

Chromatic dispersion is the pulse broadening that happens in a single mode due to the finite spectral width of the optical source. There are two causes for chromatic dispersion: material dispersion and waveguide dispersion [10]. Material dispersion is a condition where different wavelengths of light travel at different speeds [14]. Waveguide dispersions mainly happen when the propagation of light is affected by the geometry and refractive index of the fiber [15]

$$D = -\frac{2\pi c}{\lambda^2}\beta^2 \tag{2.2}$$

Where D is the dispersion. C is the speed of light; λ is the wavelength; β^2 is waveguide constant

2.3.4 Polarization-Mode Dispersion (PMD)

Polarization mode dispersion is caused by double refraction, which affects the polarization state of the optical signal, resulting in pulse broadening. Many factors cause double refraction, such as imperfections from the manufacturing process, the bending or twisting of the fiber, or weather conditions. At specific wavelengths, the signal energy of two polarization modes is taken, and because of the double refraction along the fiber, the two polarization modes will travel with different velocities. The difference of propagation time $\Delta\tau$PMD between the two polarization modes will produce pulse spreading [10].

$$\Delta\tau\mathrm{PMD} = |\frac{L}{V_{gx}} - \frac{L}{V_{gy}}| \tag{2.3}$$

Where: L is the distance that the pulse travels, and the group velocities of the two polarizations modes are V_{gx} and V_{gy}

The polarization-mode dispersion can be calculated:

$$D_{\mathrm{PMD}} = \frac{\Delta\tau\mathrm{PMD}}{\sqrt{L}} \tag{2.4}$$

2.4 Orthogonal frequency-division multiplexing (OFDM)

It is a modulation technique used in a communication system to transmit data over a wide bandwidth efficiently. In OFDM, the available frequency spectrum is divided into multiple orthogonal subcarriers, which allows for high spectral efficiency and low adjacent signal interference. [16].

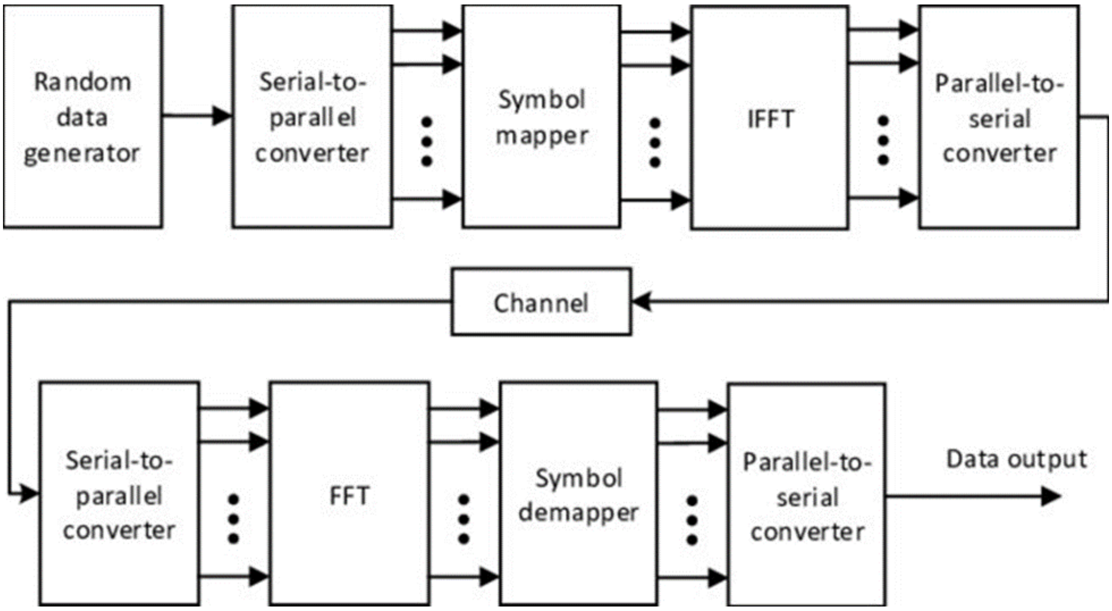


Figure 2.2: OFDM block diagram

The data to be transmitted is divided into parallel streams, and each stream is modulated onto a separate subcarrier. The modulated subcarriers are then combined and transmitted over the communication channel. FDM offers several advantages over other modulation techniques. It is highly resistant to multipath fading and interference, making it suitable for use in harsh environments for propagation [17]. It also provides efficient spectrum utilization by allowing closely spaced subcarriers, enabling higher data rates, and overlapped subcarriers are maintained while the signal is passed through a time-dispersive channel by adding a cyclic prefix [18]. In the case of the OFDM signal, using the Inverse Fast Fourier Transform (IFFT) and FFT helps to modulate and construct the original signal even if there is overlapping between the subcarriers, as shown in Fig. 2.3.

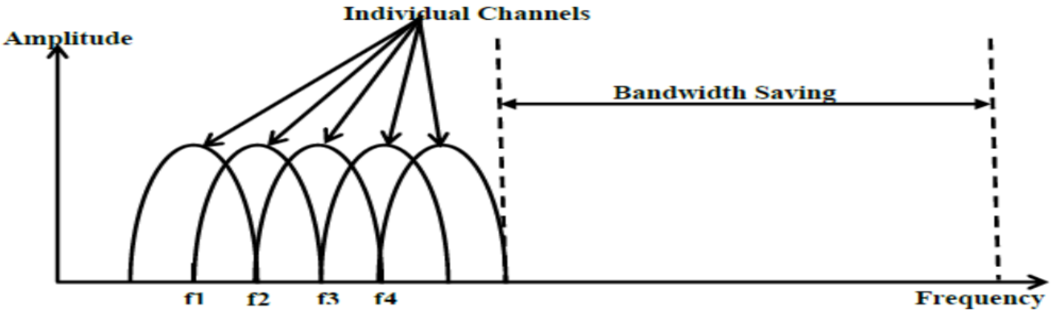


Figure 2.3: OFDM Spectral

(FDM) has a guardbandn, which is typically used between adjacent frequency bands to prevent interference or crosstalk between the signals. The guard band is a frequency range that is intentionally left unused to create a buffer zone between the adjacent channels.

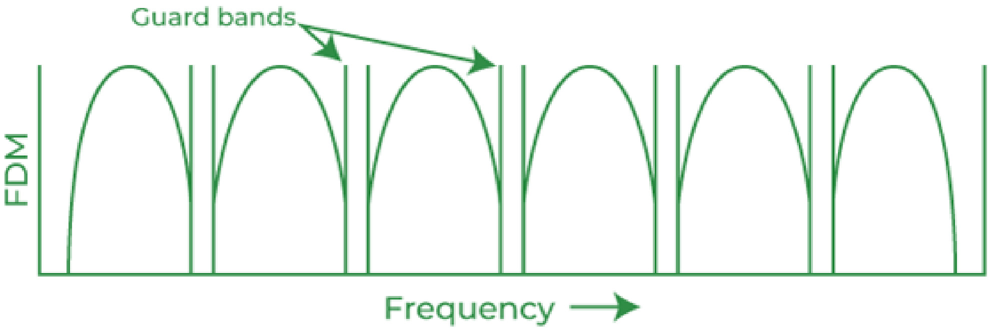


Figure 2.4: FDM Spectral

2.5 Optical amplifiers

Amplifiers in optical communication can be suitable to amplify without conversion, which means they do not need to convert from optical to electrical and back to optical. It directly amplifies the multiplexed optical signals to answer the optical power boundary [19]. There are two main types of optical amplifiers: those are the erbium-doped fiber amplifier and the Raman amplifier.

2.5.1 Erbium doped fiber amplifier (EDFA)

WDM uses it widely, and it uses a pump at the transmitter. An EDFA uses the principle of stimulated emission to amplify optical signals. It consists of a section of erbium-ion-doped optical fiber. Pumped by a high-power optical signal at a specific wavelength, the erbium ions are excited, and they emit photons at the same wavelength as the input signal. EDFA has relatively low noise figures; hence, in long-haul transmission systems [19]. The way EDFA functions is determined by the evolution of the signal pump power along the fiber and the population dynamics of the erbium ions. The erbium ions in an EDFA transition between three energy levels: ground, excited, and highly excited. The forward pumping configuration with 980nm pump energy is the most used EDFA arrangement since it maximizes the use of affordable, dependable, and low-power consumption [19].

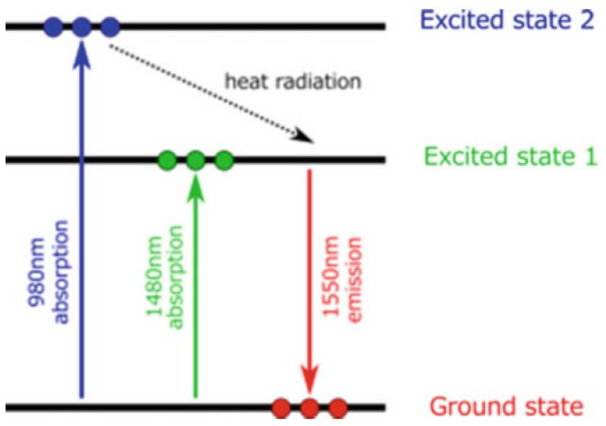


Figure 2.5: Energy diagram of Er ions

2.5.2 Raman optical amplifier

A Raman amplifier, on the other hand, utilizes the Raman scattering effect. The input signal interacts with the optical fiber material itself, which can be silica or other materials, and undergoes a process called Raman scattering. This process transfers energy from a pump laser to the signal, leading to signal amplification. Raman amplifiers exhibit higher noise figures than EDFAs. However, the noise performance can be improved by using a counter-pumping scheme or other noise reduction techniques [19].

Chapter 3: Design and Analysis of CO-OFDM with WDM

This section mainly focuses on the main ideas behind CO-OFDM integrated with WDM, looks at each communication network, key calculations, and the tools used.

3.1 Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM)

The CO-OFDM transmission system uses an optical local oscillator, which is used in optical coherent systems to generate optical signals at specific wavelengths [20]. The high-rate digital data stream is split into N parallel streams at the transmitter side. Each stream is mapped to a symbol stream using a modulation scheme (QAM, PSK, etc.). The symbols are modulated onto the subcarrier using IFFT to transform the OFDM signal from frequency domain to time domain. To stop subcarriers from overlapping, a guard interval or cyclic prefix is introduced after the IFFT operation. After performing a P/S conversion, the signal is sent through the channel [21]. The guard interval or cyclic prefix is eliminated at the receiver side after the received data has been transformed to parallel. Then the signal is demodulated by using the FFT algorithm and demodulated by either QAM or PSK. Finally, the data is converted to serial to get the original data [22].

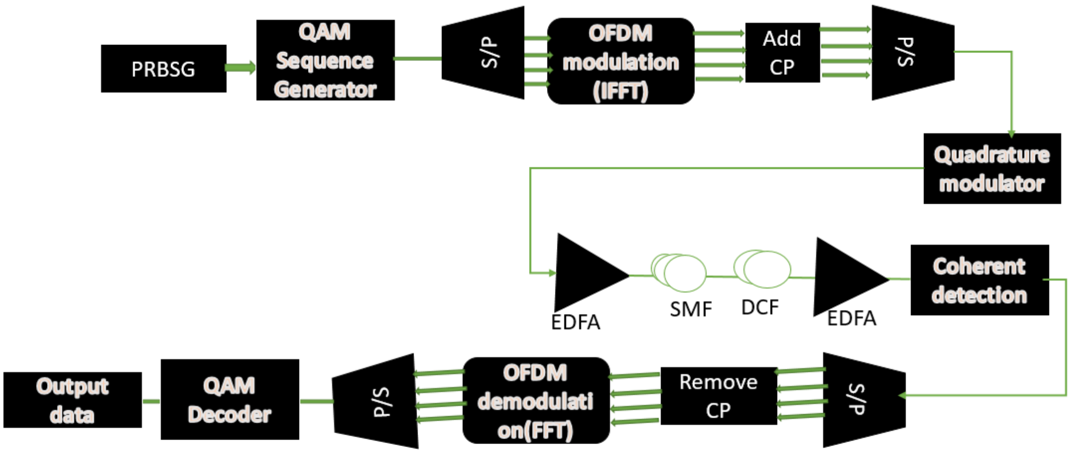


Figure 3.1: CO-OFDM block diagram

3.2 Multiplexing

Multiplexing is a technique that integrates several signals for simultaneous transmission on a single transmission channel. It is economically feasible to utilize the available bandwidth of optical fiber. Numerous multiplexing techniques are deployed, such as FDM, TDM, CDM, and WDM. Governmental commercial enterprises, such as Ethio-telecom, and personal commercial enterprises, such as Aselect WDM, use those existing advantages [23].

3.2.1 Wavelength division multiplexing (WDM)

WDM systems enhance the capacity of the system by sending multiple wavelengths over a single fiber. As a result, it increases the data rate that is carried over a single fiber by using multiple wavelengths. The optical spectrum is divided into smaller channels, which are used to transmit and receive data at the same time WDM assigns the incoming optical signals to a certain frequency range of light (either wavelengths or lambdas) [24]. The wavelength division multiplexing categories are:

- **Coarse wavelength division multiplexing (CWDM)**: In CWDM, the spacing between adjacent wavelengths is relatively large, commonly 20 nm. The system supports a smaller number of channels, usually up to 18 channels, due to the wider wavelength spacing. It is employed in short-distance transmission systems and is rarely used currently [25].

- **Dense wavelength division multiplexing (DWDM)**: In DWDM, the spacing between adjacent wavelengths is much smaller, typically 0.8 nm or 0.4 nm. The narrower wavelength spacing enables a significantly higher number of channels, typically up to 80 or more. DWDM is utilized for long-haul and ultra-long-haul applications [25].

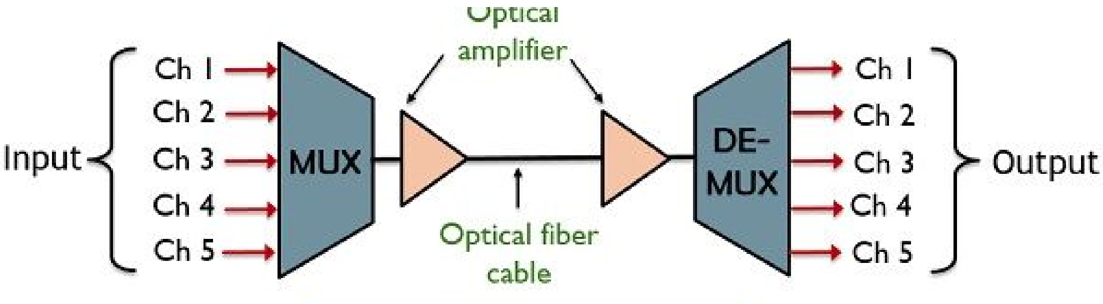


Figure 3.2: Wavelength Division Multiplexing

3.3 System Design

The system is designed based on the diagram below, which explains the function of each block in detail in the next section. Inside OFDM Tx, there is another connection based on the OFDM working principle, and also in the coherent detection part, there is a connection based on the working principle Principle of coherent detection.

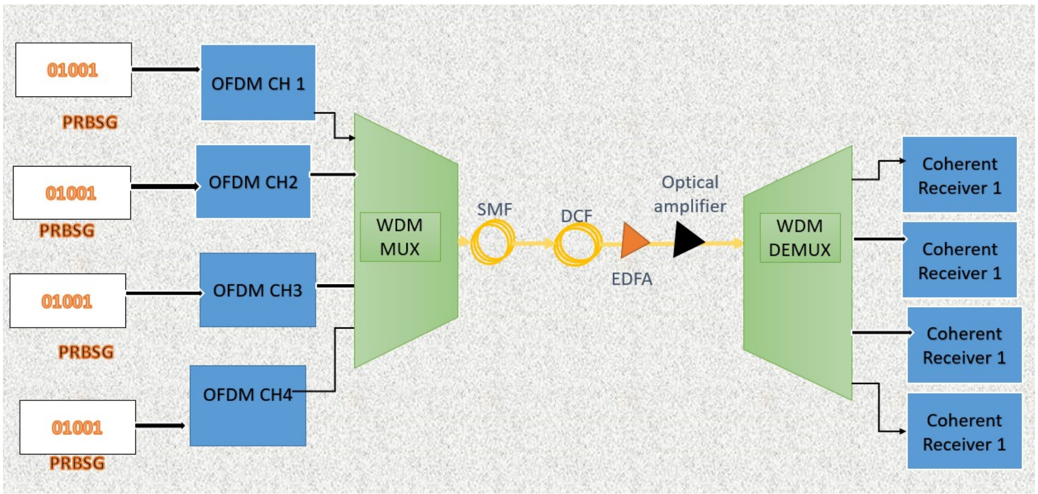


Figure 3.3: General system design

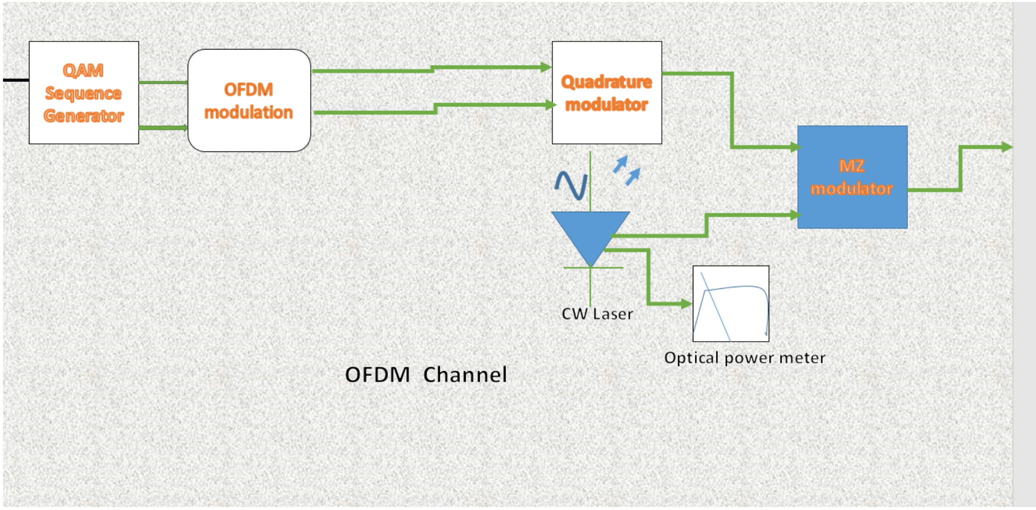


Figure 3.4: OFDM channel

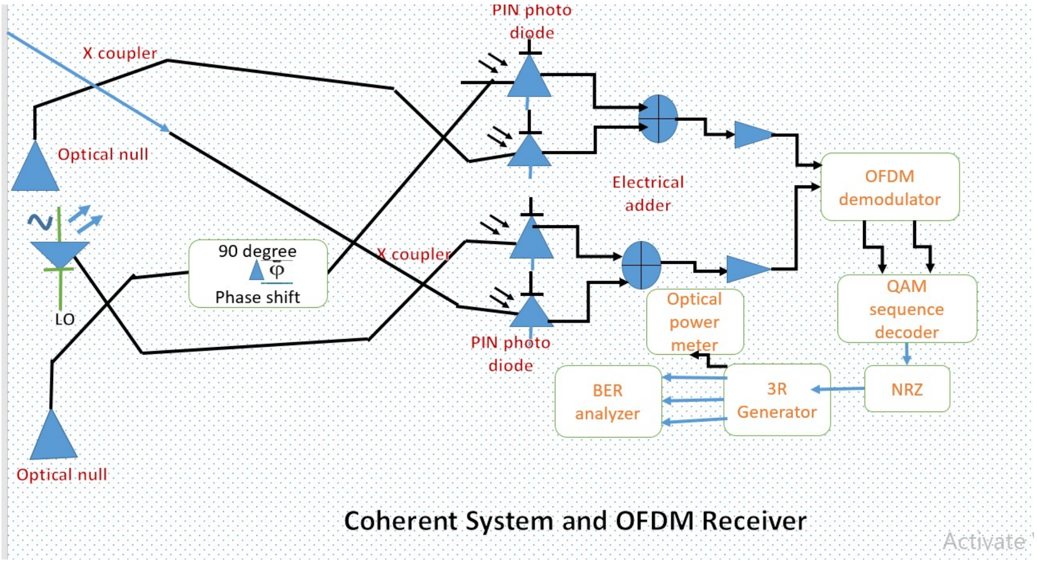


Figure 3.5: Coherent system and OFDM receiver

3.4 Overview of System Design Equipments

3.4.1 Pseudo Random Sequence Bit Generator

The system generates a pseudo-random binary sequence according to different operation modes. The purpose of the bit sequence is to approximate the properties of random data [26]. PRBSG generates a sequence of N bits:

$$N = T_w \cdot B_r \tag{3.1}$$

$$N_G = N - n_l - n_t \tag{3.2}$$

where:- T_w is the Time window;B_r is the bit rate N_G the total number of bits generated; n_l is the number of leading zeros; and n_t is the number of trailing zeros.

3.4.2 QAM Sequence generator

A QAM sequence generator is a device that produces the signals by modulating the in-phase (I) and quadrature (Q) components based on input data[27].

3.4.3 CW Laser

This type of laser discharges a continuous stream of light and has a reliable output power over time in CO-OFDM with WDM systems. CW lasers provide a constant and stable source of optical carrier signals at specific wavelengths [27]. It operates on the principle of stimulated emission of radiation, and it requires a gain medium where a population inversion is achieved, meaning more atoms are excited than in the ground state. This is typically achieved through an external energy source [27].

- **Stimulated Emission**: As demonstrated by the energy, an excited atom can interact with a photon to promote the production of a second coherent photon.

$$E = hv \tag{3.3}$$

Where:- E is the energy difference, h is Planck's constant, v is the frequency of emitted light

- **Population Inversion**: The condition for stimulated emission to dominate over absorption is[27].

$$\frac{N_2}{N_1} > 1 \tag{3.4}$$

Where:- N_2 Is the number of atoms in the excited state, N_1 Is the number of atoms in the ground state

- **Laser Gain**: The gain of the medium expressed as:

$$G = \sigma(N_2 - N_1)I \tag{3.5}$$

Where: G is the gain of the medium, σ:- the stimulated emission cross-section area, I:- Is the light intensity

- **Threshold Condition**: Laser operation begins when the gain equals the losses in the cavity [27].

$$G \geq \alpha \tag{3.6}$$

Where:- α Is the loss coefficient

- **Output Power**: The output power of the laser is given by:-

$$P_{\text{out}} = \eta G P_{\text{in}} \tag{3.7}$$

Where:- P_{out} is output power,P_{in} is input power, and η is the efficiency of the laser [27].

3.4.4 OFDM Channel

The OFDM transmitter channel should convert the input data stream into an OFDM signal by splitting the bandwidth into orthogonal subcarriers for the OFDM signal. In the

OFDM transmitter, an IFFT operation is done, and a cyclic prefix is added for efficient OFDM signal transmission [16].

3.4.5 Optical Modulation

A direct or external optical modulator is required in an optical communication system to transform an electrical signal into an optical signal [28].

- **Direct Modulation**

In direct modulation, the laser diode itself acts as both the signal source and the modulator. Output intensity can be directly controlled by varying the current given to the laser diode [28]

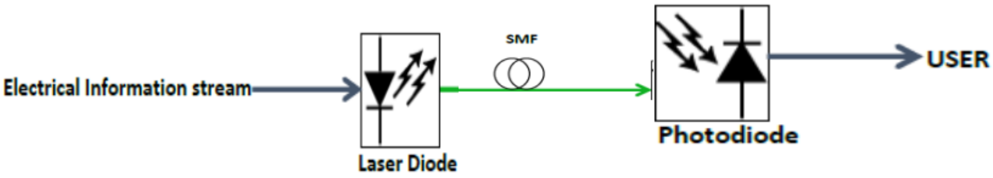


Figure 3.6: direct modulation

- **External Modulation**

In external modulation, the laser source releases a constant amplitude signal that enters the external modulator, such as a Mach-Zehnder modulator (MZM). To modify the optical power level that the external modulator will broadcast, an electrical signal enters the device. This will not change the amplitude of the light that comes originally from the laser, which then produces an optical signal with time variance. The constant amplitude signal from the laser source will help to avoid the chirp of the pulses, reducing dispersion. It provides greater flexibility in terms of modulation formats, allowing for more advanced modulation schemes like amplitude modulation (AM), frequency modulation (FM), or phase modulation (PM) [28]

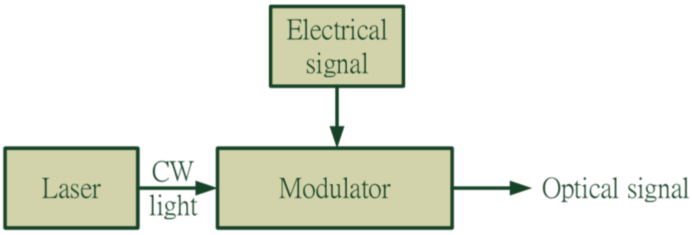


Figure 3.7: External modulation

This process is more effective for systems with high data rates as well as for the long-haul communication systems. In this paper, this type of modulator is preferable to transmit high data for long-haul optical communication.

3.4.6 Mach-Zehnder Modulator (MZM)

Specifically made for intensity modulation of optical communications is the Mach-Zehnder Modulator (MZM). MZM can produce a clean sinusoidal signal devoid of mechanical effects, improving stability and accuracy [29].

The output intensity of the MZM can be expressed as follows:

$$I_{\text{out}} = I_{\text{in}} \cdot \left(\cos \left(\frac{\phi_1 - \phi_2}{2} \right) \right)^2 \tag{3.8}$$

Where: I_{out} is the output intensity of the MZM, ϕ_1 and ϕ_2 are the phase shifts in the two arms of the modulator, andI_{in} is the input intensity.the

3.4.7 WDM multiplexer and demultiplexer

A WDM multiplexer performs the combining of multiple optical signals of various wavelengths into one to transmit in a single optical fiber. And wavelength division demultiplexers separate the combined optical signals of different wavelengths that were transmitted over a single fiber for further processing or directing them to specific receivers [30].

3.4.8 Coherent detection

In CO-OFDM systems, coherent detection is employed to recover the transmitted data. Coherent detection relies on the consistent mixing of the received optical signal with a local oscillator (LO) signal. LO signals, produced by CW lasers, have the same frequency and phase characteristics as the transmitted signals. The recovery of transmitted data, by extracting the phase and amplitude information of the transmitted signal, is accelerated by the coherent mixing process. The main operation of the converting process from optical to electrical signal is implemented by PIN photodiodes [21]. Ultimately, a BER analyzer compares the transmitted and received signals and counts the number of bit errors that occur to determine the signal quality and bit error rate [27].

3.4.9 Single-mode fiber (SMF)

In a single-mode fiber, light travels in a straight-line path. Its small core size allows light rays to propagate with high spatial coherence and minimal dispersion. Low signal attenuation is provided by standard SMF, usually at 1310nm 0.2 dB/km and 0.18 dB/km at 1550 nm. This allows for long-distance transmission without significant loss of signal quality and shows low dispersion [10]

3.4.10 Dispersion Compensation Fiber (DCF)

A special kind of fiber optic cable called dispersion-compensating fiber (DCF) is made to lessen the impact of dispersion on the signal being transferred. The phenomenon known as dispersion occurs when a signal moves more slowly through some sections of an optical fiber than others. The quality and dependability of the data that is transmitted are reduced as a result of the signal spreading out and becoming distorted. By using the opposite dispersion profile of the fiber in the system, DCF counteracts this effect. It enhances fiber optic networks' performance and is an affordable method of lowering dispersion effects[31]. DCF allows the average dispersion to be close to zero [31]. In SMF, the effect of four-wave mixing (FWM) and cross-phase modulation (XPM) is much less than self-phase modulation (SPM). To consider the role of SPM and dispersion, the signal transmission can be simulated by solving the nonlinear Schrodinger equation.

$$\frac{\partial A(z,t)}{\partial z} + \frac{\beta_2}{2}\frac{\partial^2 A(z,t)}{\partial t^2} - \gamma |A(z,t)|^2 A(z,t) = 0 \tag{3.9}$$

Where:

- $A(z,t)$ Is the complex envelope of the optical signal.
- β_2 is the dispersion coefficient.
- γ is the nonlinear coefficient.

This formulation helps you to analyze the effects of dispersion and nonlinearity on optical signal propagation in the system [31]. The length of dispersion-compensating fiber is calculated by using the following equation:

$$L_{\text{dcf}} = \frac{-D_{\text{std}} \times L_{\text{std}}}{|D_{\text{dcf}}|} \tag{3.10}$$

Where: L_{dcf} = Length of Dispersion-Compensating Fiber (in km) ; D_{std} = Dispersion of the standard single mode fiber (in ps/nm·km);

L_{std} = Length of the standard single mode fiber (in km); D_{dcf} = Dispersion of the DCF (in ps/nm·km)

3.5 Optisystem Software

Optisystem is optiwave photonic software and it is a rapidly evolving, and powerful software design tool that enables users to plan, test, and simulate almost every type of optical link in the transmission layer of a broad spectrum of optical networks including LAN, MAN, and ultra-long-haul networks also enables users to plan, test, and simulate in both the time and frequency domain It offers transmission layer optical system design and planning from component to system level and visually presents analysis and scenarios [27]. Key optical communication system designs, including

- SONET/SDH rings, OCDMA, OTDM, PON, cable, CWDM, and DWDM
- Single-mode/multi-mode transmission
- Radio over fiber (ROF), OFDM (direct, coherent), and free space optics (FSO)

- Lasers (EDFA, SOA, Raman, Hybrid, Fiber Lasers) and amplifiers
- Signal processing (Electrical, Digital, All-Optical)
- Transmitter and receiver (direct/coherent) sub-system design
- Modulation formats (DPSK, QPSK, DP-QPSK, PM-QPSK, RZ, NRZ, CSRZ, DB, 16-QAM,64-QAM)
- Evaluation of the system's performance (Eye Diagram, Q-factor, BER, Signal power, OSNR) Additionally, a project created in OptiSystem can be executed by calling the OptiSystem software from a MATLAB program.

Also, it is possible to call the OptiSystem software from a MATLAB program and run a project designed in OptiSystem [27].

Chapter 4: Result and Discussion

This section presents a performance analysis of the proposed CO-OFDM integrated with WDM within a four-channel system by investigating the parameter values that can lead to more efficient enhancement of the capacity of optical communication systems. Performance evaluation is performed using OptiSystem simulation software. The analysis focuses on main performance metrics, including the OSNR, Q-factor, BER, and eye opening height as a function of transmission distance, transmitted data rate, the power of the CW laser, the power of the EDFA forward pump power, the length of the EDF, and the length of the DCF.

4.1 Parametric Value system analysis

4.1.1 WDM System Design

The performance of the Wavelength Division Multiplexing system is simulated over different optical fiber link distances and under different transmitted data rate: where an input CW laser power that varies between 0 and 10 dBm and the operating frequency is 193.1 THz to 193.4 THz with 100 GHz spacing is selected in accordance to ensure sufficient signal intensity for effective modulation and propagation while avoiding non-linear effects

[32]

To evaluate the performance of the system, the following parameters were considered at a 1550nm operating wavelength.

CW laser Parameters	**Value**	**EDFA Parameters**	**Value**
Operating frequency	193.1-193.4 THz	Core Radius	2.2 μm
CH spacing	100 GHz	Erbium-Doped Radius	-0.45 ps/nm^2/km
Laser Power	0-10 dBm	Forward Pump Power	100-200 mW
Linewidth	10 MHz	Backward Pump Power	0 mW
The extension ratio of MZM	30dB	Pump Wavelength	980 nm
Number of channels	four	Length	5 - 10 m
		Number of Amplifiers	2 count

Table 4.1: CW Laser and EDFA Values

SMF Parameters	**Value**	**DCF Parameters**	**Value**
Dispersion	16.75 ps/nm/km	Dispersion	-80 ps/nm/km
Dispersion Slope	0.075 ps/nm^2/km	Dispersion Slope	-0.45 ps/nm^2/km
PMD Coefficient	0.2 ps/km	PMD Coefficient	0.2 ps/km
Effective Area	80 μm^2	Effective Area	30 μm^2
Non-Linearity Coefficient	2.6×10^{-20}	Non-Linearity Coefficient	2.6×10^{-20}
Attenuation	0.2 dB/km	Attenuation	0.4 dB/km

Table 4.2: SMF and DCF Values

This paper demonstrates the effect of each value in short and long haul WDM and CO-OFDM with WDM transmission system as well as on its system performance. To make an analysis and investigation of the WDM system, demonstrate the result in different scenarios.

- **Scenario One**:- In the first scenario considers to transmit 40Gbps within four channels in WDM system the CW laser power is 0dBm, DCF length is around 10km for standard 50km standard SMF based on the DCF length calculation and at 980nm pump wavelength of EDFA forward pump power 100mw and the EDF length is 5m for less effect of nonlinear issues in optical like, self phase modulation, four wave mixing.

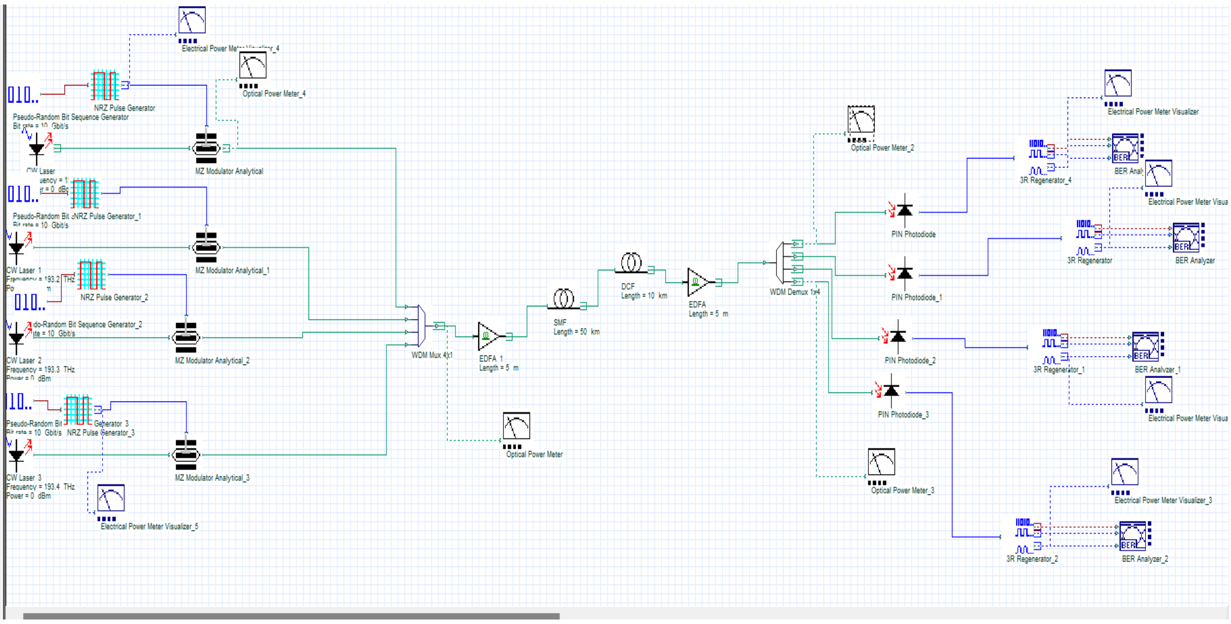
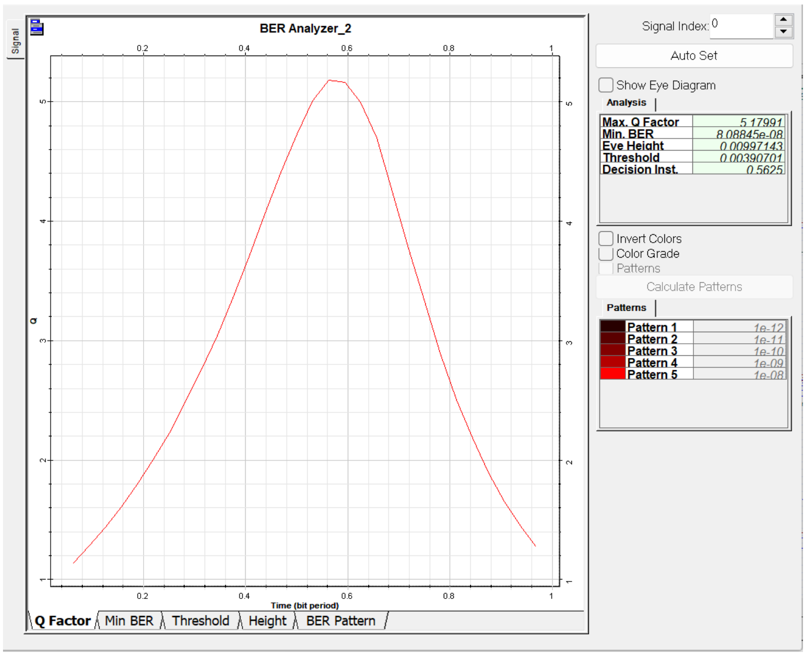


Figure 4.1: WDM System Design.

At the transmitter, the binary data supplied by PRBS (Pseudo- Random Bit Sequence) are converted into Non Return to Zero (NRZ) electrical pulses to generate a base band signal. The MZM(mach zender modulator) is used for the transmission of microwave signal into an optical signal. At the receiver, the optical modulated signal through the fiber is directly detected on the PIN photo-diode, which converts the optical signal to an electrical signal. The illustrated results from the Wavelength Division Multiplexing (WDM) system allow for a comprehensive understanding and investigation of how each optical module value affects transmission quality and capacity.

Parameter	Power Tx	Power Rx
Signal Power	1.73×10^{-3}	14.8×10^{-3}
Noise Power	1.0×10^{-13}	2.55×10^{-12}

Table 4.3: Power of Signal and Noise at Tx and Rx Sides



Signal Index: 0

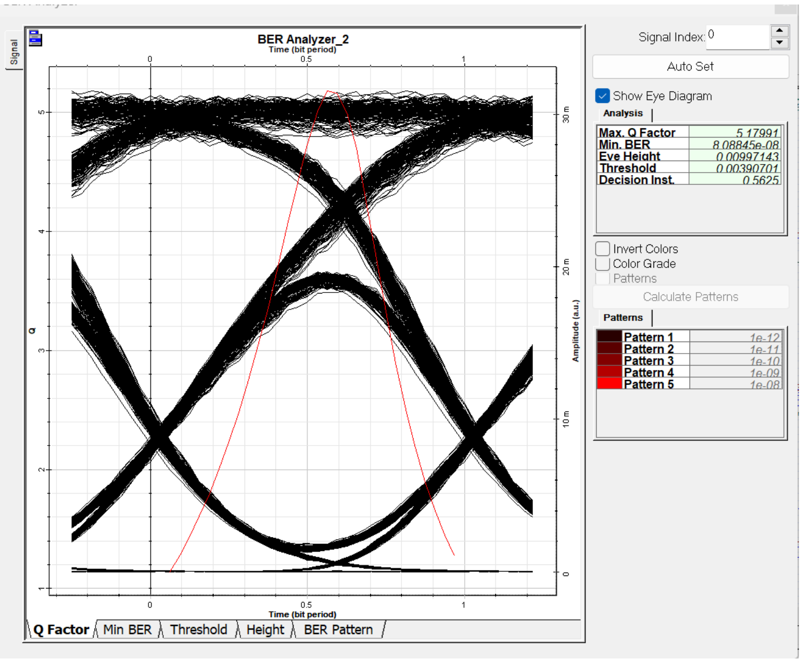
☐ Show Eye Diagram

Max. Q Factor	5.17991
Min. BER	8.08845e-08
Eye Height	0.00997143
Threshold	0.00390701
Decision Inst.	0.5625

☐ Invert Colors
☐ Color Grade
☐ Patterns

Pattern 1	1e-12
Pattern 2	1e-11
Pattern 3	1e-10
Pattern 4	1e-09
Pattern 5	1e-08

Figure 4.2: BER analyzer values when CW Laser 0dBm and EDF length 5m



Signal Index: 0

☑ Show Eye Diagram

Max. Q Factor	5.17991
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☐ Invert Colors
☐ Color Grade
☐ Patterns

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Pattern 3	1e-10
Pattern 4	1e-09
Pattern 5	1e-08

Figure 4.3: Eye opening height when CW Laser 0dBm and EDF length 5m

- Optical Signal to Noise Ratio(OSNR): It is an important metric to evaluate the performance of any type of communication network. From the signal power and the noise power, it can calculate the OSNR values.

- Eye diagrams and Q-factor: Eye diagrams are commonly used to evaluate the integrity of the received signal. The Q-factor, which is derived from the eye diagram, provides a measure of the signal quality. In terms of bit error rate (BER), the Q-factor can also be expressed as:

  $$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \tag{4.1}$$

  Where:- μ_1 is the mean of the signal distribution ; μ_0 is the mean of the noise distribution ; σ_1 is the standard deviation of the signal distribution and σ_0 is the standard deviation of the noise distribution. That the Q-factor reflects the total effect of noise on the system's performance and the larger Q-factor value demonstrates a better signal quality and the lower probability of errors[33]

- Bit Error Rate: It is another performance measurement method and it is related to the Q-factor as follows:[33]

  $$\text{BER} = \frac{1}{2} \cdot \text{erfc} \frac{Q}{\sqrt{2}} \tag{4.2}$$

Where:- BER is the Bit Error Rate; erfc is the complementary error function.

Now from the optical meter signal and noise value it calculates the OSNR to compere and contrast the parametric values on the system performance. The formula for power in dBm is:

$$P\,(\text{dBm}) = 10 \log_{10} \left(\frac{P\,(\text{W})}{1\,\text{mW}} \right) \tag{4.3}$$

Since $1\,\mathrm{mW} = 0.001\,\mathrm{W}$, it can express this as:

$$P\,(\mathrm{dBm}) = 10\log_{10}\left(\frac{P\,(\mathrm{W})}{0.001}\right) \tag{4.4}$$

This can be rewritten based on properties of logarithms:

$$P\,(\mathrm{dBm}) = 10\log_{10}(P\,(\mathrm{W})) - 10\log_{10}(0.001) \tag{4.5}$$

Simplifying $10\log_{10}(0.001)$:

$$10\log_{10}(0.001) = 10\log_{10}(10^{-3}) = 10 \times (-3) = -30 \tag{4.6}$$

Therefore, it can express the power in dBm as:

$$P\,(\mathrm{dBm}) = 10\log_{10}(P\,(\mathrm{W})) + 30 \tag{4.7}$$

$$\mathrm{OSNR}\ (\mathrm{dBm}) = 10 \times \log_{10}\left(\frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}}\right) + 30 \tag{4.8}$$

Where:- P_{signal} is the signal power (in watts);P_{noise} is the noise power (in watts). So from equation 4.8 it can be calculated OSNR(dBm)

$$\frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}} = \frac{1.737 \times 10^{-3}}{10^{-13}} = 1.737 \times 10^{10} \tag{4.9}$$

$$\mathrm{OSNR}\ (\mathrm{dBm}) = 10 \times \log_{10}(1.737 \times 10^{10}) + 30 \tag{4.10}$$

$$\text{OSNR (dBm)} = 10 \times 12.69 + 30 = 102.10 + 30 = 132.3 \text{ dBm}$$

At the transmitter side, the optical signal noise ratio before transmitting on the channel is 132.3dBm, so the same calculation is used to get the value in the receiver side.

$$\frac{P_{\text{signal}}}{P_{\text{noise}}} = \frac{14.875 \times 10^{-3}}{2.556 \times 10^{-12}} = 5.8 \times 10^{9} \tag{4.11}$$

$$\text{OSNR (dBm)} = 10 \times \log_{10}(5.8 \times 10^{9}) + 30 \tag{4.12}$$

$$\text{OSNR (dBm)} = 127.65 \text{ dBm}$$

When transmitting 40Gbps for a 50km optical link, the received signal performance measurement values listed in the table below.

Parameter metrics	**output Values**
BER	8×10^{-13}
MAX Q-factor	5.17
Eye Height	0.0099
OSNR Tx side	132.3 dBm
OSNR RX side	127.65 dBm

Table 4.4: Output Values when CW laser power is 0 dBm and EDF length is 5 m

- **Scenario Two**:- In the second scenario, we consider the values listed on Table 4.5 below to transmit 40Gbps within four channels in WDM system and analyze the impact of CW laser power as well as EDF(Erbium-Doped Fiber) length on the wdm system performance as follows:

Parameters	**Input Values**
Bit rate	40 Gbps
Transmission Distance	50 km
CW laser power	10 dBm
EDFA forward Pump Power	100 mW
EDFA length	10 m
DCF	10 km

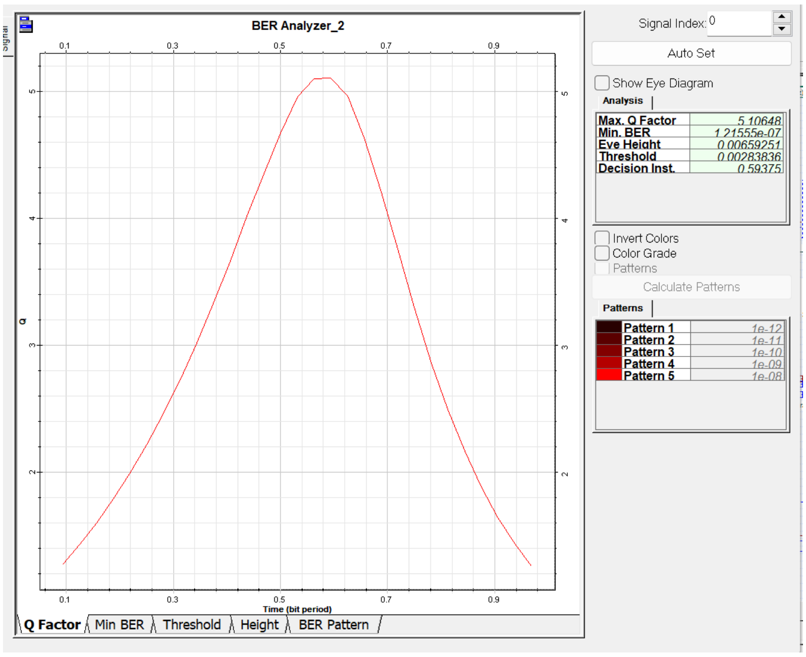
Table 4.5: Input Values when CW Laser power is 10 dBm and EDF Length is 10 m

Parameter	Power Tx	Power Rx
Signal Power	17.38×10^{-3}	8.23×10^{-3}
Noise Power	10^{-13}	7.3×10^{-14}

Table 4.6: Power of Signal and Noise at Tx and Rx Sides when CW Laser power is 10 dBm and EDF Length is 10 m

By applying the above OSNR calculation

- OSNR(dBm)Tx side =142.4
- OSNR(dBm)Rx side =130.5

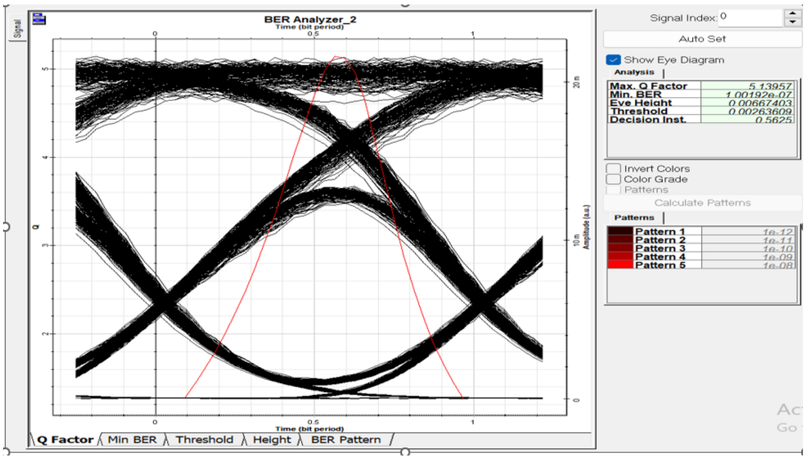


Signal Index: 0

Analysis	
Max. Q Factor	5.10648
Min. BER	1.21555e-07
Eye Height	0.00659251
Threshold	0.00283836
Decision Inst.	0.59375

Patterns	
Pattern 1	1e-12
Pattern 2	1e-11
Pattern 3	1e-10
Pattern 4	1e-09
Pattern 5	1e-08

Figure 4.4: BER analyzer value when CW laser power is 10 dBm and EDF length 10m.



Signal Index: 0

☑ Show Eye Diagram

Analysis

Max. Q Factor	5.13957
Min. BER	1.00192e-07
Eye Height	0.00667403
Threshold	0.00263609
Decision Inst.	0.5625

☐ Invert Colors
☐ Color Grade
☐ Patterns

Patterns

Pattern 1	1e-12
Pattern 2	1e-11
Pattern 3	1e-10
Pattern 4	1e-09
Pattern 5	1e-08

Figure 4.5: Eye opening height when CW laser power is 10 dBm and EDF length 10m.

Parameter metrics	**Output Values**
BER	1×10^{-12}
MAX Q-factor	5.1
Eye Height	0.0065
OSNR Tx side	142.4 dBm
OSNR Rx side	130.5 dBm

Table 4.7: Output Values when CW laser power is 10dBm and EDF length is 10m

Based on the result when increasing the power of a continuous-wave (CW) laser and the length of the Erbium-Doped Fiber (EDF), the transmitted signal power may rise; however, this can lead to an increase in the Bit Error Rate (BER) and a decrement in the Q-factor and the eye opening height. Higher power can also induce nonlinear optical effects, such as Self-Phase Modulation (SPM), which can distort the signal and further increase the BER.

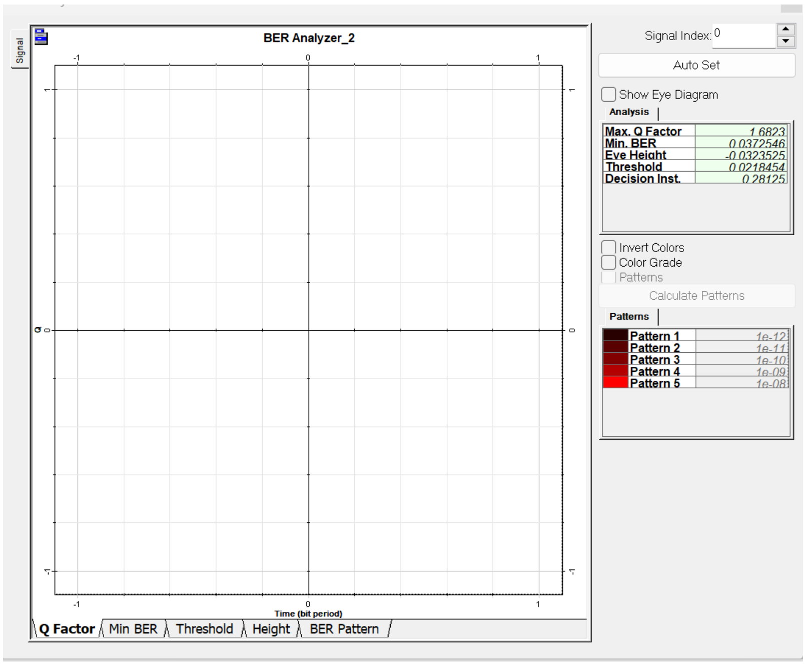
- **Scenario Three**:-In the third scenario, we consider the value listed in the Table 4.8 to transmit 40Gbps within four channels in WDM system and analyze the impact of EDFA forward pump power on the WDM system performance as follows:

Parameters	**Input Values**
Bit rate	40 Gbps
Transmission Distance	50 km
CW Laser Power	0 dBm
EDFA Forward Pump Power	200 mW
EDFA Length	5 m
DCF	10 km

Table 4.8: Input Values when EDFA pump power is 200 mW

Parameter	Power Tx side	Power Rx side
Signal Power	1.73×10^{-3}	23.55×10^{-3}
Noise Power	10^{-13}	2.6×10^{-12}

Table 4.9: Power of Signal and Noise at Tx and Rx Sides when EDFA pump power is 200 mW

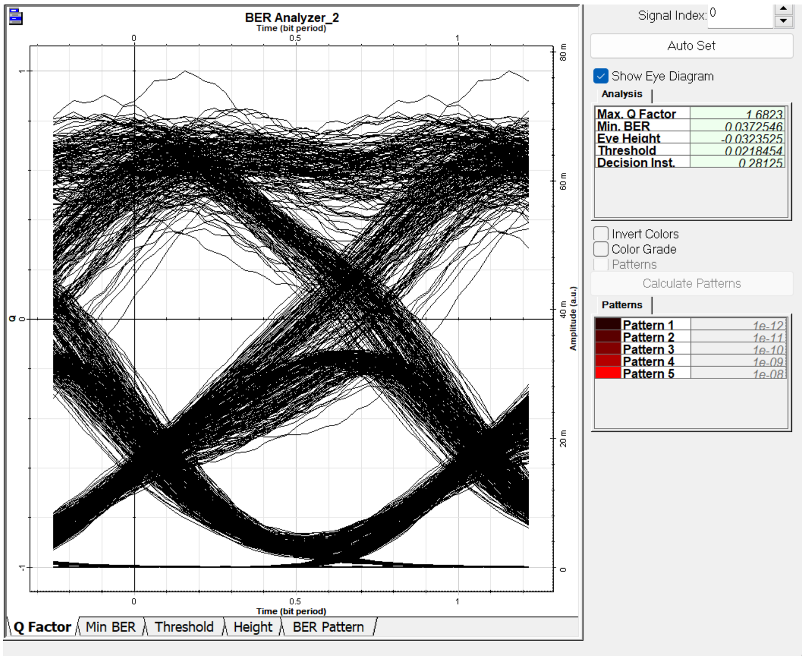


Signal Index: 0

Analysis	
Max. Q Factor	1.6823
Min. BER	0.0372546
Eye Height	-0.0323525
Threshold	0.0218454
Decision Inst.	0.28125

Patterns	
Pattern 1	1e-12
Pattern 2	1e-11
Pattern 3	1e-10
Pattern 4	1e-09
Pattern 5	1e-08

Figure 4.6: BER analyzer value when EDFA pump power is 200mw



Signal Index: 0

☑ Show Eye Diagram

Analysis

Max. Q Factor	1.6823
Min. BER	0.0372546
Eye Height	-0.0323525
Threshold	0.0218454
Decision Inst.	0.28125

☐ Invert Colors
☐ Color Grade
☐ Patterns

Patterns

Pattern 1	1e-12
Pattern 2	1e-11
Pattern 3	1e-10
Pattern 4	1e-09
Pattern 5	1e-08

Figure 4.7: Eye opening height when EDFA pump power is 200mW

Parameter metrics	**Output Values**
BER	1×10^{-3}
MAX Q-factor	1.6
Eye-opening height	-0.03
OSNR Tx side	132.3 dBm
OSNR Rx side	129.5 dBm

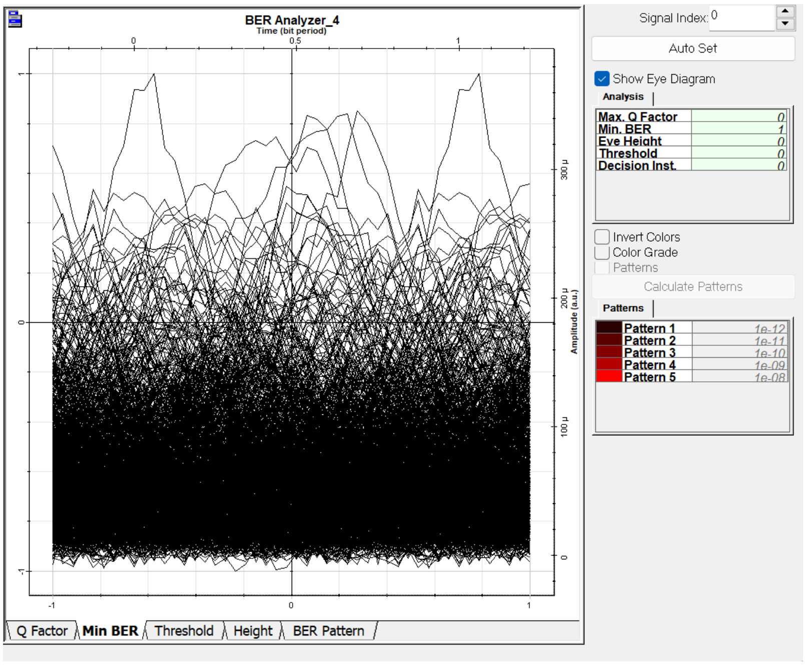
Table 4.10: Output Values when EDFA power is 200 mW

From this we demonstrate that when increasing the power of EDFA, not only the power of the signal is amplified, but also the noise power is amplified, leading to phase shifts in the signal, resulting in distortion, and the quality of the signal decreases from 5.17 to 1.6 it pushes the eye opening height become negative.

- Finally, we need to investigate what is the impact of increasing the transmitting data rate and the transmission distance on the performance of WDM even if it increases the power of CW laser and the length of DCF as well as increasing the EDFA pump power and its length of EDF.

Parameters	**Input Values**
Bit rate	1 Tbps
Transmission Distance	1000 km
CW Laser Power	10 dBm
EDFA Forward Pump Power	200 mW
EDFA Length	10 m
DCF	200 km

Table 4.11: Input Values at 1 Tbps and 1000km



Signal Index: 0

☑ Show Eye Diagram

Analysis

Max. Q Factor	0
Min. BER	1
Eye Height	0
Threshold	0
Decision Inst.	0

☐ Invert Colors
☐ Color Grade
☐ Patterns

Patterns

🟥	Pattern 1	1e-12
🟥	Pattern 2	1e-11
🟥	Pattern 3	1e-10
🟥	Pattern 4	1e-09
🟥	Pattern 5	1e-08

Figure 4.8: BER analyzer value at 1Tbps wdm system

Parameter metrics	**Output Values**
BER	1
MAX Q-factor	0
Eye Opening Height	0
OSNR Tx Side	140.45 dBm
OSNR Rx Side	80 dBm

Table 4.12: Output Values when 1 Tbps

The result listed in Table 4.12 illustrates that the WDM system is not a desirable method to transmit large data for long haul optical communication, it is highly distracted signal, therefore, that is why we need to make another analysis, to solve the problems on the existing system.

4.2 CO-OFDM with WDM System

In this section, we need to investigate the impact of each parameter value difference on the performance of CO-OFDM with WDM to identify the important mix of technologies used to reduce chromatic dispersion and polarization mode dispersion also see how to decrease the regeneration of the signal because during regeneration it needs conversion from optical to electrical and finally convert to optical signal to transmit it. As a result, the system works better and achieves its goals as intended.

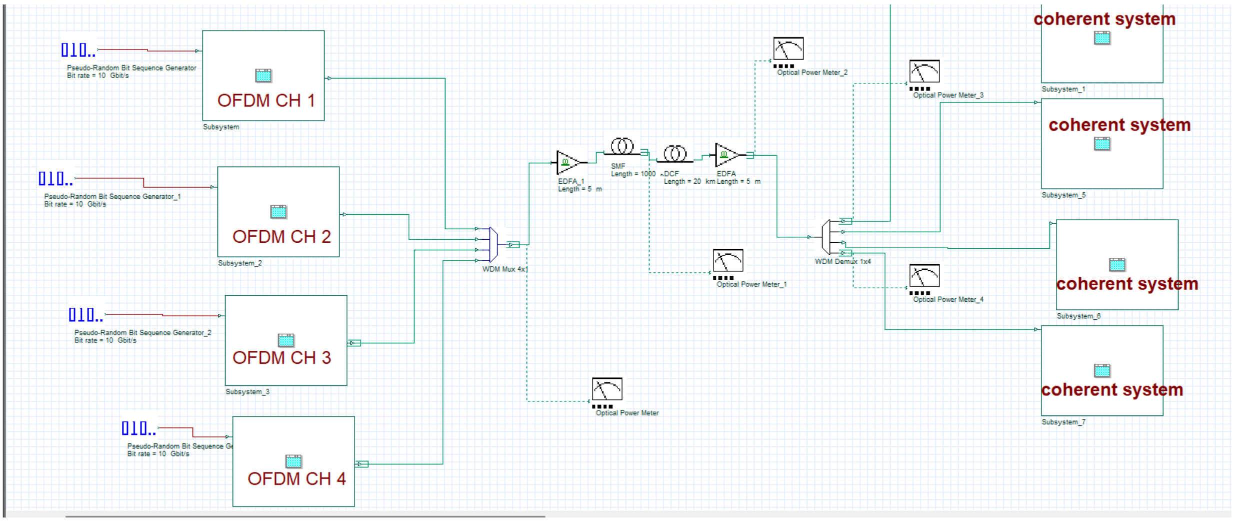


Figure 4.9: CO-OFDM with WDM system design

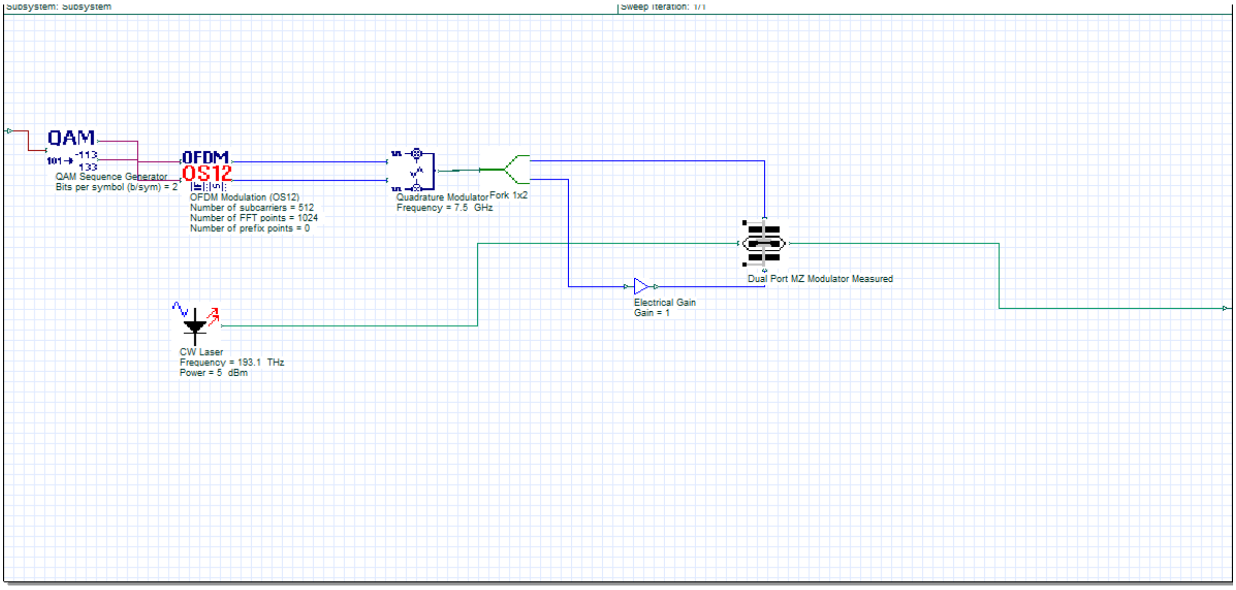


Figure 4.10: CO-OFDM transmitter

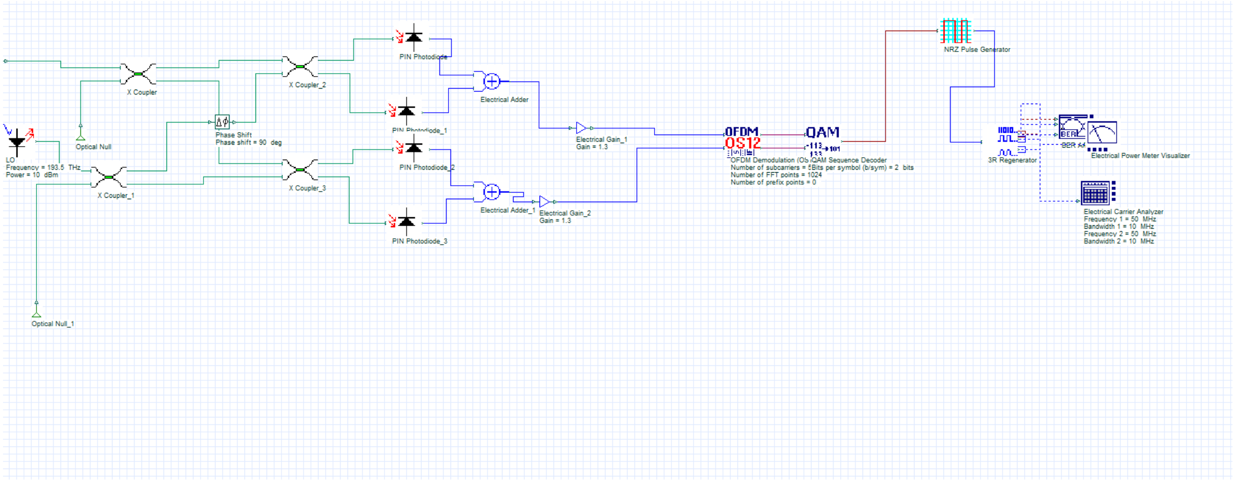


Figure 4.11: CO-OFDM receiver

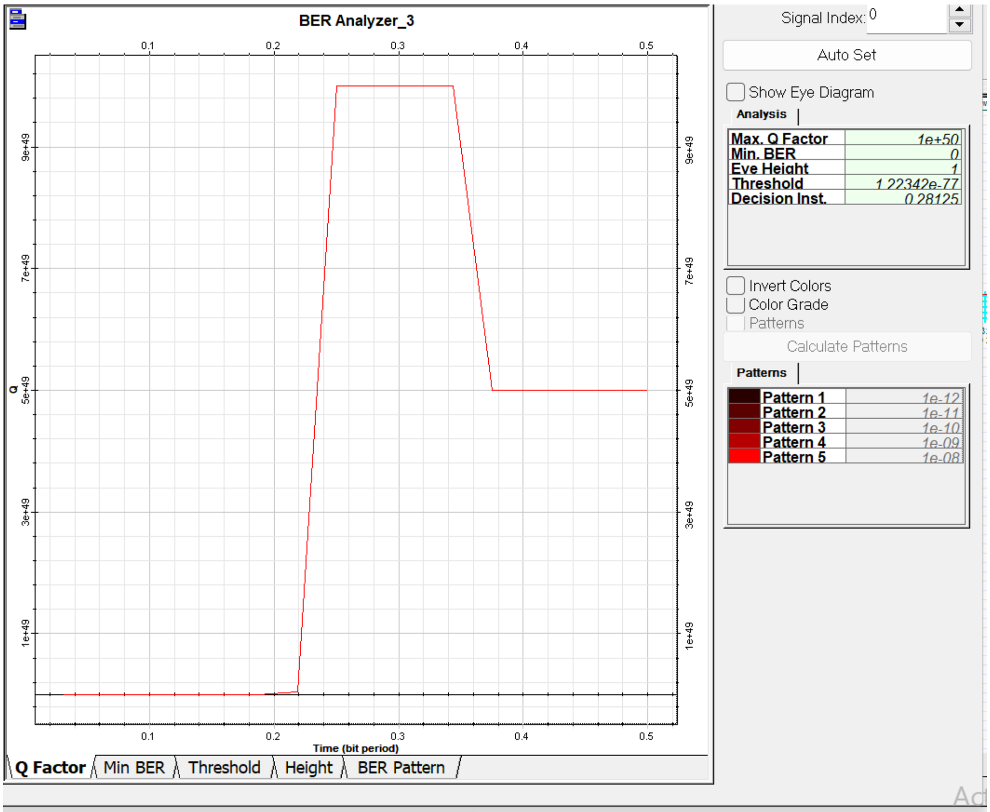
In this part, we need to analyze what is the parametric value influences rather than a WDM system in CO-OFDM with a WDM system to investigate the effect of each value difference on the integrated system performance to minimize the BER and improve the signal quality on the high data and long haul signal transmission without regenerate the signal.

Parameters	**Input Values**
Bit Rate	40 Gbps
Transmission Distance	50 km
CW Laser Power	0 dBm
EDFA Forward Pump Power	100 mW
EDFA Length	5 m
DCF	10 km

Table 4.13: Input Values at CO-OFDM System when CW laser is 0dBm EDF length is 5m

Parameter	Power Tx	Power Rx
Signal Power	39.67×10^{-6}	9.24×10^{-3}
Noise Power	10^{-13}	5.11×10^{-12}

Table 4.14: Signal and Noise power at Tx and Rx Sides when CW Laser power is 0 dBm in CO-OFDM with WDM



Signal Index: 0

Max. Q Factor	1e+50
Min. BER	0
Eye Height	1
Threshold	1.22342e-77
Decision Inst.	0.28125

■	Pattern 1	1e-12
■	Pattern 2	1e-11
■	Pattern 3	1e-10
■	Pattern 4	1e-09
■	Pattern 5	1e-08

Figure 4.12: BER analyzer of CO-OFDM with WDM when CW laser 0dBm

Parameters	**Output Values**
BER	10^{-13}
Max Q-Factor	52
Eye Opening Height	1
OSNR Tx Side	115.97 dBm
OSNR Rx Side	127.42 dBm

Table 4.15: Output Values in CO-OFDM with WDM at CW laser power 0 dBm

The result reflects when transmitting 40Gbps for 50km optical length, the integrated system performs well, according to getting a maximum quality of signal and minimum BER compared to the WDM system when the power of the CW laser power is 0dBm, the EDFA power is 100mW, and at the EDF length 5m. In the next section, we want to investigate and study what will be the performance of the integrated system even if the power of the EDFA is increased to 200mW to transmit huge data for long-haul optical link.

Parameter	**Value**
Bit rate	1Tbps
Transmission Distance	1000km
CW laser power	10dBm
EDFA forward Pump Power	200mW
EDFA length	10m
DCF	200km

Table 4.16: Input Values at 1Tbps co-ofdm with wdm

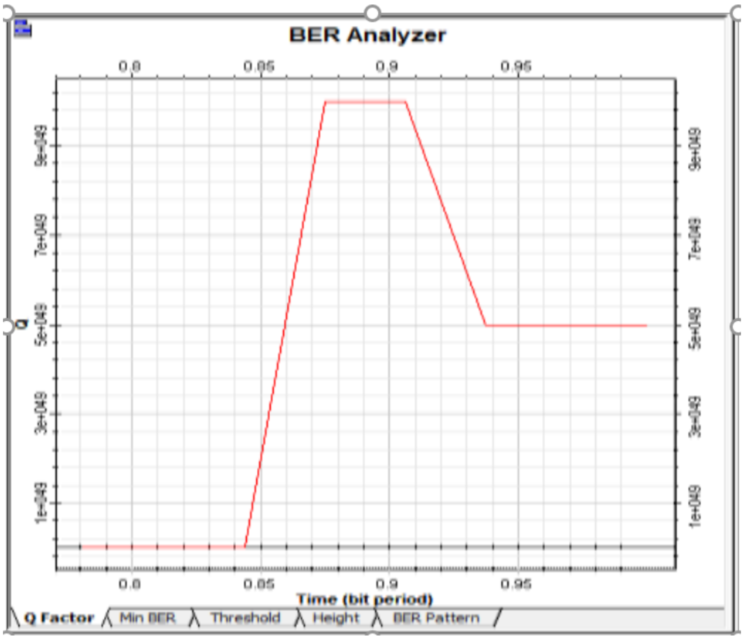


Figure 4.13: co-ofdm with wdm Q-factor values at 1Tbps

Parameter	**Value**
BER	10^{-9}
MAX Q-factor	24.95
Eye opening height	1
OSNR Rx side	61dBm

Table 4.17: Output Values at 1Tbps co-ofdm with wdm

There is signal quality degradation when the EDFA pump power increases but from this even the transmission distance is increased from 50km to 1000km there is a signal with good quality so it shows that the mixed technology is more better than Wdm system by resist against for optical dispersion which is CD and PMD mostly exist on optical communication.

Chapter 5: Conclusion and Recommendation

5.1 Conclusion

The results demonstrate the parametric value difference which affects the WDM more than CO-OFDM with WDM system. The effectiveness of WDM is more when the CW laser light intensity is 0dBm rather than at 10dBm owing to the fact that the nonlinearity effect decreases at the minimum power of CW laser. The primary goal was to investigate the impact of parametric values difference on the WDM system, then finally implement each value on the integration CO-OFDM with WDM to analyze system performance.

From this analysis, when increasing the power of the CW laser, it increases the spontaneous emission of light. On the other hand, it induces the nonlinear effects which may distort the signal and negatively impact the overall system performance. At 1550nm wavelength, the laser power must be on the range and the Q-factor value decreases when the transmitted data rate is increased, as well as the transmission link length increased, specifically in the WDM system. Q-factor value decrease means an increase in BER and a decrease in eye opening height.

5.2 Recommendation

Based on the investigation from this research on the performance of CO-OFDM with WDM for long haul communication networks, several key recommendations can be made to enhance practical applications and guide future researchers.

- This research focused only on the impact of different parametric values on the performance of the existing system, but additional researches are needed to reduce the impact of ISI during large amounts of data transmission by applying a filter.
- This work only compares the impact of each parametric value on the performance of the system, but it needs to identify the impact of different filtering techniques on the performance of the system.
- Due to the rapid growth of advancements in optical technology, future research should explore the integration of CO-OFDM with WDM, in addition to its function to transmit data, they should apply it as a sensor for different purposes.

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