REPUBLIC OF TÜRKİYE
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

DESIGN AND IMPLEMENTATION OF AN EFFECTIVE DWDM-ROF SYSTEM FOR FIBER OPTIC NETWORK USING SYMMETRICAL COMPENSATION METHOD

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MASTER OF SCIENCE THESIS
Department of Computer Engineering
Computer Engineering Program

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A thesis submitted by Ohood Hasan DAWOOD in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 14.11.2023 in Department of Computer Engineering, Computer Engineering Program.

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Ohood Hasan DAWOOD

Signature

Dedicated to my family
and my best friend

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Ohood Hasan DAWOOD

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LIST OF SYMBOLS

p	Average coefficient for photoelastic
k	Constant
TF	Fictive temperature
Pi	Input power
βc	Isothermal constant
Po	Output power
n	Refractive index
γr	Rayleigh scattering
λ	Wavelength

LIST OF ABBREVIATIONS

4G	Fourth Generation
3GPP	3rd generation partnership project
5GPP	5th generation partnership project
3D TV	Three-Dimensional TV
AAU	Active Antenna Unit
APD	Avalanche Photodetector
AM	Amplitude Modulation
BBU	Base Band Unit
BER	Bit Error Rate
BS	Base Station
CS	Central Station
CU	Central Unit
CW	Continuous Wave
CD	Chromatic Dispersion Porto
CWDM	Coarse Wavelength Division Multiplexing
DCF	Dispersion Compensation Fiber
DR	Dynamic Range
DC	Dispersion Compensation
DeMux	Demultiplexer
DGD	Differential Group Delay
DFE	Decision Feedback Equalizer
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier

EAM	Electro Absorption Modulator
EMI	Electro Magnetic Interference
EDC	Electronic Dispersion correction
FWM	Four Wave Mixing
FTTH	Fiber to The Home
FFE	Feed Forward Equalizer
FO	Fiber Optic
FBG	Fiber Bragg Grating
Gbps	Giga bit per second
GVD	Group Velocity Dispersion
GSM	Global System for Mobile communication
HDTV	High Definition TV
IPTV	Internet Protocol Over TV
IEEE	Institute of Electrical and Electronics Engineers
ISI	Inter Symbol Interference
LTE	Long Term Evaluation
LED	Light Emitter Diode
MZM	Mack Zandar Modular
MLSE	Maximum Like hood Sequence Estimation
MMF	Multi-Mode Fiber
MAN	Manipulation Area Network
Mux	Multiplexer
NRZ	Non-Return to Zero
NRT	Non-Real Time
NF	Noise Figure
NLS	Non-Linear Schrodinger
OSNR	Optical Signal to Noise Ratio
OTDR	Optical Time Domain Reflector
$OP - AMP$	Operational Amplifier

PMD	Polarization Mode Dispersion
PRBS	Pseudo Random Bit Sequencetor
PM	Phase Modulation
PD	Photo Detector
QF	Quality Factor
RoF	Radio over Fiber
RoA	Roman Optical Amplifier
RFI	Radio Frequency Interference
RT	Real Time
RF	Radio Frequency
RAU	Remote Antenna Unit
RRU	Radio Remote Unit
RIN	Relative Intensity
RZ	Return to Zero
SOPDM	Second Order PDM
SNR	Signal to Noise Ratio
SMF	Single Mode Fiber
SPM	Self Phase Modulation
SAN	Storage Area Network
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillouin Scattering
Tbps	Tera bit per second
WLAN	Wireless Local Area Network
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation

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ABSTRACT

Design and Implementation of an Effective DWDM-RoF System for Fiber Optic Network using Symmetrical Compensation Method

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Master of Science Thesis

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The utilization of a technology known as Dense Wavelength Division Multiplexing Radio over Fiber (DWDM-RoF) in 5G communication networks results in a number of advantageous outcomes. These outcomes include an increase in capacity and data rate, as well as a reduction in the cost of running the network. Because of this, a lot of academics start working on inventing methods and strategies to maximize their earnings. A hybrid strategy of compensating methods was used in the development of a 32-channel DWDM RoF system that is capable of handling efficient transmission of 1.28 terabits per second of data. The examination of the system's performance looked at three different frequency spacing scenarios: 100, 150, and 200 gigahertz. In addition, several modulation forms are investigated in order to identify the strategy that will prove to be the most trustworthy for use in the foreseeable future. Analyses and comparisons are carried out between the current system and the results concerning Quality Factor (QF) and Bit Error Rate (BER) parameters. These kinds of findings indicate that the implementation of symmetrical hybrid compensation has a significant bearing on the degree to which the suggested system's parameter outcomes may be improved. The Non-Return to Zero (NRZ) algorithm produced QF parameter values of 20.89, 15.60, 12.69, and 10.46 dBm on average when applied to distances of 60, 120, 180, and 240 kilometers, respectively. In the meanwhile, the values of the BER were as follows for the same subset of distances that were studied: 2.43 e 10–80, 2.85 e 10–29, 1.09 e 10–18, and 7.61 e 10–11, respectively. In addition, the findings suggest that the proposed system could be improved even further by employing the Return to Zero (RZ) based modulation method rather than the NRZ for regular transmission. On the other hand, the improvement of RZ is reduced significantly for transmissions that are further than 180 kilometers. In addition, the findings from the research done on the different spacings show that, for short distances, it is advised to choose a spacing range that falls between 150 and 200 GHz. Since there is less of an effect on the outcomes at greater distances, it is advised that ranges between (100-150) GHz be used when going to distances of up to 180 kilometers. It has been discovered that the QF results showed improvements of 5.15, 2.27, and 1.7 dBm for the distances of 60, 120, and 180 km, respectively. This indicates the power of using the hybrid scheme of symmetrical compensation. A comparison with recent literature found that the QF results showed improvements of 5.15, 2.27, and 1.7 dBm.

Keywords: DWDM, RoF,Symmetrical Compensation Technique, QF, BER.

ÖZET

Simetrik Kompanzasyon Yöntemi Kullanılarak Fiber Optik Şebeke İçin Etkili Bir DWDM-RoF Sisteminin Tasarımı ve Gerçekleştirilmesi

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Bilgisayar Mühendisliği.prgramı
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Danışman: Prof. Dr.Hasan Hüseyin BALIK

5G iletişim ağlarında Fiber Üzerinden Yoğun Dalga Boyu Bölmeli Çoğullama Radyosu (DWDM-RoF) olarak bilinen bir teknolojinin kullanılması bir dizi avantajlı sonuçla sonuçlanır. Bu sonuçlar, kapasite ve veri hızında bir artışın yanı sıra ağı çalıştırma maliyetinde bir azalmayı içerir. Bu nedenle, birçok akademisyen kazançlarını en üst düzeye çıkarmak için yöntemler ve stratejiler icat etmeye başlar. Saniyede 1,28 terabit verinin verimli iletimini idare edebilen 32 kanallı bir DWDM RoF sisteminin geliştirilmesinde, dengeleme yöntemlerinin hibrit bir stratejisi kullanıldı. Sistemin performansının incelenmesi üç farklı frekans aralığı senaryosuna bakıldı: 100, 150 ve 200 gigahertz. Ek olarak, öngörülebilir gelecekte kullanım için en güvenilir olduğu kanıtlanacak stratejiyi belirlemek için çeşitli modülasyon formları araştırılmıştır. Mevcut sistem ile Kalite Faktörü (QF) ve Bit Hata Oranı (BER) parametreleri ile ilgili sonuçlar arasında analizler ve karşılaştırmalar yapıldı. Bu tür bulgular, simetrik hibrit kompanzasyonun uygulanmasının, önerilen sistemin parametre sonuçlarının iyileştirilebilme derecesi üzerinde önemli bir etkiye sahip olduğunu göstermektedir. Sıfıra Dönmeme (NRZ) algoritması, sırasıyla 60, 120, 180 ve 240 kilometrelik mesafelere uygulandığında ortalama 20,89, 15,60, 12,69 ve 10,46 dBm'lik QF parametre değerleri üretti. Bu arada, çalışılan mesafelerin aynı alt kümesi için BER değerleri sırasıyla 2.43 e 10-80, 2.85 e 10-29, 1.09 e 10-18 ve 7.61 e 10-11 şeklindedir. Ek olarak, bulgular önerilen sistemin düzenli iletim için NRZ yerine Sıfıra Dönüş (RZ) tabanlı modülasyon yöntemi kullanılarak daha da geliştirilebileceğini göstermektedir. Öte yandan, 180 kilometreden daha uzun iletimler için RZ'nin gelişimi önemli ölçüde azalır. Ayrıca, farklı aralıklar üzerinde yapılan araştırmadan elde edilen bulgular, kısa mesafeler için 150 ile 200 GHz arasında bir aralık aralığı seçilmesinin tavsiye edildiğini göstermektedir. Daha uzun mesafelerde sonuçlar üzerinde daha az etkisi olduğundan, 180 kilometreye kadar olan mesafelere giderken (100-150) GHz aralığının kullanılması tavsiye edilir. QF sonuçlarının sırasıyla 60, 120 ve 180 km mesafeler için 5,15, 2,27 ve 1,7 dBm'lik iyileştirmeler gösterdiği keşfedilmiştir. Bu, simetrik kompanzasyonun hibrit şemasını kullanmanın gücünü gösterir. Yakın tarihli literatürle yapılan bir karşılaştırma, QF sonuçlarının 5,15, 2,27 ve 1,7 dBm'lik iyileştirmeler göstermektedir.

Anahtar Kelimeler: DWDM, ROF, Simetrik Telafi Tekniği, QF, BER

1
INTRODUCTION

1.1 Motivation

In recent years, numerous studies and efforts in standardization have focused on defining the objectives, applications, and objectives for Fifth Generation (5G) networks. Since 2011, the Third Generation Partnership Project (3GPP) has developed Long-Term Evolution (LTE). Consequently, a wide array of researchers and international organizations, such as 3GPP, 5GPP, and the Institute of Electrical and Electronics Engineers (IEEE), have been exploring the development of 5G networks. These organizations and research endeavors have introduced a fresh perspective on 5G, designating it as a global standard in 2020 [1, 2]. The future infrastructure for wireless communication systems is expected to result in an optimal system that delivers services effectively. Therefore, a 5G mobile network will be established by integrating various radio technologies to meet the demands of extensive connectivity scenarios. Nevertheless, such requirements can be summarized by considering the transport system with strength and flexibility to provide a higher speed efficiency system [3]. In the architecture of the 5G network, the Fourth Generation (4G) Base Band Unit (BBU), Radio Remote Unit (RRU), and the antenna would reconstruct into the Central Unit (CU), Distribute Unit (DU), and the Active Antenna Unit (AAU). The CU is located separately from the BBU Non-Real Time (NRT) part and has a major function of handling the NRT protocols and services. While the RRU and antenna have been combined to form the function of the AAU. The other functions of BBU and denoted under the concept of DU have a major responsibility of handling the protocols laying in the physical layer and Real-Time (RT) based services[4].

The enormous growth of internet traffic and the introduction of new applications might be regarded the most fascinating features of offering larger capacity with lower cost technologies that are based on Fiber Optic (FO) connection. In the meanwhile. The use of a light source in the performance of transmission between two nodes was the fundamental concept behind this kind of technology-based fiber optic communication [5]. The foundation of high-speed infrastructure relies on a communication system utilizing fiber optics. This system holds the potential to offer significant advantages, including vast bandwidth, reduced signal loss and distortion, minimal material usage, lower power consumption, higher data rates, and cost-effective laser components [6]. It enables long-distance transmissions in various applications. However, when extending transmission distances, power levels may need to be increased, leading to the emergence of various nonlinear effects from the optical transmitter [7]. Due to its minimal signal loss and dispersion, fiber optics is often seen as an ideal medium for transmitting data using light. Notably, the optical fiber conveys the light signal, and the recipient converts it back into an electrical signal, making the fiber optic medium itself non-electrical in nature [8]. The transmission of data that undergoes conversion from an electrical signal to an optical signal is a vital component of a communication system that is based on fiber optics. The optical communications system, similar to other communication systems, is susceptible to problems such as dispersion, attenuation, and non-linear effects. Each of these factors contributes to a loss in the system's performance, which in turn contributes to a decline in overall performance. Dispersion is the problem that has the most impact on the system, and it is also the one that is the most difficult to solve in comparison to the other two issues. Therefore, it is essential to devise a method of dispersion compensation that is both efficient and effective, and that ultimately results in an improvement in the optical system's level of performance. In the field of fiber optics, dispersion adjustment is an extremely essential factor. Sending light pulses over an optical fiber that has Chromatic Dispersion (CD) and hence distorts phase is the method that is used in optical fiber communication. This method allows for the transmission of information from one station to another. These light pulses go through modulation at pulses, then dispersion at the transmitter, which allows them to transport the necessary information as an electromagnetic carrier wave. If the primary weakness of optical fibers, known as dispersion, is compensated for, then the benefits of optical systems may be realized effectively. This is because dispersion is the limiting factor in optical fibers. When the group velocity of a wave relies on its frequency, a phenomenon known as dispersion occurs in fiber optics. Another way to phrase this is to say that dispersion occurs when the phase velocity depends on the frequency[9].

The Wavelength Division Multiplexing (WDM) technique was one of the most intriguing methods for 5G communication. In this method, the optical signal was combined with different wavelengths before being transmitted over long distances. At the receiver side, the signal would be separated back to each channel after having been multiplexed. A big increase in capability might be attained with the use of such a method. In addition, Dense Wavelength Division Multiplexing, or (DWDM), was the most significant and valuable type of WDM technique due to the reasons related to its long-distance transmission, wider wavelength range, and higher transmission capacity[5]. These reasons are outlined in the previous sentence. To achieve higher data rates and increase the spectrum efficiency, Radio over Fiber (RoF) technology along with the utilization of DWDM would be utilized for the 5 G-based transport architecture and using the different compensation techniques to handle the problem of CD.

1.2 Literature Review

Several enhancements have been proposed for fiber-based systems to improve performance and handle higher data rates. Among all the proposed methods was using the power of compensation techniques.

[10] proposed a WDM RoF system with only two channels and used the NRZ modulation format for the proposed transmission system. The selected distance was only 50 km, and the proposed system didn't consider the utilization of compensation methods. As a result, the data rate achieved was limited to only 1 Gbps. The pros of their work are that they study the power of using the single-mode and multi-mode Mack Zender Modulators (MZM) that are used to handle the procedure of converting the electrical signal to optical form. Meanwhile, the lower data rate achieved, and transmission distance were the main drawbacks of the proposed system that need to be improved along with improving the total number of the attached channels to meet the requirements of 5G recent applications.

[11] proposed a WDM system that consists of 16 channels and by using the NRZ modulation format, the proposed system could achieve a total of 150 km of transmission. The authors didn't provide any knowledge about using the compensation methods. However, they use the Sub Carrier Multiplexing method along with WDM which could have a significant impact on improving the data rate to reach 28.8 Gbps. The powerful points of their proposed system are, using the power of EDFA to boost the transmitted signal and improve the quality of the received signal and improve the system performance by the power of using the optical amplifier after the transmission of FO signals. While, the drawback, on the other hand, is the lower distance of transmission, using the photodetection method of APD which is not compared with another method, and the lower data rate per each channel of 1.8 Gbps which does not meet the requirement of communication

networks. As a result, the data rate per channel should be improved.

[12] proposed a WDM RoF system that includes 4 channels only and also uses the NRZ modulation type. The presented system could achieve a total distance of 60 km and a total data rate of 4 Gbps. The significant point of their system is the proposed system with lower bandwidth utilization, with very narrow channel spacing. However, the drawback of their proposed system can be summarized by the lower attached numbers, lower data rate, the lower distance of transmission, and using small channel spacing of 50 GHz would not be suitable for the higher number of channels attached which may increase the attenuation and noise between channels. Where using the lower values of channel spacing could improve bandwidth utilization but also affect the total data rate transmitted. As a result, the overall data rate should be improved to satisfy the 5G applications.

[13] proposed a WDM RoF system with only two attached channels for testing the system performance. The proposed system uses the NRZ modulation and tests the system over a 30 km of distance. The compensation technique has not been assigned to the system and the data rate achieved has not been mentioned in their research. The main advantage of their system is Increasing the Extinction Ratio of the MZM will result in improving the quality of the received signal. However, the drawback is a Lower data rate, a very lower distance of transmission, and lower channels used to form the proposed system. Which all needs to be further improved and reconsidered to meet the recent requirements.

[14] proposed a WDM RoF system that includes 10 channels and investigated the system for a distance of up to 70 km. The modulation format utilized with the proposed system is the NRZ and RZ which would be used separately and investigate their impact on the proposed system to show the optimum between their use. The proposed system didn’t use the compensation method and could achieve a total data rate of 10 Gbps. Results obtained from the proposed work indicate that using NRZ improves the system performance more than using RZ along with using the APD photodetector type and for the distances investigated. However, the lower distance of 70 km needs to be further improved and tested with NRZ and RZ, also the data rate is very low (10 Gbps) to meet the requirements of 5 G-based applications and needs to be further improved.

[15] proposed a DWDM RoF system that incorporates 80 channels and uses the RZ as a modulation format. The proposed system didn’t mention the distance that their system reaches, and they use the post type of compensation method. As a result, the system could achieve a total data rate of 960 Gbps. The main contribution of

the proposed system is using the power of the Roman Optical Amplifier (ROA) to boost the signal in the transmission stage of the proposed system, investigating different channel spacing ranging between (20-100) GHz. However, the drawback followed is represented by the lower data rate per channel which needs to be further improved, the studied distance has not been clarified and specified in their study.

[16] proposed a 16-channel DWDM RoF system by using the NRZ method for modulation with a total distance of 60 km. The proposed system utilizes post-method-based compensation and by using the Fiber Bragg Grating (FBG) based method as a base of compensation. As a result, could achieve a data rate of a total of 160 Gbps. The significance of the proposed system is that they studied different input power effects of the proposed system and concluded that using lower power is better to reduce the attenuations and noises. However, using FBG with higher distance needs to be analyzed and using also higher data rates. Also, the system needs to compare results by using the PIN photodetection method along with the used APD method.

[17] proposed a WDM RoF system with 16 channels using the NRZ modulation method. The compensation technique uses are the post method and which could achieve a total distance of 180 km and a total data rate of 640 Gbps. The advantage of the proposed system proposes a higher data rate system to handle the transmission over different distances up to 180 km using the power of EDFA along with post compensation method. Several points are considered a drawback of the implemented system such as increasing the distance of transmission, the data rates, and the overall system performance by using other forms of compensation methods. Also, make a comparison between the different compensation-based Dispersion Compensation Fiber (DCF) that should be involved with the proposed system.

In [18], a 25-channel DWDM-based RoF system has been designed and implemented based on the utilization of the optisystem program and by testing two types of modulation formats represented by the RZ and NRZ. It has been used for post-method-based compensation and with achieving a distance of 180 km. Results obtained from the proposed system show that the capability of the system was 1 Tbps of data rate transmission. The pros of the proposed system were the higher data rate system towards the Tbps of capacity to support recent 5G applications. Also, results showed that when using NRZ is much better than RZ for the proposed system. However, Analyzing the proposed system performance has been achieved by considering only the visualized eye diagram and not studying the parameters of quality factor and bit error rate. Also, among the 25 channels, only 4 channels were selected as samples for analyzing and investigating the system performance.

[19] implemented a 32-channel DWDM system that could use the NRZ as a modulation method and could achieve a total distance of 180 km. The proposed system uses the NRZ method and post-based compensation and could achieve an interesting higher data rate of 1.28 Tbps. As a result, the major advantage of the proposed system is a higher data rate system, with a compensation technique to handle the problem of chromatic dispersion and achieve a higher reliable system. Meanwhile, using another compensation method, proposing a system with higher transmission distance, and studying different channel spacing and different modulation formats for the proposed system are all considered drawback points that need to be involved in proposing such a system.

[20] presented a methodology for a 32-channel DWDM with using the RoF system and along with using the NRZ method. The system could test for 120 km of transmission distance by using the method of post-based FBG so that they could achieve a total of 256 Gbps. The significant point of the proposed work was proposing a higher data rate system with lower channel spacing values that could achieve a quality factor of about 16 dBm overall. However, several points were highlighted as drawbacks such as the distance needs to be raised, also the data rate needs to be increased along with increasing the channel spacing reducing the attenuation effects.

1.3 Thesis Objectives

The main objectives of this thesis are:

- Design and Implement a DWDM that incorporates an RoF system with multiple channels attached to improve the overall data rate and the transmission distance.
- Examine the suggested systems under various conditions, including different transmission distances, modulation formats, and the implementation of a Hybrid DCF-based compensation method. The objective is to enhance the performance of these proposed systems by improving the quality of received data over extended distances.
- Compare and analyze the results of the proposed system concerning the recent publication that is related to the given field to show the significance of the compensation method used and its effects on the DWDM system.

1.4 Thesis Contribution

As previously emphasized, there has been a significant increase in the aspects for applications that require the utilization of internet, especially in the realm of multimedia applications such as broadcasting, video streaming, and interactive Television (TV). This surge in demand has led to a rapid expansion in the requirements for higher data rates to be transmitted per channel and greater capacity, which has prompted the adoption of FO communication systems as a primary solution to address these requirements. To meet these demands effectively, it is crucial to establish and implement a 5G network system capable of delivering substantial data rates and capacities while also addressing issues related to signal distortion, dispersion, and attenuation for extended transmission distances. Consequently, this thesis aims to propose and design an FO communication system to address these concerns and requirements, employing the most reliable compensation techniques to enhance data rates and transmission distances.

1.5 Thesis Outline

This thesis is organized into five chapters as follows:

In Chapter 2, the theoretical foundations of FO communication, as well as its benefits and applications, are covered in this section. Following that, the term RoF and the components that make up this concept are presented. In addition, the many types of WDM multiplexing techniques, as well as their benefits and the role that they play in the 5G communication system, will be emphasized throughout this chapter.

Chapter 3 will demonstrate the major aspect related with the thesis methodology about the concept of chromatic dispersion and handling the dispersion compensation techniques and give an overview of each type showing the art of state of each type and their significance. Also, highlighting the different kinds of dispersion compensation fiber methods and the difference between them.

Chapter 4 tends to give a demonstration in detail for the design of our proposed systems toward the data rate of one Terabit per second by utilizing Optisystem 19, including all of its particular elements and components, and demonstrating how they will achieve this goal. In addition, the chapter would have a listing of the schematic view of the system as well as a presentation of the system parameters that are utilized in the process of analyzing the performance of the proposed system.

Chapter 5 demonstrates the outcome of the suggested systems while considering several measurement-relevant factors. Analyze the findings from system research with various transmission lengths as well. Include comparison results with more recent publications to highlight any importance. Furthermore, the conclusions from the proposed work and makes points of suggestion for future work will be demonstrated at the end of this chapter.

2
THEORITICAL ASPECTS

This chapter will demonstrate a general view of optical fiber communication, its related benefits, and its characteristics. Then, RoF technology would be illustrated to demonstrate the significance of this technology in communication. In addition, the DWDM technique will be explained in all detail. Finally, the proposed system for the proposed thesis will be presented with all related details along with the utilized Optisystem simulation software.

2.1 History of Optical Communication

Fiber optics, which were first created in the 1970s, have completely changed the landscape of the telecommunications sector and have been an essential contributor to the emergence of the Information Age. Optical fiber communications have essentially supplanted copper wire communications in the core networks of industrialized countries due to the benefits that optical fiber transmission offers over electrical transmission[20, 21].

In 1880, Alexander Graham Bell and his helper Charles Sumner Tainter invented the Photophone at Bell's newly constructed Volta Laboratory in Washington, District of Columbia. The Photophone was an extremely early forerunner of fiber-optic communications. Bell regarded it to be his most significant contribution to the field. The apparatus made it possible to transmit sound along a beam of light. On June 3, 1880, Alexander Graham Bell made the first-ever transmission of a telephone call via a wireless network between two buildings that were about 213 meters apart. Because it relied on the atmosphere as its transmission medium, the Photophone would not become a viable technology until developments in laser and optical fiber technology made it possible to carry light securely. Many decades later, the first use of the photophone in a practical setting was in the communication networks of the military [21].

In 1954, Harold Hopkins and Narinder Singh Kapany demonstrated that rolled fiberglass can enable light transmission through it. In the beginning, people believed that light could only travel through mediums that were perfectly straight.

In 1963, a Japanese researcher working at Tohoku University named Jun-ichi Nishizawa suggested that optical fibers may be used in the field of communications. Both the PIN diode and the static induction transistor, which Nishizawa created, played a part in the development of optical fiber communications. Nishizawa also invented the static induction transistor [18, 21].

At STC Laboratories (STL), Charles K. Kao and George Hockham demonstrated in 1966 that the losses of 1,000 dB/km in existing glass (compared to 5–10 dB/km in coaxial cable) were caused by pollutants that had the ability to be eliminated. This was shown by contrasting it with the fact that the losses in coaxial cable were only between 5 and 10 dB per kilometer. In 1970, Corning Glass Works was successful in creating optical fiber, which had an attenuation that was suitable for use in communication (about 20 dB/km). Around the same time, GaAs semiconductor lasers were produced that were small and, as a result, were appropriate for delivering light over FO cables across long distances[18, 21].

Optelecom, Inc., which had been co-founded by Gordon Gould, the inventor of the laser, was granted the contract for the first optical communication systems in 1973 by the APA. This contract was for the development of the first optical communication system. This technology was created for the Army Missile Command in Huntsville, Alabama. Its primary purpose was to enable the transmission of a modulated signal across a distance of five kilometers. It was composed of an optical fiber spout that was played out by a missile and a laser that was placed on the ground.

1975 marked the beginning of a period of research that was followed by the establishment of the first commercial fiber-optic communications infrastructure. This system used GaAs semiconductor lasers that worked at a wavelength of around 0.8 micrometers and ran at this wavelength throughout its operation. This first-generation system was capable of functioning at a bit rate of 45 Mbit/s and had a maximum repeater separation of 10 kilometers. Soon later, on April 22, 1977, General Telephone and Electronics carried out the first live telephone communication utilizing fiber optics in Long Beach, California, with a throughput of 6 Mbit/s[21, 22]. This event took place in the United States.

Corning Glass, CSELT, and Pirelli signed into a development agreement in October 1973 to perform tests with fiber optics in an urban context. Corning Glass was a part of all three organizations. After another three years, in September 1977, the second cable in this experimental series, which was given the designation COS-2, was installed in Turin for the purposes of testing. Fiber optics were employed for the very first time in a big metropolis for this project, reaching a distance of 9 kilometers and operating at a speed of 140 Mbit/s. The second generation of fiber-optic communication systems was made available for use in commercial applications towards the beginning of the 1980s. In these devices, the wavelength was 1.3 microns, and the InGaAsP semiconductor lasers were responsible for the light production. Nevertheless, these systems were originally constrained by constraints brought on by the dispersion in multi-mode fiber.It wasn't until 1981 that it was found out that the use of single-mode fiber could considerably boost system performance. This discovery came about. Despite this achievement, it was difficult to build connections for single-mode fiber that could be used in practical applications. During this time period, the Canadian service provider SaskTel successfully finished the building of the world's longest commercial fiber optic network. The network stretches for 3,268 kilometers (2,031 miles) and connects 52 municipalities[21, 23].

The rate of data transmission has increased gradually over the years, reaching a peak of 10 terabits per second in 2001. This rise began in 1992 and continued until 2001. In 2006, an astounding data rate of 14 Tbit/s was reached across a single line that was 160 kilometers (99 miles) in length by using optical amplifiers. This rate was attained throughout the length of the line. Expanding the wavelength range within which a Wavelength Division Multiplexing (WDM) system may function efficiently is the primary focus of research and development for the fifth generation of fiber-optic communications. This is the primary focus of research and development for the fifth generation of fiber-optic communications. Traditionally, the C band covered wavelengths from 1.53 to 1.57 micrometers, but with the low-loss window of dry fiber, this range is expected to increase to 1.30 to 1.65 micrometers. In addition to this, there are innovations in "optical solutions," involving pulses that can maintain their shape despite dispersion and nonlinear effects in the fiber. These pulses are designed with specific characteristics. Industry proponents and research firms like KMI and RHK predicted a significant surge in demand for communication bandwidth from the late 1990s through the year 2000. This was attributed to the growing use of the Internet and the commercialization of bandwidth-intensive consumer services like video on demand. A visual representation of the development of the optical communication system can be found in Figure2.1, illustrating the progression of capacity and transmission distance over time[21, 24].

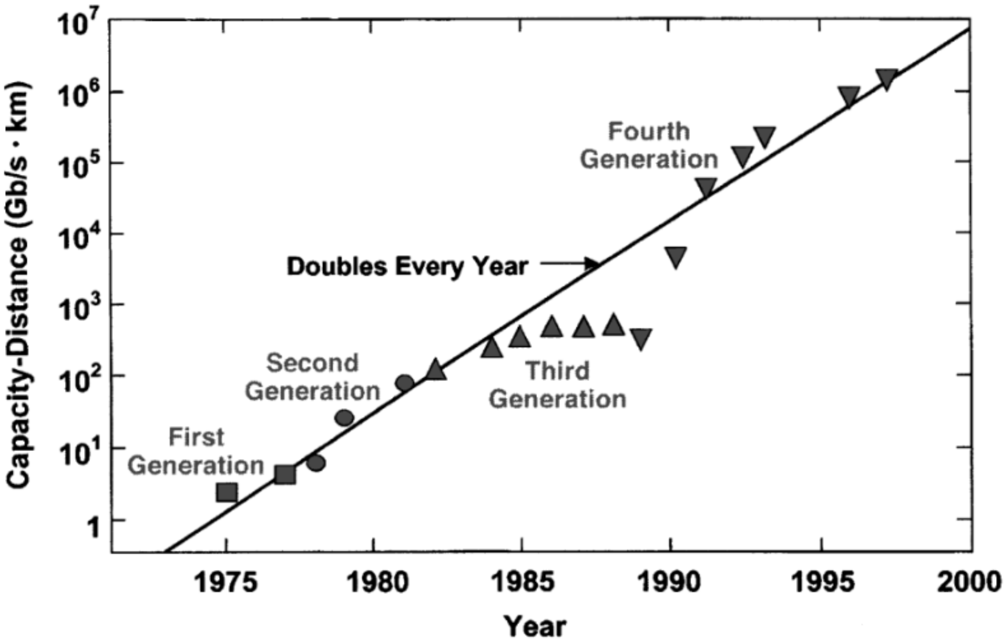

Figure 2.1 The generation of development of optical communication system [22]

2.2 Fiber Optic Communication

Fiber-optic based communication can be considered as a method that enables data to be sent from one site to another. This may be achieved by using optical fibers to connect the two locations. In order to do this, light pulses must be sent across an optical cable. An electromagnetic carrier wave may be formed by light, and this wave can then be manipulated to transmit information. Figure 2.2 shows a basic fiber optical communication system. When there is a need for high bandwidth, a long distance, or resilience to electromagnetic interference, fiber is the material of choice rather than electrical wiring. Voice, video, and telemetry may all be sent via this kind of communication, whether it's over a short or long distance, through computer networks, or in local area networks. Optical fiber is the medium of choice for the transmission of telephone signals, Internet connectivity, and cable television signals by a significant number of telecommunications firms. Researchers at Bell Labs have succeeded in increasing the speed of the internet to more than 100 Kbps by using a fiber-optic connection[23].

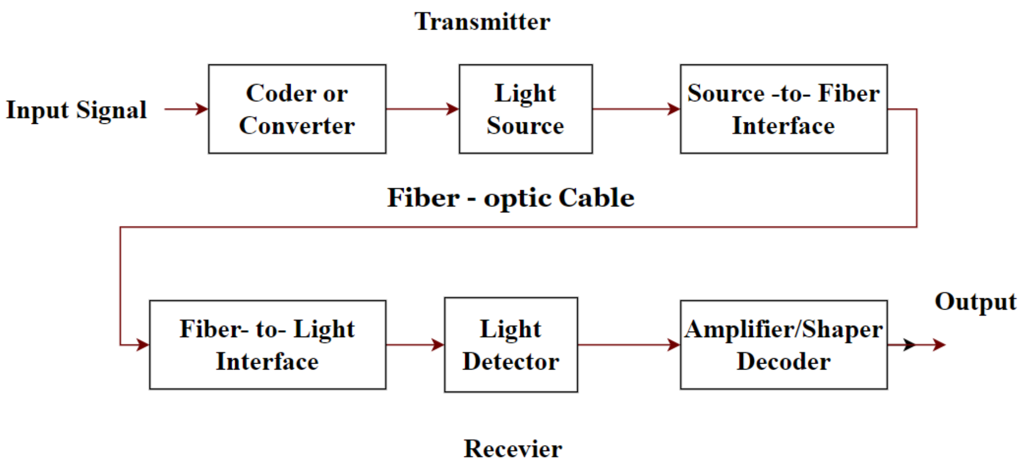

Figure 2.2 Basic fiber optical communication system [24]

The following are the fundamental stages involved in the process of communicating via the use of fiber optics [23]:

- the generation of the optical signal, which often begins with an electrical signal and involves the usage of a transmitter.
- transmitting the signal via the fiber while ensuring that it does not become too distorted or insufficiently strong.
- being in possession of the optical signal.
- transposing it so that it may be read as an electrical signal.

2.3 Fiber Optic Characteristic

Communication systems based on optical fiber provide several benefits over those based on metallic components. Interference, attenuation, and bandwidth characteristics are among these advantages and many benefits. In addition, the comparatively small size of the cross-section of fiber-optic cables makes it possible for existing conduits to accommodate a substantial expansion in their carrying capacity. The properties of fiber optics may be divided into two categories: linear and nonlinear. Bit rates, channel spacing, and power levels are all examples of factors that may affect nonlinear properties [21] .

1. **Interference**

   Electromagnetic Interference (EMI) and Radio-Frequency Interference (RFI) cannot affect light signals when they are sent over a fiber-optic connection. Additionally, lightning and interference from high voltage are obliterated. A fiber network is the superior choice in settings that experience high levels of interference from EMI or RFI, as well as in circumstances where safe operation that is free from sparks and static must be maintained. The usage of fiber-optic cable as the medium of choice in both industrial and biomedical networks may be attributed to the fact that it has several desirable qualities. There is also the option of placing FO cable inside natural gas pipelines and use the pipelines themselves as the conduit for the cable [21]. This would allow the cable to be run through the pipelines without the need for additional conduit.

2. **Linear Characteristics**

   Attenuation, CD, and Polarization Mode Dispersion (PMD) are all examples of linear properties. Another example is the Optical Signal-To-Noise Ratio (OSNR).

   A. Attenuation: Attenuation may be induced by a variety of factors, but its causes can generally be divided into two categories: internal and extrinsic. Both inherent and extrinsic factors may contribute to attenuation. Extrinsic attenuation is induced by components that are normally present in the fiber, but intrinsic attenuation is generated by forces that originate from the outside, such as bending the fiber. Intrinsic attenuation is caused by components that are naturally present in the fiber. The amount of loss in dB that occurs per kilometer of fiber is represented by the attenuation coefficient, which is written as a number in decibels per kilometer [21]. In optical communication, the attenuation is calculated based on equation 2.1 concerning the decibel per unit length.

$$Attenuation = 10 \log_{10} \left(\frac{P_i}{P_o} \right) \tag{2.1}$$

   Where pi is the input power and po is the output power.

B. Intrinsic Attenuation: Intrinsic attenuation is caused by materials that are already present inside the fiber. Impurities that are introduced into the glass throughout the production process are to blame for this issue. Despite how accurate production might be, there is no way to completely exclude the introduction of contaminants. When a light signal collides with an impurity in the fiber, there are two possible outcomes that might take place: either the light signal scatters or it is absorbed. The impact of attenuation concerning wavelengths for the SMF can be noticed as seen in Figure2.3 [21].

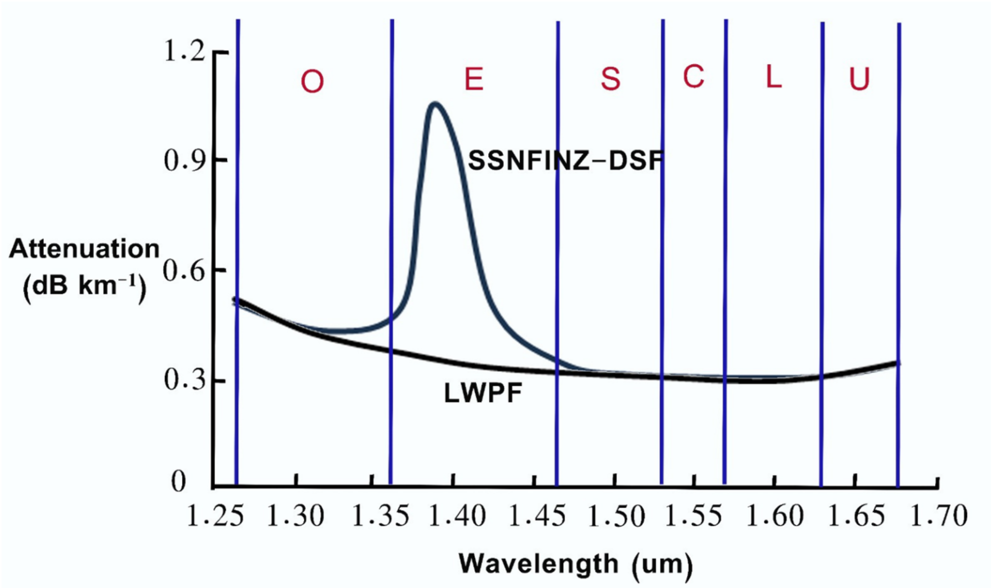

Figure 2.3 The absorption of material losses in silica glass fibers [22]

C. Material absorption: happens because the fiber has imperfections and impurities in it, which causes it to be porous. Despite the severe production procedures, the hydroxyl (OH-) molecule is the most prevalent contaminant, and it always stays as a residue in the product. The relationship between attenuation and wavelength, as determined by measurements taken across a variety of fiber-optic cable materials, is shown in Figure2.4. The three principal operating windows are made up of the wavelength bands that range from 850 nm to 1310 nm and 1550 nm respectively. These correspond to the wavelength ranges in which attenuation is low and are matched to the capabilities of a transmitter to generate light effects and the capabilities of a receiver to carry out detection, respectively. The absorption of Material losses in silica glass fibers can be seen in Figure2.4, which demonstrates a probable decrease in optical intensity as a function of wavelength for completely unadulterated glass[21, 22].

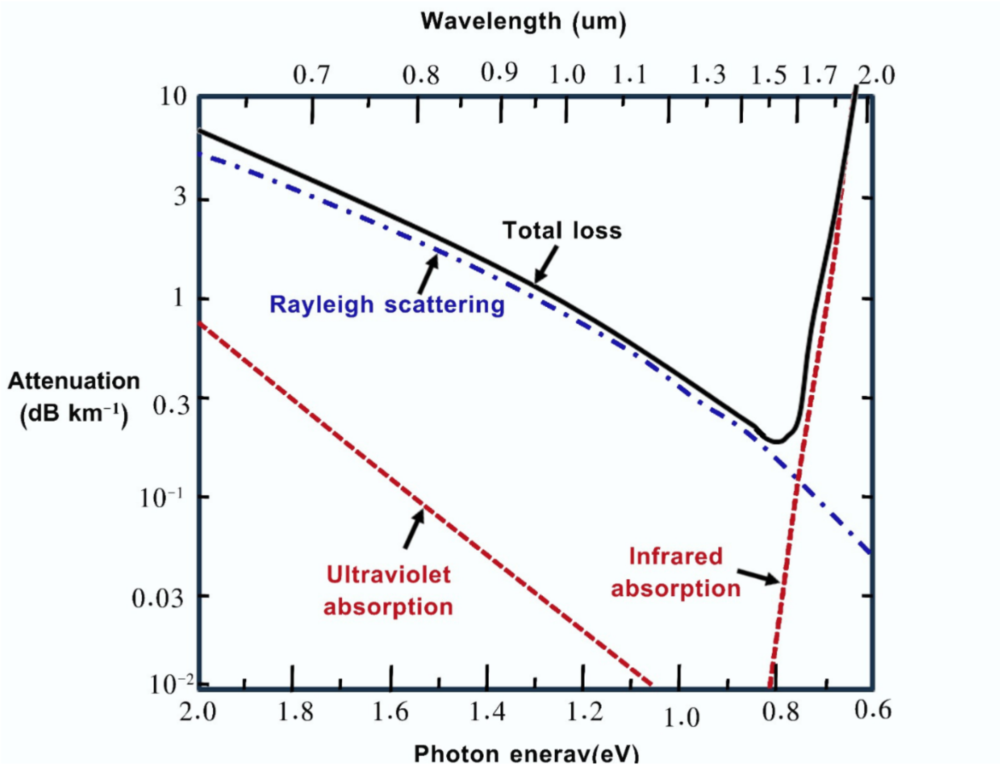

Figure 2.4 TThe absorption of material losses in silica glass fibers [21]

D. Rayleigh scattering: Light can interact with the silica molecules that make up the core as it passes through the core. Rayleigh scattering is the result of elastic collisions between the light wave and the silica molecules in the fiber. These collisions take place as the light travels through a fiber. While moving through the fiber, the light is subject to these collisions. Around 96 percent of the entire attenuation that occurs in an optical fiber may be attributed to the Rayleigh scattering process. The dispersed light does not experience any attenuation if it continues to maintain an angle that enables it to move ahead inside the core. However, if the light is dispersed at an angle that does not enable further onward movement, then the light is deflected away from the core, which results in the light being reduced in intensity [25]. There is a piece of the light that travels in a forward direction that is affected by the incidence angle, while the other portion of the light is deflected from the route of propagation and leaves the fiber core. A portion of the light that has been dispersed is sent back in the direction of its source. Fibers are put through their paces by an Optical Time Domain Reflect meter

(OTDR), which relies on this particular feature. Analyzing loss related to specific events in the fiber, such as splices, may also be addressed using the same fundamental approach. It is easier to disperse light with shorter wavelengths than with longer ones. Because of the substantial attenuation that is caused by Rayleigh scattering, any wavelength that is less than 800 nm is ineffective for use in optical communication. At the same time, it is impossible to propagate at wavelengths over 1700 nm because of the large losses that are caused by infrared absorption. The calculation for Rayleigh scattering (γr) based single-component glass can be obtained based on equation 2.2[25] .

$$\gamma r = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c \mathrm{KT}_F \tag{2.2}$$

Where λ is the wavelength, p represents the average coefficient for photo elastic, n is the refractive index, β_c is the isothermal constant, T_F denoted to the fictive temperature and finally, k is constant.

E. Extrinsic Attenuation: Macro bending and micro bending, both of which are considered to be external processes, are capable of causing extrinsic attenuation. Both of these things result in decreased optical power. Because of the bend that was created on the optical fiber in that position, the section of the fiber that was bent is now susceptible to strain. The amount of bending strain that is present in that specific location has an effect on the refractive index as well as the critical angle of the light beam. As a direct consequence of this, light that is moving through the core is susceptible to loss due to refraction [21].

F. Chromatic Dispersion (CD): CD occurs when a light pulse spreads out as it moves along a fiber in the direction of travel. Because light has a dual character, it may be analyzed both from the point of view of an electromagnetic wave and from a quantum viewpoint. Because of this, we can quantify it in terms of both quantum particles and waves. When light travels across space, each of its spectral components does so at the same time and in the same way. These spectral components move at various group velocities, which results in a dispersion that is referred to as Group Velocity Dispersion (GVD). Because of its dependency on wavelength, the dispersion that occurs as a consequence of GVD is referred to as CD. Pulse spread is the result of the CD having an impact. As the pulses raised or widen, they need to overlap one another, and the receiver is no longer able to differentiate between them as 0s and 1s. Errors and the loss of information may occur when light pulses are broadcast near one another (high data rates), but when they disperse too far (high dispersion). The variety of wavelengths that are produced by the light source is what causes the phenomenon known as a CD. Lasers and LEDs produce light that is composed of a spectrum of wavelengths, each of which travels at a speed that is somewhat different from the other wavelengths. Because of the different speeds at which different wavelengths travel, the light pulse will spread out in time as the distance increases [21].

In single-mode applications, this is the most important consideration to make. Modal dispersion is a phenomenon that plays a crucial role in multimode applications. A spreading effect is produced when these sorts of applications are carried out because the multiple modes of light that pass down the fiber arrive reach the receiver at different times.CD is something that occurs regardless of the bit rate. By using dispersion-shifted fiber, CD may be corrected for or minimized, depending on the situation DCF. Doping a fiber with contaminants that have poor dispersion properties results in the production of DCF. The unit of measurement for CD is ps/nm/km. To properly account for the effects of CD, it is customary to set aside a power buffer of 1 dB. CD is what causes distinct color components of a pulse to travel at different rates when it is sent over an SMF and as seen in Figure 2.5.

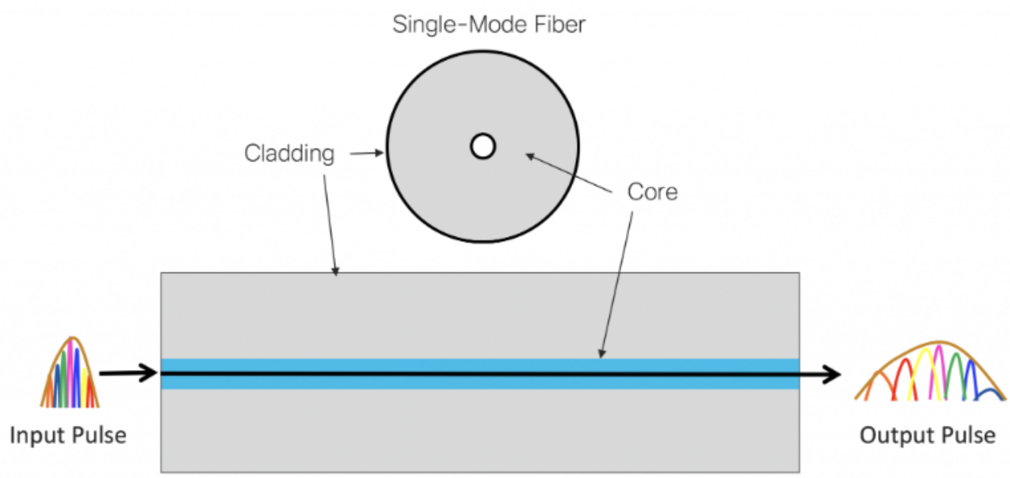

Figure 2.5 Chromatic dispersion in SMF[26]

G. Polarization Mode Dispersion: PMD occurs when the fiber undergoes random distortions, which then cause the form of the fiber to deviate from being precisely cylindrical. The fiber does not behave in the same way that the ideal cylindrical waveguide would, hence it is more correct to refer to it as a defective cylinder. This means that the fiber's physical dimensions vary over its length and diameter rather than being constant. Not only are these variances in its cylindrical form caused by external forces such as bending, and strains incurred during handling, deployment, and splicing, but they are also the consequence of faults in the manufacturing process. Figure 2.6. is a visual representation of the PMD idea[23] .

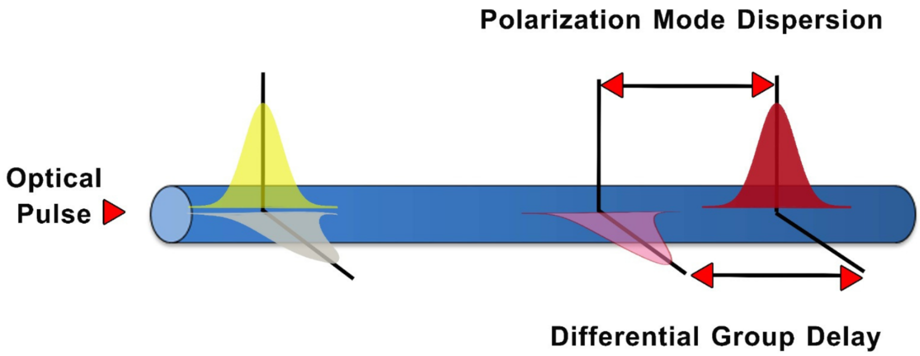

Figure 2.6 PMD concept [26]

One fundamental mode may be supported by single-mode optical fiber and components. This model is comprised of two polarization modes that are orthogonal to one another. Because of this asymmetry, there is a negligible variation in the refractive index between the two polarization states. This property is known by its technical name, birefringence. The difference in the amount of time it takes for light to pass from one polarization mode to another is referred to as the Differential Group Delay (DGD). Birefringence is the physical phenomenon that generates this discrepancy. Picoseconds are the standard unit of measurement for Differential Group Delay (DGD), which stands for Differential Group Delay. When a fiber develops birefringence, it throws off the delicate balance that exists between the various components of polarization, which ultimately results in a phase in which the various components move at different rates. This disorder has the potential to be categorized as either first-order PMD, also known as DGD, or second-order PMD, more often referred to as SOPMD. The signal's reliance on wavelength and its spectral breadth both contribute to the formation of dispersion, which is the root cause of SOPMD [24].

When dealing with low data rates, PMD is not a worry; however, when working at bit rates that are more than 5 Gigabits per second, it becomes troublesome. PMD is a major factor that contributes considerably to the performance decline that occurs in ultra-long-haul networks, which is especially noticeable at high data rates. PMD compensators, which have dispersion-maintaining fibers with changing amounts of birefringence, are one solution that may be implemented to alleviate this problem. Over a certain length of transmission, the effects of PMD are canceled out by the birefringence that has been introduced[25].

H. **Optical Signal-to-Noise Ratio**: : OSNR is a measurement that evaluates the quality of a signal by contrasting the total power of the signal with the total power of the noise. Amplifying the optical signal is one way to make up for the signal loss that occurs as a result of attenuation. On the other hand, optical amplifiers are capable of simultaneously amplifying both the signal and the noise. Receivers gradually become unable to differentiate between the signal and the noise as time and distance pass, which ultimately results in the signal being completely lost. In order to prevent these undesired effects from rendering the system useless and preventing signal identification at the receiver, regeneration is a strategy that may be used to reduce them. To do this, the receiver must first demonstrate that it is capable of picking up the signal. When optical amplifiers are used, a certain amount of noise is introduced into the channel by the amplifiers. In addition, noise components might be introduced into the system by active components such as lasers as well as passive components such as taps and the fiber itself. However, optical amplifier noise is regarded to be the primary cause of OSNR penalty and deterioration in the computation of system design. An example of the calculation of OSNR can be seen in Figure2.7[26].

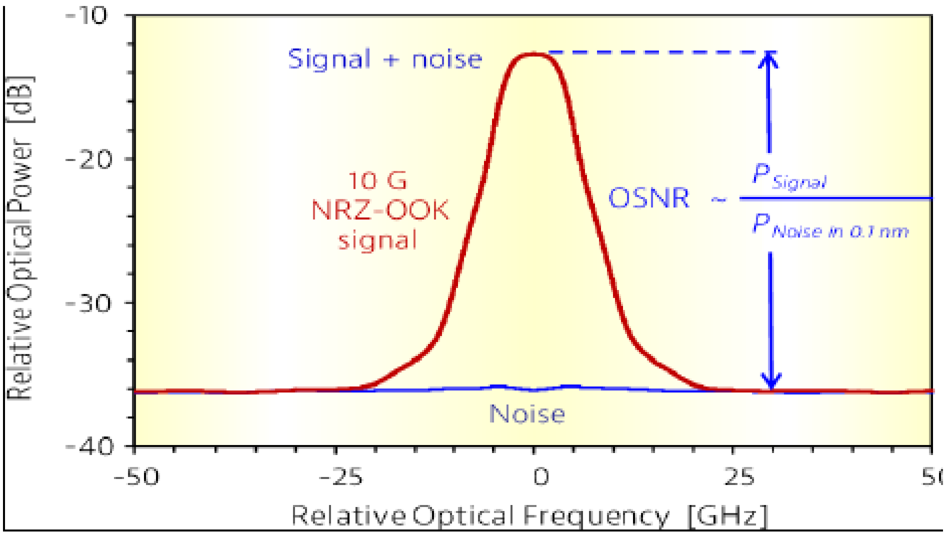

Figure 2.7 Typical example of calculation of the OSNR [26]

One of the most crucial and basic aspects to consider while designing a system is its OSNR. The Q-factor is yet another parameter that is taken into consideration by designers. A qualitative description of the receiver's performance may be obtained by using the Q-factor, which is a function of the OSNR. The Q-factor indicates the minimum SNR that must be achieved in order to generate a given BER for a particular transmission. The overall signal-to-noise ratio is reported as a decibel number. When the bit rate is increased, the minimum acceptable OSNR level also rises [27].

3. **Non Linear Characteristics**

Nonlinear behavior of fiber optic has some characteristics which will results different phenomenon that are classified as seen in Figure2.8 [28].

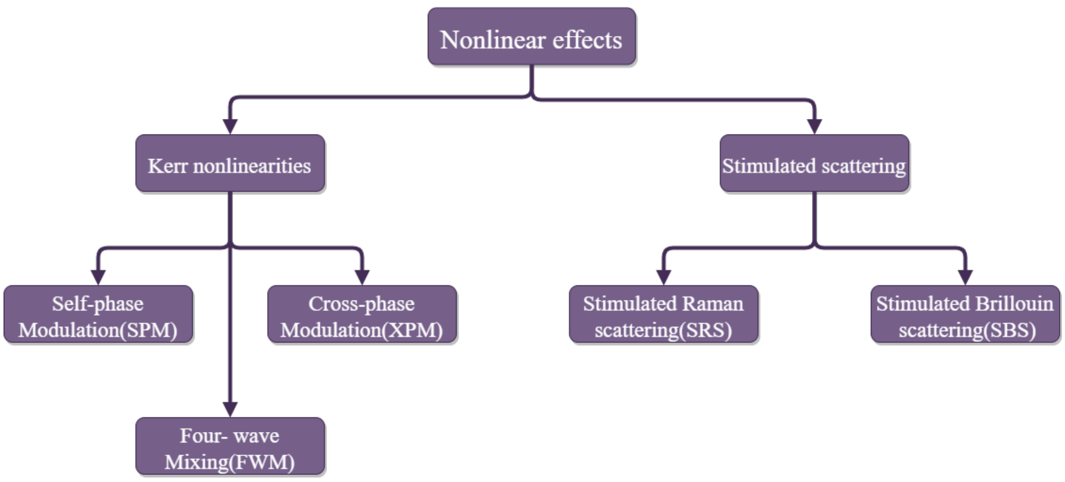

Figure 2.8 Classification of nonlinear effects [28]

2.4 Advantages of Fiber Optic Communication

Because of the many benefits that optical fiber transmission has over electrical transmission, copper wire communications in the core networks of industrialized countries have mostly been replaced by optical fiber communications. The primary benefits of transmitting data using fiber optics are as follows [29].

1. Extremely High Bandwidth:

   FO is the only data transmission medium that provides a bandwidth that is comparable to that of cable. FO cables are capable of transmitting a much higher amount of data in the same amount of time as copper lines.

2. Greater Transmission Range:

   In FO transmission, optical cables can provide minimal power loss, which enables signals to be transported over a greater range than is possible with copper cables. This allows FO transmission to take place over longer distances.

3. Resistance to Electromagnetic Interference:

   When it comes to practical cable deployment, it is unavoidable to come into contact with environments such as power substations, heating, ventilating, and other industrial sources of interference. Cables must be able to withstand these types of environments. On the other hand, fiber is so resistant to electromagnetic interference that it has a very low rate of bit error ($10e^{-13}$). This is why fiber has such a low error rate. The transmission of data via fiber optics is almost noiseless.

4. The risk of security vulnerabilities is low:

   The expansion of the FO communication industry is being driven in large part by increased awareness about data security issues as well as the usage of alternative raw materials. In a FO transmission, the data or signals are sent via the medium of light. As a result, there is no way to discover the information that is being conveyed by "listening in" to the electromagnetic energy that is "leaking" down the cable; this assures that the information is kept in complete secrecy.

5. Small size:

   The diameter of a FO cable is rather negligible. For example, the diameter of the cable that contains a single OM3 multimode fiber is around 2 millimeters, which is less than what is included inside a coaxial copper cable. In FO transmission, a smaller size saves more space than larger sizes.

6. Less Weight:

   Optical fiber cables may be composed of glass or plastic, and they are far thinner than copper cables. Because of this, they are easier to install and less weight.

7. It Is Simple to Accommodate Increasing Bandwidth:

   By using FO cable, new equipment may be connected to an already existing cable infrastructure. This makes it easier to accommodate increasing bandwidth. Because optical cable may give a significantly increased capacity in comparison to the cable that was first placed. In addition, WDM technology, which encompasses both CWDM and DWDM, makes it possible for fiber lines to provide increased bandwidth.

2.5 Disadvantages of Fiber Optic Communication

Although there are a lot of benefits to having FO transmission, there are also certain drawbacks that can't be overlooked[29].

1. The cables used to transmit optical signals are often composed of glass, which makes them more brittle than the wires used to transmit electrical signals. Glass, on the other hand, is susceptible to damage from a wide variety of chemicals, one of which is hydrogen gas, which is a common issue with underwater cables and necessitates additional precautions when installed below ground.

2. The installation process is difficult where splicing FO cable is not a simple task. In addition, they will crack if you bend them an excessive amount. In addition, FO cable is very vulnerable to being severed or otherwise damaged during the process of installation or development. Because of all of these factors, installation is made more complex.

3. Light will be attenuated and scattered as the transmission distance increases, which will need the addition of more optical components.

4. While the annual reduction in the installation costs of fiber optic (FO) cables is substantial, with up to a sixty percent decrease, it's important to note that installing FO cabling remains considerably more expensive than installing copper cables. This cost disparity arises because the installation of copper wires doesn't require the same level of specialized attention as the installation of fiber cables.

5. In Many Instances, Specialized Equipment Is Needed to guarantee the quality of the FO transmission, specialized equipment is required. For instance, to adequately offer testing of optical fiber, apparatuses like OTDR and other costly, specialized optical test equipment like optical probes and power meters are necessary at the majority of fiber endpoints.

2.6 Fiber Optic Applications

The utilization of FO cables may be found in a very broad range of different businesses and applications. The following are some applications for FO cables[29]:

a. In the medical sector, lasers serve as guides for light, aids in medical imaging, and are crucial tools for various surgical procedures.

b. Data Storage: Laser technology is harnessed for efficient data transfer.

c. Telecommunications: Optical fiber is deployed for both transmitting and receiving data in telecommunications.

d. Networking: In various network setups, lasers facilitate connections between users and servers, enhancing data transmission speed and accuracy.

e. Industrial and Commercial Applications: Lasers are employed for imaging in hard-to-reach areas, wiring in places susceptible to electromagnetic interference, and as sensors for measuring temperature, pressure, and other parameters. They are also used in automotive and industrial environments.

f. Broadcasting and Cable Television: In the broadcasting and cable television industries, optical fiber connections are used for transmitting CATV, HDTV, internet, video-on-demand, and other services. Optical fibers are versatile tools for measuring and monitoring various factors. They also find applications in lighting, imaging, research, development, and testing across these industries.

Also, FO can be used in a wide variety of applications, such as the following [21]:

Optical fibers are used in a wide variety of contexts, including but not limited to telephone systems, submarine cable networks, data linkages between computer networks, cable television systems, closed circuit television surveillance cameras, connections for emergency services such as fire and police, as well as in hospitals, schools, and traffic management systems. They play an important role in integrating and linking emergency responders, and they are used in a variety of sectors, including heavy-duty construction, where they have a broad range of practical applications.

2.7 RoF System

2.7.1 RoF Overview

When more people utilize a wireless network, there is a greater need for more spectrum to accommodate everyone's devices. Because of how crowded the RF spectrum is for wireless communication, providing additional bands for new services is becoming an increasingly difficult challenge. The RoF solution to RF issues offers not only a vast bandwidth but also a cost-effective and flexible method of addressing the issue[30]. This technology also boasts a minimal loss rate and remarkable resilience. It involves transmitting a modulated RF signal over a FO network, creating an analog optical link for transmitting information from a central location to a base station. To achieve this, a highly linear optical fiber link is employed for the transmission and distribution of RF signals from a central location, where Base Stations (BS) are located, to Remote Antenna Units (RAUs) over long distances. RAUs are relatively straightforward to construct and maintain as they only need to contain optoelectronic conversion equipment and amplifiers [30].

In a (RoF) system, the various steps of RF signal processing are centralized at a shared location, and an FO network is used to distribute RF signals to RAUs within the system. All tasks, including coding, multiplexing, RF signal generation and modulation, switching, routing, as well as network operation administration and maintenance, are managed by a Central Site (CS). Simple antennas of the BS used for wireless communication are interconnected through FO links. The network architecture was designed in a delegated manner, relieving the BS of complex processing tasks. Instead, they focus on converting optical signals into wireless signals and vice versa. Consequently, this technology is poised to play a significant role in the future of mobile communication technology [31].

In Radio-over-Fiber technology, an optical fiber network is used to distribute modulated radio frequency signals from a CS to RAU or BS. The idea behind RoF is to transmit data across optical fiber by modulating the light with a radio signal, and this is what the RoF hypothesis describes. After the Central Site completes several RF signals processing activities, including frequency up-conversion, carrier modulation, and multiplexing, the results are sent to the BS/RAUs.Figure2.9

demonstrates the general diagram of RoF technology, The RoF technology makes it feasible to concentrate the RF signal processing activities in one common place. After that, optical fiber, which provides minimal signal loss, is utilized to transfer the RF signals to the RAUs. Signal loss in optical fiber varies depending on the wavelength being transmitted; for example, the loss is 0.3 dB/km for 1550 nm wavelengths and 0.5 dB/km for 1310 nm wavelengths. RAUs are greatly simplified as a result of this action [31].

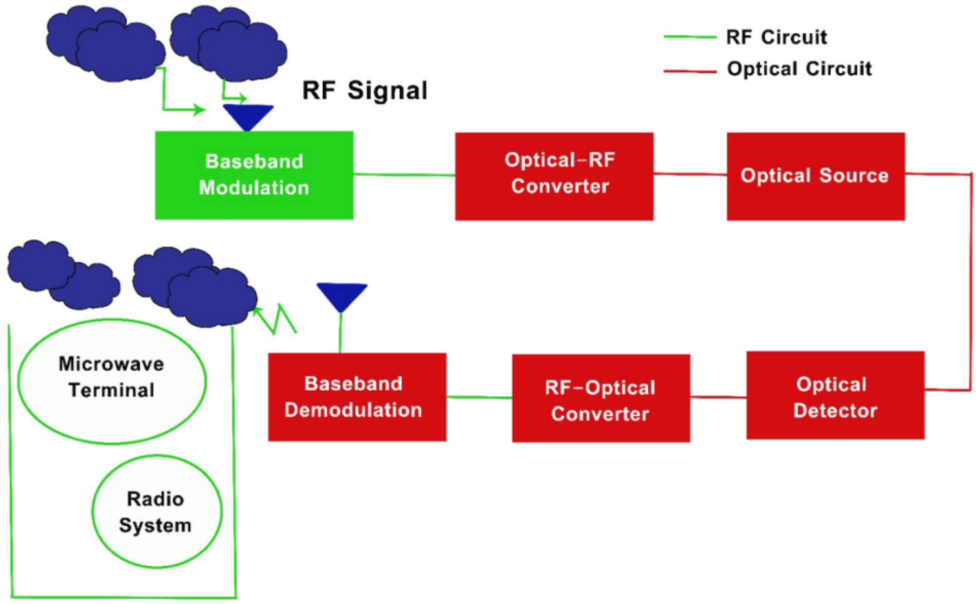

Figure 2.9 General Diagram of RoF Technology [30]

2.7.2 RoF advantages

RoF has several advantages to be used widely for communications which can be summarized in the below points [30].

A. Low Level of Attenuation:

When compared to other mediums, particularly wireless ones, the impact of attenuation is much less noticeable in optical fiber. Therefore, the transmission of an RF signal across a considerable distance utilizing a FO network is feasible. It is possible to support systems that need a larger bandwidth for traveling longer distances using a FO network, which is why it minimizes the possibility of attenuation. These systems can be supported much better than those supported by electrical cables.

B. Lower Complexity:

The Remote Antenna Unit, or RAU, is a concept that enables RoFs to function as a less complicated communication system. The sole function that the RAU is capable of performing is an Optical-to-Electrical (O/E) conversion, with the addition of frequency up or down conversion as an option. Amplifiers and the antenna are two other significant major components [32]. Therefore, we can relocate or centralize all of the circuitry concerned with resource management and signal creation in a CS. This approach also makes the network architecture easier to understand.

C. A Lower Overall Cost:

The more straightforward RAUs suggest that infrastructure costs will be reduced. The gadgets have a minimal amount of power consumption. Equipment that is both complex and expensive is stored at the Central Station, which simplifies the operation of the RAUs. However, if the overall system is maintained simply and the network structure is made plainer, it will be possible to reduce the expenses of system installation and maintenance to a minimum. Because of the less complicated network layout and maintenance, the total setup and maintenance costs are relatively cheap[32].

D. Decreased Need for Electrical Power: Because the vast majority of the heavy, sophisticated, power-hungry equipment is stored in CS, together with RAUs that are less difficult and more straightforward, the amount of power that is used can be reduced.

E. Immunity to Radio EMI: is essentially nonexistent in optical fiber communications. EMI stands for electromagnetic interference. In contrast to other forms of electrical transmission lines, fiber cables do not suffer from the phenomenon known as crosstalk. Because of this, it can be deployed in places that are susceptible to greater levels of electromagnetic interference. In particular for microwave transmission, the fact that FO communication is immune to electromagnetic interference, as well as electromagnetic pulses, is a particularly desirable quality.

F. Large Bandwidth:

The bandwidth that is available with optical fibers is enormous. There are three miracle windows, each of which has low attenuation and low dispersion. These windows have a wavelength of 850 nm, 1310 nm, and 1550 nm respectively. The aggregate bandwidth of these three windows in SMF is more than 50 THz. Because of the large bandwidth, there is a significant increase in the ability to send microwave signals. Because of this enormous optical bandwidth, high-speed signal processing is now conceivable, while in conventional electrical systems, such processing would be difficult, if not impossible.

2.7.3 RoF Applications

RoF has a wide range of applications which include:[30]

1. The network of cellular cells

   In cellular systems, the RoF technology could be the greatest alternative for optimizing cell function. Because it operates on the millimeter wave spectrum. Additionally, it has the potential to reduce the system's total cost. The RoF system is used to transfer mobile signals between the base station and the central station. Cellular networks have attained unprecedented levels of popularity, which has resulted in an ever-increasing demand for mobile network service resources. The RoF system has the potential to be the finest solution for this drastically expanding capacity.

2. Wireless Local Area Networks

   RoF may be used with operating frequencies ranging from 2.4 GHz to 5 GHz to disseminate wireless LAN signals. This helps to support the growing number of portable devices and PCs. The desire for portable devices is causing an ever-increasing demand for LANs, and the technology behind RoF is the most efficient method for meeting this demand.

3. Methods of communication and control within the vehicle

   RoF has the potential to play a pivotal role in the formation of a network of road-to-vehicle communication systems, which will be necessary to satisfy the requirements of the forthcoming intelligent vehicle transport system. To do this, there must be continuous and uninterrupted communication coverage to make transportation more efficient. It will take a very large number of BS to get the level of coverage that is necessary for the road network. The RoF can provide solutions that are both controllable and cost-efficient. RoF technology might potentially be used in this manner as one of its many applications.

4. Applications in the Military

   Since the RoF system is inherently designed to provide a high level of security, RF signal transmission for distant areas is an area in which this technology has the potential to make a significant contribution to the development of secure and sophisticated military applications.

5. Sensing at a High Rate of Speed

   RoF communication is suited for video monitoring signals that need a quick transmission mechanism on high-speed trains and jumbo planes because of its high speed and bandwidth. This makes it an ideal choice for this application.

6. Millimeter Fiber Transmission

   The wave with a frequency of 60 GHz or higher, known as a millimeter wave, has two primary characteristics, the first of which is rapid attenuation, and the second is reduced electromagnetic interference. Due to these two characteristics, RoF is an excellent contender for providing coverage inside. Two of the issues, namely electromagnetic interference, and electromagnetic pollution, may be handled more effectively with the use of RoF communication.

7. Satellite Communication

   At satellite earth stations, a short optical fiber network of little more than one kilometer in length with operating frequencies ranging from one gigahertz to fifteen gigahertz may be utilized to remotely control antennas at appropriate locations. The second potential use is remote control of the earth stations themselves. It is possible to position the antenna at a considerable distance from the base station to enhance satellite visibility and reduce interference from other terrestrial systems [33].

2.7.4 RoF Disadvantages

Even while RoF has a great many advantages to offer, there are a few disadvantages to using it as well. RoF is primarily an analog transmission system due to the fact that it makes use of analog modulation methods and requires the detection of light. This combination makes it necessary for RoF to be implemented. Signal impairments such as noise and distortion are critical features to tackle in analog communication systems, and they are equally significant in the context of RoF technology [33].

The constraints that were mentioned before in this paragraph are intricately tied to the concepts of Dynamic Range (DR) and Noise Figure (NF). The dynamic range, often known as DR and shortened as DR, is a crucial statistic for cellular communication systems such as GSM. This is because the power levels that are received at base stations may vary greatly from one another. In an optical fiber network, the total amount of background noise may be affected by a number of elements, including the shot noise of the photodiode, the thermal noise of the amplifier, the phase noise of the laser, RIN, also known as relative intensity noise, the dispersion of the fiber, and maybe many more.

CD may affect the lengths of the fiber links used in SMF-based RoF. Additionally, RF carrier phase noise may become more noticeable as a result of phase correlation[33].

The available connection bandwidth and distance are both heavily limited by modal dispersion in MMF (Multi-Mode Fiber) based RoF.

2.8 WDM (Wavelength Division Multiplexing)

2.8.1 WDM Overview

The technique known as wavelength division multiplexing, or WDM, involves sending multiple optical signals with distinct peak wavelengths simultaneously through a single optical fiber. While optical WDM shares similarities with electrical frequency division multiplexing in spectral terms, it differs in a key way: each WDM channel effectively utilizes the entire bandwidth of the intensity modulation fiber, which, given current technological capabilities, extends to several gigahertz. This provides optical WDM with an advantage over electrical frequency division multiplexing. This process is illustrated in Figure2.10, which presents a standard optical fiber communication system with a single nominal wavelength alongside a duplex system (comprising two different nominal wavelength optical signals traveling in opposite directions, enabling bidirectional transmission) and a multiplex system (where two or more different nominal wavelength optical signals are transmitted in the same direction). The figure also depicts a multiplex fiber communication system featuring two or more different nominal wavelength optical signals traveling in the same direction[34].

WDM-based optical fiber systems may be built utilizing LED or injection laser sources with either multi-mode or single-mode fiber, depending on the application's requirements. However, more recently, the widespread deployment of SMF has spurred the exploration of WDM on this transmission medium. An appealing idea in the field of telecommunications is one in which individual subscriber terminals might make use of their own specialized communication services via the prospective exploitation of independent wavelength channels[35].

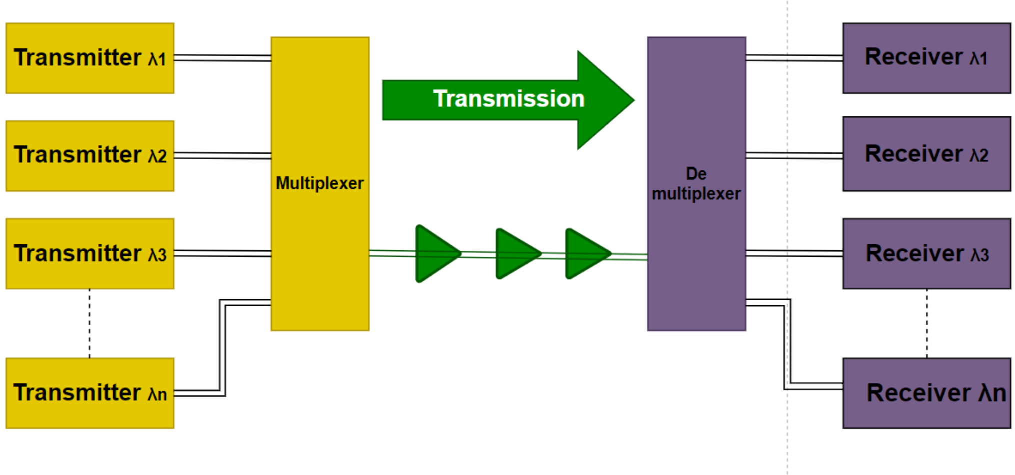

Figure 2.10 General Concept of WDM Technology [36]

2.8.2 WDM Significance in RoF system

Recently, the RoF system based WDM technology has garnered a large amount of interest due to the fact that it is capable of achieving a capacity of 1 Tbps. Furthermore, these systems offer the potential to decrease the channel's frequency spacing to either 50 GHz or 20 GHz, which can enhance the opportunity to accommodate a larger number of channels. This may be accomplished by decreasing the channel's bandwidth. Increasing the spacing, on the other hand, would make the process of updating the system more complex, particularly when considering a high value for the bit rate (equal to 40 Gbps). These kinds of problems would arise as a direct consequence of the consequences of the nonlinear phenomena. The RoF system based WDM approach is explained more clearly in the figure that can be seen in Figure2.11 [35] . The location where it is possible to view the conversion of RF signal to optical signal and then back again to RF in order to develop the notion of RoF technology.

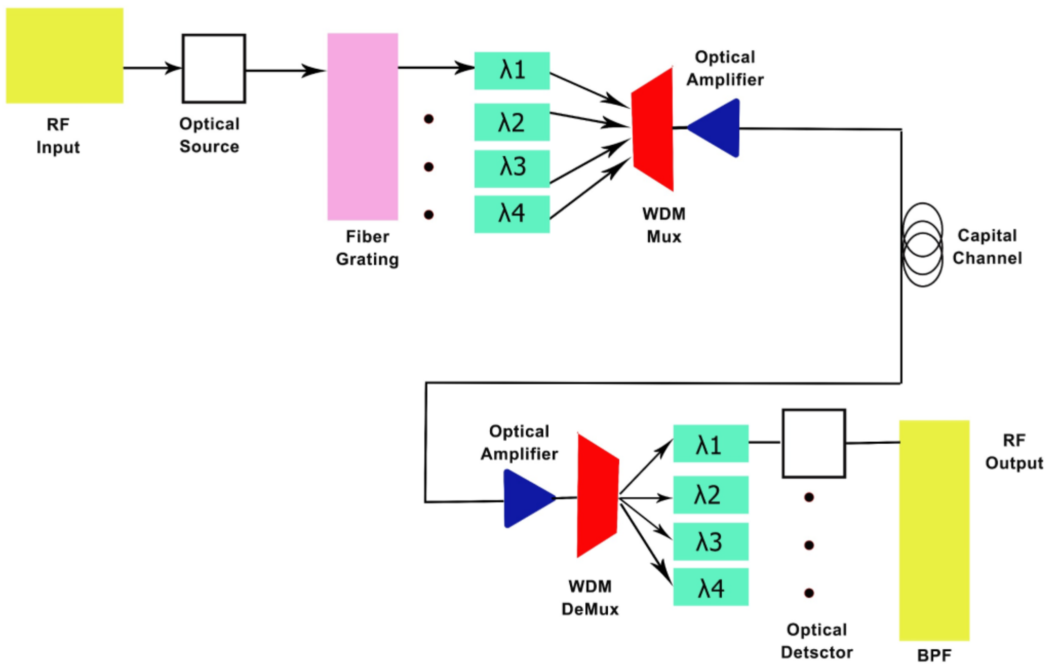

Figure 2.11 Diagram of WDM RoF System[35]

2.8.3 WDM types

The International Telecommunication Union (ITU) has identified two distinct kinds of WDM.

1. Coarse Wavelength Division Multiplexing (CWDM): In CWDM, a smaller number of channels, typically four or eight, are employed with a wider channel spacing of 20 nm. This is considered a less precise form of WDM. The wavelengths used in CWDM fall within the range of 1310 to 1610 nm, and the bit rate chosen must be between 1 and 1.3125 gigabits per second. CWDM is primarily utilized in metropolitan areas and is not suitable for Fiber to the Home (FTTH) applications due to its limitations[36].

2. Dense Wavelength Division Multiplexing (DWDM): -in this kind, it would be accomplished over longer distances with bigger data capacity, which would make them preferred. DWDM is an abbreviation for DWDM was characterized by its use of a high number of channels and a narrow channel spacing that ranged between 12.5 and 100 GHz. The resultant bit rate is more than 100 Gigabits per second[36].

   A final comparison between the CWDM and DWDM in the major aspects are listed in Table2.1. In addition, the difference in spacing between the wavelengths for both the CWDM and DWDM can be seen in Figure2.12[37].

Table 2.1 Comparison Between CWDM and DWDM

parameter	CWDM	DWDM
Channel width	13 nm	1 nm
Channel spacing	20 nm	0.8 nm
Number of channels	4 to 18	Up to 160
Optical amplifiers	Not used	Used
Range	Up to 120 km	Up to 500 km
Power /wave length	1.6 w	5 w

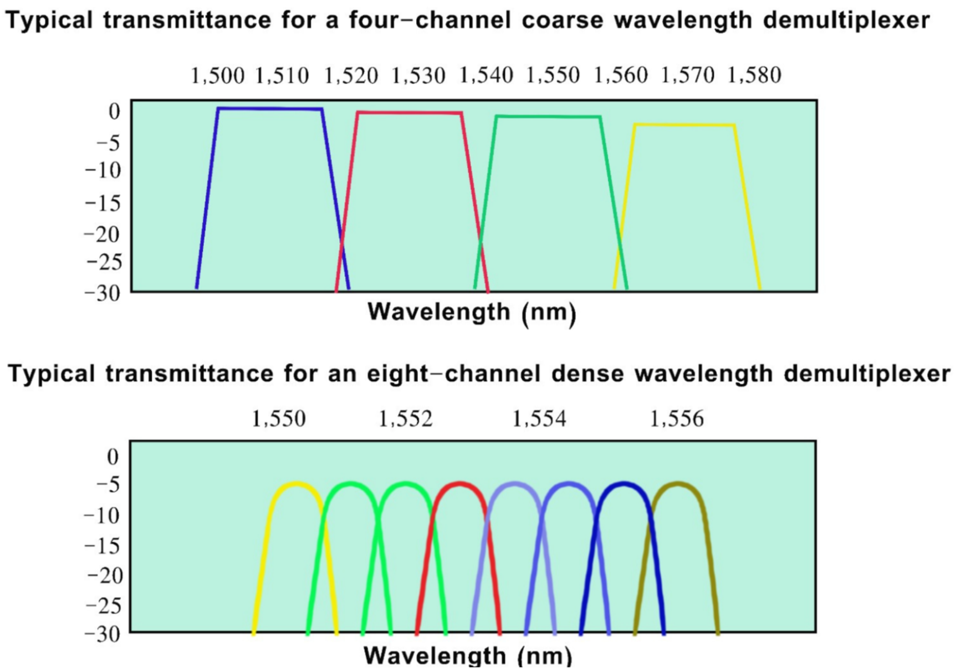

Figure 2.12 Comparison in Channel Spacing Between CWDM and DWDM [37]

3
COMPENSATION TECHNIQUE

In this section, the aspects related with the need for the dispersion compensation would be clarified in detail showing the problem related with the CD and significant of dispersion in optical transmission. Also, this section will list and highlight the different types of dispersion compensation. In addition to that, present the types of dispersion compensation fiber which will be used as a compensation method in this thesis.

3.1 Chromatic Dispersion (CD) in Optical Communication

The phenomena in which the phase velocity and group velocity of light that is moving through a medium that is transparent depend on the optical frequency is referred to as the CD of an optical material. This dependence arises primarily as a consequence of light's interaction with the electrons of the medium, and it is connected to the phenomenon of absorption in certain spectral areas. The term "chromatic" is used to differentiate this kind of dispersion from other kinds, such as inter-modal dispersion and polarization mode dispersion, which are especially important for optical fibers. CD may also take place as a result of geometrical factors, for instance; for more information on this topic, check the section that is located below the one on the CD of optical components. The presence of CD causes the light pulse that is carrying the necessary information to be scattered into a number of different components. These components then travel in different ways along the optical fiber at different velocities, and as a result, they arrive at the receiver at different times. This causes the information to be distorted, and it then cannot be used in the correct manner [38]. The phenomenon of CD can be seen in Figure3.1.

The wavelength dependency of the refractive index on the material that makes up the fiber core is what causes material dispersion. Waveguide dispersion occurs because the mode propagation constant is dependent on the fiber parameters (core radius and the difference between the refractive indices in the fiber core and the fiber cladding), as well as the signal wavelength. These two effects are capable of canceling each other out at a certain frequency, which results in a wavelength that has almost zero CD [38].

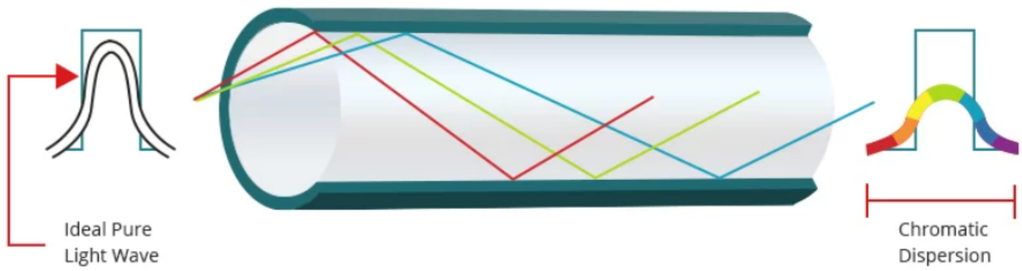

Figure 3.1 The Effect of CD [39]

CD in telecommunication consists of two major types which are:

1. **Material Dispersion**

   This is because the index of refraction of glass is wavelength dependent; more specifically, the refractive index of the core changes depending on the wavelength of the incident light [40].

2. **Waveguide Dispersion**

   This is because of the way the waveguide is constructed physically. Waveguide dispersion is not a substantial problem in a fiber with a basic step-index shape; however, waveguide dispersion may be more relevant in fibers with more complicated index profiles [40].

3.2 Dispersion Compensation

The term "dispersion" pertains to the phenomenon in an optical cable where pulses spread out. This spreading is a result of various factors such as numerical aperture, core diameter, refractive index profile, wavelength, and laser line width, all of which cause the pulse to widen as it travels through the fiber. As the length of the fiber increases, the degree of dispersion also increases. ISI stands for "inter-symbol interference," and it refers to the interference caused by the combined effects of dispersion on the functioning of an optical fiber (FO) system. ISI occurs when the widening of pulses that is generated by dispersion results in the overlap of output pulses inside the system. This overlap causes ISI to occur. As seen in Figure 3.2., the overlap renders the system useless and causes it to fail. The phenomenon known as dispersion may be broken down into three distinct types: modal dispersion, chromatic dispersion (CD), and polarization mode dispersion. Of these three types, modal dispersion is the one that occurs most commonly [38].

Because of the need for a data transfer rate that is more than 10 Gbps, it is necessary to address the potentially negative effects of dispersion and nonlinearity. As a consequence of this, various reimbursement techniques that are based on the use of substitute fiber inverse dispersion have been actualized in order to improve the system's performance and its ability to withstand wear and tear. These processes of handling the dispersion within FO communication can be broken down into three distinct categories:

1. the use of DCF for dispersion compensation.
2. the use of FBG for dispersion compensation.
3. the use of Electronic Dispersion Correction (also known as EDC) and digital filters for dispersion compensation that make use of digital signal processing are two further methods for compensating for dispersion [40].

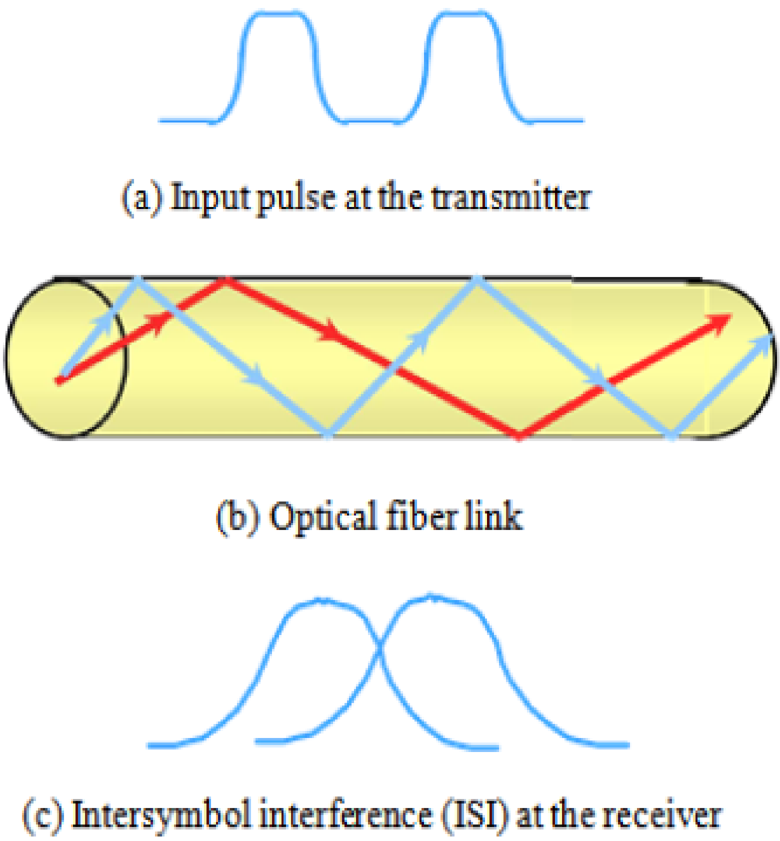

Figure 3.2 ISI Effect On The Transmitted Pulses [40].

3.2.1 Dispersion Compensation Fiber (DCF)

In the DCF (Dispersion Compensating Fiber) approach, it is possible to utilize a fiber that has a substantial negative dispersion in conjunction with a regular fiber. By using a dispersion compensating fiber that has a very large value of dispersion of opposite sign in comparison to that of regular fiber, the amount of light that is disseminated by a standard fiber may be lowered, and in some cases even eliminated entirely. Dispersion correction will generally make use of one of three approaches (fiber-pre, post, or symmetrical), all of which are outlined below. In addition, dispersion compensating fibers are used widely in the process of upgrading the already established optical fiber networks designed for 1310nm to be able to function at 1550nm [41, 42].

Because the positive dispersion of SMF is cancelled out by the negative dispersion value of DCF in a communication system that also uses dispersion compensating fiber, the total dispersion is equal to zero. The DCF operates according to this fundamental concept. There are three different ways to account for dispersion in a compensation scheme: pre-compensation, post-compensation, and symmetrical compensation and as seen in Figure 3.3. [43] .

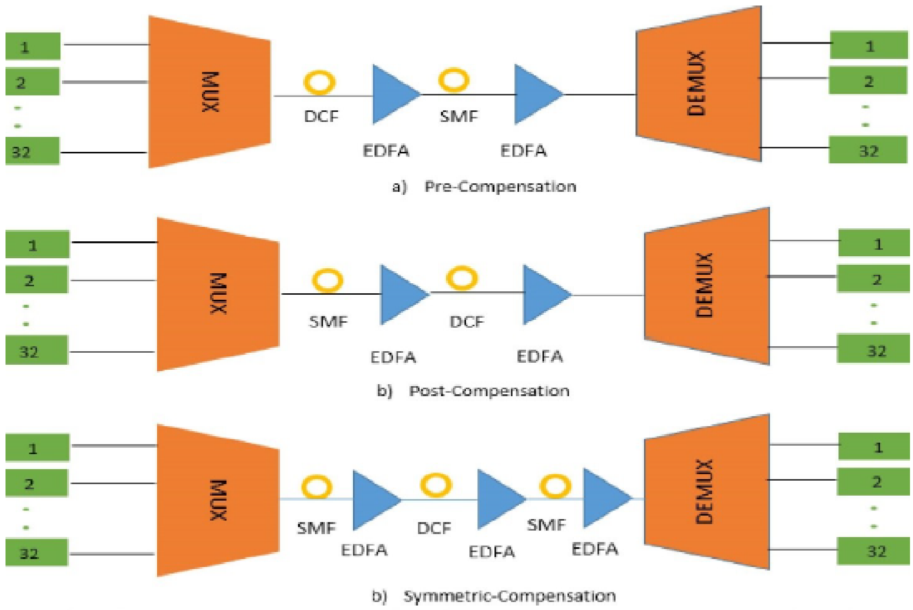

Figure 3.3 Types of DCF [41]

3.2.2 Fiber Brag Gratings (FBG)

It is a reflecting device that only reflects a certain wavelength while allowing all other wavelengths to flow through it unaffected. The phrase "Bragg's wavelength" is what is meant to be understood when referring to the reflected wavelength. The use of Bragg gratings as a method for the correction of dispersion is an efficient strategy since these gratings have a lower insertion loss than other methods, are more affordable, and are compatible with optical fiber. Altering the structure of FBG may be accomplished by modifying either the grating period or the refractive index. You have the option of having a uniform or graded grating period. FBG may be categorized as either uniform grating, chirped grating, or superstructure grating [44], depending on the sort of grating that it employs.

Moreover, the Fiber Bragg Grating (FBG) functions as a reflective device crafted from an optical fiber that exhibits variations in its core refractive index over a specific length. The incorporation of FBGs can significantly mitigate the dispersion effects associated with long transmission lines, such as those spanning 100 kilometers. When the wavelength of light traveling through the fiber aligns with the modulation frequency, the fiber grating reflects the light. Utilizing FBGs for dispersion correction proves to be a promising approach due to their compatibility with passive optical elements, minimal insertion losses, and cost-effectiveness. Beyond their role as dispersion correction filters, FBGs offer potential applications as sensors, wavelength stabilizers for pump lasers, and narrow-band Wavelength Division Multiplexing (WDM) add-drop filters. Figure3.4

provides a schematic representation of FBG, where the fiber's core undergoes refractive index modifications at regular intervals (γ). When broad-spectrum light is directed into one end of a fiber containing a Fiber Bragg grating, only the light matching the grating's wavelength is reflected back to the input end, while the remaining light continues to the other end of the fiber[45].

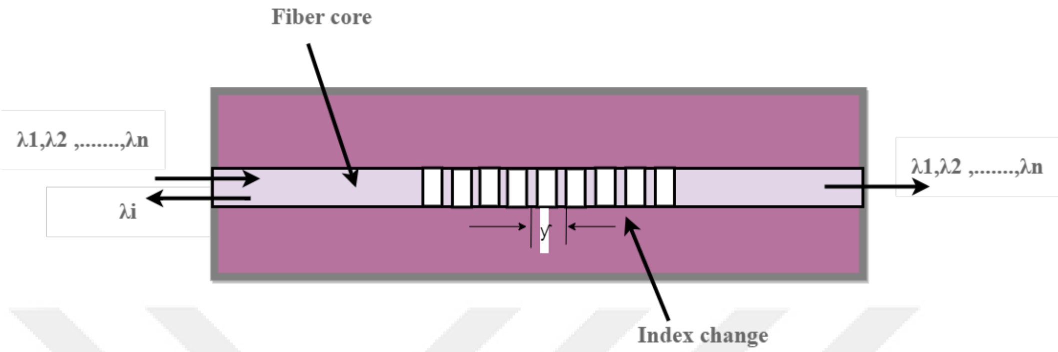

Figure 3.4 Schematic View of FBG[45]

Alterations to either the grating period or the refractive index will result in a different FBG structure. It is possible for the grating period to be either uniform or graded, and it may either be localized or disseminated throughout a superstructure. The refractive index profile and the offset are the two major properties that constitute the refractive index. In most cases, the profile of the refractive index may be uniform or apodised, and the offset of the refractive index can be positive or zero[45].

There are six different structures that are often seen in FBG's[46] :

- Index variation that is exclusively positive and uniform.
- Gaussian apodised.
- Raised cosine apodised.
- Chirped.
- A change in phase that is discrete.
- Superstructure.

3.2.3 Electronic Dispersion Compensation (EDC)

It is a technique of compensating for dispersion in an optical communications connection that makes use of electronic filtering, which is often referred to as equalization. Filtering is something that may be included into a communications channel in order to make up for the signal deterioration that is brought on by the medium. EDC is commonly implemented using a transversal filter, the output of which is the weighted sum of a number of time-delayed inputs. Inputs may be spaced out in a variety of different ways. Adaptation is the process by which the EDC solution is able to automatically alter the filter weights so that they correspond to the characteristics of the signal that has been received. Single mode fiber systems as well as multimode fiber systems are both suitable applications for EDC.

EDC is able to achieve either a considerable decrease in transmitter cost for single mode fiber systems or an increase in transmission distance for multi-mode systems while incurring just a tiny increase in receiver cost. This technology combines the use of optics and electronics in order to adjust for CD[45]. There are several different approaches to compensating for dispersion by making use of EDC that are present. It is the method that has shown to be the most successful in terms of compensating for dispersion at the electrical unit of the transmitter as well as the receiver. It is a kind of technology that does not call for any sort of adjustments to be made on either the sending or receiving sides.

4
PROPOSED SYSTEM DESIGN

This chapter will present the proposed system with its related parts and components along with highlighting the software which will be used as a simulator for designing, modeling, and analyzing the proposed transmission system. After that, the utilized parameters for the analysis of the system would be presented and clarified by showing the significance of each of them.

4.1 Optisystem Program

The Optisystem software offers a way to streamline and reduce the time and costs associated with designing optical systems, connections, and components, which is particularly crucial in sectors where cost-efficiency and productivity are paramount for success. Optisystem is an advanced and continually evolving software design tool that empowers users to plan, test, and simulate a wide range of optical links within the transmission layer of diverse optical networks. These networks span from Local Area Networks (LAN), Storage Area Networks (SAN), and Metropolitan Area Networks (MAN) to ultra-long-haul networks. Optisystem enables the design and planning of optical communication systems at both the component and system levels, providing graphical representations of analyses and scenarios. Given the increasing complexity of optical systems, scientists and engineers are increasingly turning to sophisticated software simulation approaches to gain valuable assistance in tackling design challenges. Below is a list of the benefits offered by the Optisystem software[47]:

1. Gives a comprehensive overview of the performance of the system.
2. Determines the degree to which the design tolerances are affected by the parameter sensitivities.
3. Provide potential clients with a visual representation of the many design possibilities and situations.

4. Provides a simple interface for gaining access to a comprehensive database of system characterization data.
5. Allows for the automated sweep and optimization of parameters.
6. Fits in seamlessly with the rest of the Optiwave product range.

The main window of the optisystem can be seen in Figure 4.1, where it can be noticed the screen is classified into three sub-portion of the screen which are:

1. The component library that includes all the components to be used by using the drag and drop.
2. The project browser that is used to help in browsing for a dedicated component.
3. project windows that are used to put the components and make the connection between them and also set the required configuration and parameters

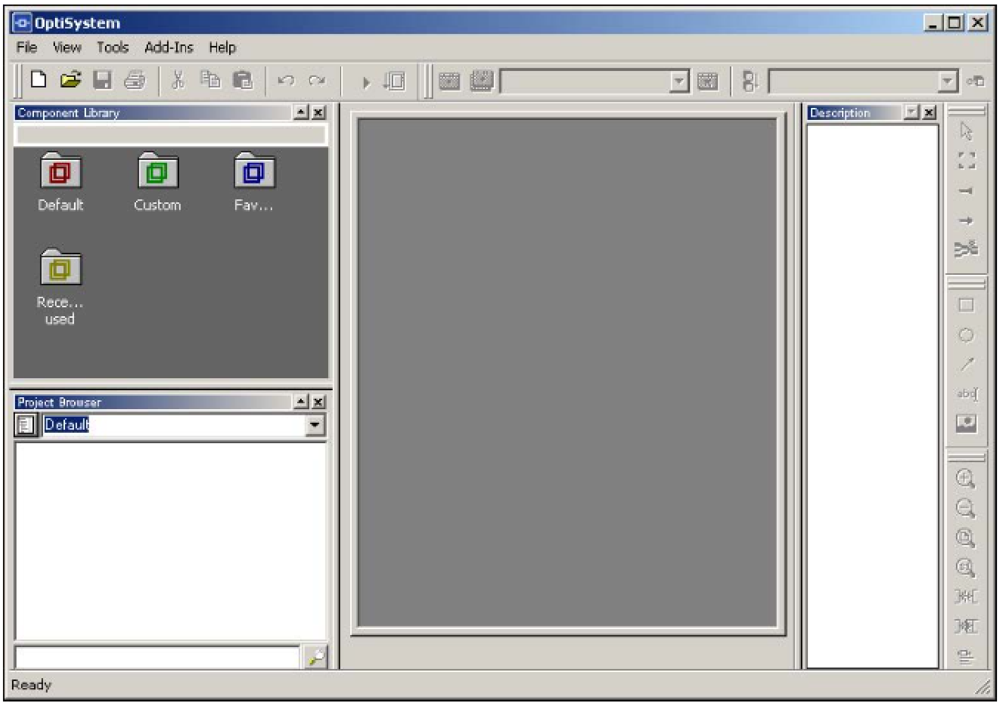

Figure 4.1 Main Window of Optisystem Simulator[48]

4.2 The Components of Proposed System

4.2.1 Component of the transmitter part

This part will include the following components:

A. Continuous Wave (CW) Laser

The generation of the optical signal with a continuous wave is one of the primary functions of this component. It contains a number of factors, but the ones that are most relevant to focus on are the power, the line width value, the beginning phase value, and the frequency that is being employed. It is essential to emphasize the existence of something called a CW laser array, which is a kind of CW laser. This sort of CW laser has the capacity to generate multiple laser signals depending on the frequency and spacing that is set, and it is considered to be the most critical component for handling large channel schemes[48, 49]. Its name comes from the fact that it emits continuous light. Figure 4.2 provides a visual representation of one kind of equipment that may be used to produce continuous-wave (CW) laser power.

Figure 4.2 CW Laser Source[50]

B. Pseudo Random Bit Sequence (PRBS) Generator

It is a component that creates a PRBS in accordance with the various operating modes that have been set. In addition to that, the features of random data are approximated as closely as possible by the bit sequence. As a direct consequence of this, the signal that is sent out is in the binary format. The values of bit rate and operational mode can be considered as the most important parameters that need to be taken into consideration. These are the parameters that are used to control the algorithm that is used in the generation procedure, and the operation mode selection has been set by default to be the order of these parameters (N). It is important to point out that the selection of order (N) is used in order to produce a sequence that has a period equal to 2N-1 [51, 52]. An example of type of PRBS can be illustrated in Figure4.3.

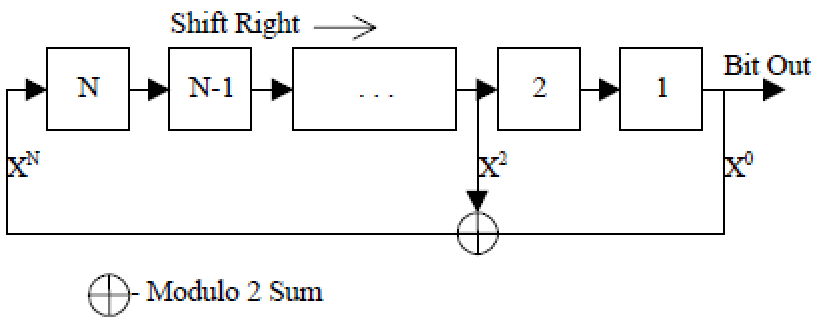

Figure 4.3 Example of The Internal Circuit For a Type of PRBS[53]

C. Pulse Generator

This component is employed to create pulses from a previously generated bit sequence, and it's responsible for generating various coded signals. Currently, one of the most widely adopted signal formats is the NRZ-coded signal format. The initiation of NRZ pulses is associated with several crucial parameters, including amplitude (representing the peak-to-peak amplitude), bias (indicating the direct current pulse offset), position, rise time, and fall time, all of which are considered individually significant. Figure4.4 provides an illustration of a pulse generator of this type[54].

Figure 4.4 Example of Pulse Generator Device[54]

D. Mack Zander Modulator (MZM)

Optical carriers are the means by which communication traffic is sent in systems that use optical transmission. The volume of traffic in the communication system may alter the strength of the carriers. Both Amplitude Modulation (AM) and Phase Modulation (PM) are viable options for the optical carriers. In a RoF-based system, the most important step in the process of modulation, in which the RF electrical signal is used to modulate the optical carrier signals, is the modulation method. These kinds of modulation techniques may be broken down into two distinct groups: those that are integrated with MZ interferometers and those that use Electro Absorption Modulator (EAM) [10]. In MZM, the application of electric fields to the arms causes variations in the lengths of the optical paths, which in turn results in phase modulation. The transformation of phase modulation into intensity modulation occurs when two arms with distinct phase modulation are combined. Figure4.5 provides an illustration of the structure of an MZM.

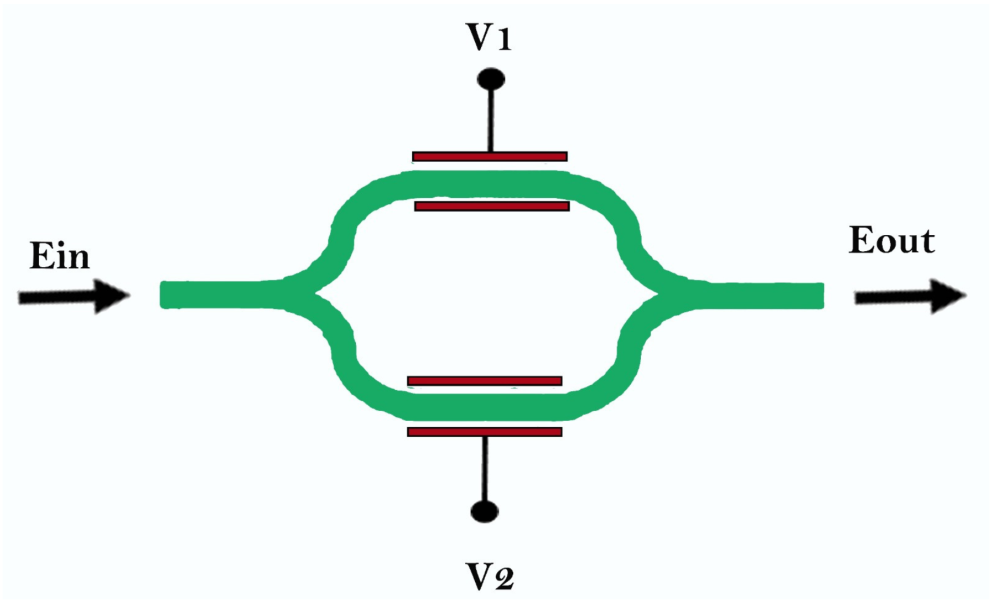

Figure 4.5 The Structure of The MZM [55]

E. Multiplexer (Mux)

A system that combines different data signals and makes it possible for them to be delivered over a single fiber network is referred to as a multiplexer, which is also referred to as a Mux. At one end of a FO cable, there is a device called a FO multiplexer that is used to enable the transmission of several data streams over the same wire. It functions similarly to a massive multi-input connection and enables the transmission of several signal inputs over a single strand of FO cable by mimicking its design. Figure 4.6 depicts a prototype of a Mux unit. [56]

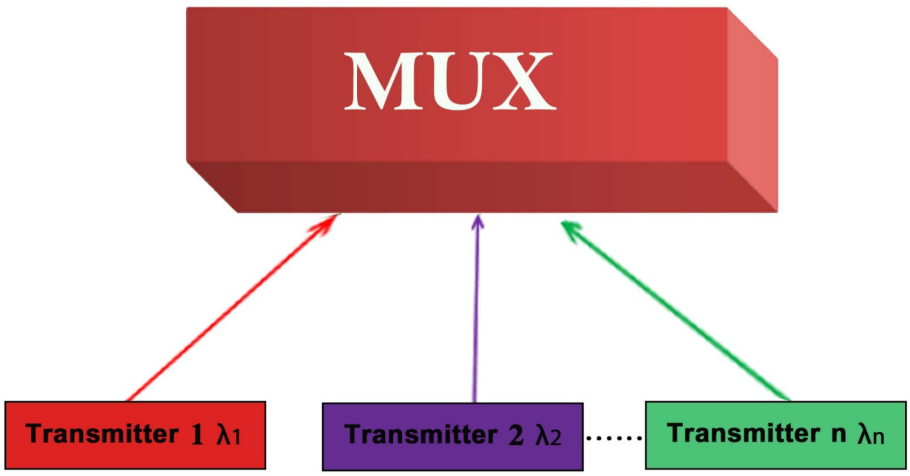

Figure 4.6 MUX Example Device[56]

4.2.2 Component of transmission part

This part will include the following components:

A. Link of Optical Fiber

The idea of an optical fiber component is concerned with the manner in which an optical field travels through a particular mode fiber. In actuality, the mode that sees the most action is called single-mode fiber, abbreviated SMF. In most cases, the direct numerical integration of the modified Nonlinear Schrodinger (NLS) equation is used in order to do an analysis of the behavior of this mode, which considers both dispersive and nonlinear effects. According to reference[57], three factors the length of the optical fiber, the reference wavelength, and the attenuation value are of the utmost importance when it comes to the process of creating a connection using optical fiber.

B. Erbium-Doped Fiber Amplifier (EDFA)

Within an optical transmission circuit, an EDFA serves various functions, such as boosting, inline amplification, or pre-amplification, as illustrated in the schematic representation found in Figure 4.7. A booster-based amplifier is positioned after the transmitter to enhance the optical power sent through the transmission link. Inline amplifiers are used along the transmission path to compensate for the signal attenuation caused by the optical fiber. To ensure that the receiver receives the appropriate optical power, a pre-amplifier is placed in front of it. EDFAs are often spaced several tens of kilometers apart from each other [57].

Prior to the development of EDFAs, signal regeneration along lengthy optical fiber transmission lines required complex Optical-to-Electrical (O-E) and electrical-to-optical (E-O) conversion processes. The introduction of EDFAs has eliminated the need for such O-E and E-O conversions, leading to a significant simplification of the system. This is particularly advantageous in the context of submarine optical transmission, where establishing a single connection may require more than one hundred EDFA repeaters [57].

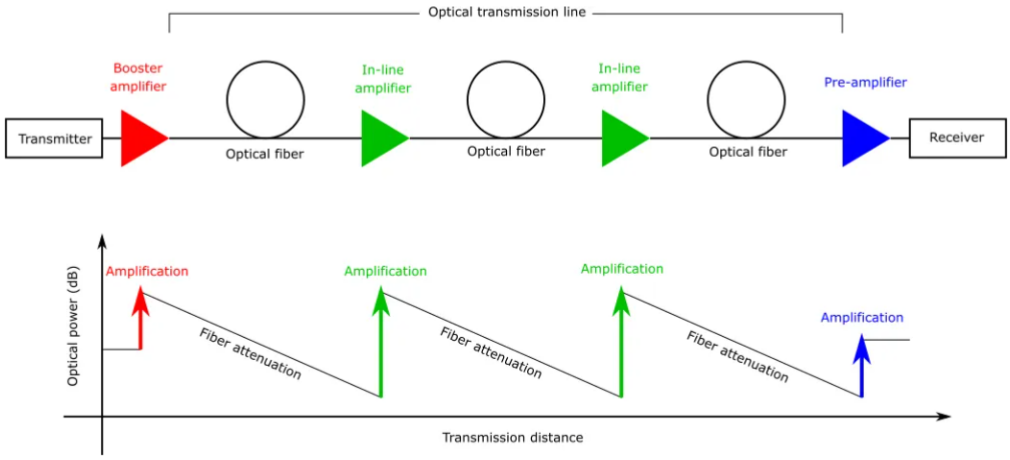

Figure 4.7 EDFA Utilization In Optical Fiber Communication [57]

C. Dispersion Compensation Fiber (DCF)

This component has been widely clarified in detail in the previous chapter.

4.2.3 Component of Receiver Part

This part will include the following components.

A. DE-Mmultiplexer (DEMux)

A multiplexer and a supplemental demultiplexer are often used together at the receiving end of a communication system. These mux/demuxers optimized the utilization of the fiber cable while reduced the expenses associated with its maintenance when several traffic channels required to be transported between various sites. A data stream may be split up into many transmission connections that run at a slower pace with the use of an inverse multiplexer, which is also known as a demultiplexer. The numerous output sources of an inverse multiplexer are linked to one another, in contrast to the multiple output sources of a demultiplexer, which are not connected to one another.In contrast to a multiplexer, which combines a number of slower connections into a single faster network, an inverse multiplexer divides a single faster connection into a number of slower connections. In order to combine numerous Integrated Services Digital Network (ISDN) networks into a single high-rate circuit, demultiplexers are used [58].

B. Photo Detector (PD)

A photodetector is an apparatus that changes light impulses into electrical signals, which may then be amplified and analyzed after the conversion has taken place. It is important to note that the photodetector (PD) in Fiber Optic (FO) devices is just as crucial as the optical fiber or the light source. The selection of photodetectors is one factor that may have an impact on the efficiency of a FO network connection. When it comes to photodetectors that are utilized in fiber optic systems, the semiconductor-based photodiode stands out as the one that is used the majority of the time. This choice may be explained by a number of variables, including the cost-effectiveness of the product and its small size. In addition, the PIN photodiode is the sort of semiconductor photodiode that is applied in this situation more often than any other [58].

C. Filters

A frequency selective circuit is a specialized sort of circuit that is used to filter out particular input signals depending on the frequencies of those signals. This kind of circuit is also known as a filter. Certain frequency signals are allowed to pass through a filter circuit unaffected or with a little boost, whilst others, depending on the kind of filter, are reduced in strength as they go through the circuit. The optical filters and the electrical filters are the two most important types of based branch filters. And in all of these categories, there is a large variety of kinds that may be used depending on the specifics of the application being considered. In addition, there would be two kinds of filters known as passive and active, and the distinction would depend on the component utilized within the designed circuit. The first kind, which is the one that is currently known, would make use of passive components like capacitors, resistors, and inductors, all of which don't need any other source of energy to function. In the meanwhile, the second kind would make use of the same passive components combined with additional active-based components such as the transistors and the Operational Amplifier (Op-Amp). When using filters, the cutoff-frequency value is the most critical parameter that has to be managed [58].

4.3 The Proposed System

This section will demonstrate and clarify the three parts of the suggested system. Where the proposed system consists of the transmitter part, transmission part, and receiver part. Figure4.8 shows the overall intended system as it appears when using the optisystem program. Figure4.9 illustrates the proposed system's schematic perspective to get a closer and clearer view of the system design.

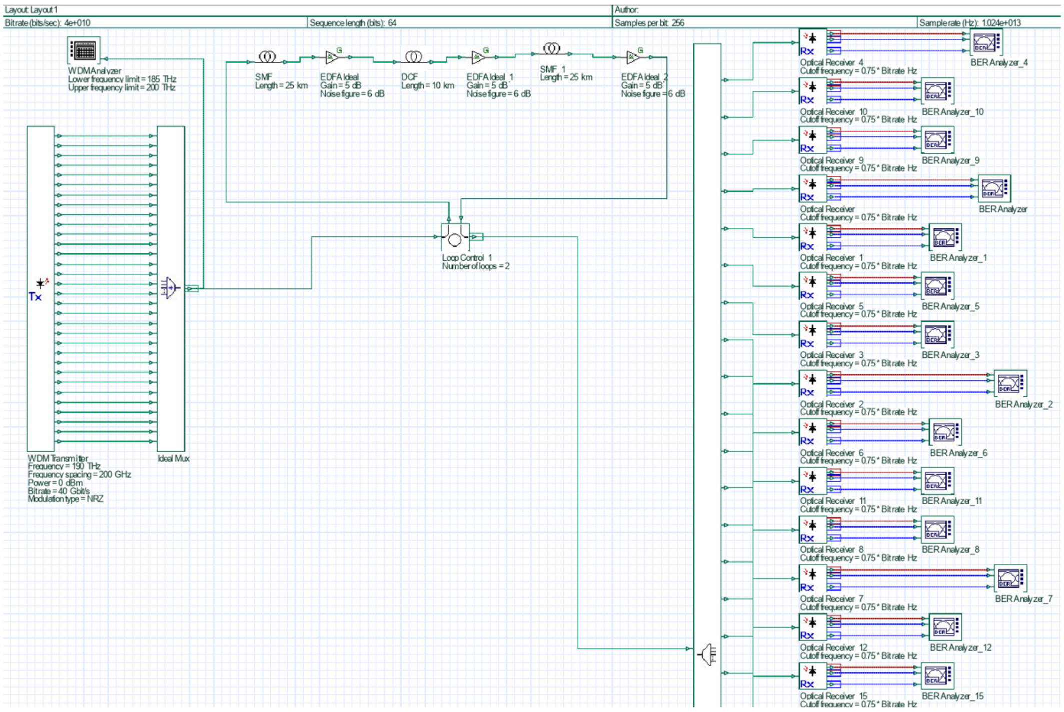

Figure 4.8 The Proposed System Designed Using Optisystem.

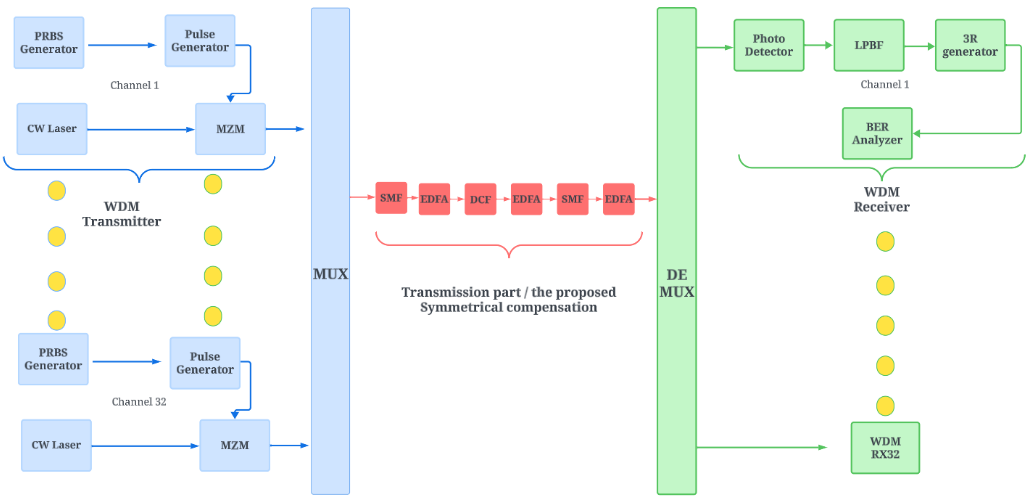

Figure 4.9 The Schematic View of The Proposed System

4.3.1 Transmitter part

The initial component, referred to as the transmitter, comprises a WDM transmitter featuring 32 channels. Inside this WDM transmitter, there are key elements including a bit sequence generator operating at a 40 Gbps data rate, an NRZ pulse generator, an MZM modulator, and a laser source component with a launched power of 0 dBm, a starting frequency of 190 THz, and specific wavelength spacing. Following the WDM transmitter, there is a Mux device equipped with an equal number of channels as the WDM transmitter. The role of this device is to consolidate the signals into a single link for subsequent transmission through the optical fiber cable. A detailed view of one of these components can be found in Figure4.10.

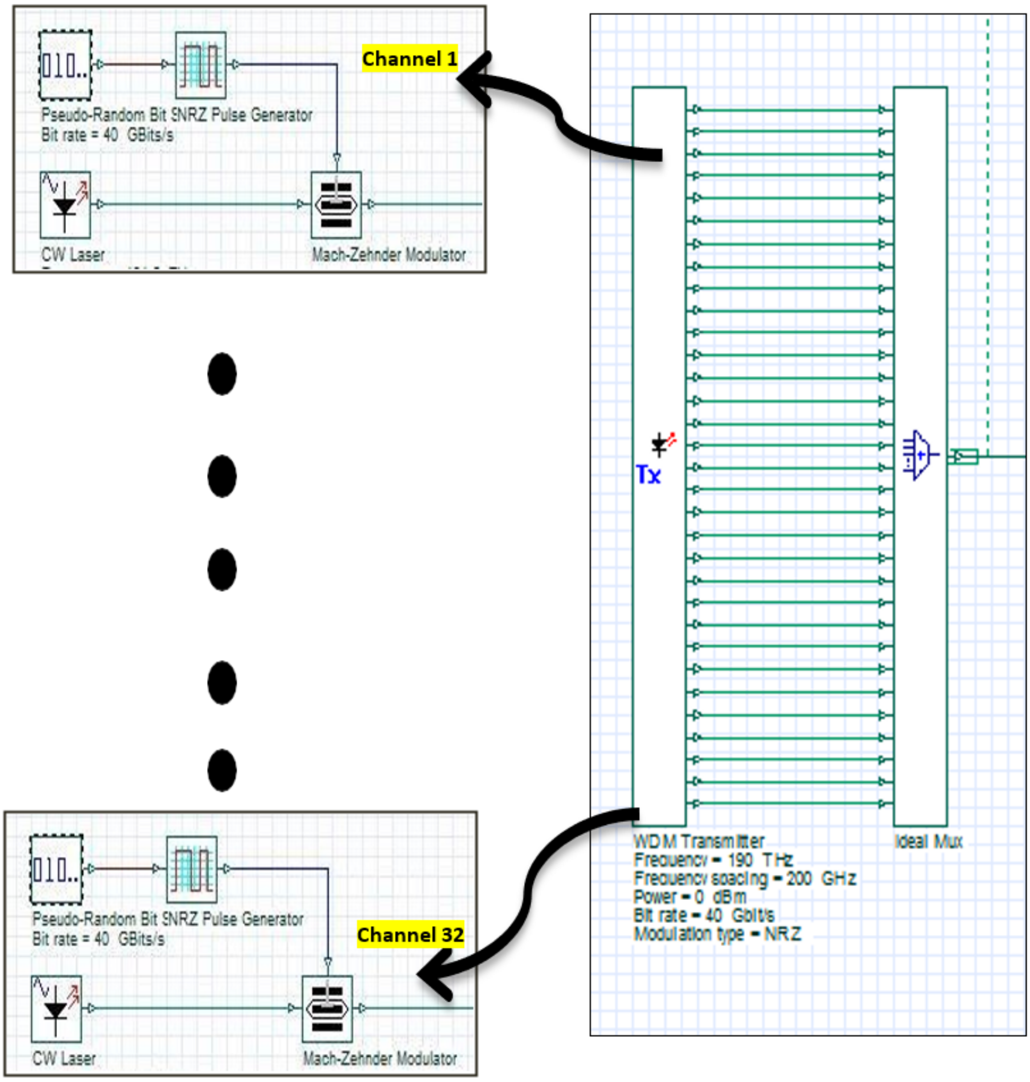

Figure 4.10 The First Part of The Implemented System.

4.3.2 Transmission part

The second segment, referred to as the transmission system, will be assembled using a SMF optical cable with a length of 25 km and a DCF component spanning 10 km. This DCF component is employed to address the issue of Chromatic Dispersion encountered in this part of the system. The cable lengths are specifically chosen to mitigate the Chromatic Dispersion challenge in this section. Additionally, an Erbium-Doped amplifier with a gain of 5 dB and a noise figure of 6 dB is employed in this area. The power of the proposed system in this section is represented by the use of a symmetrical DCF compensation technique, which holds promise for achieving optimal results due to the arrangement and distribution of its components, as illustrated in Figure4.11.

In addition, the distance that has to be investigated is managed via the use of loop control, and the goal of each iteration is to reach a total of sixty kilometers.

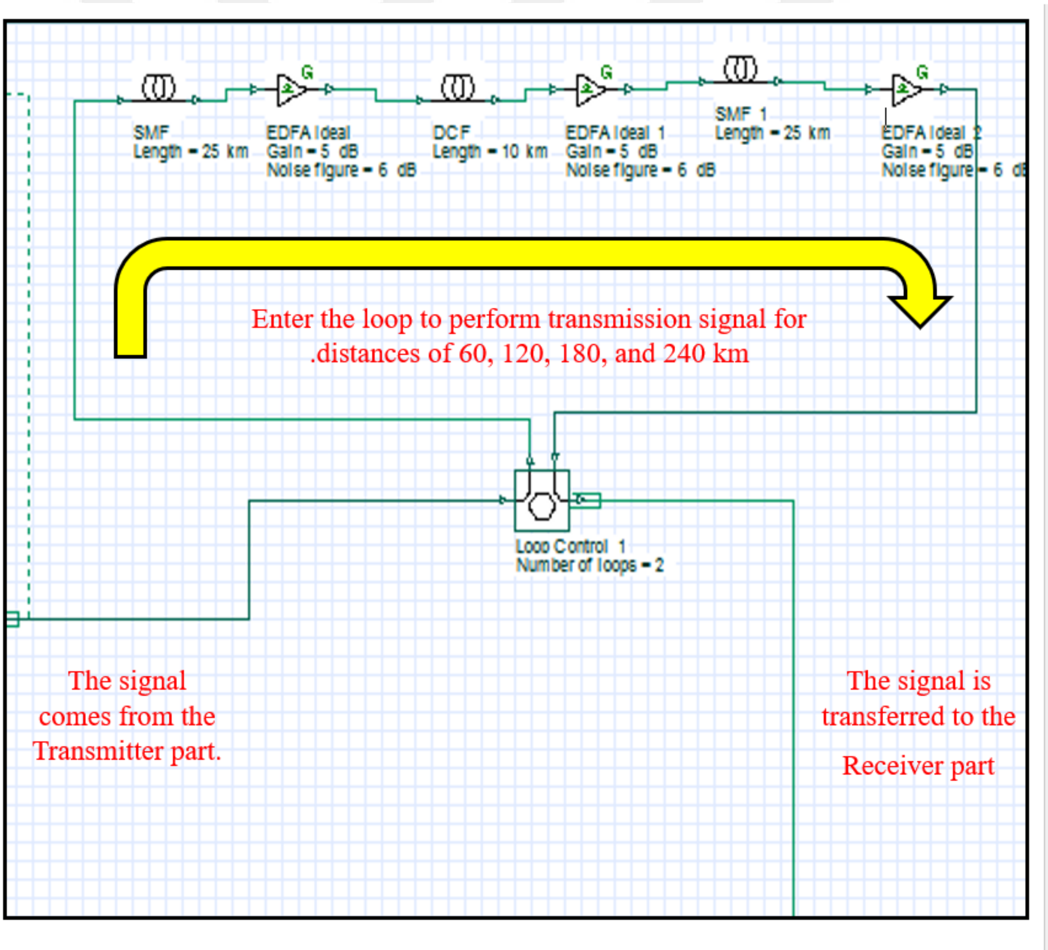

Figure 4.11 The Second Part of The Implemented System.

4.3.3 Receiver part

Lastly, the third segment is the receiver component, commencing with the implementation of a Demultiplexer device. This device segregates the transmitted optical signal from the preceding segment and splits it into 32 individual receiver channels. Each of these channels is equipped with a WDM receiver, which internally comprises a Photo Detector (PD) component of the PIN type, responsible for converting the optical signal into an electrical one. Additionally, there is a filter device, a 3R generator, and finally, a Bit Error Rate (BER) analyzer tool employed to visually assess the signal's bit error rate. Figure4.12. visually illustrates the functionality of this element within the Optisystem. In summary, Table4.1 presents a summary of the remaining parameters chosen for the proposed system.

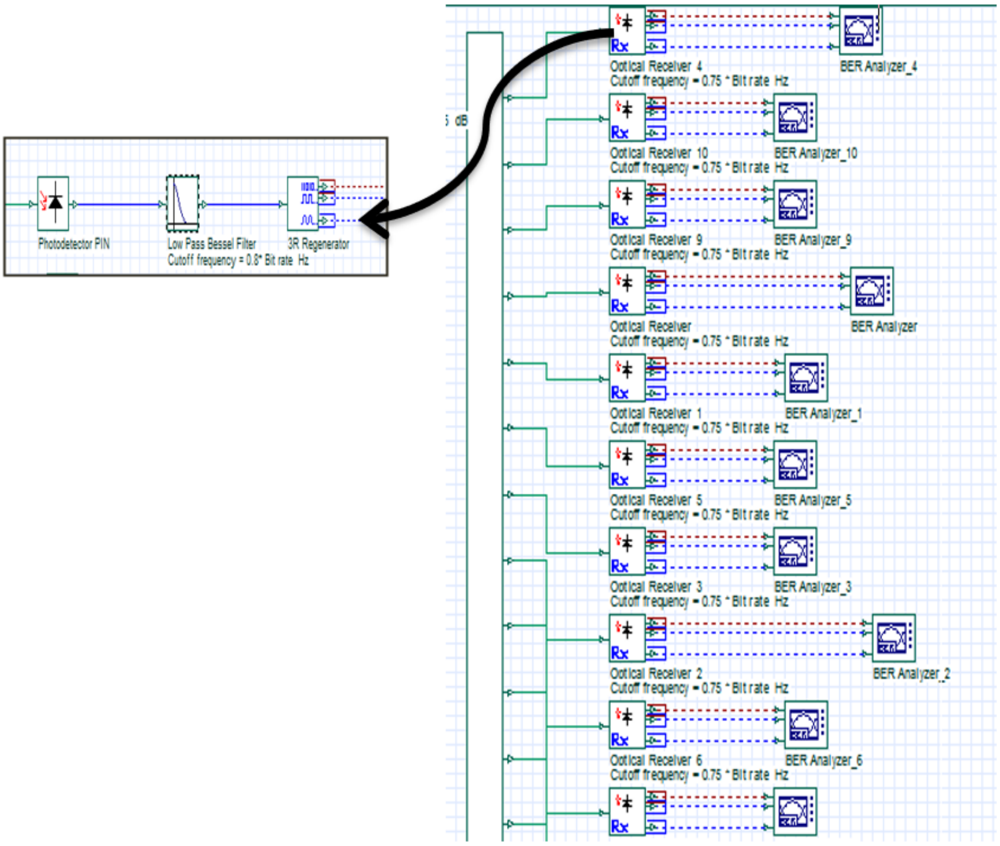

Figure 4.12 The Third Part of The Implemented System.

Table 4.1 Overview of the most significant parameters set with the proposed system.

Parameter	Value	Unit
Number of output ports	32	-
Frequency	190	THz
Frequency spacing	$200 - 150 - 100$	GHz
Power	0	dBm
Extinction ratio	30	dB
Bit rate	40	Gbit/s
Modulation type	$\mathrm{NRZ} - \mathrm{RZ}$	-
Length (SMF)	25	km
Attenuation (SMF)	0.2	dB/km
Length (DCF)	10	km
Attenuation (DCF)	0.5	dB/km
Gain (EDFA)	5	dB
Noise figure (EDFA)	6	dB
Photodiode	PIN	-

4.4 Studied Parameters

This section demonstrates the parameters to be obtained from the utilization of Optisystem program with respect to the proposed simulated model that has been shown in previous section. The parameters to be studied are selected based on the analyzer tools provided by the optisystem program and as listed

4.4.1 Bit Error Rate (BER)

Before being made available to the general public, each and every optical network has to undergo testing. During the testing, it will be determined whether or not the optical network is linked appropriately and whether or not it is enough for the secure and error-free transmission of data. When it comes to data transfers involving telecommunications, the BER value denotes the proportion of corrupted bits to the total number of bits that were received by the receiver at the beginning of the transfer path [59]. Additionally, the BER is the statistic that describes how often the data has to be resent because of the possibility of errors happening. BER deteriorates in situations in which the level that is crucial expands beyond the interference, which leads to an inaccurate interpretation of the optical impulses that have been received as a consequence. In fact, the optical line is supplied to the network provider together with a comprehensive documentation package and the individual values of BER used to evaluate individual lines (BER serving as the quality criterion for the line) [60]. The number of recognized errors that were received in a specific optical signal is used to compute BER.

4.4.2 Eye Diagram (ED)

The ED is by far the most popular kind of analytical tool used in the area of communications, and it is used to evaluate the signal that has been received. It is easy to pinpoint individual problems in the system by looking at the output diagram. The figure, which can be seen here, is used as a basis for the evaluation of the optical line of a system (in this example, the individual lines of DWDM)[61, 62] The Q-factor, the bit error rate, and the signal-to-noise ratio are a few examples of the many different ideas that have a direct relationship to the eye diagram. Both the "1" and the "0" that are being communicated need to be included in the best possible form of the eye, which is equal to 10e-40. Figure4.13 presents a representation of the ideal eye, which may be found on page [62].

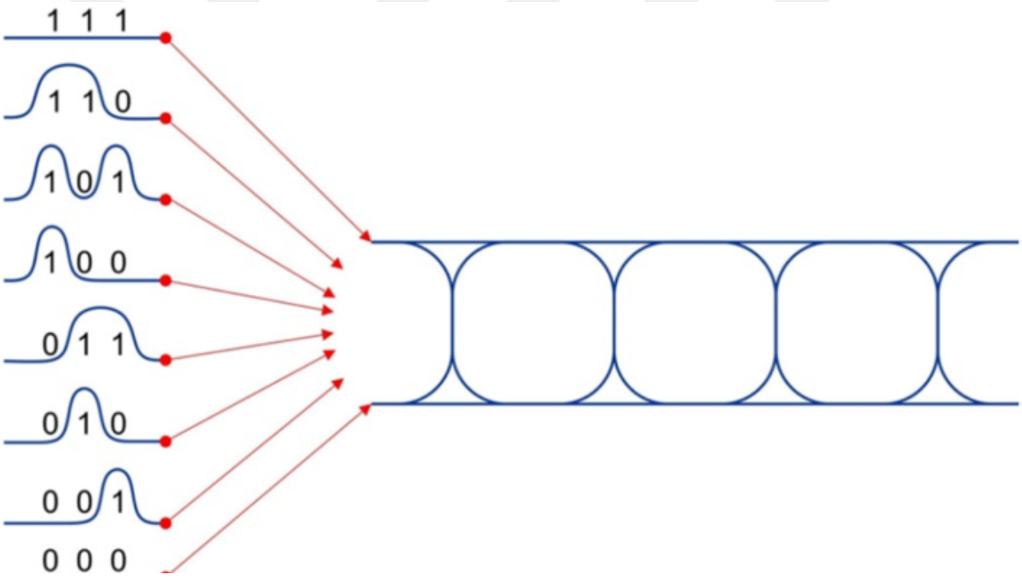

Figure 4.13 Demonstration of ED[62]

4.4.3 Quality Factor (QF)

The Quality (Q) of the signal output analysis performed by the SMF communication system is another factor that influences the rate at which data is received and sent. When simulating an optical device, one of the most important aspects to investigate is the quality factor. After that, one uses an eye diagram to examine the signal that is produced by the device. The quality factor is a measurement that determines how noisy a pulse is for the purposes of diagnostics. It provides the minimum SNR that must be met in order to achieve a certain BER for a given signal. The Quality Factor is a crucial criterion that determines how well a communication channel. [63].

5
CONCLUSION

This chapter will demonstrate the results of the studied parameter for the proposed 32-channel system of this thesis. These results would be started by analyzing the QF and BER results for four sets of distances. After that, analyzing the effect of different channel spacing is studied to show the impact of varying the spacing between the 32 channels on the quality of the data received and on the rate of error in received bits. Finally, an optimization method will be considered by handling two different modulation formats to show the most significant among them and followed by a final comparison between the proposed methodology system of this thesis with the recent previous publication proposed by other others.

5.1 Results Based QF And BER Parameters

The outcomes of the suggested 32-channel system that was mentioned earlier will be evaluated based on the investigated parameters of QF and BER, and this evaluation will include all 32 channels that were tested. The effectiveness study of the system would be able to deal with a transmission distance of (60,120,180, and 240) kilometers. These kinds of findings have been removed from Table5.1 and Table5.2, both of which have been subjected to analysis and may be seen, respectively, as Figure5.1 and Figure5.2 for QF and BER parameters.

Table 5.1 Results of the QF parameter obtained from the proposed system.

Channel	Proposed system results of QF			
	60 km	**120 km**	**180 km**	**240 km**
1	20.96	16.21	11.0868	7.55933
2	20.2253	16.9811	12.4908	7.72126
3	19.1369	13.8238	12.4592	8.22423
4	19.7133	18.0337	12.1776	10.0533
5	18.858	16.2357	16.5592	13.4562
6	24.0089	17.73	12.792	11.349
7	20.5128	19.3816	14.7009	11.4138
8	20.0421	16.1109	14.9225	13.6429
9	23.4161	20.9923	12.8714	11.4631
10	20.0861	18.1	16.0962	13.4701
11	24.1024	17.4117	16.8789	15.0712
12	23.4044	17.7717	16.2204	13.3047
13	22.7188	18.0639	14.6122	12.94
14	21.6177	19.524	14.2715	12.6634
15	23.2885	15.4109	13.3306	12.4421
16	19.5882	16.6861	14.5272	13.5638
17	19.217	13.92	12.7762	12.8842
18	17.0107	16.19	12.4276	11.3807
19	20.8624	14.0655	13.4312	12.0753
20	25.0586	15.5713	12.8465	12.7083
21	19.0623	17.5436	11.8484	11.7781
22	20.852	14.2175	13.4821	13.102
23	17.6263	15.6476	15.0115	10.1227
24	20.5498	15.1189	12.0962	10.3155
25	21.3134	17.0557	11.5061	9.06625
26	16.5143	14.7151	11.9427	7.72
27	21.7328	15.9409	11.2839	7.74969
28	19.8872	13.9097	11.8057	6.93435
29	20.1269	14.1156	9.72623	7.13702
30	19.4953	15.8089	9.31507	6.82116
31	16.9695	12.0051	9.24	6.42756
32	18.8245	10.9724	8.50	6.05912

Table 5.2 Results of the BER parameter obtained from the proposed system.

Channel	Proposed system results of BER			
	60 km	**120 km**	**180 km**	**240 km**
1	6.46E-98	2.07E-59	7.13E-29	2.01E-14
2	2.64E-91	5.46E-65	4.17E-36	5.73E-15
3	5.43E-82	8.40E-44	6.04E-36	9.53E-17
4	7.32E-87	5.14E-73	1.98E-34	4.37E-24
5	1.09E-79	1.30E-59	6.84E-62	1.42E-41
6	9.89E-128	1.08E-70	8.50E-38	3.60E-30
7	7.32E-94	4.95E-84	3.01E-49	1.73E-30
8	1.03E-89	9.37E-59	1.07E-50	1.06E-42
9	1.20E-121	3.52E-98	2.71E-38	9.27E-31
10	4.12E-90	1.37E-73	1.20E-58	1.08E-41
11	1.03E-128	2.88E-68	2.78E-64	1.13E-51
12	1.70E-121	4.77E-71	1.45E-59	8.25E-41
13	1.21E-114	2.53E-73	9.63E-49	1.14E-38
14	5.17E-104	2.81E-85	1.24E-46	3.58E-37
15	2.50E-120	5.66E-54	6.15E-41	5.49E-36
16	8.08E-86	6.32E-63	3.12E-48	2.70E-42
17	1.17E-82	1.77E-44	9.12E-38	2.34E-38
18	2.77E-65	2.35E-59	7.31E-36	2.12E-30
19	4.68E-97	2.36E-45	1.57E-41	6.02E-34
20	6.31E-139	4.69E-55	3.89E-38	2.46E-37
21	2.16E-81	2.96E-69	9.66E-33	2.41E-32
22	6.30E-97	3.08E-46	9.15E-42	1.54E-39
23	6.95E-70	1.58E-55	3.02E-51	2.14E-24
24	3.25E-94	5.62E-52	5.22E-34	2.93E-25
25	3.76E-101	1.51E-65	5.89E-31	6.08E-20
26	1.26E-61	2.44E-49	3.49E-33	5.78E-15
27	4.65E-105	1.61E-57	7.85E-30	4.60E-15
28	2.37E-88	2.63E-44	1.82E-32	2.04E-12
29	2.02E-90	1.50E-45	1.17E-22	4.73E-13
30	5.58E-85	1.35E-56	6.09E-21	4.50E-12
31	6.30E-65	1.64E-33	1.19E-20	6.40E-11
32	2.18E-79	2.56E-28	9.85E-18	6.83E-10

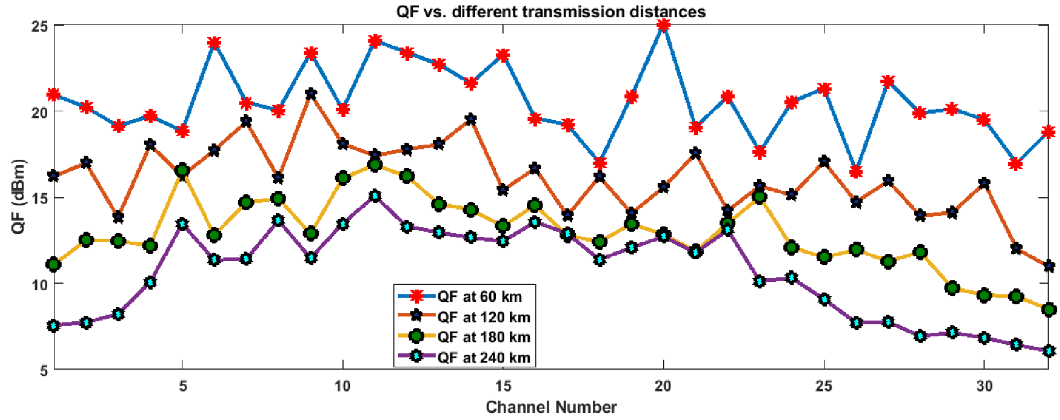

Figure 5.1 The Relation of QF vs. Different Transmission Distances.

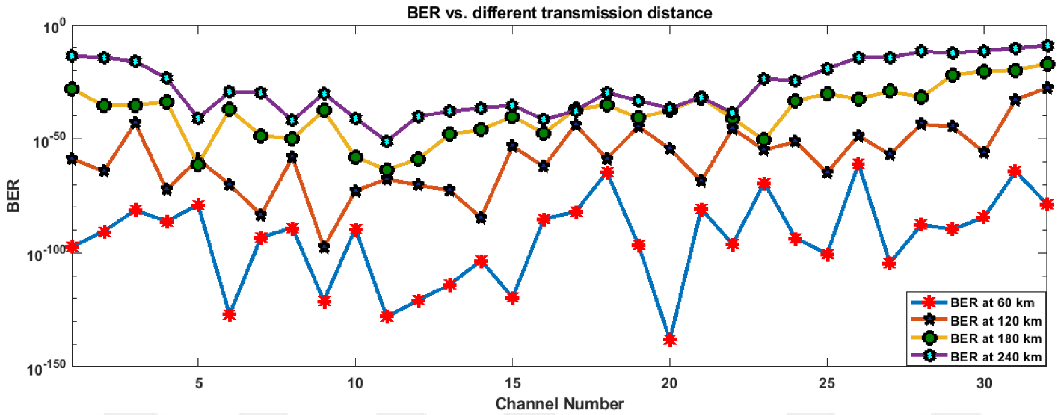

Figure 5.2 The Relation of BER vs. Different Transmission Distances.

A reverse relation can be found between the increase in distance and the QF values, and this is because of the higher influence of the attenuation that is caused by pushing the sent signals via a FO medium. This can be seen by looking at Figure5.1. It is important to point out that the case of 240 km transmission has produced QF results that are over the QF minimum threshold of 6 dBm, which suggests that the proposed system is reliable. This is something that should be mentioned. Regarding the observation of Figure5.2, it is possible to discern a direct link, since an increase in the distance would increase the number of errors in the transmitted bits. Even though there was a growing influence of error with the bits that were communicated, all of the obtained results that were seen were higher than the threshold of E-10. The use of the symmetrical compensation approach is the one item that has the potential to validate the dependability of the suggested system in its current state.

5.2 Results of Different Channel Spacing

A second observation for the proposed system would be formed by considering three cases of (200, 150, and 100) GHz for channel spacing values between the allotted 32 channels. In this case, a set of sample channels with numbers (1, 4, 8, 12, 16, 20, 24, 28, and 32) were selected and studied for spacing variation and their effect on the results of QF and BER parameters. This would lead to the formation of a third observation for the proposed system. Figure5.3 with Table5.3 and Figure 5.4 related to Table5.4, respectively, illustrate these findings for the analysis of the proposed system. To begin, Figure 5.3 demonstrates a clear connection between channel spacing and quality factor. Increasing the channel spacing would result in a reduction in the amount of channel overlapping and interference, which would lead to an increase in the QF values. In addition, it is possible to deduce from the same image that the disparity that existed between the three possible configurations of channel spacing decreased as the distance increased. indicating that the critical relevance of wider separation is less than 180 kilometers apart. Second, increasing the distance would result in a smaller gap in BER reduction across the three scenarios that were tested, as shown by Figure's 5.4 inversion of the expected relationship between increasing the channel spacing and the BER. Consequently, using the spacing of 200 GHz was verified to be the most effective choice for the suggested system.

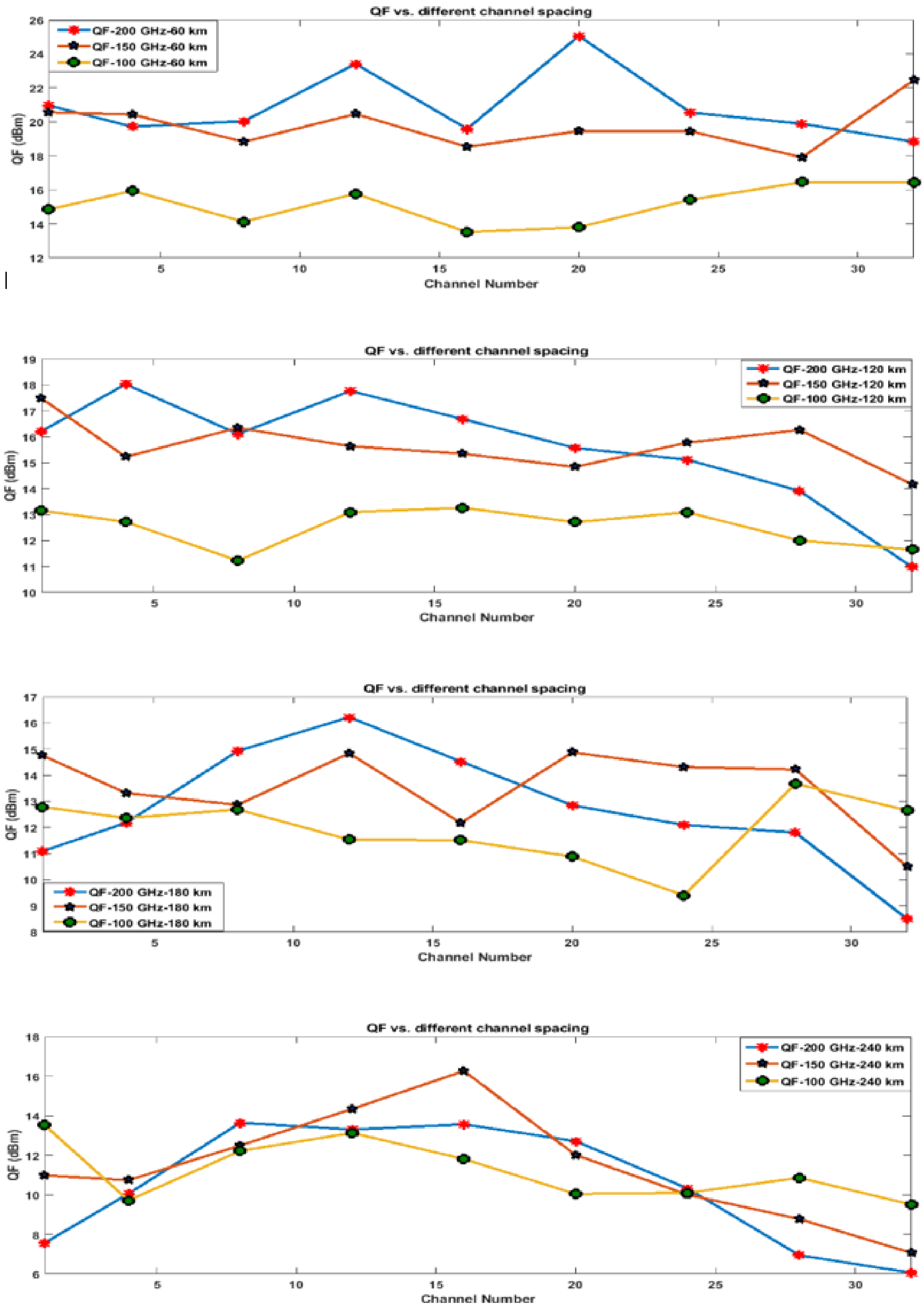

Figure 5.3 QF Vs. Different Channel Spacing For (a) 60 km, (b) 120 km, (c) 180 km and (d) 240 km.

Table 5.3 QF results obtained from different cases of channel spacing per each selected sampled channel.

Channel	spacing 100 GHz/ NRZ/ PIN			
	60	**120**	**180**	**240**
1	14.8467	13.15	12.7852	13.5203
4	15.9388	12.7225	12.3615	9.71177
8	14.1248	11.2193	12.6882	12.2195
12	15.7727	13.0931	11.5337	13.1259
16	13.5182	13.2645	11.5114	11.8077
20	13.8018	12.7116	10.8854	10.0395
24	15.417	13.0891	9.40069	10.096
28	16.4569	11.9996	13.6748	10.8586
32	16.4524	11.6472	12.6549	9.50626
Channel	**spacing 150 GHz/ NRZ/ PIN**			
	60	**120**	**180**	**240**
1	20.5654	17.49	14.7586	10.9818
4	20.4305	15.2283	13.3163	10.7365
8	18.8242	16.3448	12.8646	12.4925
12	20.4607	15.6369	14.8381	14.3391
16	18.5255	15.3473	12.1738	16.2596
20	19.4529	14.8397	14.874	12.0099
24	19.4435	15.7756	14.3113	10.0042
28	17.9131	16.2646	14.2214	8.77148
32	22.4524	14.171	10.50	7.06063
Channel	**spacing 200 GHz/ NRZ/ PIN**			
	60	**120**	**180**	**240**
1	20.9630	16.21	11.0868	7.55933
4	19.7133	18.0337	12.1776	10.0533
8	20.0421	16.1109	14.9225	13.6429
12	23.4044	17.7717	16.2204	13.3047
16	19.5882	16.6861	14.5272	13.5638
20	25.0586	15.5713	12.8465	12.7083
24	20.5498	15.1189	12.0962	10.3155
28	19.8872	13.9097	11.8057	6.93435
32	18.8245	10.9724	8.50	6.05912

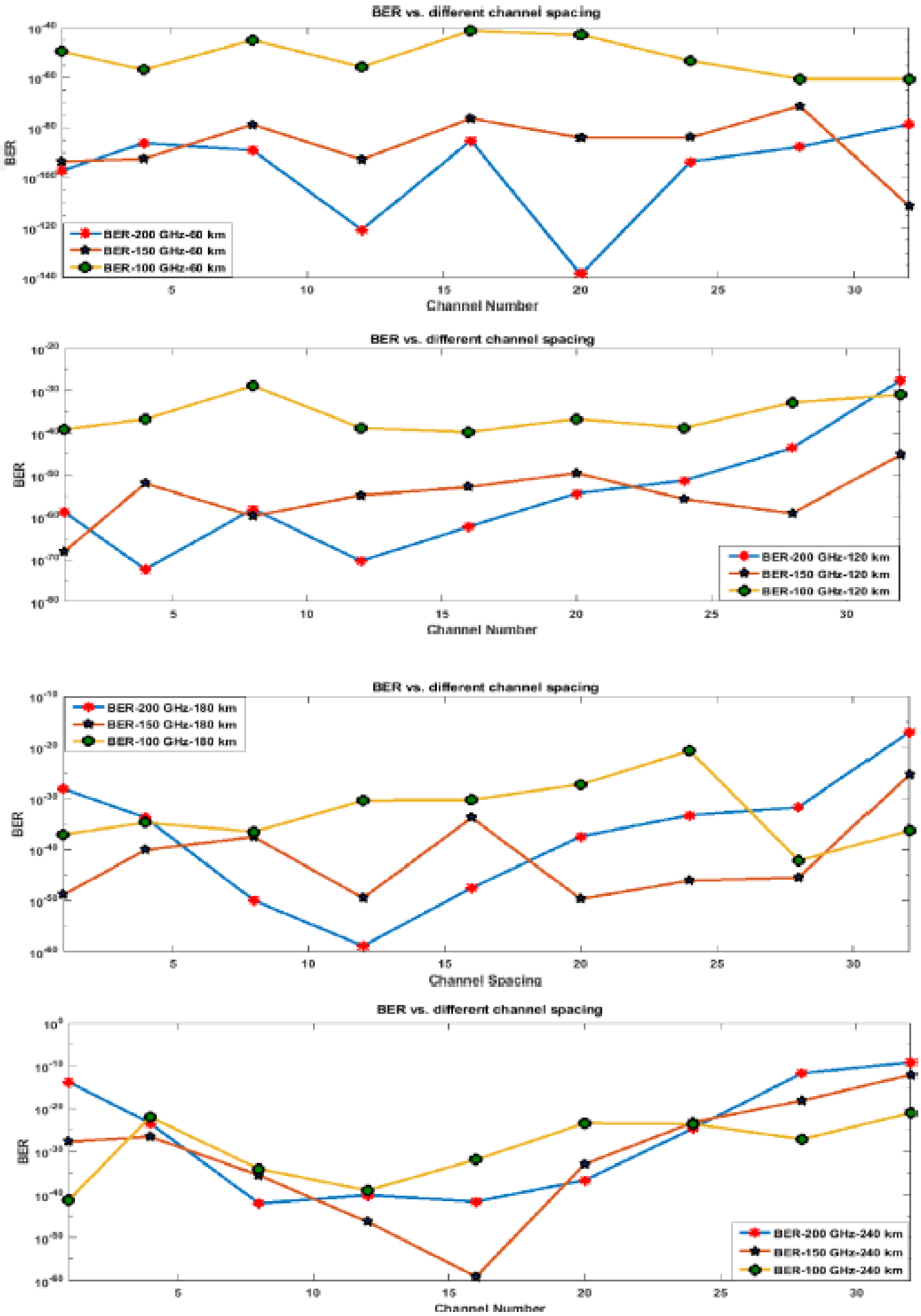

Figure 5.4 BER vs. Different Channel Spacing For (a) 60 km, (b) 120 km, (c) 180 km and (d) 240 km.

Table 5.4 BER results obtained from different cases of channel spacing per each selected sampled channel.

Channel	spacing 100 GHz/ NRZ/ PIN			
	60	**120**	**180**	**240**
1	3.15E-50	7.08E-40	8.52E-38	5.48E-42
4	1.49E-57	1.89E-37	1.93E-35	1.24E-22
8	1.18E-45	1.41E-29	3.04E-37	1.05E-34
12	2.19E-56	1.60E-39	3.74E-31	1.04E-39
16	5.40E-42	1.65E-40	5.15E-31	1.56E-32
20	1.05E-43	2.15E-37	5.61E-28	4.27E-24
24	5.71E-54	1.68E-39	2.19E-21	2.59E-24
28	3.52E-61	1.65E-33	6.87E-43	8.98E-28
32	3.66E-61	1.07E-31	5.10E-37	9.58E-22
Channel	**spacing 150 GHz/ NRZ/ PIN**			
	60	**120**	**180**	**240**
1	2.44E-94	8.10E-69	1.31E-49	2.31E-28
4	3.81E-93	1.02E-52	8.44E-41	3.30E-27
8	1.97E-79	1.96E-60	2.92E-38	3.59E-36
12	2.04E-93	1.67E-55	3.32E-50	4.96E-47
16	5.13E-77	1.49E-53	1.73E-34	8.14E-60
20	1.13E-84	3.21E-50	2.05E-50	1.42E-33
24	1.41E-84	2.02E-56	8.67E-47	7.03E-24
28	4.02E-72	8.65E-60	3.30E-46	8.78E-19
32	5.60E-112	6.63E-46	4.36E-26	8.20E-13
Channel	**spacing 200 GHz/ NRZ/ PIN**			
	60	**120**	**180**	**240**
1	6.46E-98	2.07E-59	7.13E-29	2.01E-14
4	7.32E-87	5.14E-73	1.98E-34	4.37E-24
8	1.03E-89	9.37E-59	1.07E-50	1.06E-42
12	1.70E-121	4.77E-71	1.45E-59	8.25E-41
16	8.08E-86	6.32E-63	3.12E-48	2.70E-42
20	6.31E-139	4.69E-55	3.89E-38	2.46E-37
24	3.25E-94	5.62E-52	5.22E-34	2.93E-25
28	2.37E-88	2.63E-44	1.82E-32	2.04E-12
32	2.18E-79	2.56E-28	9.85E-18	6.83E-10

5.3 Optimization-Based Modulation Format

In this section, more optimizations would be examined and handled by researching the employment of various modulation formats represented by the NRZ and RZ. This would be done to handle further optimization. to verify the dependability of each approach, as well as its influence on the proposed system. An analysis of this kind would be contemplated concerning the same samples, for the two kinds for each of the four transmission lengths, and the QF and BER parameters as shown in Figure 5.5 with Table5.5 and Figure5.6 with Table5.6, respectively.

When dealing with transmissions over short distances, employing the RZ technique for modulation rather than the NRZ approach is recommended since the former produces superior results in terms of QF and BER. In addition, increasing the distance that data is sent across helps lessen the variance in results between the two tested modulation schemes. Despite this, RZ continued to perform much better than the suggested system when contrasted with the NRZ-based system.

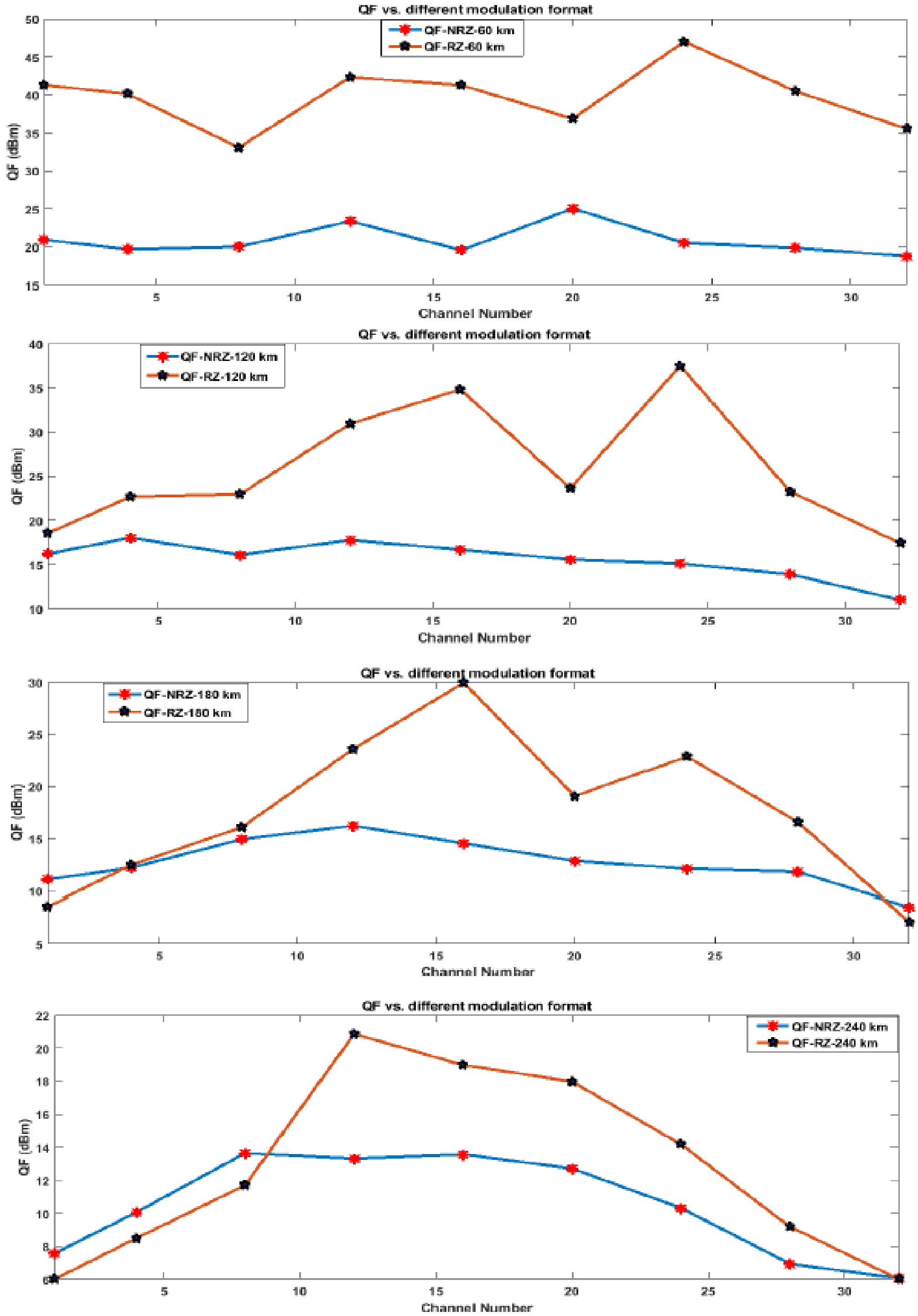

Figure 5.5 QF vs. Different Modulation Format (a) 60 km, (b) 120 km, (c) 180 km and (d) 240 km.

Table 5.5 QF results obtained from the proposed system for both cases of NRZ and RZ modulation format.

Channel	**proposed QF/ NRZ**			
	60	**120**	**180**	**240**
1	20.96	16.21	11.0868	7.55933
4	19.7133	18.0337	12.1776	10.0533
8	20.0421	16.1109	14.9225	13.6429
12	23.4044	17.7717	16.2204	13.3047
16	19.5882	16.6861	14.5272	13.5638
20	25.0586	15.5713	12.8465	12.7083
24	20.5498	15.1189	12.0962	10.3155
28	19.8872	13.9097	11.8057	6.93435
32	18.8245	10.9724	8.50	6.05912
Channel	**proposed QF/ RZ**			
	60	**120**	**180**	**240**
1	41.30	18.53	8.5451	7.2852
4	40.1233	22.684	12.4461	8.47988
8	33.0859	22.9739	16.0709	11.7017
12	42.336	30.9394	23.5733	20.8641
16	41.2774	34.8252	29.9647	18.9885
20	36.8665	23.6303	19.0692	17.978
24	46.9987	37.4899	22.868	14.1743
28	40.4908	23.251	16.5495	9.17895
32	35.5387	17.4106	7.08626	6.7856

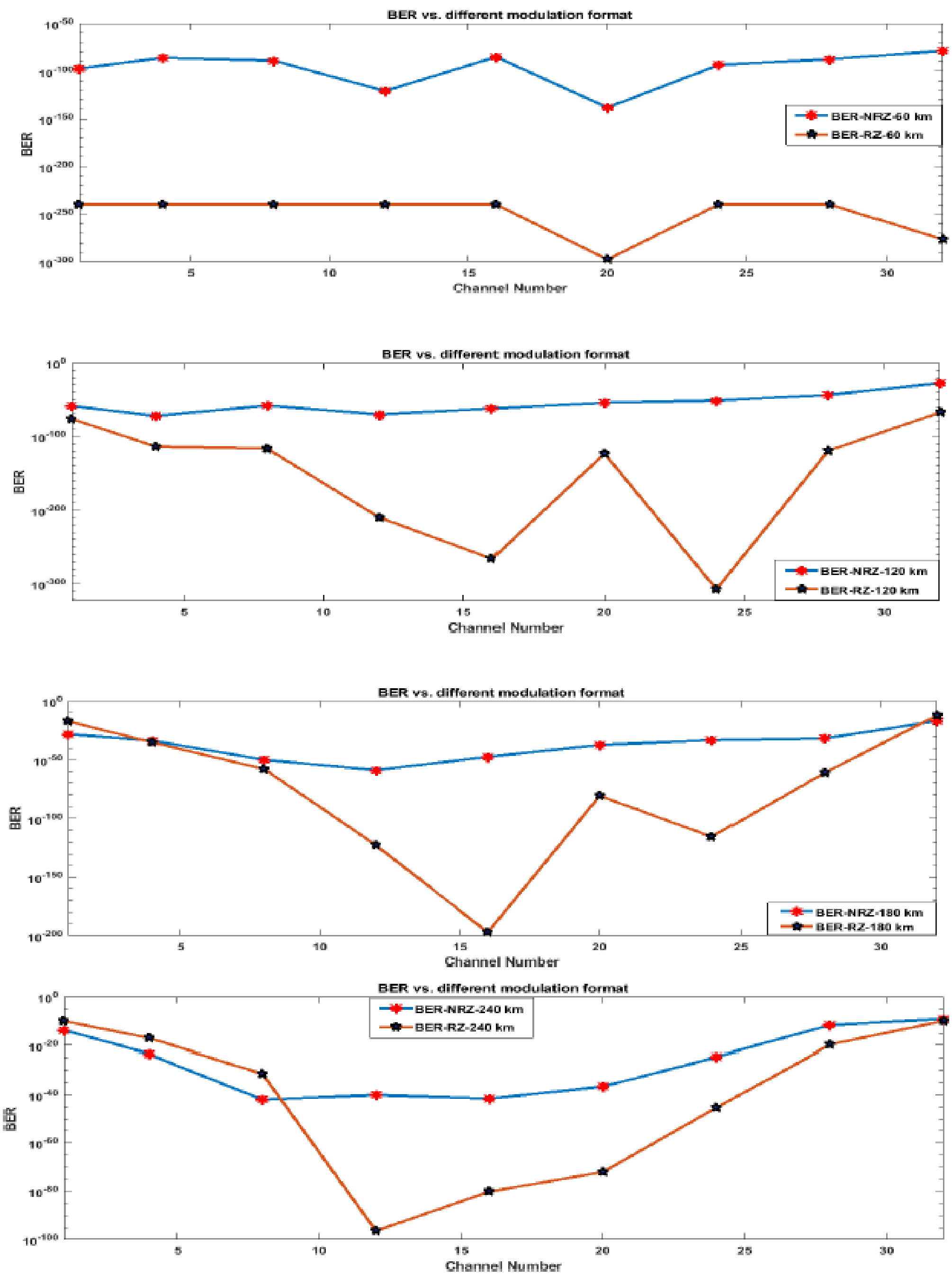

Figure 5.6 BER Vs. Different Modulation Format (a) 60 km, (b) 120 km, (c) 180 km and (d) 240 km.

The improved performance of the RZ is because the pulse width of the RZ signal is smaller than that of the NRZ signal. As a result, the RZ has higher peak power than the NRZ does for a given average power. Because of this, the eye opening of the RZ signal format is larger than that of the NRZ, which results in higher receiver sensitivity in comparison to the NRZ for a given level of average power.

Table 5.6 BER results obtained from the proposed system for both cases of NRZ and RZ modulation format .

Channel	proposed BER/ NRZ			
	60	**120**	**180**	**240**
1	6.46E-98	2.07E-59	7.13E-29	2.01E-14
4	7.32E-87	5.14E-73	1.98E-34	4.37E-24
8	1.03E-89	9.37E-59	1.07E-50	1.06E-42
12	1.70E-121	4.77E-71	1.45E-59	8.25E-41
16	8.08E-86	6.32E-63	3.12E-48	2.70E-42
20	6.31E-139	4.69E-55	3.89E-38	2.46E-37
24	3.25E-94	5.62E-52	5.22E-34	2.93E-25
28	2.37E-88	2.63E-44	1.82E-32	2.04E-12
32	2.18E-79	2.56E-28	9.85E-18	6.83E-10
Channel	**proposed BER/ RZ**			
	60	**120**	**180**	**240**
1	2.51E-255	5.09E-77	6.07E-18	5.21E-25
4	6.98E-305	2.61E-114	6.53E-36	1.07E-17
8	1.44E-240	2.91E-117	1.35E-58	4.27E-32
12	7.89E-297	1.14E-210	2.20E-123	3.58E-97
16	1.15E-276	3.11E-266	9.09E-198	6.42E-81
20	4.91E-298	5.59E-124	1.39E-81	8.63E-73
24	5.98E-328	5.26E-308	3.22E-116	4.91E-46
28	2.51E-187	4.53E-120	7.53E-62	2.08E-20
32	4.35E-277	3.06E-68	6.42E-13	3.65E-12

5.4 Results Based on OSNR

In this section, the results of the proposed system are analyzed for the parameter of OSNR and all 32 channels of the DWDM system. OSNR is used to quantify the degree of optical noise interference on optical signals. Also, it has been tested this parameter for three cases of channel spacing represented by 100, 150, and 200 GHz to show the impact of varying the spacing between channels on the OSNR. The results obtained from analyzing this parameter can be seen in Table5.7. From analyzing the results, it can be concluded that OSNR has a direct relation with QF and reverse with BER as raising the OSNR will raise the QF and this is related to using higher channel spacing of 200 GHz, where the average OSNR obtained for spacing of 100, 150 and 200 GHz were 23.7, 29.4 and 29.6 dB. However, it should mention that using higher spacing between channels would require using a higher amount of bandwidth which may be considered a bandwidth consumption.

Table 5.7 OSNR results from each channel of the proposed system.

Channel	Frequency (THz)	100 GHz spacing	150 GHz spacing	200 GHz spacing
		OSNR (dB)	OSNR (dB)	OSNR (dB)
1	190	25.768718	29.532772	29.779373
2	190.1	23.466293	29.035005	29.144782
3	190.2	23.466189	28.785897	28.881898
4	190.3	23.939211	29.010293	28.796164
5	190.4	24.215373	29.850093	29.534755
6	190.5	23.910113	30.013997	30.28969
7	190.6	23.715762	30.008263	29.744885
8	190.7	23.68539	28.430486	29.539952
9	190.8	23.137858	29.184791	29.475743
10	190.9	23.467038	29.345642	29.337118
11	191	23.953091	29.658995	29.422094
12	191.1	23.843461	29.65064	29.401713
13	191.2	23.723747	28.915796	29.12387
14	191.3	23.066872	29.585474	29.622395
15	191.4	23.146463	29.516071	29.026734
16	191.5	23.387245	29.521861	30.311646
17	191.6	22.948122	29.729509	31.14481
18	191.7	23.608165	30.017548	30.433269
19	191.8	22.465309	28.978596	29.144215
20	191.9	23.189826	30.21813	29.49708
21	192	23.780596	29.176519	29.673173
22	192.1	23.693362	29.619703	29.47013
23	192.2	23.561808	29.864702	30.360443
24	192.3	23.328906	29.490587	30.793475
25	192.4	24.101674	29.77494	30.062079
26	192.5	23.868957	28.914673	29.351109
27	192.6	23.806772	30.447706	30.226809
28	192.7	24.7133	29.95667	30.186408
29	192.8	23.469198	29.564858	29.752505
30	192.9	24.41502	29.414379	29.174992
31	193	23.103265	28.851081	29.228821
32	193.1	25.271343	29.216907	29.206558

5.5 Comparison With Previous Literature

we will analyze the similarities and differences in the research methodology, data analysis, and findings to identify discrepancies or consistencies. between results from the proposed system of this thesis and the most recent previous publications by the authors in[17], [18], [19], and [20].Table5.8, will be used to clearly illustrate the differences and significance of the proposed system and the methodology used.

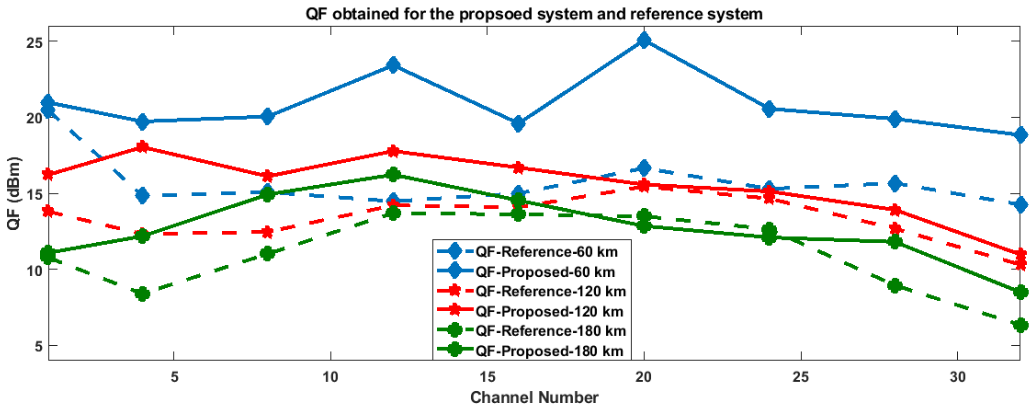

Figure 5.7 QF obtained for the proposed system Vs. reference [19]

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Table 5.8 Comparison of the proposed system Vs. previous studies.

Parameter	**Proposed**	**Ref.[20]**	**Ref.[19]**	**Ref.[18]**	**Ref.[17]**
Data rate (Gbps)	1280	256	1280	1000	640
channel number	32 analyze 32ch	32 analyze 4ch	32 analyze 9ch	25 analyze 4ch	16 analyze 5ch
Modulation format	NRZ-RZ	NRZ	NRZ	NRZ-RZ	NRZ
Power input(dBm)	0	0	0	5	$0-5$
Compensation method	Symmetrical	Post -based FBG	Post	Post	Post
Transmission distance (Km)	240	120	180	180	180
Channel spacing (GHz)	$(100-200)$	$50-100$	Fixed 200	Fixed 200	$50-60$
QF at 60 km	20.89/NRZ 39.77949/RZ	14.9023	15.74	-	15.168
QF at 120 km	15.60/NRZ 25.74819/RZ	15.7209	13.33	-	14.28
QF at 180 km	12.69/NRZ 17.35256/RZ	-	10.99	17.459/NRZ 11.0958/RZ	13.954 at $p=0$dBm 14.486 at $p=5$dBm
QF at 240 km	10.46/NRZ 12.82625/RZ	-	-	-	-

5.6 Conclusion And Recommendation

The final section of this chapter contains the conclusion and suggestions for future work and as summarized in below points:

1. In this thesis, it has been designed and implemented 32 channel DWDM RoF system that was based on using the compensation technique of symmetrical type to handle the problem of chromatic dispersion by using the DCF component with the transmission part.

2. The significant impact of using the symmetrical method has been shown in a clear manner where the proposed system could achieve distances up to 240 km along with using the NRZ as a format of modulation. Also, the values of QF and BER showed much higher values with using the symmetrical compensation type.

3. From the results of QF and BER concerning the distance of transmission, it showed a reverse relation between the QF and distance. Meanwhile, the BER showed a direct relation as analyzed concerning the distance.

4. For the analysis of the channel spacing, it has been concluded that using a higher value of channel spacing would increase the QF and reduce the BER. However, using large spacing could be considered bandwidth consumption and needs to be used properly.

5. For the analysis results of the utilization of different modulation formats. It has been concluded that using RZ instead of NRZ could further improve the proposed system and in conclusion, further raise the distance to reach above 240 km. For example, the average QF obtained from the selected sampled channels for 240 km was raised by 2.5 dBm using the RZ modulation method.

6. For the analysis results of OSNR, it has been concluded that increasing the channel spacing could increase the OSNR. For instance, the average OSNR obtained for spacing of 100, 150, and 200 GHz were 23.7, 29.4, and 29.6 dB respectively. This indicates good detection and receiving of the data as we raise the channel spacing.

For the recommendation for future studies, the following points could be followed in the future:

1. studying the impact of different compensation methods by using advanced modulation techniques such as QPSK and using a different format for modulation.
2. studying the impact of using the symmetrical compensation concerning its effect on the utilization of different nonlinearity effects and proposed methods to further reduce its effects .
3. using different approaches for the hybrid amplification method to further boost the transmission distance of the system and incorporated it along with using the symmetrical compensation-based method .

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PUBLICATIONS FROM THE THESIS

Conference Papers

1. Dawood, O. H., Balik, H. H. (2022, December). Implementation of Symmetrical Compensation based DWDM RoF system Toward Tbps of data transmission for 5G Fiber Optic Networks. In 2022 4th IEEE Middle East and North Africa COMMunications Conference (MENACOMM) (pp. 59-64). IEEE. DOI: 10.1109/MENACOMM57252.2022.999830373