REPUBLIC OF TÜRKİYE

ALTINBAŞ UNIVERSITY

Institute of Graduate Studies

Electrical and Computer Engineering

DESIGN AND IMPLEMENTATION OF HIGH DATA RATE IS-OWC SYSTEM BASED DWDM TECHNIQUE

Mohamed Jafar Ghani MAJEED

Master's Thesis

Supervisor

Asst. Prof. Dr. Ayça Kurnaz TÜRKBEN

Istanbul, 2022

DESIGN AND IMPLEMENTATION OF HIGH DATA RATE IS-OWC SYSTEM BASED DWDM TECHNIQUE

Mohamed Jafar Ghani MAJEED

Electrical and Computer Engineering

Master's Thesis

ALTINBAŞ UNIVERSITY

2022

The thesis titled DESIGN AND IMPLEMENTATION OF HIGH DATA RATE IS-OWC SYSTEM BASED DWDM TECHNIQUE prepared by MOHAMED JAFAR GHANI MAJEED AND and submitted on 13/12/2022 has been **accepted unanimously** for the degree of Master of Science in Electrical and Computer Engineering.

____

Asst. Prof. Dr. Ayça Kurnaz TÜRKBEN

the Supervisor

Thesis Defense Committee Members:

Asst. Prof. Dr. Ayça Kurnaz TÜRKBEN	Department of Software Engineering, Altınbaş University	___________________
Asst. Prof. Dr. Abdullahi Abdu IBRAHIM	Department of Computer Engineering, Altınbaş University	___________________
Asst. Prof. Dr. Serdar KARGIN	Department of Biomedical Engineering, İstanbul Arel University	___________________

I hereby declare that this thesis meets all format and submission requirements of a Master's thesis.

Submission date of the thesis to Institute of Graduate Studies: ___/___/___

hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Mohamed Jafar Ghani MAJEED

Signature

DEDICATION

I would like to express my sincere gratitude to all the instructors that have taught me more than just science, especially my supervisor Asst. Prof. Dr. Ayça Kurnaz TÜRKBEN, for all the time, support and guidance provided to me along the journey to accomplish this work. Thank you all for all the knowledge and advice that made me overcome all the difficulties that I have faces.

ABSTRACT

DESIGN AND IMPLEMENTATION OF HIGH DATA RATE IS-OWC SYSTEM BASED DWDM TECHNIQUE

Majeed, Mohamed Jafar Ghani

M.Sc., Electrical and Computer Engineering, Altınbaş University,

Supervisor: Asst. Prof. Dr. Ayça Kurnaz TÜRKBEN

Date: 12/2022

Pages: 73

The use of optical wireless communication for high data rate applications is made possible by the use of license-free and wide-bandwidth access techniques, as well as cost-effective solutions. Inter-Satellite Optical Communication (ISOC), a unique technique targeted at creating transmission between satellites, has just lately been offered to the public at large. The transmission of targeting errors, which generates turbulence in the connection, is the most difficult obstacle in creating an inter-satellite communication. This thesis describes the design of a 32-channel DWDM IS-OWC system that has a greater data rate of 1.28 Tbps and uses the NRZ modulation as a consequence of this. The utilized power is 30 dBm and the extension ratio selected was 30 dB, the selected frequency spacing between channel selected to be 1.58 nm. The suggested system was tested across distances ranging from 1000 to 9000 kilometers and was designed around the criteria of QF and BER by using the most appropriate software of optisystem. The collected results show that the proposed method has a better degree of accuracy.

In addition, the examination of alternative modulation formats (NRZ and RZ) will be considered in this work. Thus, employing NRZ is much superior than using RZ in terms of producing a higher quality signal while experiencing fewer bit rate error. Obtaining greater performance systems is shown by the average QF and BER acquired at 7000 km, for example, which were 8.11dBm and 1.62e-16, respectively, indicating higher system performance. The results of eye opening compared between the proposed work and a reference work, and it can be seen that the proposed work achieve much clear eye results indicating a less bit errors of 1 and 0 that has been send over 7000 km, indicating the reliability and the efficiency of the proposed system.

Keywords: 5G, OWC, WDM, BER, QF.

TABLE OF CONTENTS

LIST OF TABLES

Pages

LIST OF FIGURE

Pages

ABBREVIATIONS

5G	:	Fifth Generation
BER	:	Bit Error Rate
CWL	:	Continuous Wave Laser
CWDM	:	Coarse Wavelength Division Multiplexing
DWDM	:	Dense Wavelength Division Multiplexing
DE Mux	:	Demultiplexer
DCF	:	Dispersion Compensation Fiber
EDFA	:	Erbium Doped Fiber Amplifier
ED	:	Eye Diagram
E/O	:	Electrical to Optical
FTTH	:	Fiber To the Home
FSO	:	Free Space Optic
Gbps	:	Giga bit per second
GEO	:	Geostationary Earth Orbit
IoT	:	Internet of Things
IS-OWC	:	Inter- Satellite Optical Wireless Communication
ISL	:	Inter Satellite Link
IR	:	Infrared
ITU	:	International Telecommunication Union
LPBF	:	Low Pass Bessel Filter
LED	:	Light Emitting Diode

LEO	:	Low Earth Orbit
Mux	:	Multiplexer
MZM	:	Mack Zander Modulator
MEO	:	Medium Earth Orbit
NRZ	:	Non-Return to Zero
NFPA	:	National Fire Protection Agency
OFDM	:	Orthogonal Frequency Division Multiplexing
O/E	:	Optical to Electrical
PD	:	Photo Detector
PRBS	:	Pseudo Random Bit Sequence
QF	:	Quality Factor
RFoF	:	Radio Frequency over Fiber
RZ	:	Return to Zero
RF	:	Radio Frequency
TDM	:	Radio Frequency
Tbps	:	Tera bit per second
TUBITAK	:	Turkish Scientific and Technological Research Council
UV	:	Ultra Violet
VLC	:	Visible Light Connection
WDM	:	Wavelength Division Multiplexing
OSNR	:	Optical Signal to Noise Ratio
OFM	:	Optical Fiber Multiplexing

OFDM	:	Orthogonal Frequency Division Multiplexing
OWC	:	Optical Wireless Communication
OTD	:	Optical Time Domain

1. INTRODUCTION

1.1 MOTIVATION

Coupled with the expansion in the number of clients, we have seen a huge expansion in the interest in data transmission too. These days, clients want broadband remote administrations, for example, video calls, high-velocity web access, superior quality TV, and different administrations that require a lot of transmission capacity, like Wi-Fi. Microwave correspondence, RF-based cell correspondence, Fiber-To-The-Home (FTTH), and different innovations are instances of arrangement. All of these are hampered by various limits, including confined transmission capacity, blocked range, restrictively costly authorizing, and high establishment costs. Optical Wireless Communication (OWC) seems, by all accounts, to be a suitable response to this issue. Essentially, the issue of transfer speed imperative happens in satellite correspondence also. As indicated by a study distributed in 2009, there were around 6124 satellites in the circle, and as the quantity of satellites has extended, so has the requirement for radio recurrence range [1].

With headways in innovation, lasers are presently equipped for sending information over distances of a few a great many kilometers. The idea of Inter Satellite Optical Wireless Communication (IS-OWC) was brought into the world subsequently. The earth station and the connection-based station stay in the microwave system in Is-OWC, however, the connection interfacing two satellites in space are supplanted by an optical sign [2]. The benefits of doing so incorporate handing off GEO which stands for Geostationary Earth Orbit-based satellites with LEO satellites are commonly used for global coverage, where several satellites are launched into space to perform a single mission [2]. LEO orbit altitudes vary between 160 km and 2000 km and have a rotational period of approximately 90 minutes. Therefore, these satellites quickly change their position relative to a corresponding ground station. In order to achieve global coverage, a large number of satellites are needed for continuous connectivity. These incorporate satellite-to-ground correspondence as well as the other way around, as well as satellite-to-satellite correspondence, in addition to other things. It is important to highlight the Characteristics of LEO and GEO and show the significance of Orbit as seen in Table 1.1.[3]

Table 1.1: Comparison of characteristics between LEO,MEO and GEO [3].

	GEO (36,000km)	MEO (5,000-20,000km)	LEO (500-1,200km)
Altitude latency[1]	High	Low	Very low
Earth coverage	Very large	Large	Small
Satellites required	Three	Six	Hundreds
Data gateways	Few fixed	Regional flexible	Local numerous
Antenna speed	Stationary	1-hour slow tracking	10-minute fast tracking
Advantages	High throughput (HTS) technologies enable basic broadband internet applications	Proven low latency comparable to terrestrial networks, offers fibre-equivalent performance	Claims support for high-frequency trading, virtual gaming, and high-performance computing applications
Advantages	Fewer satellites over very large fixed geographical areas	Simple equatorial orbit covers 96% of global population	Smaller, lower power satellites batch-launched more cheaply than GEO
Disadvantages	High altitude and distant ground networking impacts latency-sensitive applications	Dual tracking antennas required to maintain continuous connectivity	Very complex tracking and ground network, plus complete constellation must be in place before service starts
Disadvantages	Signal power losses require larger satellites and antennas	Inclined plane orbits needed to cover high latitudes	Unproven business model, risky technology, and space debris risk

Advances in satellite technology have given rise to a healthy satellite services sector that provides various services to broadcasters, Internet service providers (ISPs), governments, the military, and other sectors. There are three types of communication services that satellites provide: telecommunications, broadcasting, and data communications. Telecommunication services include telephone calls and services provided to telephone companies, as well as wireless, mobile, and cellular network providers. Data communications involve the transfer of data from one point to another. Corporations and organizations that require financial and other information to be exchanged between their various locations use satellites to facilitate the transfer of data through the use of Very Small-Aperture Terminal (VSAT) networks. With the growth of the Internet, a significant amount of Internet traffic goes through satellites, making ISPs one of the largest customers for satellite services. [3]. ISL can be clarified as seen in Figure 1.1[2].

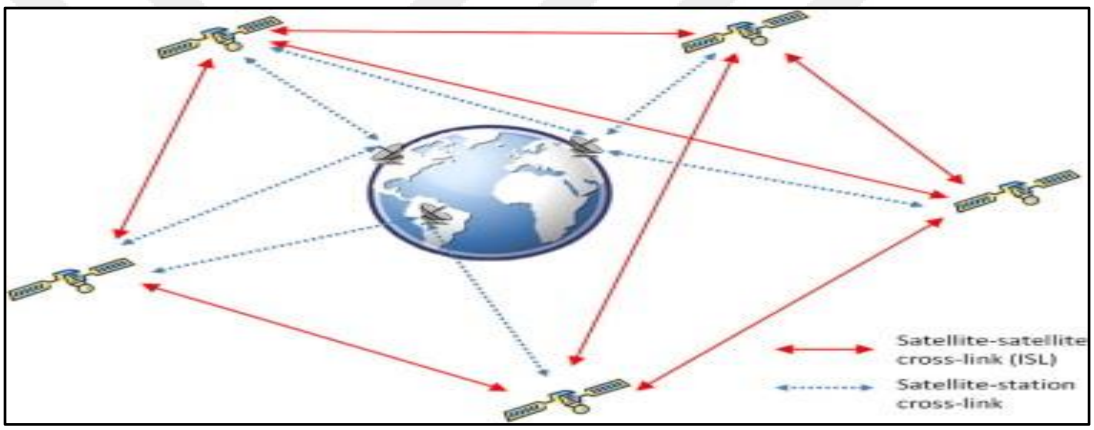

Figure 1.1: ISL connection between the satellite [2].

1.2 OPTICAL WIRELESS COMMUNICATION (OWC)

It is generally perceived as one of the most groundbreaking improvements throughout the entire existence of innovation, and the multiplication of remote correspondences is no exemption. It is difficult to imagine how rapidly remote devices and innovations have spread in current culture thirty a long time back, and they will keep on being an essential part of present-day life for years to come. In this day and age, the expression "M. Uysal" as well as the Turkish Scientific and Technological Research Council (TUBITAK) Grant 111E143. Due to the wide sending and utilization of distant RF devices and systems, the maxim "remote" has become indivisible from RF advancement. The radio recurrence band of the electromagnetic range, then again, is restricted in limit and costly because of the way that most sub-groups are authorized only. The interest in radio recurrence range is exceeding inventory because of the rising fame of information serious remote correspondences. It is a previous opportunity to painstakingly examine extra practical decisions for remote correspondence that use the upper segments of the electromagnetic range. Transmission employing unguided spread media using optical transporters, like those working in the apparent, infrared (IR), and bright (UV) groups, is alluded to as optical remote correspondence OWC. The utilization of guide blazes, smoke, transport banners, and the semaphore broadcast [4] can be generally viewed as chronicled kinds of OWC flagging. Since exceptionally old times, daylight has likewise been utilized for significant distance flagging purposes. Daylight was first utilized for correspondence purposes by antiquated Greeks and Romans, who utilized their cleaned safeguards to convey messages to far-off stations by reflecting daylight during fights [5].

The heliograph, created by Carl Friedrich Gauss in 1810, uses several mirrors to direct a controlled light discharge to a distant location. Although the heliograph was initially intended for geodetic research, it was extensively employed for military purposes in the late nineteenth and early twentieth centuries. The picture telephone, considered the first distant phone system in the world, was developed by Alexander Graham Bell in 1880 [4]. The vibrations were reflected and radiated by daylight, and at the receiver, they were transformed into voice. Bell praised the picture telephone as "the finest innovation had ever devised, far more conspicuous than the phone" [6], but it was never made available as a commercial product. However, the photographic phone's tactical advantage continued. For instance, the German Army developed a picture telephone in 1935 that used a tungsten fiber lamp with an infrared transmission channel as a source of illumination. Additionally, military research facilities in the US and Germany continued to study and promote high tension circular segment lights for optical correspondence into the 1950s. In the high-level relevance of the word, OWC transmits information using either lasers or Light-Emitting Diodes (LEDs) [7].

In a relatively short span of time, satellite technology has developed from the experimental (Sputnik in 1957) to the sophisticated and powerful. Mega-constellations of thousands of satellites designed to bring Internet access to anywhere on Earth are in development. Future communication satellites will have more onboard processing capabilities, more power, and larger-aperture antennas that will enable satellites to handle more bandwidth. Further improvements in satellites' propulsion and power systems will increase their service life to 20–30 years from the current 10–15 years. In addition, other technical innovations, such as low-cost reusable launch vehicles are in development. With increasing video, voice, and data traffic requiring larger amounts of bandwidth, there is no dearth of emerging applications that will drive demand for the satellite services in the years to come. The demand for more bandwidth, coupled with the continuing innovation and development of satellite technology, will ensure the long-term viability of the commercial satellite industry well into the 21st century [8,9].

Long-term, interest in OWC has traditionally been focused on stealthy military applications [10, 11] and aerospace, such as those between satellites and deep space links1 [10,11] and other such applications. Except for IrDA, which has shown to be a very successful remote short-range transmission system [12]. With the recent increase in the number of companies offering earthbound OWC connections, as well as the introduction of visible light Connection (VLC) devices [13]-[19], the industry has begun to show signs of stability for the foreseeable future [20], [21]. It should be possible to see the Entomb Satellite OWC connects all across the world in Figure 1.2.

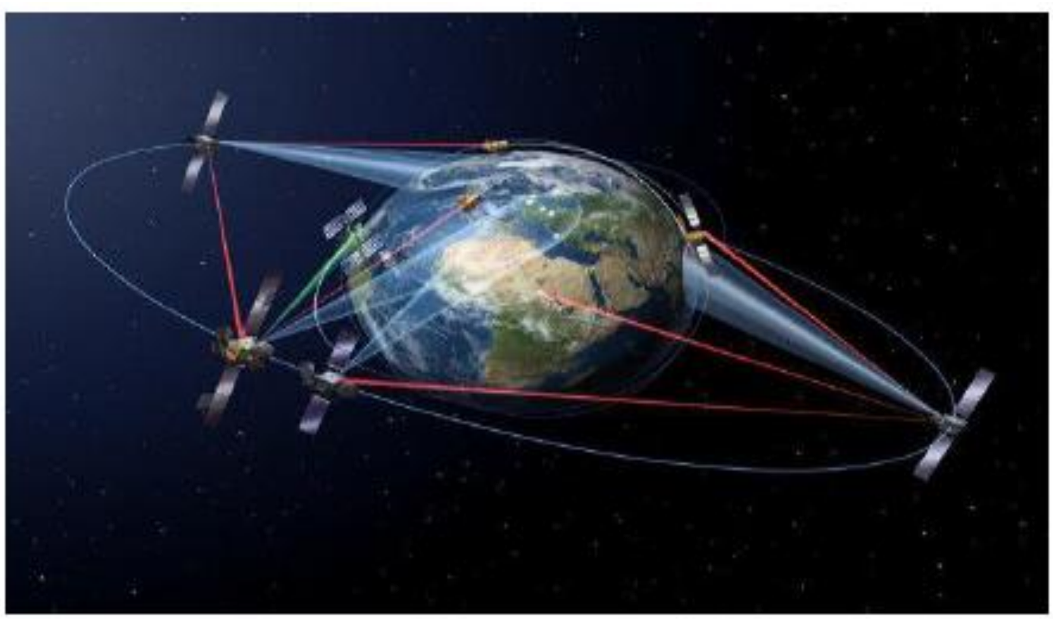

Figure 1.2: IS-OWC link around the earth [22].

Traditional inter-satellite communication uses radio frequencies (RF). With this method of communication, however, interference has to be avoided, so it has various limitations. Also, it is hard to achieve high-speed communication due to limited bandwidth. Compared to RF communications , high-speed , high-capacity optical inter-satellite communications can be achieved because of its high frequency carrier waves and large bandwidth. Another important feature is that it is not affected by radio interference. Also, optical antennas can be smaller and lighter than RF antennas, because their short wavelengths provide high energy and high gain even with a small antenna diameter. The weight reduction of a satellite is a great advantage because launch costs are then greatly reduced. [21]. According to Figure 1.3, the OWC system may be reduced to its most fundamental diagram.

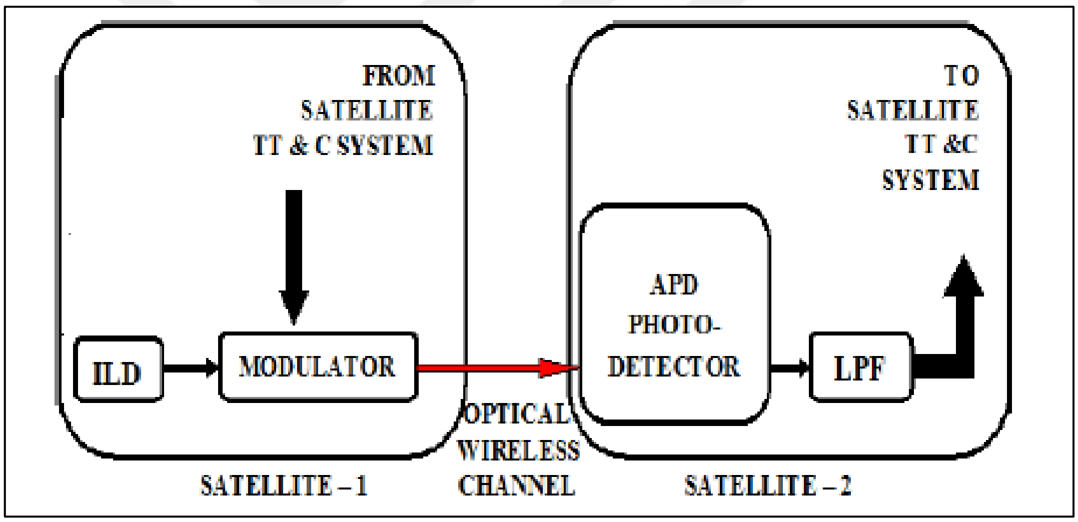

Figure 1.3: Simplified block diagram for the OWC system [22].

The OWC can be classified into two broad categories, namely indoor and outdoor optical wireless communications. Indoor OWC uses IR or visible light for communication within a building where the possibility of setting up a physical wired connection is cumbersome. Indoor OWC is classified into four generic system configurations i.e., directed line-of-sight (LOS), non-directed LOS, diffused, and tracked. Outdoor OWC is also known as free space optical (FSO) communication. The FSO communication systems are further classified into terrestrial and space optical links that include building-to-building, ground-to-satellite, satellite-to-ground, satellite-to-satellite, satellite to-airborne platforms (unmanned aerial vehicles (UAVs) or balloons), etc. [23]. Figure 1.4 illustrates the classification of the OWC system.

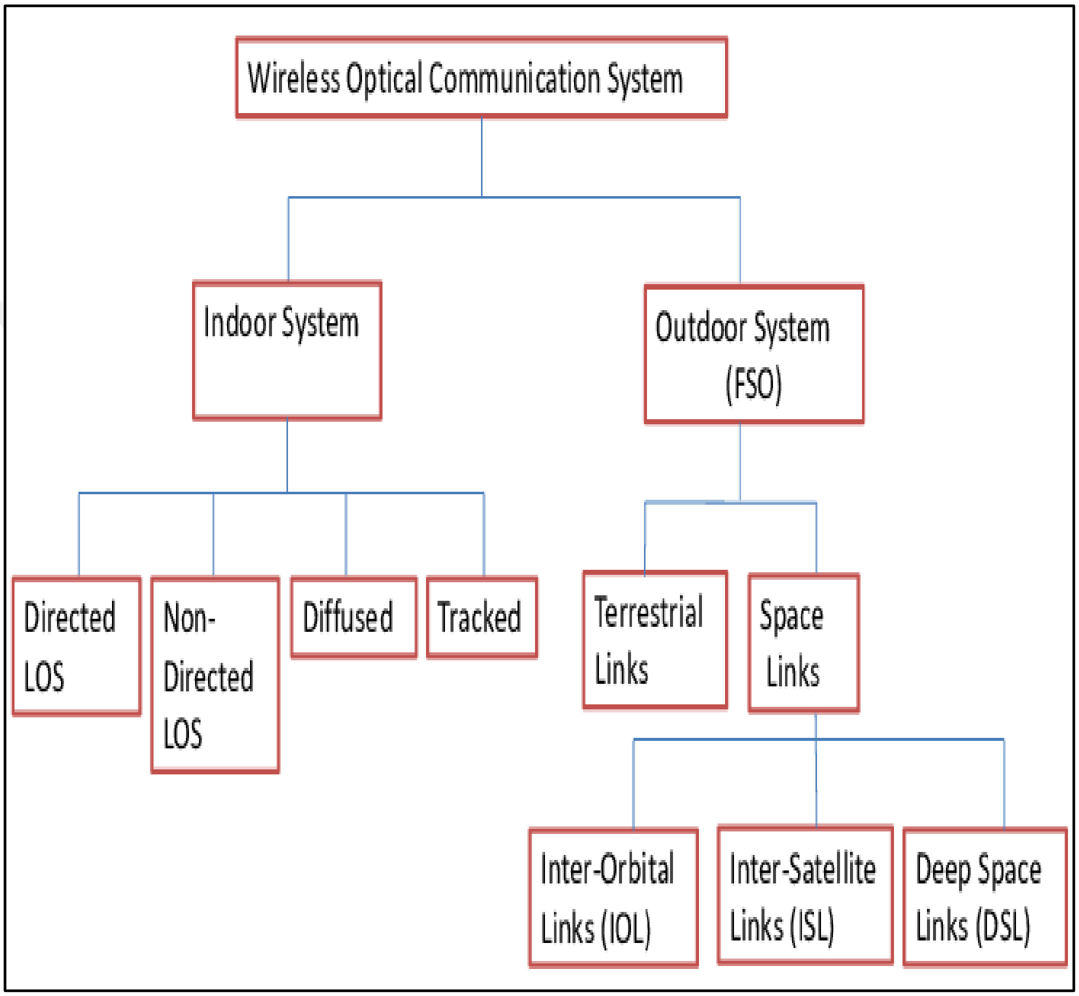

Figure 1.4: OWC classification [23].

1.3 OWC ADVANTAGES

Satellites face competition from other media such as fiber optics, cable, and other land-based delivery systems such as microwaves and even power lines.

i. The main advantage of satellites is that they can distribute signals from one point to many locations. As such, satellite technology is ideal for "point-to-multipoint" communications such as broadcasting. Satellite communication does not require massive investments on the ground—making it ideal for underserved and isolated areas with dispersed populations.

ii. Unrestricted spectrum: The range accessible for optical frameworks is unhindered and is multiple times more than the range accessible for radio recurrence beams. In a variety of applications, RF rays have been used, and now there is a pressing need to find a suitable substitute in all feasible sectors. In addition, the radio frequency spectrum is extremely expensive [23].

iii. Decreased Delay: Because GEO satellites are situated at a tallness of 35768 kilometers over the Earth's surface, they create a critical setback while speaking with ground stations. To decrease this postponement, they are handed off with LEO satellites that are available at a tallness of around 1000 km over the world's surface through optical lines to diminish delay [23].

iv. Less weight: When contrasted with RF-based satellite correspondence, is-OWC limits the size of the payload and the heaviness of satellites because the parts required are minimized and light in weight [23].

v. Because of the way that RF frequencies are longer than optical frequencies, the pillar made by optical frequency is smaller. However, for satellites to be properly aligned, a very accurate tracking system is required [23].

vi. In comparison to radio frequency communication, it has lower maintenance costs once it has been established since the system components have longer life periods [23].

vii. Simple configuration: In the event of a network breakdown or outage, it is simple to modify the Is-OWC network if necessary. It can deploy and redeploy with more ease [23].

1.4 PARAMETERS AFFECTING IS-OWC

i. Wavelength: Wavelength was picked for space-put-together optical applications concerning the premise of a compromise between beneficiary awareness and pointing inclination attributable to warm vacillations; a more drawn-out frequency additionally assists with lessening sun-based dispersing [23].

ii. These wavelengths are further subdivided into the following classes: Near Infrared, which ranges from 750 nanometers to 1450 nanometers for fiber optics, Short Infrared, which ranges from 1400 nanometers to 3000 nanometers, with (1530-1560) nanometers being used to cover greater distances, and Mid Infrared, which ranges from (3000-8000) nanometers for military-based applications. On the other hand, the most often used frequency is 1550 nanometers because, with a longer wavelength, the effects of Rayleigh and Mie fading will be less obstructed, and it is also compatible with current hardware [24].

iii. Modulation Formats: These frameworks can utilize an assortment of different balance designs. Beforehand, NRZ was a predominant organization viable because of the solid specialized establishment it had. Progressed configurations, for example, transporter smothered other progressed designs are being utilized increasingly more to make a more powerful framework.

iv. Power Levels: System execution can be expanded by expanding the power level. Eye security rules are likewise not thought about concerning satellite correspondence. However, by and by, there are imperatives associated with framework parts that put limits on the info power levels of the framework, and subsequently, it is preposterous to expect to build the framework's result power endlessly. Expanding the information rate at 1550 nm while changing the separation from 200 to 1200 kilometers was concentrated in [24] to see what impact it had on the sign. It was found that when information rates are high and distances are expanded, the upsides of the quality component and SNR decline. The development of innovation has brought about an ascent in information transmission rates.

v. When using an electronic channel in an IS-OWC framework, the objective is to acknowledge the fundamental sign while dismissing any unessential foundation clamor. Entry to the Lower Levels in Is-OWC, the Bessel channel with a cut-off recurrence of 0.75*Bit rate is the most often seen channel. The effect of applying various channels on framework execution, as estimated by the Q-factor and the BER, was researched. As indicated by the discoveries of other examinations, for example, [25].

vi. Aperture measurement: In OWC, the gap width of the sending and getting receiving wires is basic since it decides how well the transmission is sent. The essential benefit of utilizing light as a transporter for data move is that it requires the utilization of receiving wires with little gap widths, which brings about frameworks that are low in weight and easy to oversee [26].

1.5 OWC APPLICATIONS

i. The use of an OWC link in space activities could be a more cost-effective solution for information exchange, experimental data sharing, and fast Internet connectivity on board spacecraft. [27]. Automatic-based OWC application can be demonstrated as seen in Figure 1.5.

Figure 1.5: OWC automotive applications [27].

ii. They require onboard technologies with greater precision and high resolution for earth monitoring missions in particular. Satellites as of now get information at paces of a few gigabits each second, and because a solitary satellite doesn't work in a particular region yet rather covers the whole globe, Gbps class frameworks are a reasonable prerequisite in the ongoing climate [28].

iii. In exercises including intergalactic space travel, where the weight, power, and volume of installed hardware are seriously confined. Perhaps the clearest probability is to utilize an optical stage with an altogether enormous opening or a transfer framework with a little client terminal, the two of which are somewhat reasonable. A solid spine correspondence station, unaffected by the deceivability states of the earth stations, would be conveyed accordingly. [29]. OWC applications that were connected with 5G and IoT can be recorded as found in Figure 1.6.

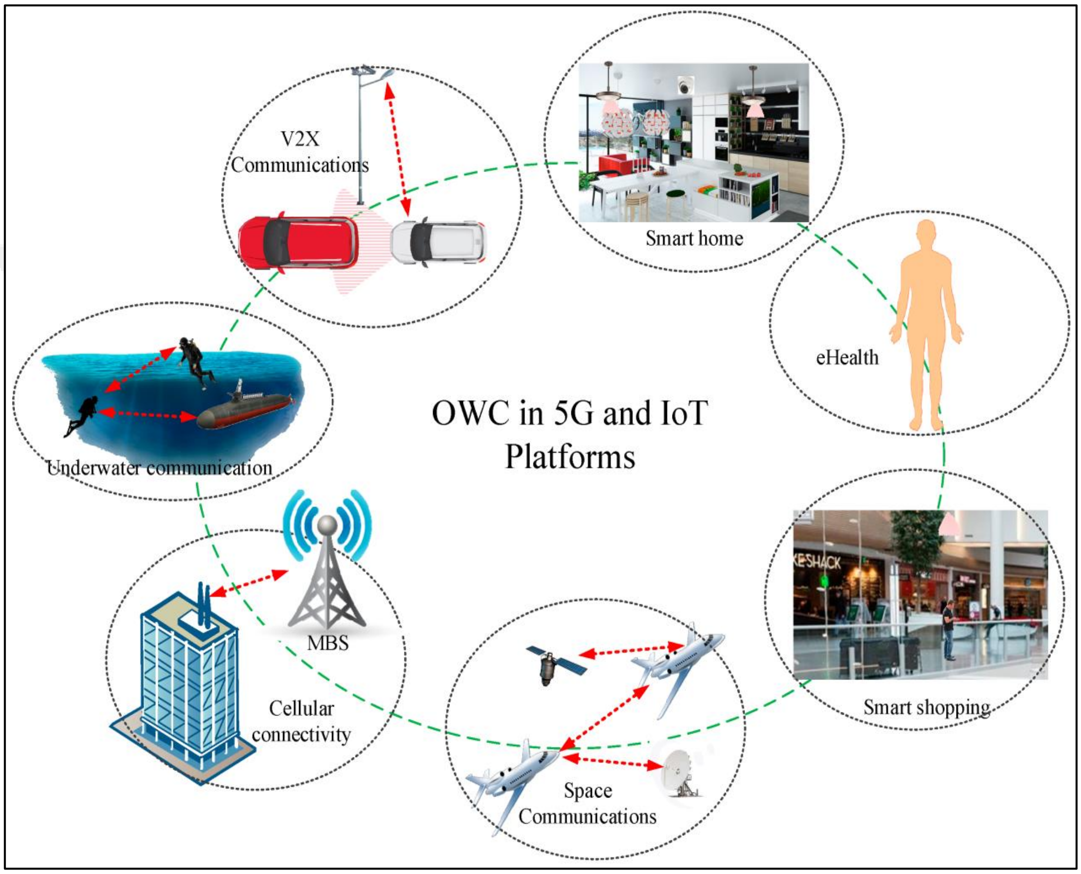

Figure 1.6: OWC in 5G and IoT-based applications [29].

iv. Communication among satellites: Because many satellites are orbiting the Earth and their task is divided across several satellites, a robust network is required to transmit data between them. To accomplish this, adequate control and synchronization are required, and Is-OWC is the most effective choice [29].

1.6 DENSE WAVELENGTH DIVISION MULTIPLEXING (DWDM)

Dense wavelength-division multiplexing (DWDM) is an optical fiber multiplexing technology that is used to increase the bandwidth of existing fiber networks. It combines data signals from different sources over a single pair of optical fiber, while maintaining complete separation of the data streams. A separate light wavelength carries each signal, and the dense in DWDM refers to its ability to accommodate up to 80 different wavelengths. Each wavelength is about 0.8 nanometer wide and shares a single optical fiber.

Fiber optic cables now commonly form the backbone of carriers' interoffice networks, representing the standard for the telecommunications infrastructure. DWDM enables enormous amounts of data to traverse a single network link by creating multiple virtual fibers, significantly multiplying the capacity of the physical medium As data flows through distinct wavelengths, the streams or channels do not interfere with each other. This approach helps maintain data integrity. As a result, this enables security-related partitioning or separate tenants in the same data center.

This strategy contributes to the preservation of data integrity. As a result, security-related partitioning, or the separation of tenants within the same data center is made possible. Because of its ability to handle large amounts of data, DWDM is widely used by telecommunications and cable providers alike. The network is a critical component of their core networks. DWDM is also an excellent choice for anyone who manages densely populated data centers, such as hyper-scale cloud service providers who provide infrastructure as a service or colocation providers that have large numbers of tenants in a little amount of space. DWDM is a predecessor to a similar technology: time-division multiplexing (TDM), which telecommunications operators use to routinely transmit information at 2.4 gigabits per second (Gbps) on a single fiber. Some also deploy equipment that quadruples that rate to 10 Gbps. However, demand for high-bandwidth applications created capacity demands that exceeded traditional TDM limits. As a result, DWDM was developed to quadruple the capacity of a single fiber. Figure 1.7 clarify the general concept of the DWDM technique [30].

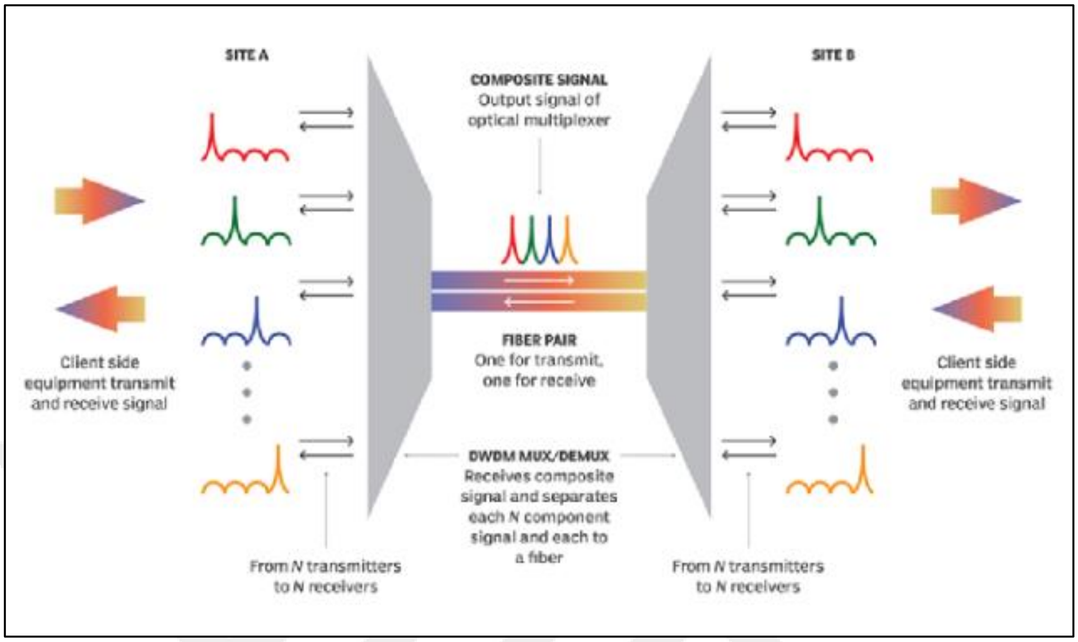

Figure 1.7: DWDM structure based technique [31].

It is worth to mention that the original technique of WDM is classified basically into DWDM and Coarse Wavelength Division Multiplexing (CWDM). Both of them have significant in different factors as listed below For the CWDM it is preferable to be utilized for [31]:

i. Low Cost

Because of the lower cost of the CWDM gear, DWDM is more expensive. When compared to DWDM systems, which employ uncooled lasers, the cost of CWDM systems' cooled lasers is much lower. Additionally, the cost of DWDM transceivers is often four to five times higher than the cost of corresponding CWDM modules. Even when it comes to running expenses, DWDM is more expensive than CWDM. Therefore, CWDM is an excellent option for those who have restricted financial resources.

ii. Minimum Amount of Power

The power needs for CWDM are far lower than those for DWDM, which are much greater. DWDM lasers, together with the related monitoring and control equipment, use around 4 watts of power for each wavelength. In the meanwhile, the power consumption of an uncooled

CWDM laser transmitter is around 0.5 W. The CWDM technology is a passive one that does not need any kind of electrical supply. The companies that run the internet stand to benefit financially from this development.

iii. Simple in its operation

In comparison to DWDM, the technology used in CWDM systems is more straightforward. The power comes from an LED or a laser. CWDM systems have wave filters that are more compact and less expensive. Because of this, they are simple to set up and employ.

On the other hand, the DWDM is preferable for [31] :

iv. Flexible Upgrade

When it comes to the many sorts of fibers, DWDM is both flexible and strong. Both G.652 and G.652.C fibers are capable of supporting DWDM upgrades of up to 16 channels. The origin of this misconception lies in the fact that DWDM will always use the low loss section of the fiber. While transmission in 16 channel CWDM systems takes place in the range between 1300 and 1400 nm, an area with significantly increased attenuation,

v. Scalability

The capacity of DWDM systems may be increased by a factor of eight channels up to a maximum of forty channels. In comparison to CWDM solutions, they make it possible to have a substantially larger overall capacity on the fiber.

vi. A Great Distance in the Line of Sight

DWDM makes use of the 1550 wavelength band, which may be amplified using the same kind of optical amplifiers that are used in traditional applications (EDFAs). It extends the range of the broadcast to many hundreds of kilometers.

As a result, a final comparison between the DWDM and CWDM can be formed as seen in Table 1.2, where the real difference is in the quantity of channels that are required by the consumer as well as the expenses connected with the deployment of each system.

Table 1.2: Comparison between DWDM and CWDM [31].

CWDM vs DWDM	
CWDM	**DWDM**
WDM systems with a max of 16 active wavelengths per fiber	WDM systems with a max of 160 active wavelengths per fiber
Defined by wavelengths	Defined by frequencies and wavelength
Designed for shorter distance	Designed for long-haul transmission
Wavelengths spread far apart	Wavelengths are tightly packed
Light signal is not amplified	Light signal amplification may be used
Compact equipment; cost effective	More costly to operate
Ability to transport up to 16 channels from 1270nm to 1610nm with a 20nm channel spacing	Ability to transport up to 80 channels with 100GHz spacing and up to 160 channels with 50GHz spacing in the C-band spectrum, with all channels in the 1550nm area
Breaks spectrum into larger sections	Breaks spectrum into smaller sections
Uncooled lasers used due to longer channel spacing	Cooled lasers may be used due to tighter control of wave-lengths

1.7 SIGNIFICANT OF THIS STUDY

As it has been previously mentioned that the development of internet applications required the utilization of higher data rate communication to support these applications, especially for satellite communication. As a result, there is a need for designing a reliable system using the dedicated parameters to boost its performance to its limit against higher distances of transmission and to achieve a higher data rate system concerning the appropriate utilized parameters. As a result, this work proposes a system of DWDM IS-OWC that consists of 32 channels and a total data rate of 1.28 Tbps. The system would be tested over longer distances and compared with recent publications in the same context to clarify the significance of the proposed system.

1.8 PROBLEM STATEMENT

When developing 5G-based applications, the necessity for higher data rates and bandwidth was a crucial element to consider, particularly when evaluating the use of fiber optic-based communication technologies. Furthermore, when dealing with the architecture of greater data rate networks and schemes, another significant element to consider is propagation across longer distances and varied attenuation factors, which are represented by the impact of changing the suitable parameters to improve the performance of the network. Because of this, our proposed solution will consider these difficulties and address them in a manner that is compatible with the criteria for 5G communication networks.

1.9 OBJECTIVE OF THE PROPOSED SYSTEM

The main objective of this proposed system is to handle and prepare a scheme for the 6 G-based communication with supporting the following aspects:

i. Propose and design a DWDM IS-OWC system with a higher data rate and used the most suitable modulation format to increase the data rate to support higher speed-based applications.
ii. Study the proposed system for different modulation formats, transmission distances, and other effective parameters.

1.10 THESIS OUTLINE

Chapter one incorporates an overall outline of the issues related to the fiber optic correspondence framework, the WDM procedure, and it’s really three sorts would be examined in this section. Then, at that point, Is-OWC communication and framework would be given regard to its qualities. At long last, the point and targets of this introduced framework would be handled in the remainder of this section.

In chapter two, many specialists and businesses added to our writing survey, which was proposed and recorded, featuring the huge and various focuses between each review. The writing audit was pertinent to our proposition subject, and numerous analysts and ventures added to it.

Chapter three examines the hypothetical foundation connected with fiber optic correspondence in light of the Is-OWC DWDM system and the model plan for our proposed plot by using the Optisystem v.18 programs. Additionally, the three primary pieces of the proposed framework would be dealt with in this part. Moreover, the different hypothetical perspectives connected with different remuneration methods would be shown in this section.

Chapter four presents the result of the proposed structures by pondering different methodologies for compensation and close-by different transmission distances. These presented results would be established on the limits of Quality Factor (QF) and Bit Error Rate (BER). Furthermore, this part handles the last connection between the proposed system and the reference work proposed by various researchers to assess the basics and efficiency of the proposed structure.

Chapter five talks about the ends and ideas for future work.

2. LITERATURE REVIEW

i. In [32] presented a 32-channel DWDM IS-OWC system and investigated it using several different modulation formats. The OWC made use of a wavelength of 1550 nm, and the distance that was looked at was up to 3000 kilometers long. In terms of the bit rate, the system has been evaluated at data transfer speeds of 10, 20, and 30 Gbps. According to the results that were obtained, the system demonstrates its efficiency against various modulation formats at data rates lower than 20 Gbps, up to a maximum of 20 Gbps. In contrast, the MDRZ-based modulation approach had the highest overall performance when compared to the other modulation methods when it came to increasing the data rate to more than 40 Gbps. There is room for improvement in terms of the data rate that can be attained with the method that has been suggested.

ii. In [33] The authors presented an IS-OWC system that makes use of optisystem 7 software and can accommodate a maximum of 16 channels. The distance reached was 5000 kilometers, and the data rate that was attained was 40 Gbps. The OWC system decided on 1.1 microrads as the appropriate value for its point of error. In the meanwhile, the wavelength that was employed was 1550 nm, and the input power was 15 dBm accordingly. This research essentially shows that its findings are substantial; nevertheless, it employs a huge aperture diameter for both the Tx and Rx, which is said to be equivalent to 25 cm. This is a value that has not been used by any other publications in the past. In addition, the efficacy of the system was shown using a six-channel system design or higher as Quality Factor (QF) results that were more than six dBm, which is the minimum threshold determined to be acceptable. A system like this one requires additional improvement, namely an increase in both the QF values and the transmission distances. As the goal of future research is to handle the distance to reach the GEO region to be satisfied with a wide range of applications.

iii. In [34] A proposal was made for an IS-OWC system that employs a variety of encoding strategies in addition to supporting 16 channels. The technology was capable of transmitting data at a rate of 100 Gbps across a distance of 10,000 kilometers.

Duobinary encoding yielded the best overall results in terms of the examined parameters of Bit Error Rate (BER) and QF, according to the findings that were obtained after experimenting with a variety of various encoding techniques. The timing error value was set up to be 3 microrads, and the input power that was picked was 20 dBm. Despite all of these achievements, the data rate that was analyzed in this research was significantly lower. To attain the Tbps, the system will need to be able to handle far greater numbers.

iv. In [35] It was suggested, constructed, and put into action a WDM-based OWC system with high power consumption, which comprises 8 channels with a data rate of 40 Gbps each. The frequency that was settled on for OWC was 1550 nm, and the extra losses that were settled on were just 1 dB lower. It was decided that the transmissions section of the proposed system would contain two Erbium-Doped Fiber Amplifiers (EDFA), and this decision was made to improve the QF and BER over the longer distances of 10,000 kilometers that the proposed system reached. The QF and BER values that were attained were respectively 7.68 dBm and 5.60e-15. As a consequence of this, the author should investigate if there is another approach to compensating for the EDFA that would be more successful in obtaining outcomes that are more accurate with fewer mistakes.

v. In [36] The authors presented a system that was based on a subsystem transmission medium and had lower data rates equivalent to 1.5 Gbps. This system made use of both the Free Space Optic (FSO) transmission and the OWC transmission. The distance that was looked at was between one hundred and ten thousand meters for the OWC channel and between one hundred and one thousand meters for the FSO channel. The obtained results demonstrated that the researched parameters of QF and BER were effective up to a distance of 800 m for the FSO channel and 80 km for the OWC channel respectively. The recommendations of a minimum QF threshold of 6 dBm and BER of 10e-9 were the basis for this observation. However, the data rate that was attained has to be enhanced further and then evaluated using a system that consists of two hybrid channels. In addition, the distance covered by the FSO channel has not been connected to any of the calculated attenuation values, resulting in findings that are not practical.

vi. In [37] The authors suggested using a DWDM-based IS-OWC system with 64 channels. The wavelength of 860 nm was the one that was used, and the input power was set at 12 dBm. The distance that was decided upon was 15 cm. The results that were achieved from the study that was suggested were based on the variation of various distances ranging from 500 to 3000 kilometers and data speeds of up to 2.5 gigabits per second for each channel. The obtained results indicated that the system is effective up to a distance of 1,500 kilometers; however, for greater distances, the QF-based results were lower than the minimum threshold recommendation; as a result, the proposed system is unable to perform transmissions of more than 2,000 kilometers based on the achieved values of the parameters of QF were based on many publications it set the minimum threshold to be around 6 dBm.

vii. In [38] The researchers came up with an idea for an IS-OWC system that included a transceiver with 16 channels. In addition to the suggested system, a variety of wavelengths that spanned from 850 to 1550 nm were examined and tested. In addition, a variety of broadcast powers ranging from 10 to 25 dBm were used. In addition to that, the experiment comprised a variety of data rates as well as distances. According to the results that were obtained, increasing the value of the input power will result in a greater data rate. On the other hand, the consequences of nonlinearity that are associated with increasing the transmission distance have not been taken into account. In addition, the data rate that can be reached by the proposed system has to be enhanced and expanded, particularly when it comes to the management of apps that are based on 5G and demand faster speeds of communication.

viii. In [39] It was suggested to use a 16-DWDM IS-OWC system that would be capable of achieving a data throughput of 160 Gbps. The range of kilometers that was looked at was from 1000 to 7000. It was tested across a distance of 7,000 kilometers by employing an amplifier device, and the results were compared to those obtained when the device was not used. The standards outlined by the International Telecommunication Union (ITU) served as the basis for the decision to settle on a wavelength of 1550 nanometers (nm). The NRZ modulation technique was used, and the channel spacing was determined to be 1.58 nm. Following an assessment of QF, BER, and Eye Diagram (ED) parameters, the following results were obtained: These findings demonstrated that in the absence of the amplifier, the system is unable to execute transmission at a distance of 7000 kilometers. When the optical amplifier is used, however, the system achieves QF results of 6.616 dBm. This value is quite near the minimal threshold of the QF parameter, which is 6 dBm. The things that show that the usage of the required amplifier has a modest influence on the proposed system performance are the things that are referred to in the previous sentence. As a result, the technique of amplification has to be further enhanced where it could be improved for example by using the compensation method, and at the same time, the data rates need to be increased to satisfy the recent application supported for the 5G based communication. As it has been assigned 10 Gbps per each attached channel which is considered a low rate for future communication.

3. THEORETICAL BACKGROUND AND HYPOTHESES

3.1 INTRODUCTION

This chapter will illustrate brief details about the proposed system that has been implemented via using the most dedicated software of optisystem. The proposed system consists of three main parts which will be discussed in detail along with highlighting all the details parameters that were set. The software used as a simulator for the study would be clarified in detail. Also, the parameters studied to analyze the system performance also would be highlighted in this section.

3.2 IS-OWC DWDM SYSTEM

The suggested system includes three primary pieces. The broad perspective for the complete system may be shown in Figure 3.1 as recorded by optisystem software. The system comprised 32 DWDM channels.

i. Transmitter Part

The binary bit generator (PRBS) is the initial component of the proposed system, and it is used to determine the quantity of bit rate that will be broadcast in the first phase. In which it has been set to be equal to 40 Gbps per channel. Then there is a pulse generator that aims to convert the binary generated data to electrical pluses. Then, a modulator of the type of Mack Zander is used to combine the electrical signal described previously with the optical signal generated from the optical source which is in our case the LASER device. The values set for all of these parameters mentioned up were listed in Table 3.1. It's worth mentioning that the optisystem software provides the ability to combine all these tools mentioned above in one tool known as the optical WDM transmitter component. The design of this part can be seen in Figure 3.2. Then each link output from the modulator would go as an input to the multiplexer device, which is used as a basis for the DWDM technique and combine multiple links (in our proposed system 32 link) from various sources in a single link.

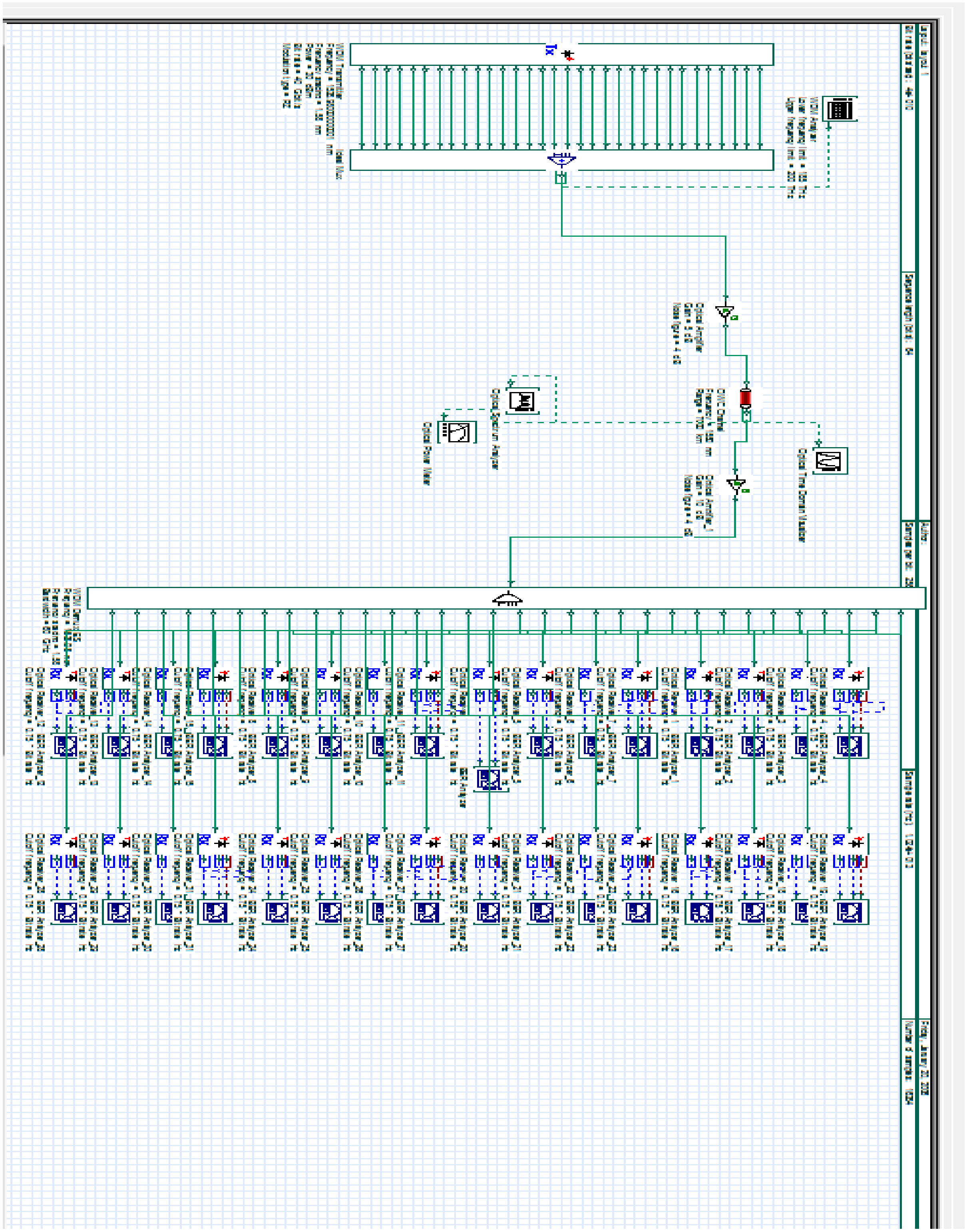

Figure 3.1: The proposed DWDM IS-OWC system.

Table 3.1: The parameter of the transmitter of the proposed system.

parameter	value	unit
Number of output ports	32	
Frequency	1538.98	nm
Frequency spacing	1.58	nm
Power	30	dBm
Extinction ratio	30	dB
Line width	0.1	MHz
Initial phase	0	deg
Bit rate	40	Gbit/s
Modulation type	NRZ	
Duty cycle	0.5	bit

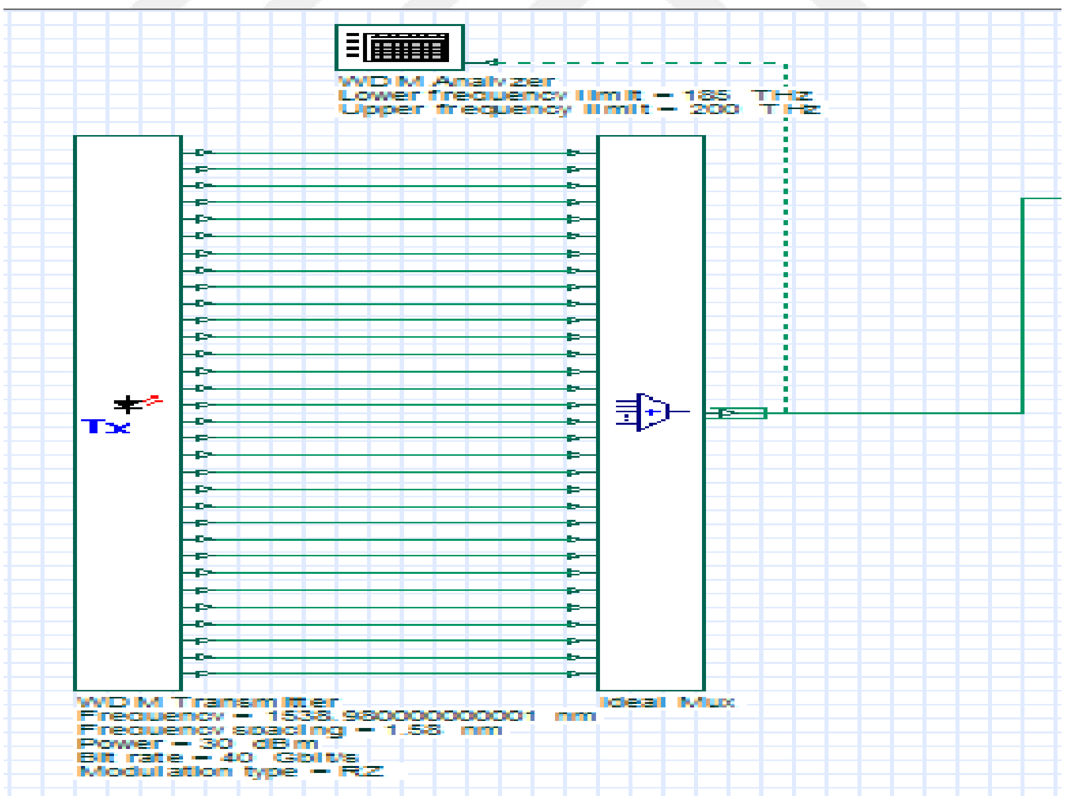

Figure 3.2: The transmitter part.

ii. Transmission part

The second part of forming the proposed system would consist of the optical amplifier with a dedicated amplification procedure before the signal transmission and then the second component of OWC would be utilized to perform the wireless communication. The distance tested in this part varied from 1000- 9000 km. Additionally, in this part, a second amplifier device would be utilized after the OWC component to improve the system performance as an amplification-based technique. The parameters set for the optical amplifier and the OWC channel were shown in Table 3.2, and Table 3.3 respectively. And the design of this section in the optisystem can be seen in Figure 3.3. For Table 3.2, the most important parameter to handle is the amount of the gain and power and the mode of operation. From Figure 3.3, it has attached several analyzer tools provided by the software of optisystem to get a quantified number of results to be handled in the next chapter and analyze in the proper manner

Table 3.2 Optical amplifier-based utilized parameters.

parameter	value	unit
Operation mode	Gain Control	
Gain	5	dB
Power	10	dBm
Saturation power	10	dBm
Saturation port	Output	
Include noise	1	
Noise figure	4	dB

Table 3.3: OWC channel parameters.

parameter	value	unit
Frequency	1550	nm
Range	varied	km
Free space path loss	1	
Geometrical gain	1	
Transmitter aperture diameter	15	cm
Receiver aperture diameter	15	cm
Transmitter telescope gain	0	dB
Receiver telescope gain	0	dB
Transmitter optics efficiency	1	
Receiver optics efficiency	1	
Transmitter pointing error angle	1.1	urad
Receiver pointing error angle	1.1	urad
Attenuation	0	dB/km
Additional losses	5	dB
Propagation delay	0	ps/km

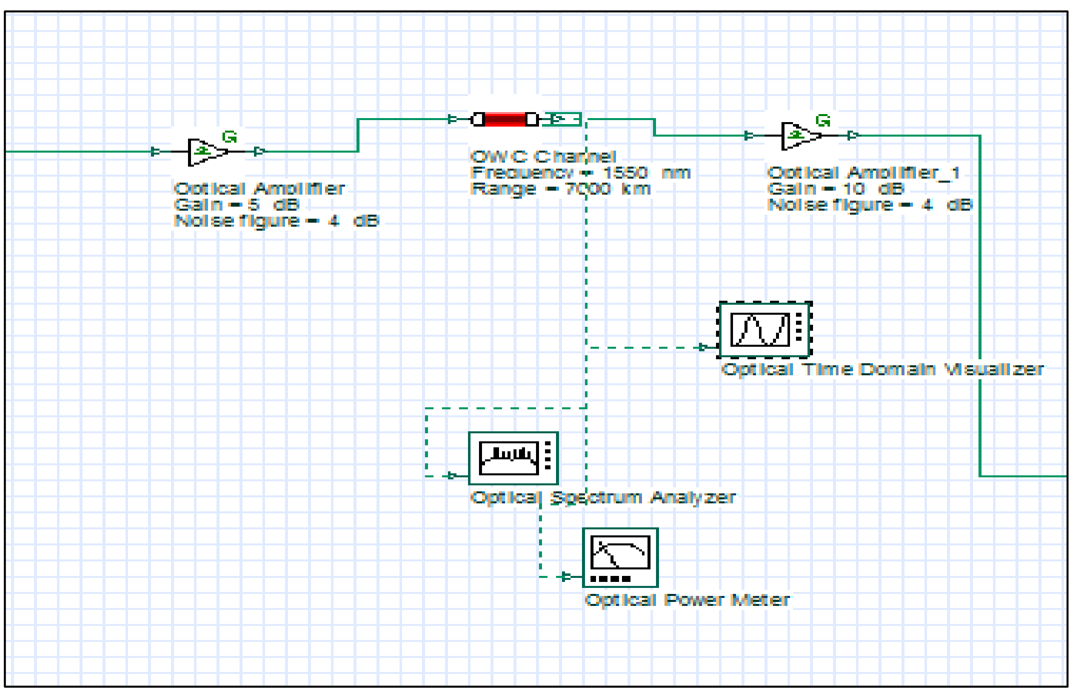

Figure 3.3: The transmission part.

iii. Receiver part

The last part of the proposed system consists of the demultiplexer device with a size of 1x32 which is used to recombine the optical signal sends over the OWC channel for different transmission distances to be delivered to each receiver station. Then each optical link out from it would be handled by a Photo Detector (PD) device which is used to convert the signal from the optical form back to the electrical form. The type of PD used in this section is the PIN. Then after converting the optical signal back to electrical, it would enter a low pass filter with Bessel type. Notice, that all these mentioned components were gathered in a single tool in the optisystem software known as WDM receiver. The parameters set for this part were shown in Table 3.4. Figure 3.4 clarify the design of this section using the simulati.on software.

Table 3.4: Parameters of the receiver part.

.

parameter	value	unit
Number of output ports	32	
Frequency	1538.98	nm
Frequency spacing	1.58	nm
Bandwidth	60	GHz
Insertion loss	0	dB
Depth	100	dB
Filter type	Bessel	
Filter order	2	

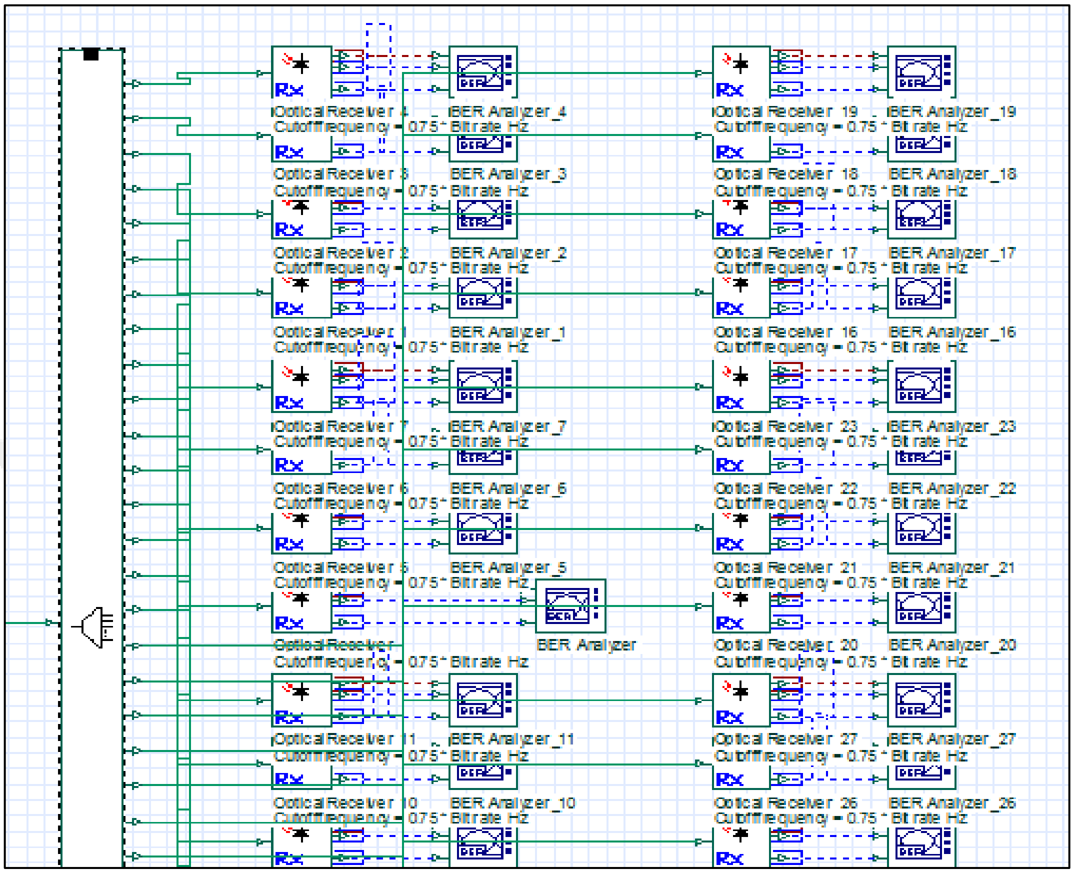

Figure 3.4: The receiver part.

3.3 OPTISYSTEM SOFTWARE

This section provides a quick description of the software that has been utilized to create and implement the proposed system. The system features a robust graphical setup that could handle the development of diverse optical networks and apply the most interesting and new techniques. This program is provided by optiwave corporation for optical solutions. And among many software, it has been selected owing to its feasibility and reliability in managing the vast set of parameters associated with each component utilized with the proposed system design. The general window for the optisystem software is illustrated in Figure 3.5.

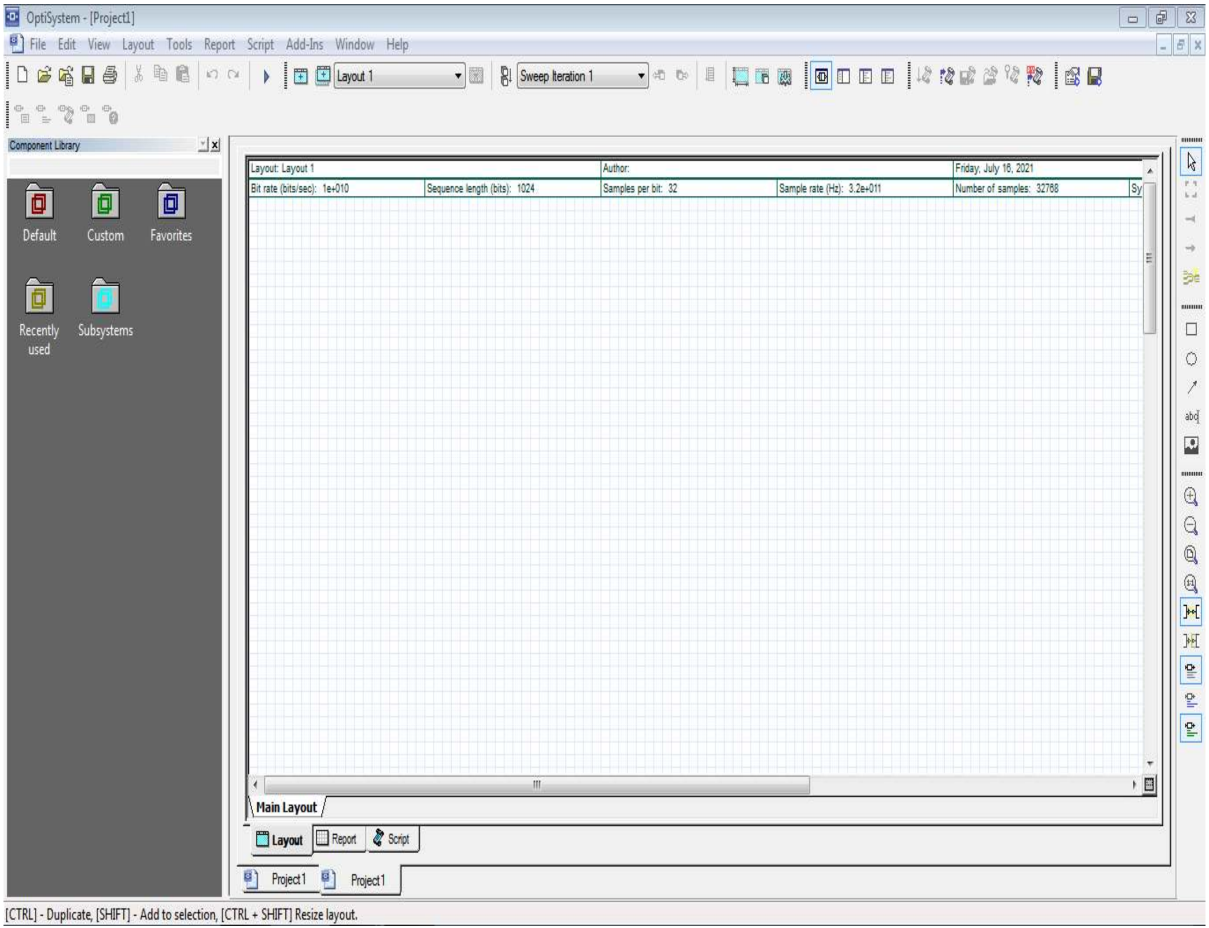

Figure 3.5: GUI window for optisystem program.

Optisystem provides several benefits including :

i. Offers a comprehensive view of the functioning of the system.

ii. Identifies design tolerance standards by evaluating the sensitivity of design parameters.

iii. Offers potential clients a graphical representation of the many design possibilities and situations.

iv. Provides uncomplicated access to a comprehensive range of system characterization data.

v. Offers automated parameter sweeping as well as optimization.

vi. Integrates with the other Optiwave products in the family.

The most important feature provided by Optisystem is providing three distinct options to influence the computation while using OptiSystem, which are:

vii. Perform an overall calculation on the project: every iteration of the sweep for a variety of layouts.

viii. Perform the following calculations for each sweep iteration in the current layout: every iteration of the sweep for the currently active layout.

ix. Determine the current sweep iteration, which is the current sweep iteration for the layout that is being used. The calculation window can be seen in Figure 3.6.

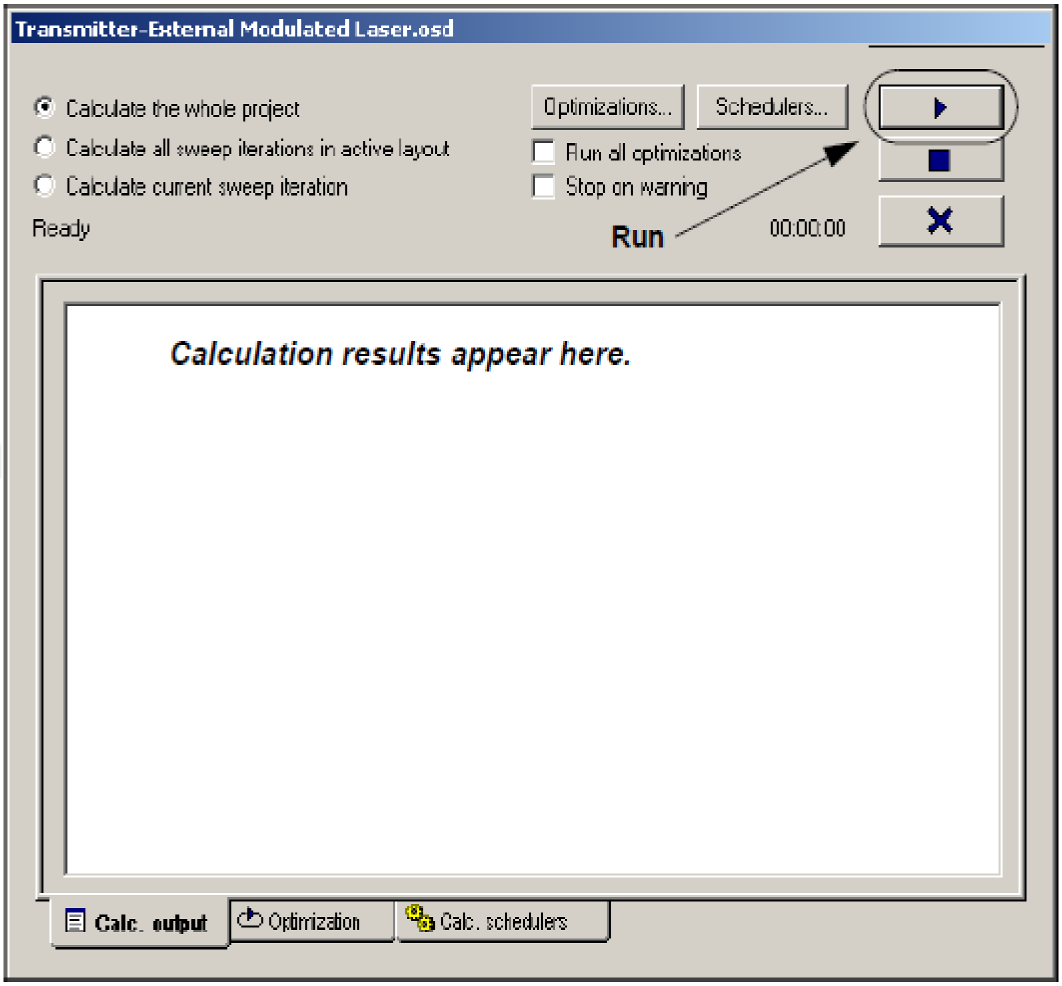

Figure 3.6: Optisystem window for calculation.

3.4 STUDIED PARAMETERS

This segment will depict the boundaries that will be considered to examine the exhibition of the proposed framework.

i. Bit Error Rate (BER)

With regards to transmission frameworks, digit mistake rate (BER) is characterized as the rate at which blunders happen in a transmission framework, as the name infers. On the other hand, how many blunders that happen in a line of a predefined number of pieces can be straightforwardly converted into this. To work on the meaning of spot mistake rate, we can utilize the accompanying equation [40,41]:

$$BER = \frac{Errors\ bit}{Total\ bits\ send} \tag{3.1}$$

ii. Quality Factor (QF)

The Q factor is a dimensionless boundary that shows how much energy is lost inside a full component, which may be anything from a mechanical pendulum to a component in a mechanical development to an electronic circuit like a thunderous circuit, in addition to other things. While the QF of a component is connected with the misfortunes, the transfer speed of a resonator concerning its middle recurrence is straightforwardly connected with the QF of the component. The QF addresses the amount of energy that has been lost comparable to how much energy has been put away inside the framework. Thus, the higher the QF, the lower the pace of energy misfortune, and that implies that motions will drop all the more leisurely, for example, they will have a low degree of damping and will ring for a more prominent time allotment. With regards to electronic circuits, obstruction is answerable for energy misfortunes inside the circuit. Despite the way that this can happen at any place in the circuit, the inductor is the most well-known place where obstruction happens. The overall recipe of the QF should be visible in condition (3.2) [42].

$$QF = \frac{E\ stored}{E\ lost\ per\ each\ cycle} \tag{3.3}$$

When working with RF-tuned circuits, there are a variety of reasons why QF is crucial to consider. Generally speaking, a high degree of QF is advantageous; but, in particular situations, a set level of QF may be required instead.

Q is a notion that may be implemented in a wide variety of subfields within physics and engineering. It is possible to refer to it as the Q factor and its symbol is the letter Q. Another name for it is the Q factor. The QF is a dimensionless parameter that indicates the energy losses within a resonant element, which could be anything from a mechanical pendulum to an element in a mechanical structure or even within an electronic circuit such as a resonant circuit. The QF measures the amount of energy that is lost within the resonant element. Although the Q factor of an element is related to the losses, this factor is directly connected to the bandwidth of a resonator with its center frequency. The value of Q represents the quantity of energy that has been lost in comparison to the total amount of energy that has been stored in the system. Therefore, a greater Q results in a lower rate of energy loss, and as a consequence, oscillations will die off more gradually, meaning that they will have a low amount of damping and will continue to ring for a longer period. When it comes to electrical circuits, resistance is the culprit behind any energy losses that occur inside the circuit. Even while this can take place elsewhere inside the circuit, the inductor is where the majority of resistance is generated.

When working with RF-tuned circuits, having a good understanding of the Q factor is essential for a variety of reasons. In most circumstances, a high level of Q is advantageous; nonetheless, some applications may call for a certain degree of Q. The following is a summary of some of the factors to consider regarding Q in RF-tuned circuits [42]:

i. Bandwidth: As the Q factor, also known as the quality factor, increases, the bandwidth of the tuned circuit filter decreases. When losses are reduced, energy may be stored in the circuit more effectively, which results in the tuned circuit being sharper. It is clear that when the value of Q rises, the value of the 3 dB bandwidth falls, and the overall responsiveness of the tuned circuit rises. This is something that can be seen. It is necessary to have a high Q factor in many different situations to guarantee that the requisite level of selectivity will be obtained.

ii. Operation across a broad bandwidth is necessary for a great number of RF applications, hence this characteristic must be supported. Broad bandwidth is necessary for some types of modulation, while other applications need the use of fixed filters to achieve wide band coverage. Although a high level of rejection of undesirable signals could be necessary, there is also a demand for rather broad bandwidths. As a consequence of this, the necessary level of Q has to be calculated in many applications to offer the overall performance that is required to fulfill requirements for a broad bandwidth and appropriate rejection of undesirable signals.

iii. Phase noise is something that is generated by any oscillator, and it is known as oscillator phase noise. This consists of jerky changes in the signal's phase at random intervals. This is shown by the presence of noise that radiates outward from the primary carrier. This noise is unwanted, and as a result, efforts should be made to lessen its impact as much as possible. The architecture of the oscillator may be modified in several different ways to bring this number down, the most important of which is to boost the Q, which stands for the quality factor of the oscillator-tuned circuit.

Tuned circuits and filters are common tools used in the process of removing spurious signals.

iv. General spurious signals. When the filter is finer and the level of Q is greater, the circuit will be able to eliminate spurious signals more effectively.

v. Ringing: The losses in a resonant circuit will decrease as the Q value of the circuit rises. This implies that it will take longer for any oscillation that is built up inside the circuit to fade away completely. To put it another way, the circuit will have a greater propensity to "ring." Because there is less energy wasted in the tuned circuit, this is an excellent component to employ inside an oscillator circuit. As a result, it is much simpler to initiate and sustain an oscillation. The concept of QF can be seen in Figure 3.7 and Figure 3.8.

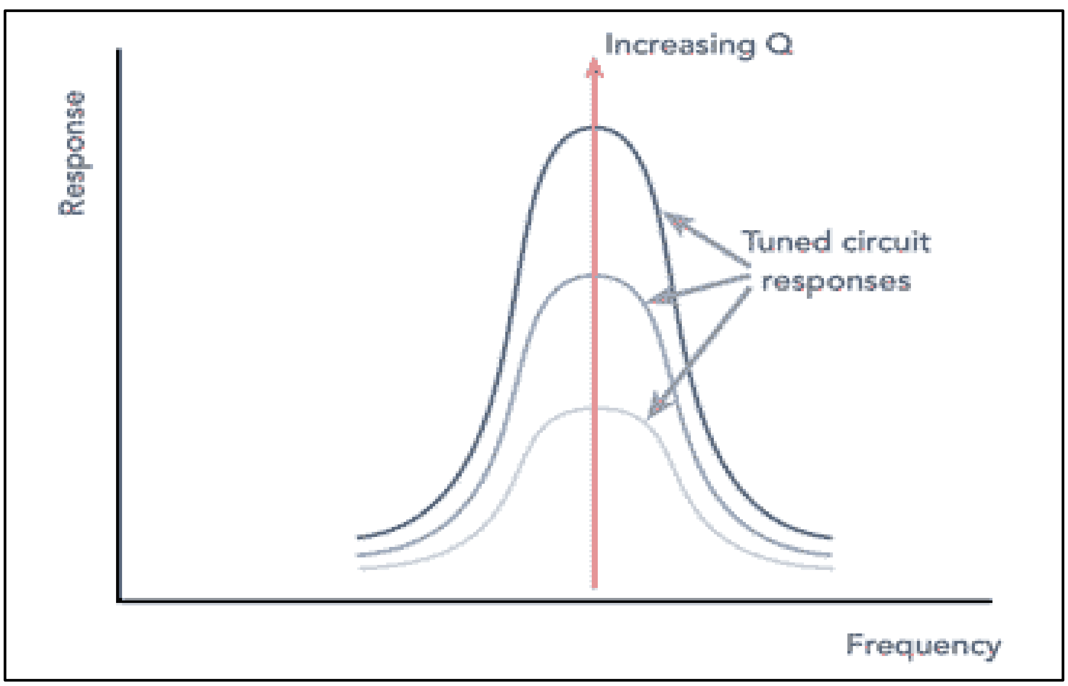

Figure 3.7: QF concept [42].

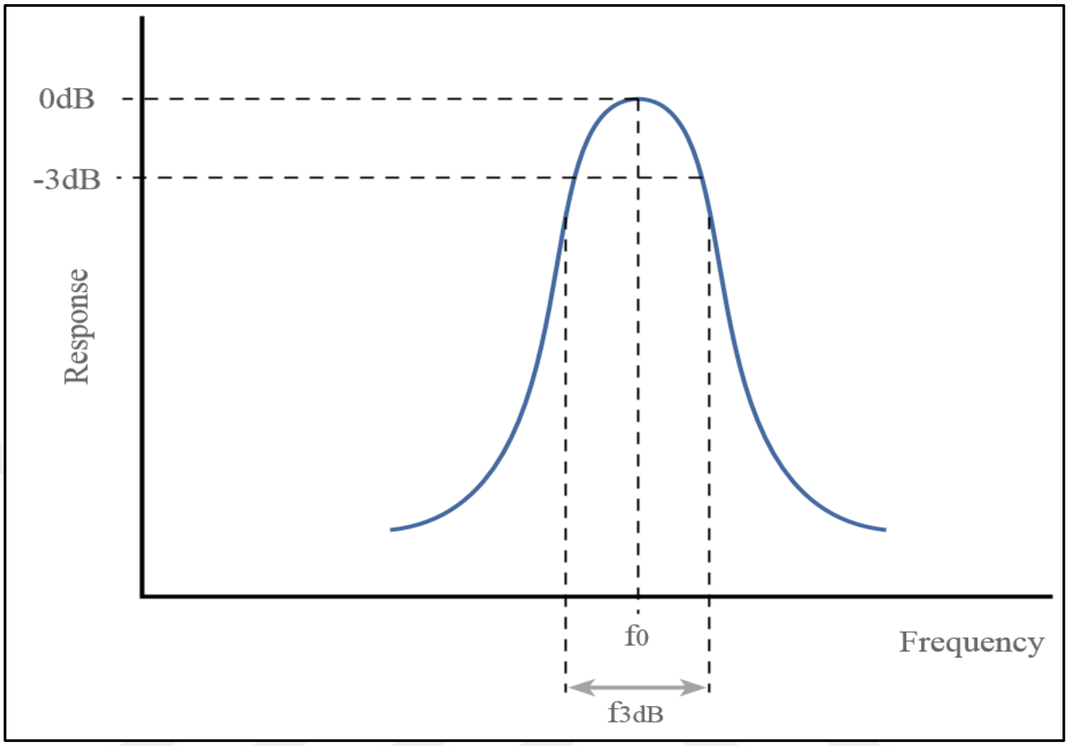

Figure 3.8: QF concept showing center and -3dB point [42].

iii. Eye Diagram (ED)

An eye configuration generally called an eye frame, is a kind of oscilloscope given in which a high-level indication from a beneficiary is again and again reviewed and applied to the vertical commitment, while the data rate is used to set off the level broadness. An eye configuration is a sort of oscilloscope given in which a high-level indication from a beneficiary is on and on investigated and applied to the vertical data. An eye configuration is regularly insinuated as an eye frame in the field of transmission interchanges. It was given the expression "eyes between rails" because the example seems, by all accounts, to be a grouping of eyeballs between a couple of rails, as indicated by certain kinds of coding. This device is utilized to assess the united effects of channel commotion, dispersing, and picture impedance on the introduction of a baseband beat transmission system, as the name proposes. The SIGSALY-protected voice transmission framework, which was created during World War II and was the primary framework to utilize the procedure, was quick to do as such. ED's capacity is delineated in Figure 3.9, which portrays the detachment between zero pieces and one-pieces in the got information [43,44].

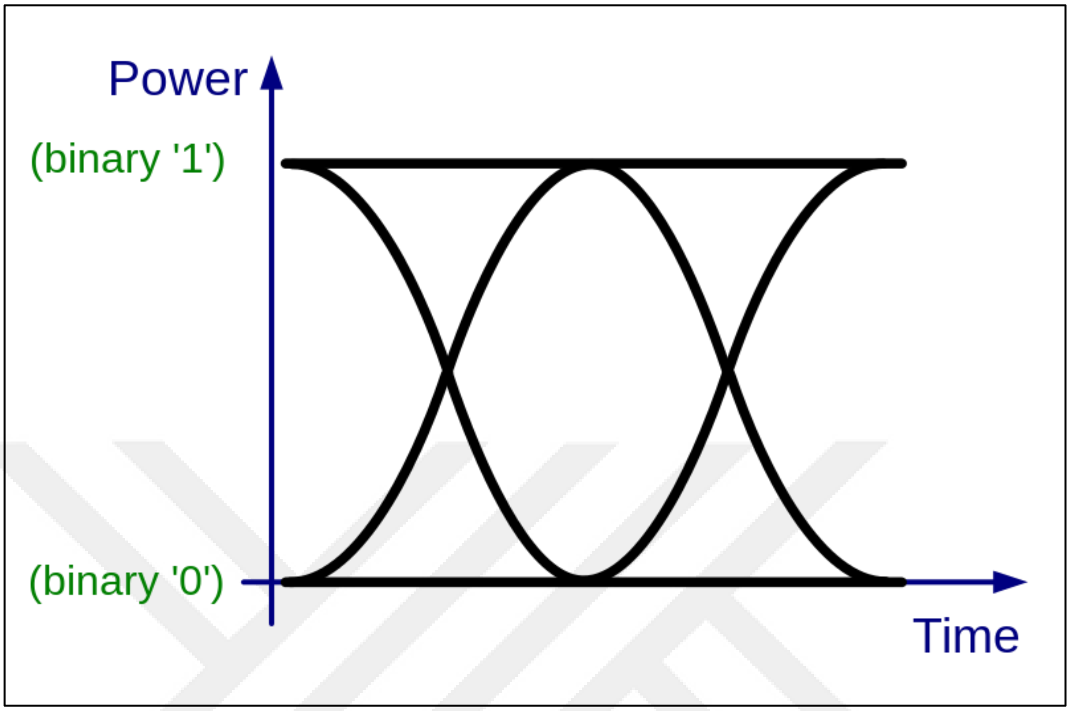

Figure 3.9: ED representation [43].

Also, eye patterns have a great significance in communication to illustrate several performance metrics where it can give a high notification amount the amount of distortion, and other important factors as seen in Figure 3.10.

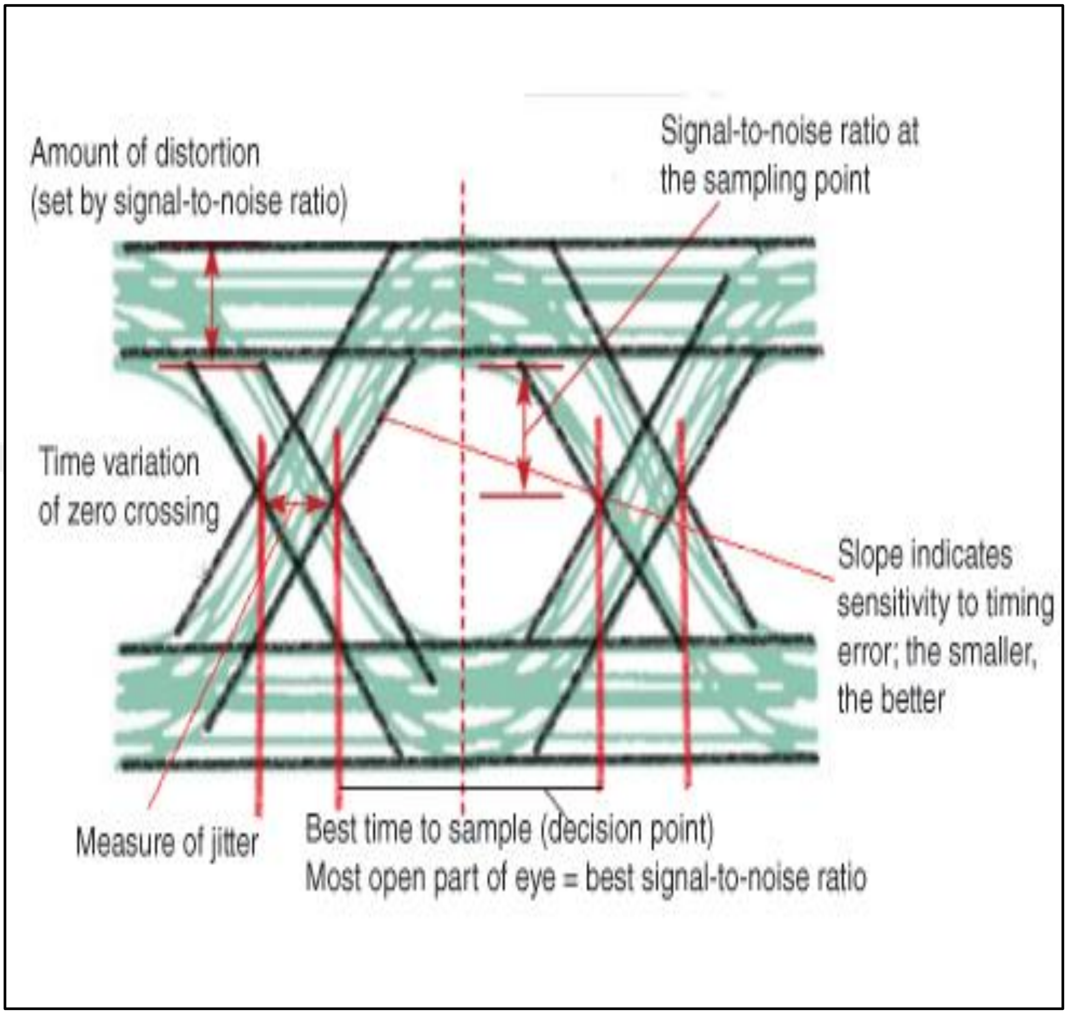

Figure 3.10: Eye pattern with analyzing metric [44].

4. PRESENTED SYSTEM RESULTS

4.1 INTRODUCTION

Based on the parameters provided in the previous chapter, the results acquired from the suggested system will be discussed in this chapter. Afterward, a comparison between the suggested study and previous work on the same issue will be explored to exhibit the commitment of our proposed framework.

4.2 RESULTS BASED SIGNAL POWER AND SNR

The first results were calculated for obtaining the signal power impact, noise power, and SNR per each of the utilized wavelengths and as listed in Table 4.1. Such results indicate high-performance results showed encouraging results.

Table 4.1: Showing the value of signal power and noise power per each selected frequency.

Frequency (THz)	Signal Power (dBm)	Noise Power (dBm)	SNR (dB)
188.79094	25.361023	2.4377567	22.923267
188.97897	25.559026	2.9355672	22.623459
189.16738	25.150857	2.6853724	22.465485
189.35616	25.616138	2.1718926	23.444246
189.54532	25.404033	1.642059	23.761974
189.73486	25.440731	1.6427022	23.798029
189.92477	25.511589	2.4009088	23.11068
190.11507	25.390506	1.7448012	23.645705
190.30575	25.445822	1.369837	24.075985
190.49682	25.543022	2.0772356	23.465786
190.68826	25.324748	1.7369001	23.587848
190.88009	25.597217	2.3278528	23.269364
191.07231	25.155143	2.2965665	22.858576
191.26492	25.287103	2.4674937	22.819609
191.45791	25.532748	2.1551448	23.377603
191.6513	25.431958	1.9300173	23.50194
191.84507	25.536919	2.2173672	23.319552
192.03924	25.521246	2.561446	22.9598
192.2338	25.598736	1.8654362	23.7333
192.42876	25.486763	2.4022676	23.084496

Table 4.1: Showing the value of signal power and noise power per each selected frequency "tables continued".

192.62411	25.503367	2.3067695	23.196597
192.81986	25.584773	2.5015569	23.083216
193.016	25.598316	2.5506272	23.047689
193.21255	25.15353	1.8970029	23.256527
193.4095	25.436834	2.3107763	23.126057
193.60685	25.536403	2.1173461	23.419057
193.8046	25.534796	1.9497489	23.585047
194.00276	25.506509	2.1827048	23.323804
194.20132	25.418019	2.7181238	22.699895
194.40029	25.419054	2.8327978	22.586256
194.59966	25.260083	2.3500256	22.910057
194.79945	25.280899	1.9586873	23.322212

4.3 RESULTS BASED QF AND BER

This section will list and draw the two-parameter results with respect to different distance transmission.

4.3.1 QF Results

QF results have been analyzed by calculating it at various distances ranging between (1000 - 9000) km for the 32 DWDM channels and as listed in Table 4.2 and Figure 4.1. Results obtained indicate that there is a reverse relation between QF and distance as raising distance would reduce to impact of the received signals. To get a closer look at the amount of reduction in QF at every 1000 km distance increasing. The average QF has been calculated for each transmission distance and each of the 32 channels. Figure 9 depicts these average results. The average QF decrease would be between (1-2) dBm for distances up to 4000 km. And by (4-8) dBm for higher than 4000 km which indicates a good system performance. Noted that based on the utilized amplification method the maximum distance achieved was 9000 km and this was based on the consideration of the QF minimum threshold of 6 dBm.

Table 4.2: QF results obtained from the proposed DWDM IS-OWC system for the 32 channels.

Channel	1000	2000	3000	4000	5000	6000	7000	8000	9000
1	35.19	27.89	22.32	18.08	15.12	12.97	11.28	9.97	8.88
2	35.41	28.26	22.55	18.49	15.46	13.27	11.53	10.18	9.10
3	27.68	20.84	16.45	13.39	11.27	9.68	8.39	7.41	6.61
4	38.81	31.07	24.28	19.56	16.09	13.64	11.71	10.25	9.08
5	37.57	29.68	23.15	18.39	15.11	12.69	10.90	9.49	8.38
6	35.23	28.56	22.85	18.58	15.56	13.20	11.56	10.07	9.13
7	34.30	24.11	17.77	13.88	11.28	9.47	8.11	7.11	6.28
8	35.92	29.00	22.60	17.93	14.66	12.30	10.51	9.14	8.07
9	32.52	24.35	18.97	15.21	12.76	10.80	9.44	8.27	7.39
10	34.65	25.41	19.08	15.04	12.35	10.36	8.99	7.90	7.04
11	36.58	28.16	21.83	17.58	14.44	12.16	10.45	9.12	8.12
12	35.17	24.63	18.04	13.98	11.42	9.55	8.25	7.18	6.38
13	37.31	30.82	24.84	20.32	16.89	14.32	12.42	10.79	9.76
14	33.95	26.71	20.96	16.67	13.79	11.67	10.07	8.80	7.76
15	32.92	25.05	19.38	15.48	12.87	10.92	9.44	8.31	7.41
16	37.65	28.49	21.59	17.05	13.99	11.72	10.05	8.80	7.82
17	34.16	26.57	20.85	16.73	13.86	11.81	10.21	8.97	8.06
18	30.57	22.71	17.57	14.15	11.72	10.00	8.68	7.64	6.81
19	38.37	31.10	24.43	19.54	16.00	13.56	11.56	10.13	8.95
20	35.44	26.04	19.36	15.17	12.33	10.37	8.93	7.81	6.94
21	38.15	30.10	23.77	19.14	15.95	13.55	11.80	10.34	9.21
22	33.16	25.41	19.59	15.61	12.85	10.85	9.38	8.21	7.28
23	36.27	29.10	22.76	18.34	15.14	12.78	11.06	9.71	8.65
24	31.11	26.16	21.52	17.91	15.16	13.11	11.37	10.10	9.06
25	38.07	28.65	21.40	16.82	13.71	11.45	9.83	8.59	7.62
26	37.88	29.75	22.84	18.05	14.68	12.24	10.48	9.10	7.96
27	34.69	29.27	23.70	19.36	15.98	13.62	11.57	10.13	8.94
28	33.54	25.46	19.85	16.10	13.52	11.46	9.93	8.76	7.83
29	29.69	22.51	17.58	14.18	11.83	10.09	8.75	7.63	6.81
30	34.45	25.71	19.34	15.15	12.25	10.28	8.73	7.68	6.73
31	40.75	30.64	22.39	17.10	13.68	11.32	9.55	8.26	7.25
32	32.93	26.54	21.39	17.44	14.65	12.45	10.80	9.51	8.46

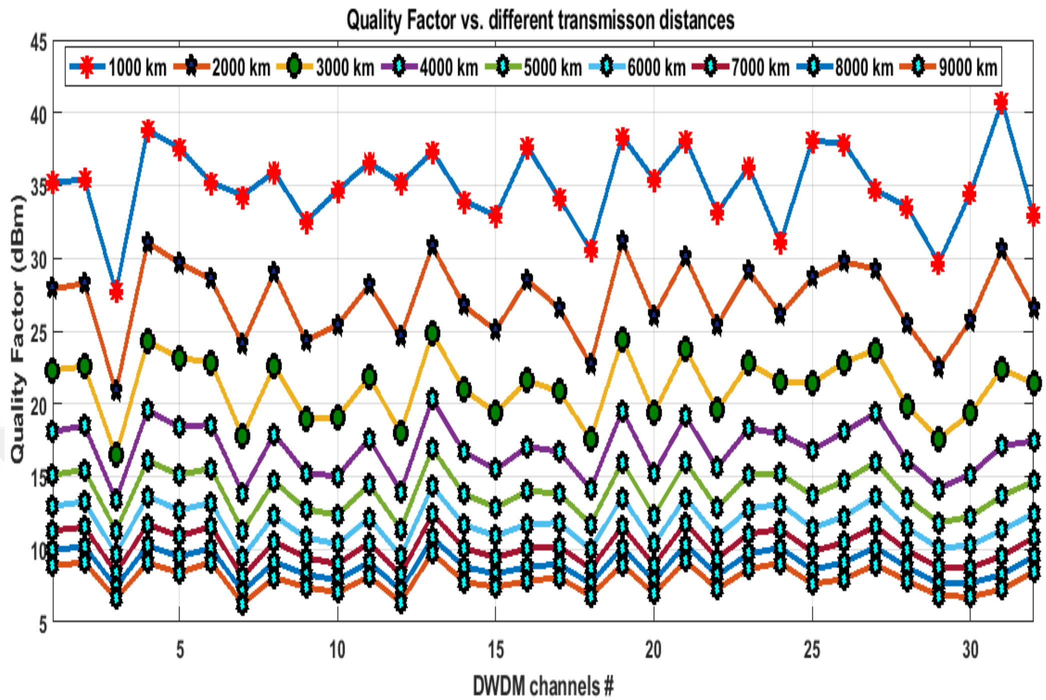

Figure 4.1: QF vs. distance variation for the proposed system.

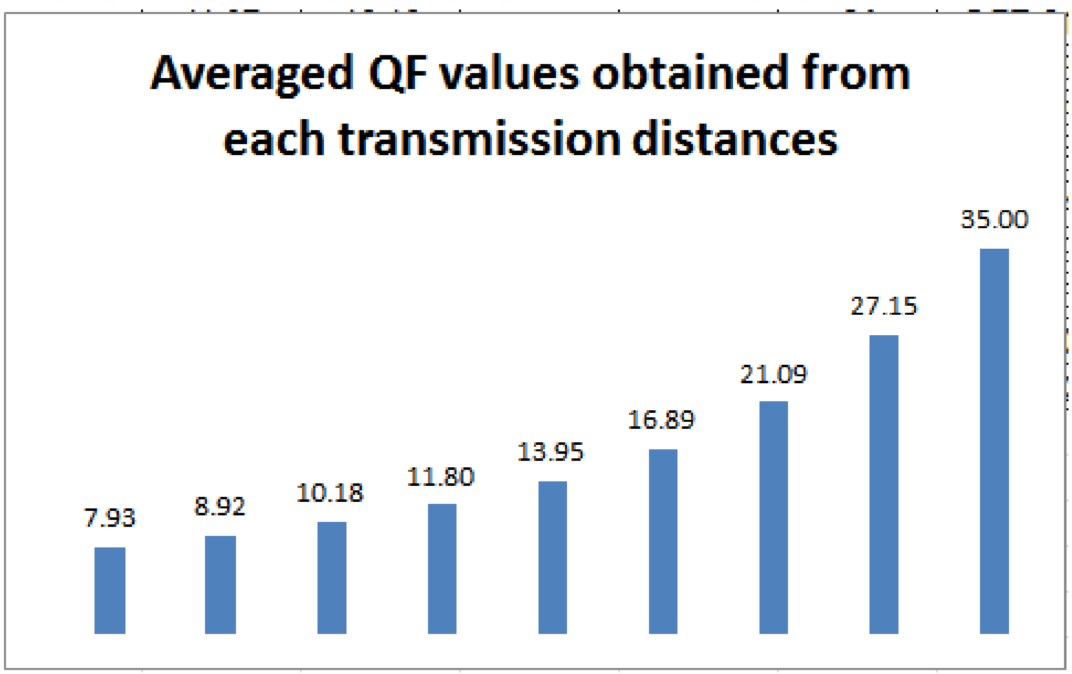

Figure 4.2: Averaged QF with respect to each distance variation for the proposed system.

4.3.2 BER Results

The BER parameter would be investigated based on the observation of its relationship with regard to the fluctuation of the distance between two points. Table 4.3 and Figure 4.3 show the findings, which are shown graphically in Figure 4.3. There is a direct relationship between BER and distance, since increasing the distance would result in an increase in the amount of error in the received bits. To have a quick overview of BER, the average value for each distance for the 32 channels would be determined as shown in the graph below, which indicated a variance between (e-170 - e-12) for distances ranging from (1000 – 9000) km. It seems from this observation that the values produced from the suggested system were more than the BER minimum threshold of e-9. This indicates that the system's performance has improved and that there have been fewer mistakes.

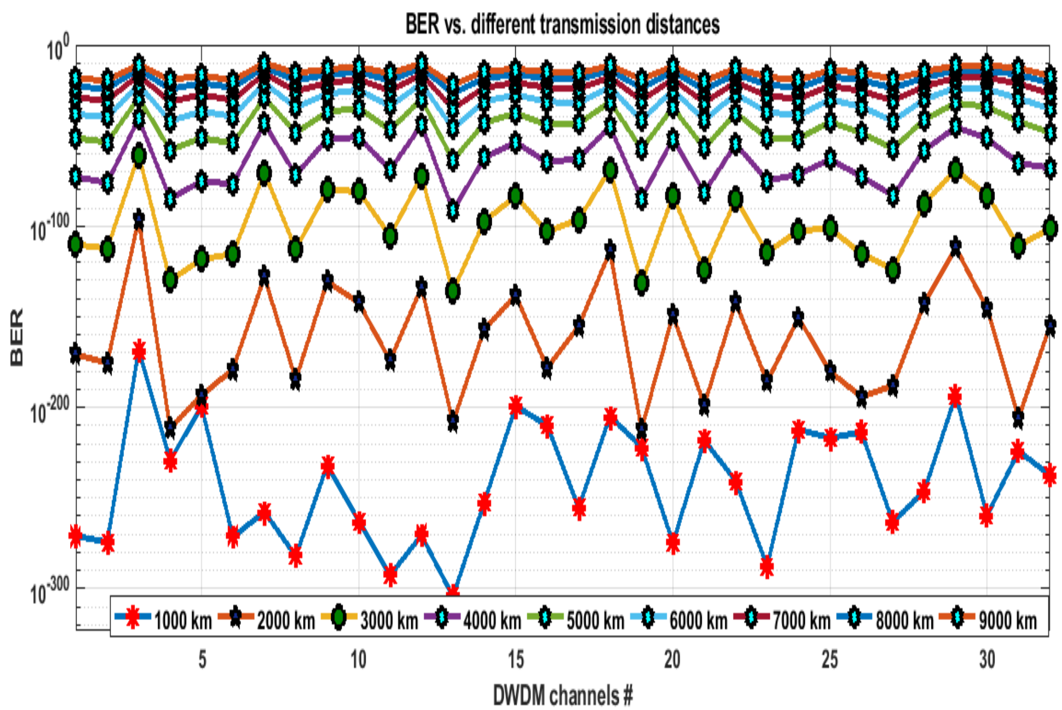

Figure 4.3: BER vs. distance variation for the proposed system.

Table 4.3: BER results obtained from the proposed DWDM IS-OWC system for the 32 channels.

Channel	1000	2000	3000	4000	5000	6000	7000	8000	9000
1	8.9E-272	1.3E-171	7.5E-111	1.4E-73	3.9E-52	5.7E-39	5.2E-30	6.8E-24	2.0E-19
2	4.6E-275	3.3E-176	4.0E-113	7.2E-77	2.1E-54	1.1E-40	2.9E-31	8.4E-25	3.2E-20
3	4.2E-169	6.2E-97	2.5E-61	2.2E-41	5.5E-30	1.1E-22	1.5E-17	3.9E-14	1.2E-11
4	0.0E+00	2.4E-212	9.8E-131	1.2E-85	1.0E-58	8.2E-43	3.8E-32	4.0E-25	3.8E-20
5	0.0E+00	4.5E-194	5.2E-119	5.5E-76	4.6E-52	2.3E-37	3.8E-28	7.7E-22	1.8E-17
6	2.3E-272	8.3E-180	4.8E-116	1.7E-77	4.7E-55	2.9E-40	2.2E-31	2.5E-24	2.4E-20
7	2.6E-258	7.6E-129	4.3E-71	2.9E-44	5.7E-30	9.1E-22	1.6E-16	4.0E-13	1.2E-10
8	6.1E-283	2.5E-185	1.4E-113	2.3E-72	4.1E-49	3.0E-35	2.6E-26	2.3E-20	2.6E-16
9	1.7E-232	2.2E-131	1.1E-80	9.6E-53	8.5E-38	1.1E-27	1.2E-21	4.4E-17	4.8E-14
10	1.5E-263	7.2E-143	1.3E-81	1.2E-51	1.6E-35	1.3E-25	8.3E-20	9.7E-16	6.4E-13
11	2.5E-293	6.5E-175	4.4E-106	1.2E-69	9.7E-48	1.8E-34	4.8E-26	2.4E-20	1.6E-16
12	2.4E-271	2.3E-134	3.4E-73	6.6E-45	1.1E-30	4.1E-22	5.0E-17	2.3E-13	5.8E-11
13	3.5E-305	5.1E-209	1.1E-136	3.0E-92	1.8E-64	5.8E-47	6.9E-36	1.4E-27	6.0E-23
14	5.3E-253	1.2E-157	5.3E-98	7.0E-63	9.7E-44	6.4E-32	2.7E-24	4.9E-19	3.2E-15
15	4.0E-238	5.9E-139	3.5E-84	1.5E-54	2.2E-38	2.9E-28	1.2E-21	3.2E-17	4.1E-14
16	1.16e-310	6.1E-179	7.3E-104	1.3E-65	6.1E-45	3.2E-32	3.2E-24	4.6E-19	1.8E-15
17	3.7E-256	5.0E-156	5.7E-97	2.8E-63	3.5E-44	1.1E-32	6.2E-25	9.7E-20	2.6E-16
18	1.1E-205	1.3E-114	1.4E-69	6.4E-46	3.2E-32	5.0E-24	1.3E-18	7.2E-15	3.4E-12
19	1.63E-322	7.3E-213	2.6E-132	1.7E-85	4.5E-58	2.5E-42	2.2E-31	1.4E-24	1.2E-19
20	1.4E-275	6.6E-150	5.4E-84	1.6E-52	2.0E-35	1.1E-25	1.3E-19	1.8E-15	1.2E-12
21	8.230E-319	1.9E-199	2.9E-125	4.5E-82	1.0E-57	3.2E-42	1.5E-32	1.9E-25	1.3E-20
22	1.6E-241	7.1E-143	6.8E-86	2.0E-55	2.8E-38	6.6E-28	2.3E-21	7.4E-17	1.1E-13
23	1.7E-288	1.3E-186	3.6E-115	1.4E-75	2.9E-52	7.3E-38	6.2E-29	9.4E-23	1.7E-18

Table 4.3: BER results obtained from the proposed DWDM IS-OWC system for the 32 channels "tables continued".

24	5.7E-213	2.8E-151	3.3E-103	3.2E-72	2.1E-52	9.4E-40	1.9E-30	2.0E-24	4.5E-20
25	1.270e-317	5.6E-181	4.6E-102	5.9E-64	2.9E-43	7.3E-31	2.7E-23	2.8E-18	8.6E-15
26	1.849e-314	5.6E-195	6.9E-116	2.7E-73	2.8E-49	6.5E-35	3.7E-26	3.1E-20	6.1E-16
27	4.7E-264	9.8E-189	1.4E-124	6.4E-84	6.3E-58	1.1E-42	2.1E-31	1.5E-24	1.5E-19
28	5.4E-247	1.9E-143	4.1E-88	9.0E-59	4.4E-42	7.0E-31	1.1E-23	6.8E-19	1.8E-15
29	4.1E-194	1.2E-112	1.2E-69	4.1E-46	9.7E-33	2.2E-24	7.6E-19	8.2E-15	3.4E-12
30	1.7E-260	3.2E-146	8.3E-84	2.5E-52	5.5E-35	2.8E-25	8.1E-19	4.9E-15	5.3E-12
31	0.0E+00	1.4E-206	1.7E-111	4.8E-66	4.7E-43	3.5E-30	4.2E-22	5.0E-17	1.4E-13
32	3.4E-238	1.0E-155	3.7E-102	1.4E-68	4.4E-49	4.7E-36	1.2E-27	6.9E-22	9.9E-18

4.4 RESULTS BASED OPTICAL TIME DOMAIN (OTD)

In order to clarify the transmitted signal after each distance investigation (1000-9000) km. The OTD component has been utilized before the OWC channel to demonstrate the tweaked optical sign in the time area and as found in Figure 4.4.

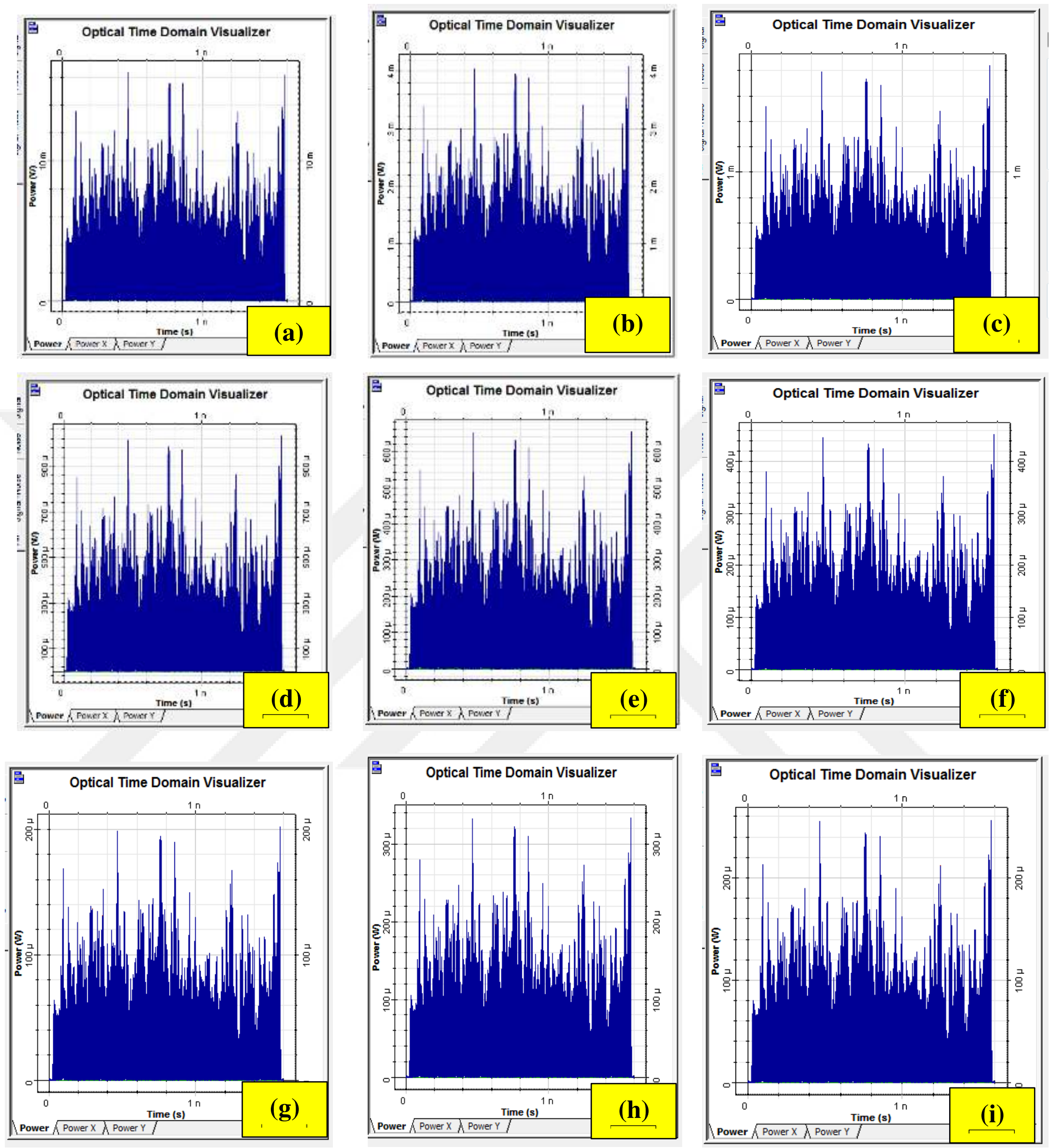

Figure 4.4: OTD obtained after OWC channel transmission for distance of (a) 1000 km, (b) 2000 km, (c) 3000 km, (d) 4000 km, (e) 5000 km, (f) 6000 km, (g) 7000 km, (h) 8000 km and (i) 9000 km.

4.5 RESULTS BASED DIFFERENT MODULATION FORMAT

In this section, a comparison between the utilization of both NRZ and RZ for the proposed system would be considered at the distance of 7000 km in order to be further compared with the previous publications. These results would be compared with respect to the parameters of QF and BER for all the 32 channels as illustrated in Figure 4.5 and Figure 4.6. These results indicate that using the NRZ is much better than the RZ modulation for the proposed system, that's confirms the reliability of the proposed system in this thesis. All these results drawn and obtained were listed in Table 4.4.

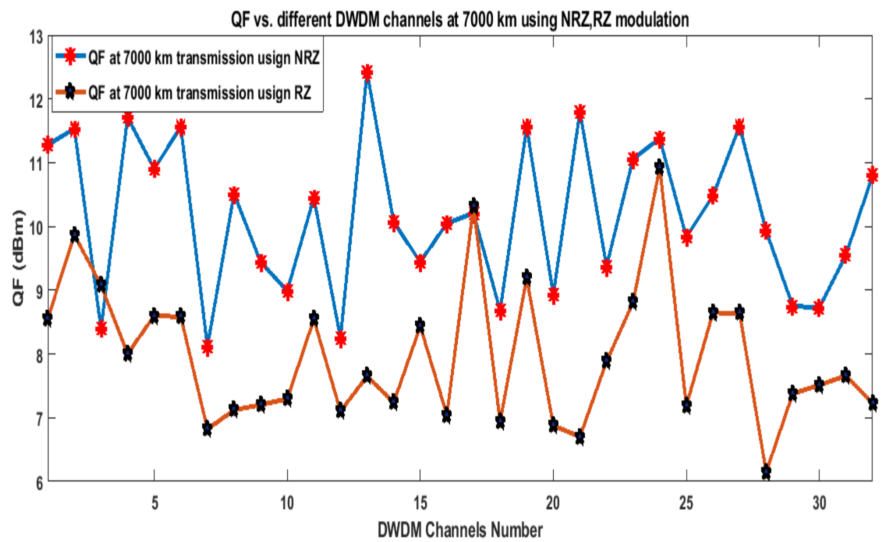

Figure 4.5: QF vs. different modulation format at 7000 km.

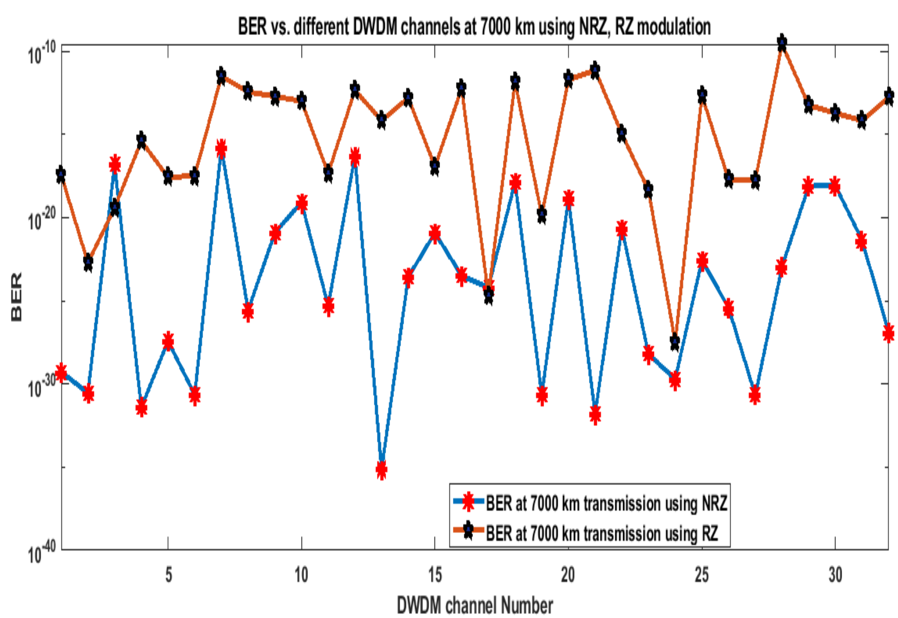

Figure 4.6: BER vs. different modulation format at 7000 km.

Table 4.4: Variation of modulation format on the QF and BER-based parameters.

channel	QF/NRZ	QF/RZ	BER/NRZ	BER/RZ
1	11.2798	8.55676	5.17E-30	3.60E-18
2	11.5331	9.865	2.93E-31	1.93E-23
3	8.39368	9.07906	1.46E-17	3.83E-20
4	11.7109	8.00244	3.76E-32	3.88E-16
5	10.9029	8.59865	3.84E-28	2.64E-18
6	11.5596	8.5835	2.25E-31	3.16E-18
7	8.11433	6.82063	1.62E-16	3.09E-12
8	10.5125	7.12026	2.62E-26	3.54E-13
9	9.44174	7.20268	1.19E-21	1.89E-13
10	8.98944	7.296	8.28E-20	9.98E-14
11	10.4513	8.5448	4.84E-26	4.39E-18
12	8.25119	7.10028	4.99E-17	4.40E-13
13	12.4227	7.65239	6.88E-36	6.82E-15
14	10.07	7.2381	2.69E-24	1.50E-13
15	9.44317	8.43437	1.19E-21	1.14E-17
16	10.0491	7.04206	3.16E-24	5.82E-13
17	10.208	10.3136	6.18E-25	2.14E-25
18	8.68037	6.94176	1.34E-18	1.40E-12
19	11.5613	9.18903	2.21E-31	1.32E-20
20	8.93223	6.87754	1.32E-19	1.89E-12
21	11.8008	6.70186	1.54E-32	7.04E-12
22	9.37542	7.8808	2.31E-21	1.07E-15
23	11.0649	8.81383	6.24E-29	4.24E-19
24	11.3749	10.9216	1.92E-30	3.25E-28
25	9.83222	7.18933	2.69E-23	2.13E-13
26	10.4782	8.647	3.70E-26	1.92E-18
27	11.5728	8.64411	2.08E-31	1.77E-18
28	9.92807	6.14682	1.11E-23	2.61E-10
29	8.74943	7.37809	7.59E-19	5.60E-14
30	8.72793	7.51219	8.13E-19	1.88E-14
31	9.55298	7.65657	4.25E-22	6.56E-15
32	10.8002	7.22816	1.20E-27	1.67E-13

4.6 RESULTS BASED COMPARISON WITH REFERENCE WORK

A comparison between the proposed system and the reference system in [39] was proposed by other researchers. Before comparing the results, a comparison between the major points was listed in Table 4.5, and as can be seen that our system has achieved a much higher transmission distance and the QF was better along with a small amount of BER, which indicates the reliability and adaptability of the proposed system.

Table 4.5: Comparison between proposed work and reference work.

Parameters	Reference [39]	Proposed
Bit rate	160 Gbps	1280 Gbps
Power	30 dBm	30 dBm
Min distance	1000 km	1000 km
Max distance	7000 km	9000 km
Modulation format	NRZ	NRZ
total channels	16	32
channel spacing	1.58 nm	1.58 nm
QF at 7000 km	6.61 dBm	8.11 dBm
BER at 7000 km	1.62E-11	1.62E-16

Another significant comparison would be based on the shaping of the eye diagram between the reference work that studies only 16 channel systems and the proposed system that consists of 32 channels, in which only the first 16 channels would be analyzed to be compared with the reference work as seen in Figure 4.7. From an eye-opening comparison between the two works it can be seen that the proposed work achieves much clear eye results indicating a fewer bit errors of 1 and 0 that has been sending over 7000 km

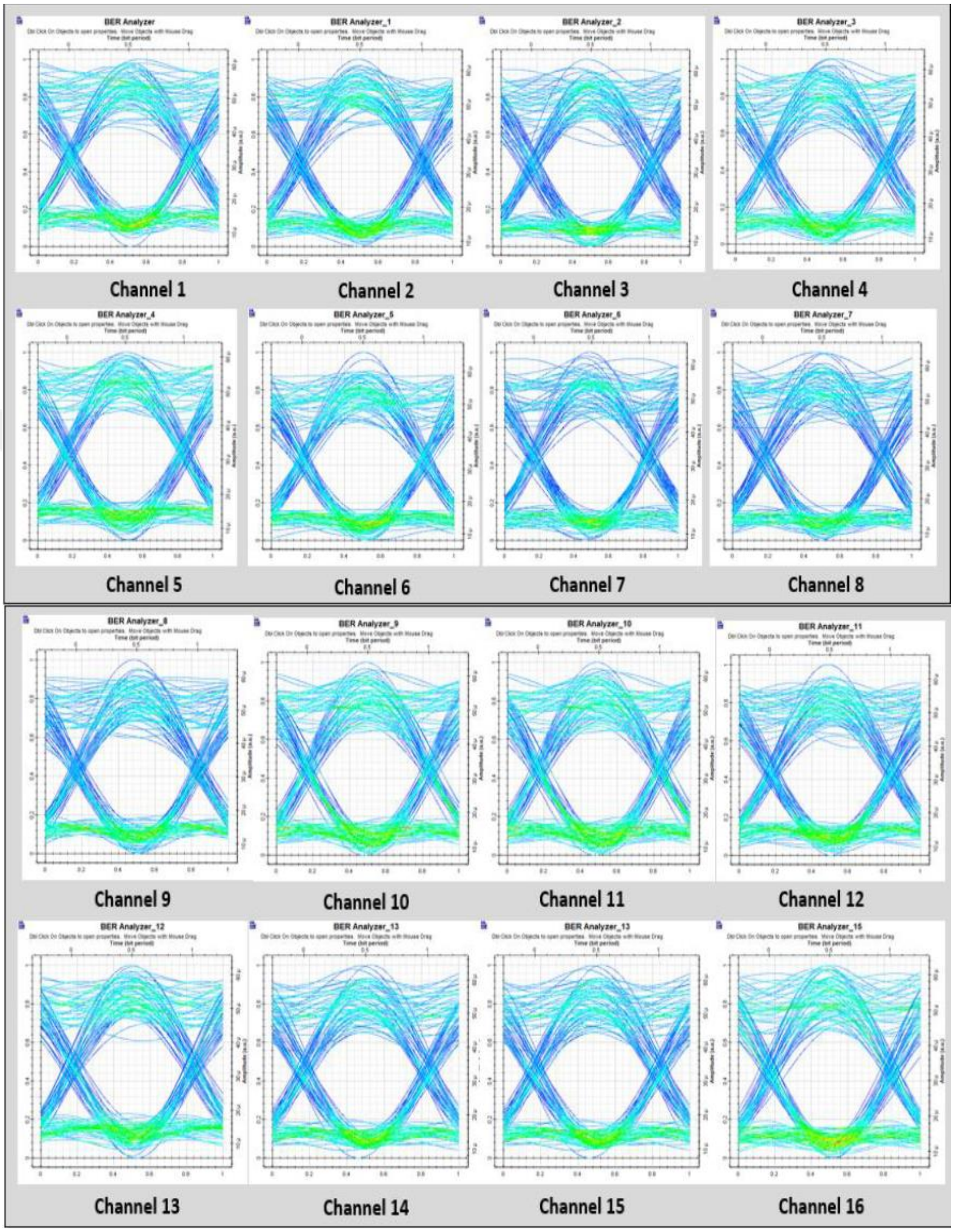

Figure 4.7 :ED results for Reference work [39].

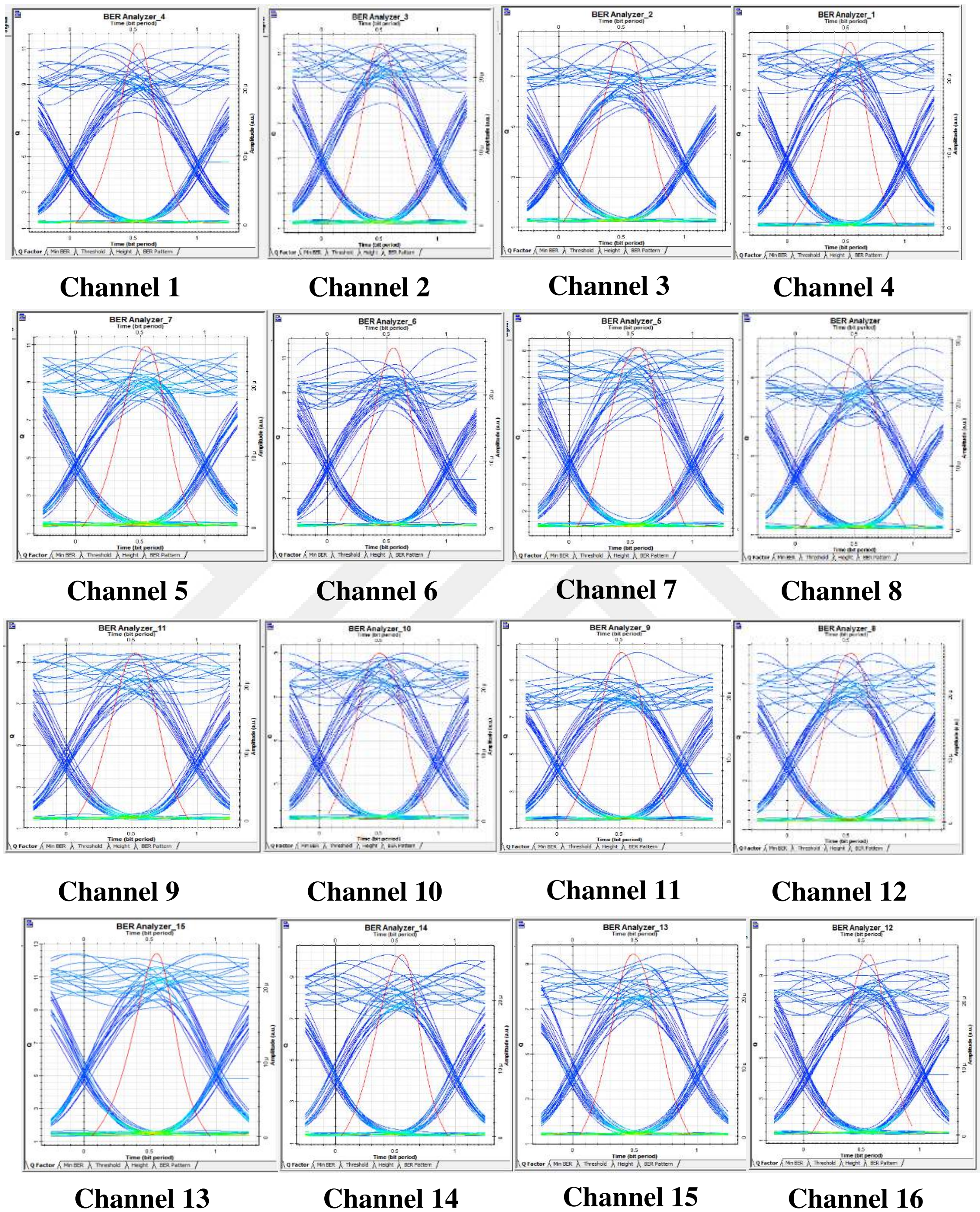

Figure 4.8: ED results for Proposed work.

4.7 RESULTS BASED OSNR

In this section the results of OSNR and noise power was calculated from optisystem and listed as seen in Table 4.6. It confirms the reliability of the proposed system and as seen in Figure 4.8 and Figure 4.9.

Table 4.6: OSNR results obtained from Optisystem.

Frequency (THz)	Noise Power: (dBm)	OSNR (dB)
188.79094	2.4377567	22.92327
188.97897	2.9355672	22.62346
189.16738	2.6853724	22.46549
189.35616	2.1718926	23.44425
189.54532	1.642059	23.76197
189.73486	1.6427022	23.79803
189.92477	2.4009088	23.11068
190.11507	1.7448012	23.64571
190.30575	1.369837	24.07599
190.49682	2.0772356	23.46579
190.68826	1.7369001	23.58785
190.88009	2.3278528	23.26936
191.07231	2.2965665	22.85858
191.26492	2.4674937	22.81961
191.45791	2.1551448	23.3776
191.6513	1.9300173	23.50194
191.84507	2.2173672	23.31955
192.03924	2.561446	22.9598
192.2338	1.8654362	23.7333
192.42876	2.4022676	23.0845
192.62411	2.3067695	23.1966
192.81986	2.5015569	23.08322
193.016	2.5506272	23.04769
193.21255	1.8970029	23.25653
193.4095	2.3107763	23.12606
193.60685	2.1173461	23.41906
193.8046	1.9497489	23.58505
194.00276	2.1827048	23.3238
194.20132	2.7181238	22.6999
194.40029	2.8327978	22.58626
194.59966	2.3500256	22.91006
194.79945	1.9586873	23.32221

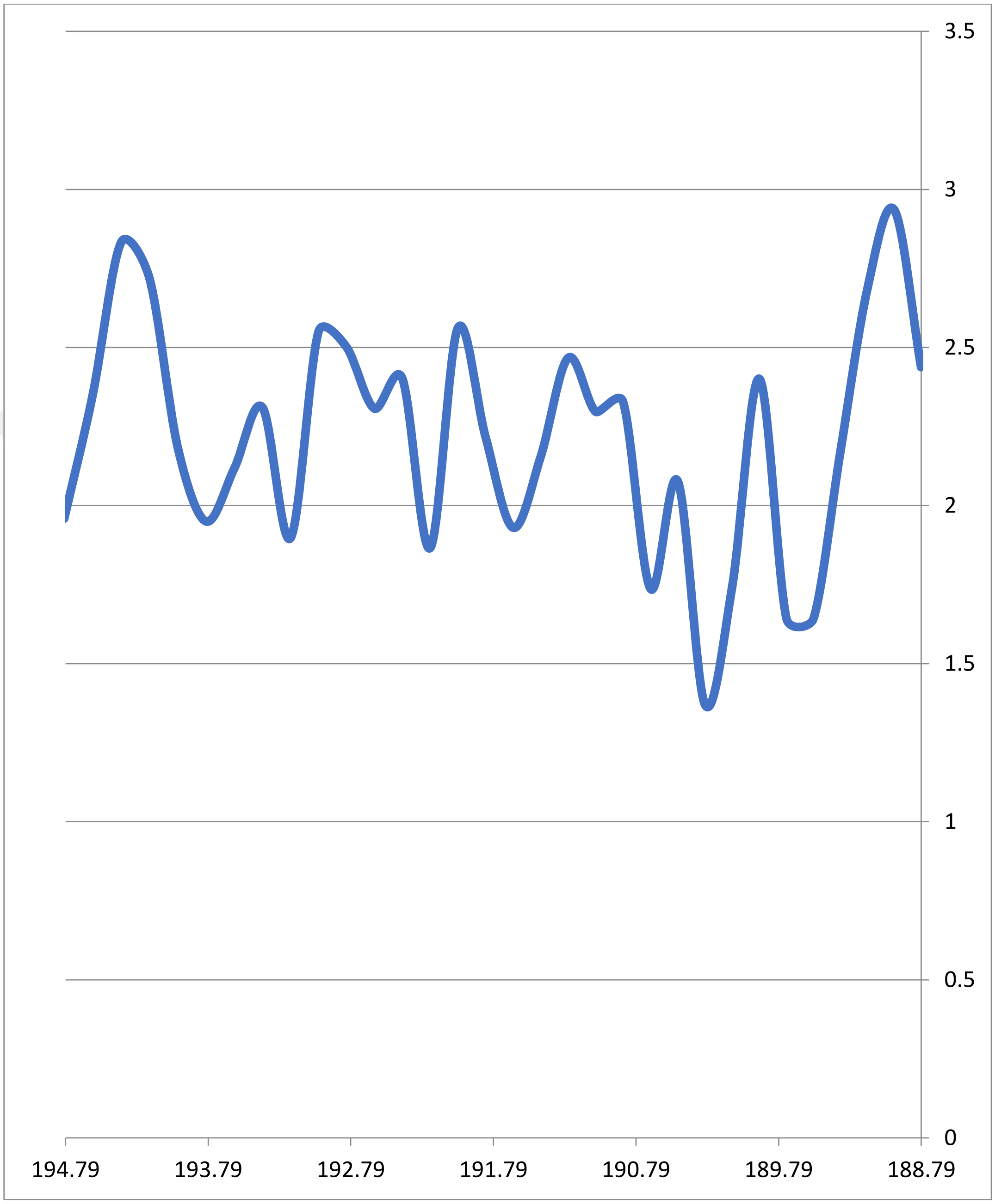

Figure 4.9: Variation of wavelength with respect to noise power in dBm.

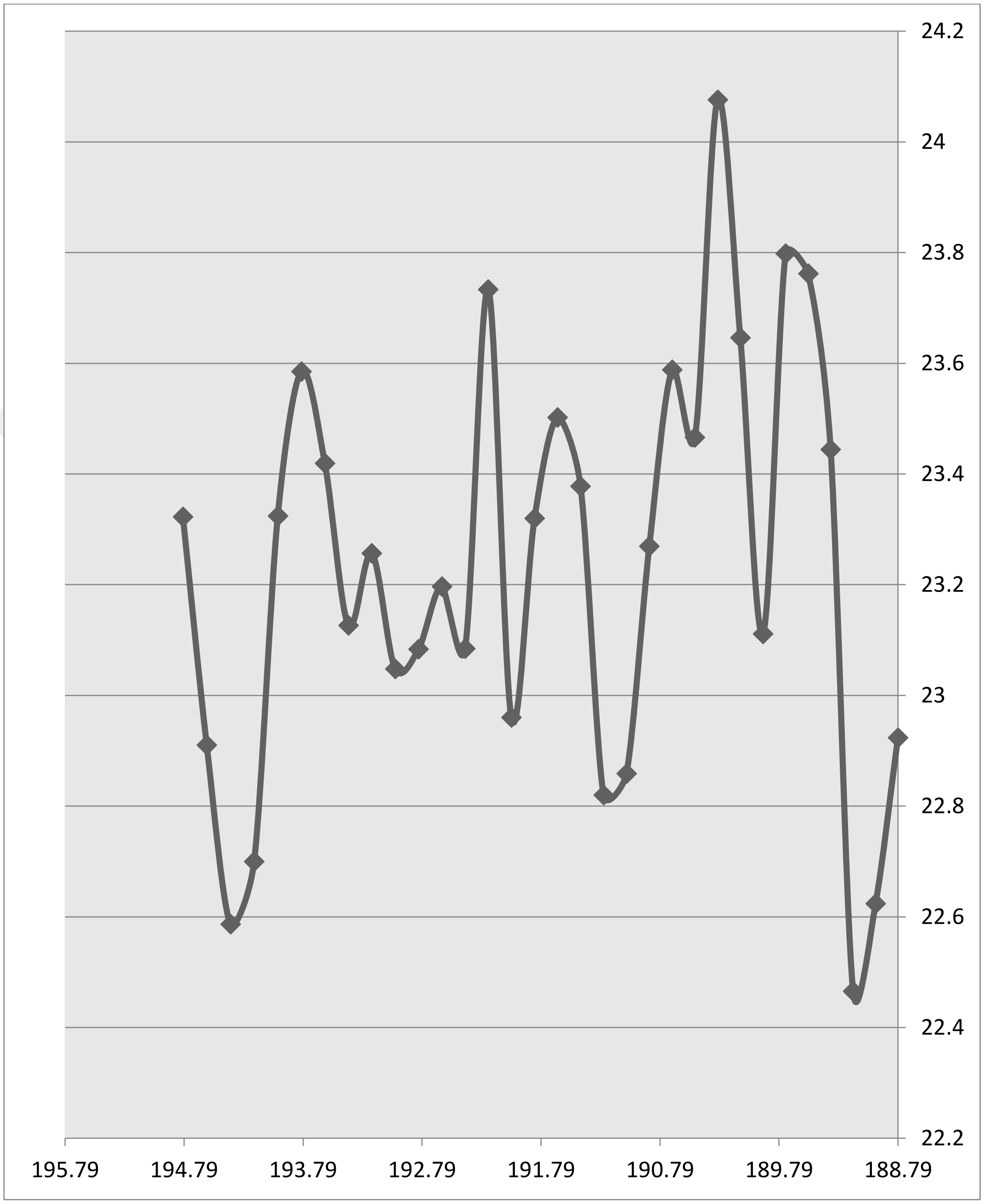

Figure 4.10: Variation of wavelength with respect to OSNR in dB.

4.8 RESULTS BASED OPTICAL POWER METER

The fiber optic power meter is a specialized kind of light meter that measures the amount of light that is emanating from the termination point of the fiber optic cable.

The power meter must be able to measure light at the correct wavelength and at the correct power range in order to be useful. As seen in Figure 4.10 it has been calculate this parameter for the transmission of each distance between (1000-9000) km, with showing the impact of total power used from each transmission case.

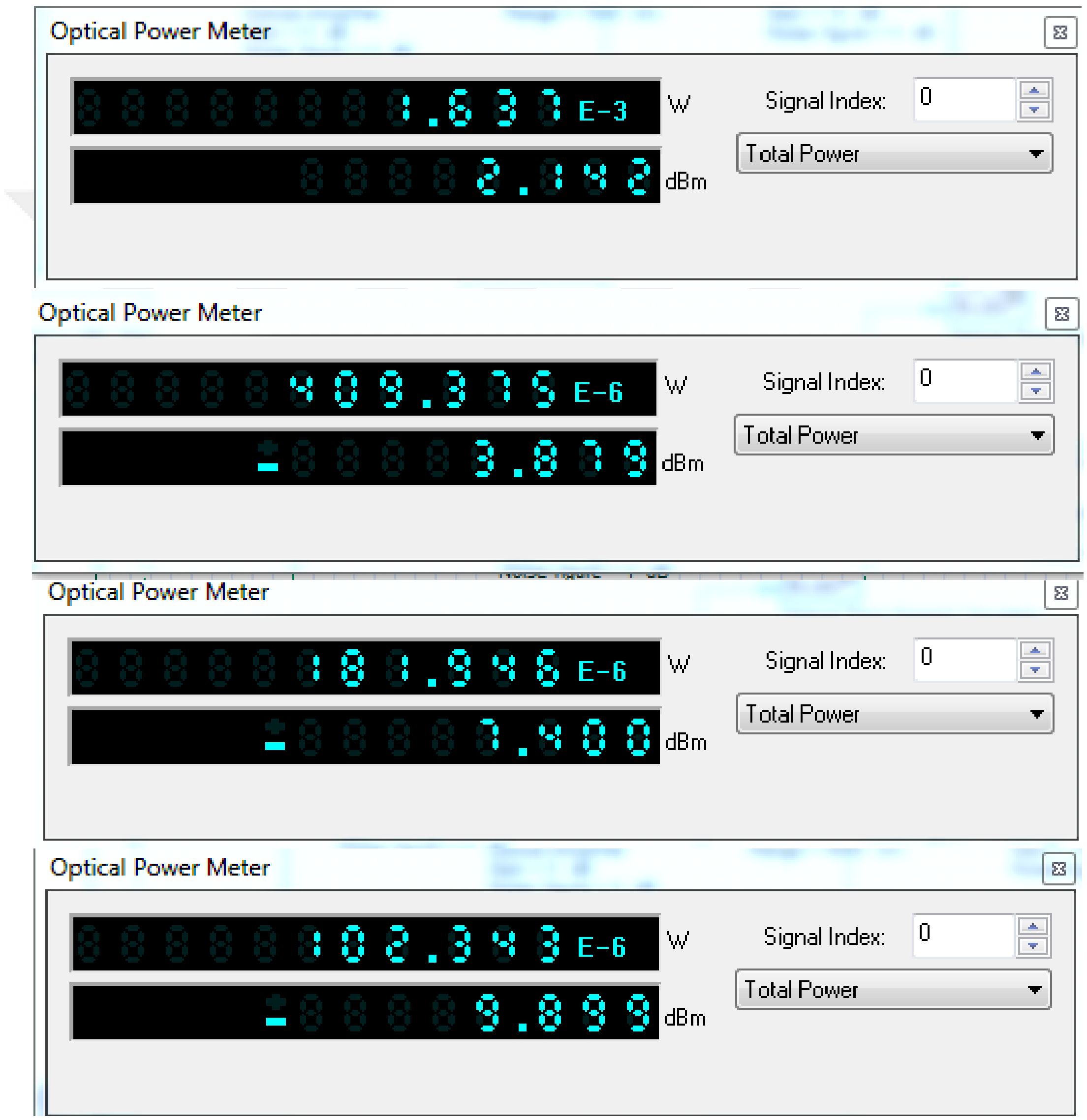

Figure 4.11: Total power from optical power meter component.

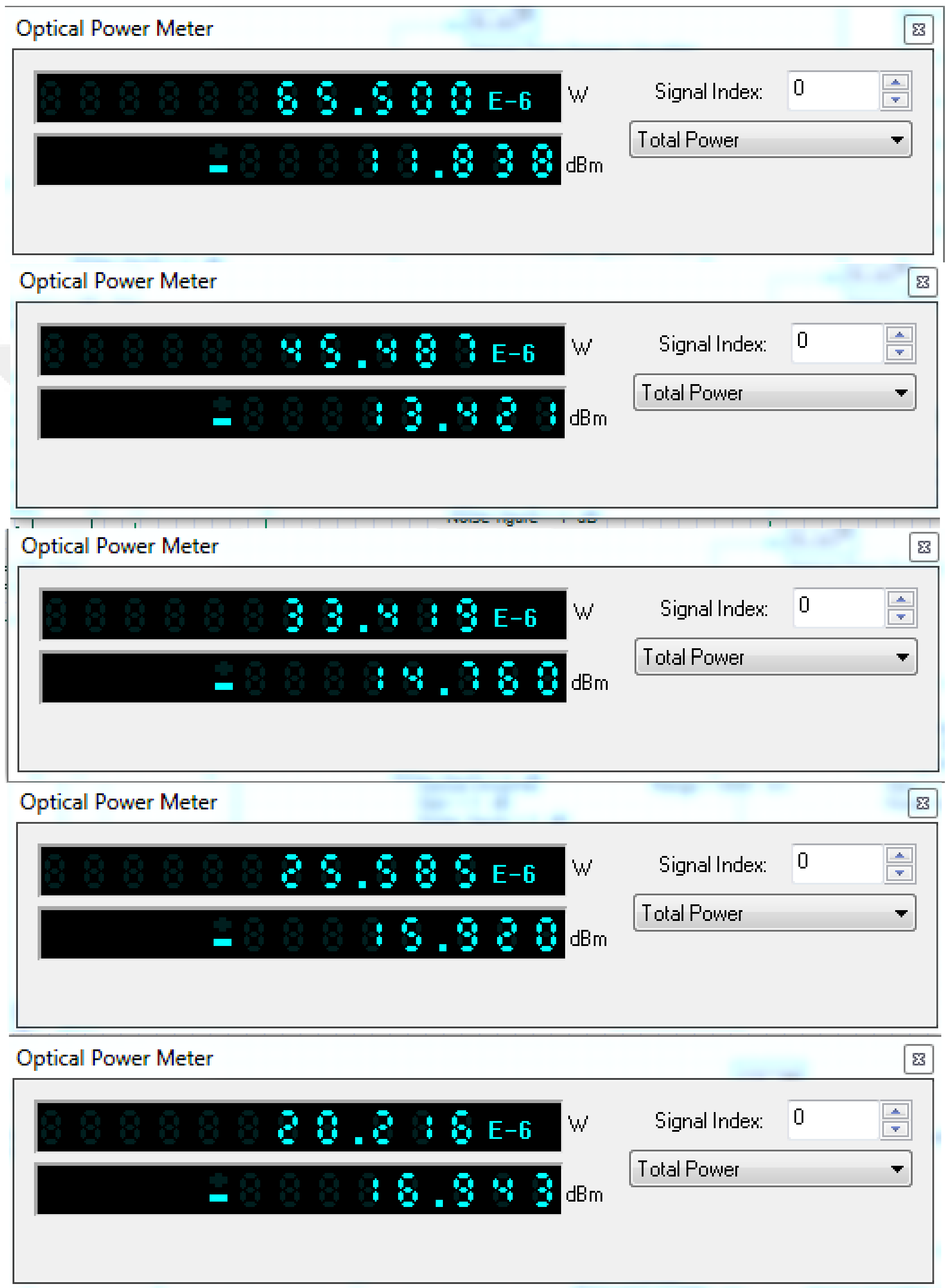

Figure 4.11: Total power from optical power meter component "figure continued".

5. CONCLUSION AND FUTURE WORK SUGGESTIONS

5.1 CONCLUSION

The conclusion is formed in this section and based on the achieved and analyzed results from the previous chapter, these conclusions would be formed in the below points.

i. In this work, it has been designed a 32 channel DWDM IS-OWC system to perform satellite-to-satellite communication which can handle a higher data rate of 1.28 Tbps.

ii. The proposed system was tested over a distance reached 9000 km and by using channel spacing of 1.58 nm. Results would be studied based on the parameter of QF and BER for the utilization of NRZ modulation which is then compared with the RZ to demonstrate the power of each method in performing a reliable transmission.

iii. Results obtained indicate a higher performance system where the average QF and BER obtained at 7000 km as an example was 8.11 dBm and 1.62 e-16 respectively. Such results showed a great improvement from previous publications.

iv. The average QF decrease would be between (1-2) dBm for distances up to 4000 km. And by (4-8) dBm for higher than 4000 km which indicates a good system performance.

v. Also, it has been found that using NRZ performs well than the RZ for performing such type of communication between the transmitter satellite and the receiver satellite.

5.2 SUGGESTIONS FOR FUTURE

Several points could be withdrawn as a suggestion for future work and as listed below

i. Increase the number of associated channels in order to achieve Ultra-dense distribution; nevertheless, numerous parameters, such as channel spacing and the input power provided for the proposed system, should be considered.

ii. Experiment with various amplification methods to see if you can increase the transmission distance.

iii. As a result, in the future, the influence of various nonlinearity effects might be included in the analysis to ensure that the optimum system design is achieved.

iv. Pointing error and the diameter of the satellite for both the transmitter and receiver are very important parameters that could be focused on in the future and studied concerning the use of another advanced modulation format such as using the Phase Shift Keying with polarization characteristics.

REFERENCES

[1] SATCAT Boxscore website. Retrieved April 29, 2009, https://celestrak.com/satcat/boxscore.asp.

[2] Rodríguez-Pérez, I., García-Serrano, C., Catalán, C. C., García, A. M., Tavella, P., Galleani, L., & Amarillo, F. " Inter-satellite links for satellite autonomous integrity monitoring". *Advances in Space Research*, Vol.47, No. 2, pp. 197-212, 2011.

[3] Vasiliev, E., Belokurov, V., & Evans, N. W. " Radialization of satellite orbits in galaxy mergers". *The Astrophysical Journal*, Vol. 926, No. 2, p. 203, 2022.

[4] Mohsen, D. E., Abbas, E. M., & Abdulwahid, M. M. "Design and Implementation of DWDM-FSO system for Tbps data rates with different atmospheric Attenuation". In 2022 International Congress on Human-Computer Interaction, Optimization and Robotic Applications , pp. 1-7, 2022.

[5] G. J. Holzmann and B. Pehrson, "The Early History of Data Networks (Perspectives)", *Wiley*, 1994.

[6] D. J.C. Phillipson, "Alexander Graham Bell," The Canadian Encyclopedia, http://www.thecanadianencyclopedia.com/articles/alexandergraham-bell.

[7] M. Groth, "Photophones revisited," http://www.bluehaze.com.au/modlight/GrothArticl-e1.ht.

[8] J. Hecht, "Laser evolution," *SPIE Professional Magazine*, http://spie.org/x34446.xml.

[9] F Edwards, B. L., Israel, D. J., & Vithlani, S. K.. " Latest changes to NASA's laser communications relay demonstration project ". *In Free-Space Laser Communication and Atmospheric Propagation XXX* , Vol. 10524, pp. 204-213, 2018.

[10] D Raj, A. B., & Majumder, A. K. " Historical perspective of free space optical communications: from the early dates to today's developments ". *IET Communications*, Vol. 13, No.16, pp.2405-2419., 2019. \

[11] W. S. Rabinovich, C. I. et al., " Free space optical communications research at the US naval research laboratory*," Proceedings of SPIE, Free-Space Laser Communication Technologies XXII*, Vol. 757, Feb. 2010, San Francisco, CA.

[12] Infrared Data Association (IrDA), http://www.irda.org/, Accessed 15-9-2022.

[13] Kumar, S., & Sharma, N., " Emerging Military Applications of Free Space Optical Communication Technolog : A Detailed Review ". *In Journal of Physics: Conference Series* , Vol. 2161, No. 1, p. 012011, IOP Publishing., 2022.

[14] Y. Tanaka, T. Komine, S. Haruyama, and M. Nakagawa, "Indoor visible light data transmission system utilizing white LED light," *IEICE Transactions on Communications*, Vol. E86-B, No. 8, pp. 2440–2454, Aug. 2003.

[15] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lightings," *IEEE Transactions on Consumer Electronics*, Vol. 50, No. 1, pp. 100–107, Feb. 2004.

[16] J. Grubor, S. Randel, K.-D. D. Langer, and J.W. Walewski, "Broadband information broadcasting using LED-based interior lighting," *IEEE/OSA Journal of Lightwave Technology*, Vol. 26, No. 24, pp. 3883– 3892, Dec. 2008.

[17] H. Le Minh, D. C. O'Brien, G. Faulkner, M. Wolf, L. Grobe, J. Lui, and O. Bouchet, "A 1.25 Gbit/s indoor optical wireless demonstrator*," IEEE Photonics Technology Letters*, Vol. 22, No. 21, pp. 1598–1600, Nov. 2010.

[18] H. Elgala, R. Mesleh, and H. Haas, "Indoor optical wireless communication: Potential and state-of-the-art," *IEEE Communications Magazine*, Vol. 49, No. 9, pp. 56–62, Sept. 2011.

[19] D. K. Borah, A. C. Boucouvalas, C. C. Davis, S. Hranilovic, and K. Yiannopoulos, "A review of communication-oriented optical wireless systems," *EURASIP Journal on Wireless Communications and Networking*, Vol. 2012:91, pp. 1–28, Mar. 2012.

[20] Visible light communication (VLC) - a potential solution to the global wireless spectrum shortage," GBI Research, 2011, http://www.gbiresearch.com/Report.aspx?ID=Visible-LightCommunication-(VLC)-A-Potential-Solution-to-the-Global-WirelessSpectrum-Shortage&ReportType=Industry Report.

[21] Global visible light communication (VLC)/Li-Fi technology & free space optics (FSO) market (2013-2018)," MarketsandMarkets, 2013, http://www.marketsandmarkets.c-om/PressReleases/visible-lightcommunication.asp, Accessed 15-9-2022

[22] Shekhar S and Gupta A., "Inter-Satellite Optical Wireless Communication Link (IsOWC)", *LAP Lambert Academic Publishing*, 2014.

[23] Kaushal, H., & Kaddoum, G. " Free space optical communication: challenges and mitigation techniques". *arXiv preprint arXiv*:1506.04836., 2015.

[24] Sarth ganga et.al, "Design of a Standardized Inter Satellite Optical Wireless Communication (IsOWC) System with Minimum Input Power" *Procedia Technology* ,Vol.25, pp.567 – 573, 2017.

[25] Asmaa Zaki M. et.al, "The Influence of Varying the Optical Wavelength on ISL Performance Recognizing High Bit Rates" *published in IOSR- journal of electronics and communication engineering* ,Vol. 9, Issue 1, Ver. II ,pp 64-70,2014.

[26] S. Saini and A. Gupta, "Investigation to find optimal modulation format for low power inter-satellite optical wireless communication (LP-IsOWC)," *in Wireless and Optical Communications Networks (WOCN), Eleventh International Conference* , pp. 1–4, 2014.

[27] Kaur, H., & Kaur, H. " Review on Inter-satellite Optical Wireless Communication system ". *International Journal of Advanced Research in Computer Science*, Vol. 8, No. 4., 2017.

[28] K. Wilson, and M. Enoch, "Optical Communications for Deep Space Mission," *IEEE Commun. Magazine,* Vol. 38, pp.134-139, 2000.

[29] Telecommunication website , Avilable online, accessed 14-9-2022,

http://telecom.esa.in-t/telecom/www/object/index.cfm?fobjectid=8929

[30] Puttnam, B. J., Rademacher, G., & Luís, R. S. "Space-division multiplexing for optical fiber communications". *Optica*, Vol. *8*, No. 9, pp.1186-1203, 2022.

[31] Mohammed Ali, F., E. Al-Hilo, and M. Gamil Tarbul. "Performance analysis of radio over optical fiber system with OFDM using multiplexing techniques." *Int J Appl Eng Res*, Vol.13 pp. 10831-44, 2018.

[32] Sarath, V. S., Kumar, V., Turuk, A. K., & Das, S. K. " Performance Analysis of Inter-Satellite Optical Wireless Communication ". *International Journal of Computer Network & Information Security*, Vol. 9, No. 4.

[33] Sharma, P., & Meena, S. " Performance Analysis of Inter-Satellite Optical Wireless Communication (Is-OWC) System by using Channel Diversity Technique". In *2018 International Conference on Inventive Research in Computing Applications (ICIRCA)* ,pp. 477-480. IEEE., 2018.

[34] Sharma, P., & Meena, S. "Analysis of pointing error at 100 Gbps by using different encoding technique in spatial diversity based inter-satellite optical wireless communication (IS-OWC) system ". *International Journal of Engineering Research & Technology (IJERT)*, Vol. 7, No.9, pp.1-4., 2019.

[35] Sharma, R., & Sharma, A.. IS OWC WDM System Performance Optimization at 40 Gbps Bit Rate with Improved Link Distance of 10000 km. In *2018 International Conference on Inventive Research in Computing Applications (ICIRCA)* , pp. 795-799. IEEE., 2018.

[36] Pottoo, S. N., Goyal, R., & Gupta, A. " Performance Investigation of Optical Communication System using FSO and OWC Channel ". *In 2020 Indo–Taiwan 2nd*

International Conference on Computing, Analytics and Networks (Indo-Taiwan ICAN) pp. 176-180. IEEE., 2020

[37] Eid, M. M., Rashed, A. N. Z., & El-gammal, E. M. " Influence of dense wavelength division multiplexing (DWDM) technique on the low earth orbit intersatellite systems performance ". *Journal of Optical Communications*., 2020

[38] Mohamed, A. E. N., Rashed, A., El-gammal, E., & Hashim, E. Multiple Transceivers Inter-satellite Optical wireless communication System Performance. *Menoufia Journal of Electronic Engineering Research*, vol. *29*, No. 1, pp.109-114., 2020

[39] Ashwani, S. A. A. " Investigation and analysis of inter-satellite-optical wireless communication system based on dense-wavelength-division multiple-access". *Periodicals of Engineering and Natural Sciences (PEN)*, Vol. 9, No. 2, pp. 491-499, 2021.

[40] Online website , https://www.electronics-notes.com/articles/radio/bit-error-rate-ber/what-is-ber-definition-tutorial.php, Accessed 15-9-2022.

[41] Jahangir Alam, S. M., et al. "Improvement of Bit Error Rate in Fiber Optic Communications." *International Journal of Future Computer and Communication*, Vol. 3 No.4, pp. 281-286, 2014.

[42] https://www.electronics-notes.com/articles/basic_concepts/q-quality-factor/basics-tutorial-formula.php, Accessed 15-9-2022.

[43] Miller, C. M. " High-speed digital transmitter characterization using eye diagram analysis ". *Hewlett Packard Journal*, Vol. *45*, pp.29-29, 1994.

[44] JG, P. " Digital communications". Me Graw-Hill, pp.777-778, 2001.