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IMPLEMENTATION OF ULTRA-DENSE DISTRIBUTION OF WDM ROF CHANNELS FOR 5G NETWORKING USING A HYBRID COMPENSATION SCHEME

Mustafa Dheyaa Oudah AL-YASIRI

Master's Thesis

Supervisor

Asst. Prof. Dr. Ayça KURNAZ TÜRKBEN

İstanbul, 2023

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The thesis titled IMPLEMENTATION OF ULTRA-DENSE DISTRIBUTION OF WDM ROF CHANNELS FOR 5G NETWORKING USING A HYBRID COMPENSATION SCHEME prepared by MUSTAFA DHEYAA OUDAH AL-YASIRI and submitted on 22/12/2023 has been **accepted unanimously** for the degree of Master of Science in Electrical and Computer Engineering.

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

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I hereby declare that all information 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.

Mustafa Dheyaa Oudah AL-YASIRI

Signature

DEDICATION

I dedicate this thesis to ….

To my father, my mother, and everyone who assisted and inspired me, as well as to my family and acquaintances. I have a special appreciation for my parents, whose words of encouragement and drive for perseverance continue to resound in my ears. I also dedicate this dissertation to my advisor, Dr. Ayça Kuranz TÜRKBEN, for all her assistance throughout my studies.

ABSTRACT

IMPLEMENTATION OF ULTRA-DENSE DISTRIBUTION OF WDM ROF CHANNELS FOR 5G NETWORKING USING A HYBRID COMPENSATION SCHEME

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The development of 5G communication networks intends to transmit data across great distances with better capacity to meet user requirements. Several academics and communication firms sought to solve the difficulty of managing a dense communication channel network. This thesis proposes and designs an 80-channel Dense Wavelength Division Multiplexing (DWDM) Radio over Fiber (RoF) system employing the NRZ coding scheme and 0 dBm laser source input power. The suggested system may reduce chromatic dispersion by utilizing the strong symmetrical compensation mechanism. The sample channels were 1,4,8,12,16, ..., and 80, and the transmission distance spanned from 60 km to 300 km. The proposed system is further analysed for multiple coding schemes of RZ and NRZ with varied input power values ranging from -5 dBm to 5 dBm to determine its optimal dependability. The mean QF and BER were 9.577 dBm and 2.34E-14, respectively, for 300 km transmission. RZ performs better for short distances (less than 100 km), whereas NRZ performs better for long distances up to 300 km. NRZ with a ± 5 dBm input power fluctuation also increased the BER by roughly E-4 and had an average effect variation of about ± 0.3 dBm in the QF values. However, raising the input power to 5 dBm lowered the mean total BER by approximately E-2, showing that power may lessen the effect of errored bits conveyed. However, RZ with ±5 dBm input power fluctuation lowered input power to -5 dBm and reduced QF by 1 dB. The suggested system's performance improves by 3 dBm by increasing the input power to 5 dBm. confirming the input power-QF connection. Increased input power may produce long-range transmission nonlinearity. BER values ranged from E-10 to E-20. Additionally, altering input power by ± 5 dBm has a modest effect on QF outcomes, with mean QF ranging by roughly ± 0.1 dBm. RZ coding has a variance effect of less than 0.1 dBm. These findings demonstrate the proposed system's reliability for 2 Tbps transmission up to 300 km.

Keywords: 5G, RoF, WDM, BER, Symmetrical Compensation.

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ABBREVIATIONS

3GPP	:	Third Generation Partnership Project
4G	:	Fourth Generation
5G	:	Fifth Generation
AM	:	Amplitude Modulation
APD	:	Avalanche Photodetector
ATM	:	Asynchronous Transfer Mode
BER	:	Bit Error Rate
BS	:	Base Station
CATV	:	Cable Television
CD	:	Chromatic Dispersion
CPA	:	Chirped Pulse Amplification
CS	:	Central Station
CW	:	Continuous Wave
CWDM	:	Coarse WDM
DC	:	Dispersion Compensation
DCF	:	Dispersion Compensation Fiber
DCI	:	Data Center Interconnect
DeMux	:	Demultiplexer
DM	:	Direct Modulation
DWDM	:	Dense WDM
EAM	:	Electro Absorption Modulator
EDFA	:	Erbium Doped Fiber Amplifier
EM	:	External Modulation
E-O	:	Electrical to Optical
ER	:	Extinction Ratio
FBG	:	Fiber Bragg Grating
Gbps	:	Giga bit per second
GHz	:	Gigahertz
HDTV	:	High-Definition Television

IEEE	:	the Institute of Electrical and Electronics Engineers
IoT	:	Internet of Things
IP	:	Internet Protocol
IPTV	:	IP television
ISDN	:	International Standard Book Number
KPIs	:	key performance indicators
LAN	:	Local Area Network
LEDs	:	Light Emitter Diode
LTE	:	Long Term Evolution
MMF	:	Multi-Mode Fiber
MM-MZM	:	Multi-Mode MZM
Mux	:	Multiplexer
MZM	:	Mack Zandar Modulator
Nd: YAG	:	Ti: sapphire, and Neodymium-Doped Yttrium Aluminium Garne
nm	:	nano meter
NRZ	:	Non-Return to Zero
O-E	:	Optical to Electrical
OFDM	:	Orthogonal Frequency Division Multiplexing
Op-Amps	:	Operational Amplifier
PD	:	Photodetector
PIN	:	Photon Isolator Neutron
PM	:	Phase Modulation
PRBS	:	Pseudo-Random Bit Sequence
PW	:	Pulsed Wave
QF	:	Quality Factor
RAUS	:	Remote Antenna Units
RF	:	Radio Frequency
RoA	:	Roman optical Amplifier
RoF	:	Radio over Fiber
RZ	:	Return to Zero
SD-MZM	:	Single Drive MZM

SMF	:	Single Mode Fiber
SONARs	:	Sound Navigation and Ranging
SONET/SDH	:	Synchronous Optical Network/Synchronous Digital Hierarchy
Tbps	:	Tera bit per second
TDM	:	Time Division Multiplexing
TPC-5CN	:	Trans-Pacific Cable 5 Cable Network
VLANs	:	Virtual LAN
WDM	:	Wavelength Division Multiplexing
XOR	:	Exclusive OR

1. INTRODUCTION

1.1 MOTIVATION

Fiber Optics (FO), invented in the 1970s, revolutionized telecommunications and helped launch the Information Age. Due to its advantages over electrical transmission, optical fiber communications have replaced copper wire communications in the core networks of developed nations. At Bell's new Volta Laboratory in Washington, DC, Alexander Graham Bell and Charles Sumner Tainter devised the Photophone in 1880. The Photophone pioneered fiber-optic communications. Bell considered it his greatest contribution to the discipline. The device transmitted sound through light. Bell made the first wireless telephone call between two 213-meter-apart buildings on June 3, 1880. [1-3] The Photophone was unviable until laser and optical fiber technologies made it feasible to safely transmit light through the atmosphere. The photophone was first used in military communication networks decades later. Harold Hopkins and Narinder Singh Kapany showed in 1954 that rolled fiberglass transmits light. Light is used to move solely via straight media. Tohoku University researcher Jun-ichi Nishizawa proposed using optical fibers in communications in 1963. Nishizawa's PIN diode and static induction transistor helped optical fiber communications. Nishizawa devised the static induction transistor [4]. In 1966, Charles K. Kao and George Hockham of STC Laboratories (STL) showed that current glass lost 1,000 dB/km, compared to 5–10 dB/km in coaxial cable, due to impurities that may or may not be removed. In 1970, Corning Glass Works developed optical fiber with 20 dB/km attenuation for communication. Compact GaAs semiconductor lasers for long-distance FO transmission were created at the same time [5].

Optelecom, Inc., co-founded by laser inventor Gordon Gould, won the first optical communication system contract from the APA in 1973. The Army Missile Command in Huntsville, Alabama developed this technique to broadcast a modulated signal five kilometers. A missile emitted optical fiber from a ground laser. The first commercial fiber-optic communications system was built after 1975 research. This system used 0.8-micrometer GaAs semiconductor lasers. This first-generation system operated at 45 Mbit/s with a maximum repeater separation of 10 kilometers. On April 22, 1977, General Telephone and Electronics made the first live FO telephone call in Long Beach, California, at 6 Mbit/s.

Corning Glass contracted with CSELT and Pirelli to test urban FOs in October 1973. Three years later, in September 1977, the second cable in this test series, COS-2, was experimentally put on two lines (9 kilometers) in Turin, for the first time in a big city, at 140 Mbit/s [6,7]. The second generation of fiber-optic communication was commercialized in the early 1980s. InGaAsP semiconductor lasers ran at 1.3 microns. Multi-mode fiber dispersion limited early systems. Single-mode fiber dramatically improved system performance in 1981. Despite this discovery, building single-mode fiber links proved challenging. SaskTel built the world's longest commercial FO network. The 3,268-kilometer (2,031-mile) network linked 52 municipalities [8]. These networks might reach 1.7 Gb/s with 50-kilometer repeater spacing by 1987. Desurvire optimized laser amplification for the TAT-8, the first optical fiber line across the Atlantic Ocean.

It worked in 1988. Third-generation FOs worked at 1.55 microns and lost 0.2 decibels per kilometer. Indium gallium arsenide and Pearsall's photodiode drove this technological advancement. Engineers solved pulse spreading at that wavelength using standard InGaAsP semiconductor lasers. Researchers overcame this problem by restricting the laser spectrum to a single longitudinal mode or employing dispersion-shifted fibers with minimal dispersion at 1.55 m. These developments let third-generation systems operate commercially at 2.5 Gbit/s with repeater spacing of over 100 kilometers (62 miles). The fourth generation of fiber-optic communication networks used wavelength-division multiplexing and optical amplification to send more data without repeaters. These two advances started a revolution that doubled system capacity every six months from 1992 to 2001, reaching 10 Tb/s [8,9]. In 2006, a 160-kilometer (99-mile) optical amplifier line reached 14 Tbit/s. The fifth generation of fiber-optic communications research and development focuses on expanding the wavelength range of a Wavelength Division Multiplexing (WDM) system. Dry fiber's low-loss window promises to extend the C band's wavelength range from 1.53–1.57 m to 1.30–1.65 m. "Optical solutions," pulses that can withstand dispersion and fiber nonlinearity, are another improvement. Shaped pulses do this. KMI and RHK predicted massive communications bandwidth demand from the late 1990s until 2000. Internet use and the commercialization of bandwidth-intensive consumer services like video on demand caused this [9]. Internet Protocol data was expanding exponentially, faster than Moore's Law projected integrated circuit complexity would develop. Since the dotcom bust and through

2006, the sector's main trend has been consolidation and outsourcing to cut pricing. Verizon and AT&T provide high-throughput data and internet services thanks to fiber-optic connections. These services are home-delivered [10,11].

In recent years, multiple articles have described the various experiments and standardized procedures used to establish Fifth Generation (5G) network goals, applications, and priorities. The Third Generation Partnership Project (3GPP) has developed LTE since 2011. Due to this, academic institutions and international organizations including the 3GPP, 5GPP, and the Institute of Electrical and Electronics Engineers (IEEE) are contemplating 5G networks. Several organizations and research have addressed 5G and urged for its global adoption by 2020 [12,13]. Future wireless networking systems will have more sophisticated infrastructure and better service delivery. As a result, a mobile-based 5G network will be constructed using many radio technologies to meet large-scale connection situations. To build a speedier, more efficient system, analyze the transportation system's power and stability [14,15]. This allows a system to fulfill both needs.

1.2 FIBER OPTIC COMMUNICATION (FOC)

FOC refers to a method of conveying data from one site to another by sending infrared light pulses over optical fiber. This approach may be used to connect several locations. In this case, the light is sent as a carrier signal, which is then altered to store the data. When it is essential to cover great distances, have high bandwidth, and be resistant to electromagnetic interference, the use of FO cables has replaced traditional electrical lines. The transmission of audio, video, and telemetry through local area networks is the primary function of fiber-optic communication. Optical fiber is the medium of choice in the majority of telecommunications businesses for the transmission of signals such as those used for the telephone, cable TV, and Internet connection. With fiber-optic communication, the researchers at Bell Labs have studied and achieved a record distance of 100 petabit kilometers per second with their work [16,17].

Communication through optical fiber is a technique in which light is utilized as the information carrier and optical fiber is used as the transmission medium. This kind of communication is known as optical fiber communication. Following the successful conversion of an electrical signal to an optical signal, the optical signal is then sent over the optical fiber, which is a kind of wired communication. After being modulated, the light can be transmitted. Fiber-optic communication systems have been at the forefront of a revolution within the telecommunications sector since the 1980s. These technologies have also been crucial in the development of the digital era. Communication using optical fiber offers both a high capacity for data transfer and a high level of discretion. Communication using FOs has recently emerged as the most significant and useful kind of wired communication available today [18].

FOs, light sources, and photodetectors are the three fundamental types of material components that are required for the operation of a FOC system. Communication optical fibers and sensing optical fibers are the two categories that may be used to categorize optical fibers according to their applications. Optical fibers are often classified according to their uses in addition to being categorized according to the manufacturing method, the material composition, and the optical properties of the fibers. The term "general purpose" and "special purpose" are the two categories that general purpose and special purpose medium fiber fall under, respectively. The term "fiber" refers to an optical fiber, which is a kind of cable that may be used to conduct a variety of operations on light waves, including amplification, shaping, frequency division, frequency multiplication, modulation, and optical oscillation. Fiber is often used in some functional devices [19]. The fundamental components that make up the communication system based on FOs are shown in Figure 1.1 [20].

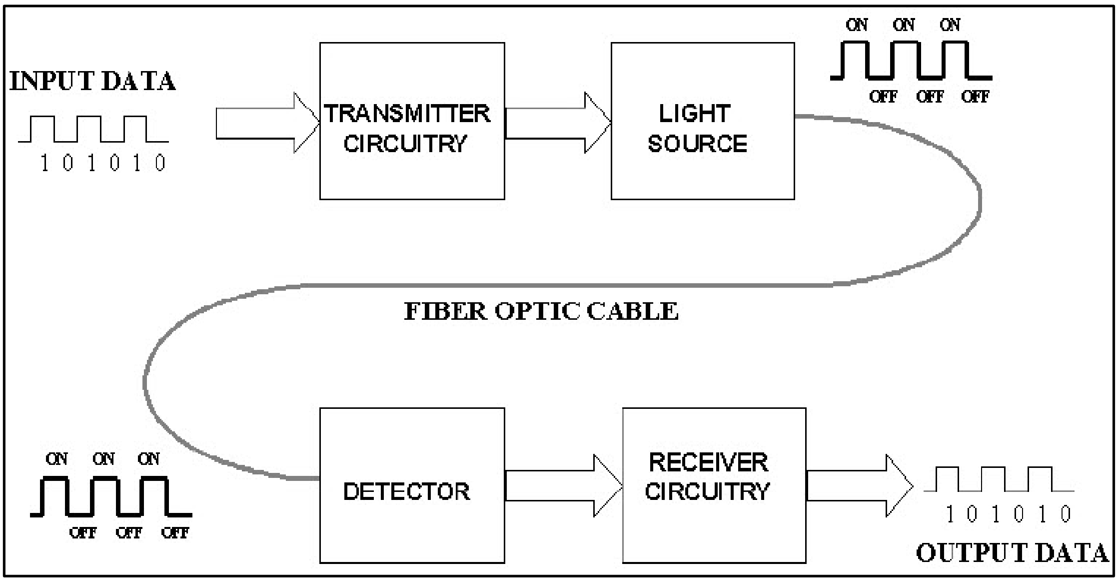

Figure 1.1: Component of Fiber Optic Communication System.

In contrast to transmission over copper wires, which is fully reliant on the electrical signals that go through the cable, transmission via FOs includes the transfer of signals in the form of light from one location to another.

The data, which arrives at the transmitter circuitry in the form of electrical impulses, are converted into a light signal with the assistance of a light source when the data is sent to the transmitter circuitry. LEDs serve as this transmission's source; hence, the amplitude, frequency, and phases of their signal must be kept constant and unaltered by any fluctuations for it to be effective. A FO cable transports the light beam from the source to the destination circuitry, where an information reception circuit converts the light beam to an electrical signal. The light beam is then returned to the source. A photodetector and an appropriate electronic circuit make up the Receiver circuit. Together, these components can measure the amplitude, frequency, and phase of the optic field. This kind of communication makes use of wavelengths that are located close to the infrared band, which is located slightly above the visible range. Depending on the task at hand, either LEDs or lasers may serve as the source of illumination [21,22].

1.3 CHARACTERISTICS OF FIBER OPTIC

The following is a list of the main characteristics that are associated with communication using FOs. Within the confines of the optical connection, the light signal may function as a signal to communicate the communication being carried out [20,23].

a. Bandwidth: The dispersion of a single laser light is a good amount of signal that can be transferred for every second, which results in high BW over long distances. b. Frequency: The frequency of laser light is constant [20].

b. Smaller diameter: The diameter of an optical fiber cable measures about 300 micrometers [20].

c. A lower overall weight: In comparison to copper-based cables, the cable that is utilized for FO transmission has a lower overall weight [20].

d. The transmission of signals over prolonged distances: Since the laser light does not dissipate, it may simply be transferred across very long distances [20].

e. Less attenuation: Since the FO cable is made of glass and a laser light is used to move through it, the attenuation of the signal, while it is being sent, is just 0.2 dB per kilometer [20].

f. Securing the transmission: The data that is sent through an optical fiber cable may be encrypted using optical technology, and there will be no electromagnetic signal to compromise the security of the transmission [20].

g. The Impact of optical fiber on the Internet of Things (IoT): The IoT will have a significant influence on FOC for the reasons that are represented by the transmission of media and data that is both rapid and secure, with no data being lost due to interference in the process [20].

1.4 SIGNIFICANCE OF FIBER OPTIC COMMUNICATIONS

The introduction of communication technologies based on FOs had a significant impact on the telecommunications industry. In recent years, FOs have emerged as the most preferred solution for backbone networks, higher-impact services, and a standard data networking framework [24]. As a consequence of this, the idea of communication systems that are supported by FO cable comes with the following four significant advantages:

a. Protected communication system: FO cabling is widely recognized as one of the safest networking techniques. Because of developments in cabling, it is becoming more difficult to interfere with or disrupt transmissions through hailing. Any efforts to break through the glass connection will result in "light spilling," which will lead to a detectable decrease in communication [25].

b. Electromagnetic Compatibility: Although FO cabling is resistant to enormous amounts of external pressures, defective copper cabling is not resistant to electromagnetic interference. In some applications, such as those involving the use of mechanical equipment that contain motors [26], the installation of cabling made of FOs is highly recommended.

c. The rate of transmission: FO cabling is far quicker than traditional copper cable. Trading rates of more than 10 gigabits per thread may be maintained using glass filaments with short diameters. Even though copper cabling may be able to keep up with these rates, vast quantities of gigantic width with 6 affiliations need to be accessible [26].

d. Transmission measurement: - A fiber connection is an excellent choice for establishing point-to-point hardline communication across an extended distance. Traditional copper cabling has restrictions on long-distance communication, which makes it necessary to install extra hardware to increase the volume of sign exchange. There may be a little slowdown in gigabit transmission speeds if the best reach of copper connections is getting closer. This decline will occur if the best reach is getting closer. Fiber joins are significantly better and more cost-effective than copper joins for basic long-distance network connections [26]. Fiber joins can transmit more than 10 gigabytes of data per second across lengths of more than 40 kilometers.

In addition, the following is a summary of some of the other general advantages that are linked with the idea of FOC systems: [26].

a. Making extensive use of the bandwidth's effect values.

b. Disturbance in the portion of the medium that has been traversed.

c. the loss that occurs when executing transmission is much lower.

d. optical cables are smaller and lighter than copper cables.

e. to strengthen the protection afforded to the transmission.

f. increasing the resistance to various interferences in the signal.

g. Power utilization is reduced.

As a result, summarizing the advantages and disadvantages of utilizing the FO-based communication system can be shown in Table 1.1

Table 1.1: Advantages And Disadvantages Of Fiber Optic Communication.

Advantage	Disadvantage
Lightweight and simple	require complex Tx and RX tools
Able to transmit large amount of data in digital or analogy form	Vulnerable to fibre flux at greater optical power
Radar and other signals will not cause disruption in the fibre. It has great bandwidth	It is an expensive investment or installation and maintenance

1.5 RADIO OVER FIBER (ROF)

RoF is often a straightforward optical connection that allows for the transmission of controlled RF signals. In RoF technology, the transmission of RF signals from a central location to Remote Antenna Units (RAUS) is accomplished by the use of optical fiber links. It performs both downlink and uplink communication of RF signals. It relays a Radio Frequency (RF) signal from the Base Station (BS) to the Central Station (CS), as well as the other way around [28]. Because of the rise in rush hour congestion, for example, video on demand, online usage, voice over Internet Protocol (IP), web-based video, and voice, there is a tremendous interest in network data transmission capacity. This is something that the RoF framework can provide because of its many benefits, which include a high transfer speed, resistance to RF impedance, decreased power consumption, multi-administrator and multi-administration activity, dynamic asset allocation, and several other similar attributes. As a consequence of this, it is superior to the preparation of RF signals in every respect. Duplex activity (downlink-uplink), reasonable length, and elite optical segments are the primary requirements for RoF connect engineering [29].

Figure 1.2 provides visual evidence of the demonstration of a system based on RoF. In this example, the control station is responsible for the creation of the signal. During this process, the RF signal is sent down the path of an optical fiber connection. Building the baseband signal requires modulation and signal processing, both of which are performed at the control office. Since the attenuation loss in this sent signal is almost nonexistent, the BS can pick up the signal that was communicated. Both the electrically to optically (E/O) and the optically to electrically (O/E) conversion processes are carried out at the BS Unit (BSU) [30]. An antenna is installed at the base station unit, and it is used to aid and facilitate the transmission of signals between the Wireless Terminal Unit (WTU), the Base Station Unit (BSU), and the user. The BSU and the CS can communicate with one another with the use of an optical signal. As a consequence of this, the price of transmission equipment like antennas and amplifiers is becoming more affordable. Therefore, the RoF system is a more effective system than the more traditional wireless networks [31].

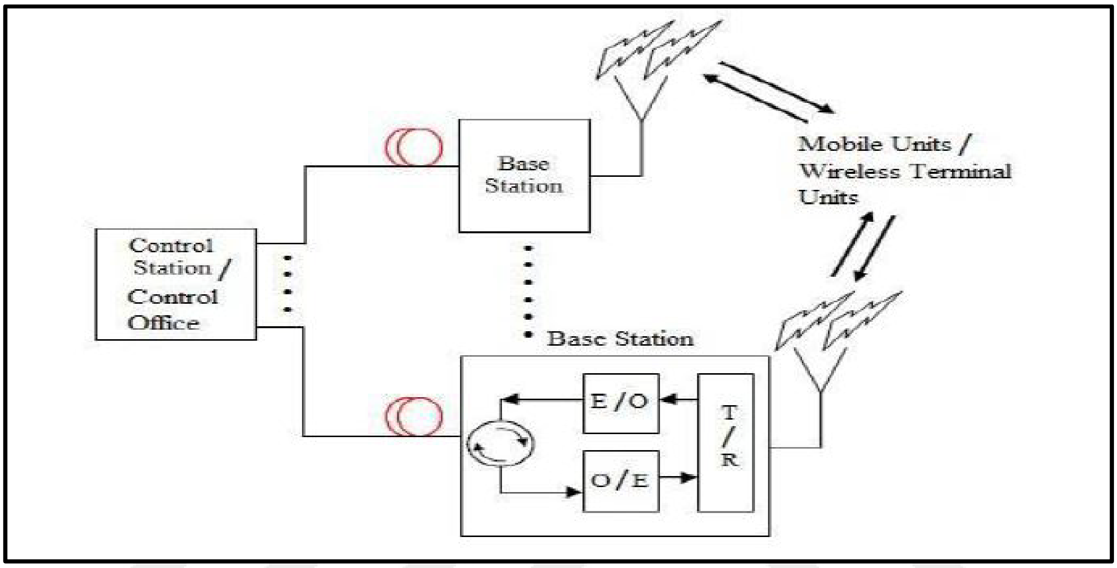

Figure 1.2: General Diagram of the RoF System.

1.6 SIGNIFICANT OF ROF

Considered to be the primary benefit of using a RoF system is a decrease in the amount of money spent. In addition to this, the RoF innovation makes it possible to combine several types of mobility capabilities, such as full-scale variety, to achieve consistent handover. There are a lot of positive aspects that come along with having easy access to distant locations. As a result, below is the major point that confirms the significance of the:

a. Large Bandwidth: Bandwidth may be sent across optical fiber without any limitations. The high data rate guarantees that there will be an increase in the amount of information that is transported through the medium of optical fiber. Most optical systems typically operate at a data rate of 10 gigabits per second. We have noticed that there is a significant opportunity for enhancing the bandwidth of the system. Two primary technologies may be used to improve the bandwidth of the system: WDM and Optical Time Division Multiplexing (OTDM) are both forms of multiplexing that may be found in [32].

b. Low Attenuation Loss: In a RoF system, optical fiber is employed in the backhaul network. This transmission medium has various benefits over free space and copper cable transmission in that it has a low attenuation loss. Because the optical fibers that are now on the market have extremely low attenuation, they may be utilized to accomplish the goal of decreasing the losses that occur between CO and CS, even when these two entities are physically separated by a great distance [33].

c. Installation and Maintenance That Are Simple: RAU is made easier to understand thanks to RoF systems. The majority of RoF procedures do away with the need of using associated components at the RAU. This framework encourages RAUs that are more modest and lighter, which appropriately decreases the expenses associated with the development and management of the framework. Following this line of action will result in a reduction of the costs required to set up and maintain the system at an apparent level [34].

d. Resistance to interference from RF signals: Optical fiber communications provide several extremely useful properties, including protection against electromagnetic interference, which offers confidentiality and security for microwave transmissions. This is because the signals go through the fiber in the form of light rather than electrical impulses [35]. There is no possibility of electromagnetic interference since the RF signal is sent across the optical fiber. This eliminates the possibility of interference. When information is sent by optical means, neither its quality nor its integrity can be compromised.

e. Flexible and dynamic resource allocation in addition to operational adaptability: Because it employs modern modulation equipment and switches at the CS, it makes it possible to partition the available bandwidth. It is feasible to assign greater capacity to particular places during peak hours while simultaneously lowering the amount of capacity assigned to such areas during off-peak hours. It is possible to dynamically assign various users to different channels to ensure the effective management of resources. This is necessary since assigning capacity to an area that is not densely occupied would result in a waste of resources. [36].

f. Utilization of less required power: To lower the amount of electricity that is used, complicated pieces of equipment are stored at the CS. Because of this, the BS that are not actively being used at any one moment in time might have their mode switched to passive. In optical fiber, the likelihood of nonlinear effects as well as dispersion should not be discounted. To alleviate problems of this kind that are inherent to RoF systems, it is suggested that various modulation strategies be developed as a potential solution. Research is also being done on the many kinds of modulation strategies that are capable of reducing the amount of nonlinear effect and dispersion. [37] RoF is a consistent solution for consumers that allows connectivity without a significant decrease in wireless range.

1.7 ROF APPLICATIONS

The following is a list of the different applications for optical fibers in various fields:

a. The applications of optical fibers in the medical business: It is employed in a variety of devices to examine interior body parts by putting them into empty places in the body. Because it is exceedingly thin and flexible, it is utilized in this equipment. Surgical procedures, endoscopy, microscopy, and research in the field of biomedicine all make use of it as a laser [38].

b. The Role of Optical Fibers in Communication The field of telecommunication, which is an integral part of the communication system, makes extensive use of optical fiber cables for sending and receiving information. It has applications in a variety of networking domains and has even been shown to improve both the speed and accuracy of data transfer. FO cables are more advantageous than copper lines because they are less heavy, more flexible, and can transport more data [38].

c. Optical Fibers that are Employed for Defensive Reasons: For applications requiring a high degree of data security, such as those found in the military and aerospace industries, FOs are employed for data transmission. These are used in a variety of applications including wirings in airplanes, hydrophones for SONARs, and seismic work [38].

d. Optical fibers find applications in a variety of industries: These fibers are put to use for imaging in regions that are difficult to access, such as the inside and outside of vehicles, where they serve the goal of providing safety measures and illumination, respectively. They are capable of transmitting information at the speed of light and are used in traction control and airbags. They are also put to use in the industrial sector for research and testing reasons [38].

e. Optical Fibers that are Utilized in the Broadcasting Process: Signals for high-definition television, which need a bigger bandwidth and are sent at a faster rate, are sent through these lines. When compared to the same amount of copper cables, optical fiber is more cost-effective. Optical fibers are used by broadcasting firms for the wiring of High-Definition Television (HDTV), Cable Television (CATV), video-on-demand, and many more applications [38].

f. Applications of Optical Fiber in Lighting and Other Aesthetic Purposes: To this point, we have a good understanding of what optical fiber is. In addition, it offers an appealing, cost-effective, and simple method of illuminating the area; for this reason, it is commonly used in the production of decorations and Christmas trees [38].

g. The Application of Optical Fibers in Mechanical Inspections: Engineers doing on-site inspections use optical fibers to locate defects and faults that are located in difficult-to-access areas. Optical fibers are used for pipe inspections by everyone from plumbers to plumbers [38].

1.8 WAVELENGTH DIVISION MULTIPLEXING (WDM)

The process of multiplexing numerous optical carrier signals across a single optical fiber channel may be accomplished using a method called WDM. This method does this by adjusting the wavelengths of the laser beams. WDM makes it possible for the fiber line to provide communication in both directions [39]. In WDM, an optical multiplexer, which is, in essence, an optical combiner, is used to combine the optical signals coming from several sources or transponders. They are blended in such a way that the wavelengths of the resulting product are distinct [40].

A single strand of optical fiber is used for the transmission of the combined signal. A demultiplexer is used at the receiving end to separate the incoming beam into its component beams, and then each of those beams is sent to the receivers that are appropriate for it. Figure 1.3 is a demonstration of the WDM technique's overarching conceptual framework [40].

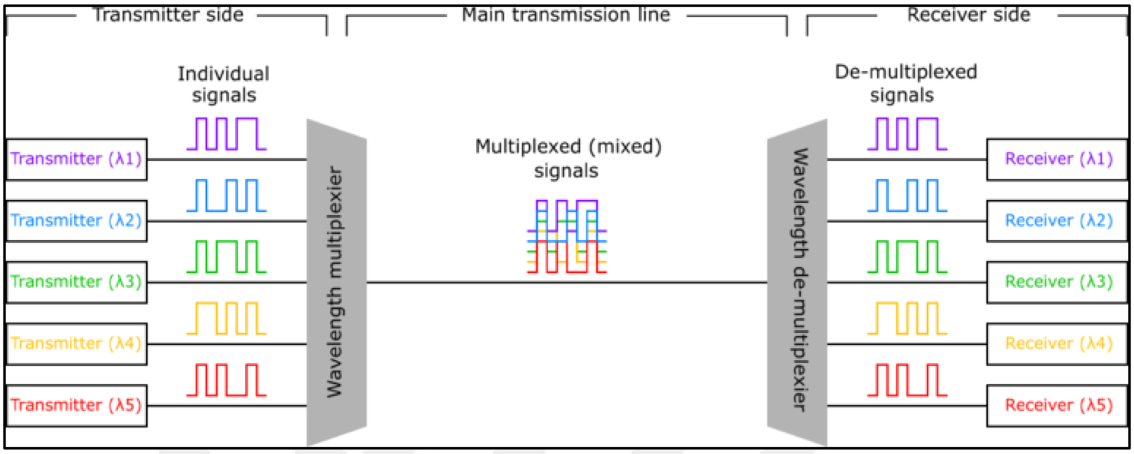

Figure 1.3: Concept of WDM Technique.

The two varieties of WDM are described below [40-42]:

a. Dense Wavelength Division Multiplexing, sometimes known as DWDM.

It is a method in which many optical signals (laser light) of a few different wavelengths or colors are aggregated into one signal and then sent through the connecting channel over an extensive region. When the distance for the transmission of an optical signal is measured in thousands of kilometers. After then, there will be very little signal loss. To compensate for this signal loss, the DWDM transmission system makes use of amplifiers that are based on optical fiber. This gain bandwidth is required by the DWDM technology for diverse optical signals to be combined efficiently. DWDM can transmit up to 80 channels, or 80 optical signals, with a separation of 100 GHz (0.8 nm).

b. CWDM, which stands for "coarse wavelength division multiplexing."

The CWDM technology allows for optical signals (laser light) of several wavelengths or colors to be combined into one signal before being delivered through the transmission channel for a short period. This process is known as the "carrier wavelength division multiplexing" technique. Transmission across distances of more than 100 kilometers often benefits from the use of DWDM technology. However, if the distance between the sending and receiving locations is less than 100 kilometers, we are exempt from the need to provide optical amplifiers. In addition, the CWDM system features a medium separation between the optical signals that are set at 20 nm. Because of this, it is possible to facilitate the use of low-cost parts, such as uncooled lasers, multiplexer (MUX), and demultiplexer (DEMUX) devices.

The operation of DWDM is broken down in the following section [42,43]:

a. After modulating numerous data channels into optical signals that have distinct frequencies, DWDM multiplexes these signals into a single stream of light that is sent through a fiber-optic cable. This allows for the transmission of a greater amount of data over the same amount of bandwidth.

b. Because each optical signal has its frequency, the fiber may support the transmission of up to eighty distinct data streams concurrently, even though there are only eight distinct light wavelengths.

c. DWDM-based networks are capable of handling bit rates ranging from 100 Mb/s to 2.5 Gb/s and may transfer data via the Internet Protocol (IP), Asynchronous Transfer Mode (ATM), SONET/SDH, and Ethernet protocols. As a result, DWDM-based networks have the capability of transporting various kinds of traffic at varying speeds over a single optical channel.

d. At the other end, a multiplexer demultiplexes the signals so that they may be distributed to the several data channels that they belong to.

e. Devices that enable DWDM are more expensive than those that do not because the laser light sources that are used for producing signals through fiber have to be very reliable.

The following points explain the technical benefits offered by DWDM [42,43]:

a. Transparency Because DWDM is an architecture for the physical layer, it may handle TDM in addition to other data formats with open interfaces such as ATM, Gigabit Ethernet, ESCON, and Fiber Channel. This is possible since the physical layer is shared by DWDM and other architectures.

b. scalability DWDM has the potential to rapidly satisfy the demand for capacity on point-to-point connections and spans of existing SONET/SDH rings by using the quantity of dark fiber that is present in many business networks and metropolitan area networks.

c. Provisioning of network connections that is quick, easy, and dynamic allows service providers to provide high bandwidth services in a matter of days rather than months.

Furthermore, the feature of using the DWDM-based technique can be summarized by the two below points:

a. It is a form of technology that expands the bandwidth while data signals are being sent across the fabric.

b. It is possible to significantly improve the signal-carrying capacity of the system. The data transmissions may travel at speeds of up to 400 gigabits per second.

1.9 SIGNIFICANT OF THIS STUDY

As was said before, there has been a growth in the demand for Internet applications, namely in the field of multimedia-based applications such as YouTube, live video streaming, interactive television (TV), and Internet Protocol Television (IPTV). Because of this, the need for increasing data speeds and capacities has soared, and therefore, FO networking networks have become an essential choice for satisfying these requirements. To meet these requirements, a 5G network architecture that can provide greater data rates and capacities will need to be developed and put into operation. As propagation lengths increase, the impact of different types of distortions, dispersions, and attenuations on the signals being transmitted will begin to diminish. As a direct consequence of this, there is an ongoing need for the provision of trustworthy approaches to manage and treat these issues. Because of this, this thesis proposes and builds a fiber-optic communication network that can manage dense channel deployment via the use of dedicated optimal power needs and modulation formats. Therefore, it is necessary to meet the needs and problems.

1.10 PROBLEM STATEMENT

The researchers and academic staff have several challenges to overcome, the most significant of which is managing effective transmission to get a greater data rate by using adequate bandwidth and accomplishing the requisite long distance to fulfill the needs for 5G-based networks. When it comes to managing transmission through fiber-optic networks, one of the other crucial factors that must be taken into consideration is finding an efficient way to address the challenges linked to authentication and distribution. Because of this, the system that is suggested in this thesis would consider these problems and solve them in a manner that is suitable for the requirements of a 5G network.

1.11 THESIS OBJECTIVES

The major objective of this proposed system is to handle and prepare a scheme towards 6GG-based communication with support for the following aspects:

a. Propose and design an effective system for RoF-based DWDM techniques that has the powerful capability to handle a massive number of attached channels and achieve a data rate of more than 1 Tbps to meet 5G and beyond requirements and for long transmission distances.

b. Improve the proposed system's reliability by investigating different line coding techniques for non-Return to Zero (NRZ) and Return to Zero (RZ) methods. Also, utilize the symmetrical method of compensation technique to control the problem of Chromatic Dispersion (CD).

c. Evaluate the proposed system performance concerning different input power values to address problems of nonlinearity with optical transmission systems.

1.12 THESIS OUTLINE

a. In chapter one, the motivation for handling the topic related to optical fiber communication with the dense deployment of channels is expressed by clarifying the first generation of FO networks and their continuous development over time. Then the technique of RoF will be mentioned, illustrated by its significance and benefits. Additionally, in this chapter, the major concept behind the technique of WDM will be mentioned. Furthermore, the significance of this study, the problem statement, and the thesis objectives will be listed in this chapter.

b. In chapter two, the demonstration of the recent previous literature related to the selected topic of this thesis will be mentioned and clarified in detail to show the latest developments in the field of optical communication and the pros and cons related to each proposed system and methodology carried out by different researchers.

c. In chapter three, the methodology of the proposed DWDM RoF system will be mentioned, describing the components that form the system. Also, the program Optisystem, which is used to simulate and design the structure of the proposed system, will be mentioned in this chapter. Additionally, the parameters involved in evaluating the performance of the proposed system will be defined in this chapter.

d. In chapter four, the evaluation of the proposed system will be included, analyzed, and evaluated to confirm the reliability of the system and meet the objective requirements.

e. In chapter five, the conclusions and future recommendations will be mentioned.

2. LITERATURE REVIEW

a. In [44], authors proposed a dual-channel RoF system concerning the utilization of NRZ-based modulation formats. The proposed system was tested for only 50 km without considering the impact of the compensation technique. The obtained data rate was limited to only 1 Gbps. Their work helped by looking into and judging the proposed system performance of the single and multi-mode-based Mack Zandar Modulator (MZM), which is used to change electrical signals into optical signals. However, the achieved data rate and distance were not satisfied with 5G applications and required more modifications.

b. In [45], the authors proposed a 16-channel system by utilizing the NRZ modulation technique with a total transmission distance of only 150 km. Also, the compensation method utilized has not been properly clarified in their work. The contribution demonstrated was related to highlighting the significance of using sub-carrier multiplexing along with the 16-channel system, which resulted in achieving a total data rate of 28 Gbps. Additionally, using the Erbium-Doped Fiber Amplifiers (EDFA)-based amplifier indicates significance in boosting the transmitted data and improving the quality of the received signals and overall system performance. On the other hand, the main drawback represented by the limited lower distance achieved is due to many reasons related to not selecting the appropriate compensation technique and using the Avalanche Photodetector (APD)-based photodetection method. As a result, the proposed system needs to be improved to meet the ongoing developments in the field of FOCs.

c. In [46], researchers proposed a 4-channel WDM RoF system using the NRZ-based modulation format with a total distance achieved of 60 km and a data rate of 4 Gbps. Utilizing 50 GHz's lower bandwidth and condensed channel spacing is one advantage of the proposed system. However, the drawback of the proposed system is related to a lower channel attached to a lower data rate, which all needs to be improved to satisfy the recent 5 G-based requirements.

d. In [47], a 2-channel WDM RoF system was designed and implemented using the NRZ modulation and tested for short distances, represented by 30 km only. Results obtained indicate that raising the Extinction Ratio (ER) of the MZM resulted in an improvement in recent signal quality. In contrast, handling various ER values has not been considered with raising the transmission distance and increasing data rate limits.

e. In [48], authors proposed a 10-channel WDM RoF system for distances reaching only 70 km and investigated the performance of both NRZ and RZ as modulation formats. The compensation method has not been assigned to the proposed system. The total data rate achieved was up to 10 Gbps. Results obtained showed that using the NRZ-based modulation can further improve the overall performance as compared to utilizing the RZ modulation via the APD photodetector. However, the distance achieved per the proposed system needs to be further increased and tested for both the investigated modulation formats. Also, the low data rate needs to be further improved to satisfy 5G applications.

f. In [49], another 16-channel DWDM RoF system was implemented based on using the NRZ modulation method with post-compensation. The achieved total distance of 180 km was obtained by the proposed system. The achieved data rate was up to 640 Gbps. The main contribution of this work was related to using the EDFA-based amplifier to boost the transmitted data for the mentioned data rate and distance. Even with the significance of the achieved data rate and distance, the system required testing over different methods of compensation techniques based on using Dispersion Compensation Fiber (DCF) to achieve optimum performance.

g. In [50], a 25-channel system was carried out and tested for two modulation formats, RZ and NRZ, selecting the post-compensation method as the basis of the dispersion compensation technique. The system capacity was up to 1 Tbps, with a total transmission distance of only 180 km. The contribution carried out in this work was related to the higher data rate obtained to handle five G-based applications. Additionally, NRZ indicates better performance as compared to RZ for the proposed system. The disadvantage of such a system was that the Optisystem program-based simulator could only provide the eye diagram's parameters for visualizing the performance evaluation. Also, the authors didn’t include the calculation of the Bit Error Rate (BER) and Quality Factor (QF)-based parameters. Furthermore, only two channels of the 25-channel system were tested and involved in the entire investigation.

h. In [51], a 32-channel DWDM RoF system with NRZ as its base modulation method was designed and built with the help of the Optisystem program's powerful optical network simulator. The post-compensation method was selected with the designed system as a compensation technique to handle and reduce the impact of CD. The achieved data rate and distance of transmission were 1.28 Tbps and 180 km, respectively. However, the authors didn't include the investigation of different channel spacing between 32 channels or the system performance concerning different modulation formats.

ı. In [52], researchers proposed an 80-channel DWDM RoF system that utilizes the RZ as a modulation technique and post-compensation method. The achieved total data rate was up to 960 Gbps. The major significance behind the proposed system is related to utilizing the Roman Optical Amplifier (RoA) as a booster to improve the quality of the transmitted data. However, several drawbacks were related to the presented system, such as the lower channel spacing, which was between 20 and 100 GHz; the lower data rate obtained, which needs to be improved; and the need to handle longer distances to satisfy the continuous improvement of the fields of optical networks.

j. In [53], the researchers proposed a 16-channel DWDM RoF system by using the NRZ as modulation, with an overall transmission distance of up to 60 km. The selected method of compensation was the post, which was utilized via the Fiber Bragg Grating (FBG). The total data rate achieved was up to 160 Gbps. This study includes the investigation of different input power values and their impacts on the performance of the proposed system. Results obtained indicate that using lower input power can be considered the best choice to reduce the attenuation effects. However, selecting the FBG for longer distances has not been analyzed. Also, the authors didn't compare the performance of different photodetectors to reach optimum performance.

k. In [54], the authors proposed an 80-channel DWDM RoF system and tested three compensation techniques (pre- and post-symmetrical). The authors aim to solve the challenge related to utilizing a large data rate per channel in a dense communication-based system. The proposed densely deployed system could perform transmission for only 120 km. Results obtained indicate that using pre-compensation is the most suitable for long-distance transmission, while for short-distance transmission, the other two methods are the most suitable. However, the reach distance of 120 km is not considered a long reach distance to handle the reliable transmission of the fronthaul-based RoF system and needs to be improved. Also, the overall capacity, which was less than 1 Tbps, needs to be further increased to satisfy future needs and the continuous growth in traffic requirements.

l. In [55], another 32-channel DWDM RoF system was designed that uses the NRZ coding method. The proposed system was tested for distances up to 120 km only. The selected method of compensation was the post-based FBG technique, which could achieve a total of 256 Gbps of data rate. The main contribution carried out in this work was related to achieving a higher data rate with narrow channel spacing. On the other hand, the cons related to this system were related to the achieved distance, which needs to be raised along with the data rate to reach the Terabit to meet the recent needs of 5G and IoT-based applications.

m. In [56], a 50-channel DWDM RoF system was designed using the Optisystem program and tested for distances up to 180 km only, with a total capability to transmit 2 Tbps of data rate. The output analysis was conducted using the eye-opening criteria of QF and BER over the specified distance. The findings demonstrated a greater data rate performance for the system that was suggested, with the capacity to achieve 2 Tbps for use in applications in the future. In addition, the findings of the QF parameters were encouraging, as the values that were obtained on average were higher than the threshold, falling within the range of (0.22-13) dBm. Furthermore, the outcomes of the inquiry indicate that there is a direct association between the distance and the BER, with the amount of error within the transmitted bits growing as the transmission distance rises, and there is a reverse relation between the QF and the distance. The main drawback related to this study is the distance, which needs to be improved.

To get an accurate demonstration of the recent literature related to the topic of the proposed system of this thesis, Table 2.1 will summarize the most critical points to quantify with each proposed system.

Table 2.1: Literature Summarizing.

Ref.	Year	Ch no.	Distance	Data rate	Pros.	Cons.
[44]	2017	2	50 km	1 Gbps	Single and multi MZM	Low data rate short distance
[45]	2019	16	150 km	28 Gbps	EDFA improvement	Using APD photodetection Limited distance and data rate
[46]	2020	4	60 km	4 Gbps	Low BW Narrow channel	The low data rate, a short distance
[47]	2020	2	30 km	-	ER significant	The low data rate, short distance.
[48]	2020	10	70 km	10 Gbps	NRZ significant	The low data rate, short distance.
[49]	2020	16	180 km	640 Gbps	EDFA significant	Optimum compensation technique.
[50]	2020	25	180 km	1 Tbps	Improve data rate via NRZ	Lack of analyzing the system.
[51]	2020	32	180 km	1.28 Tbps	Improve data rate	Different channel spacing impact.
[52]	2020	80	-	960 km	ROA powerful	Distance improvement.
[53]	2021	16	60 km	160 Gbps	Optimum input power	The low data rate, a short distance
[54]	2021	80	120 km	> 1 Tbps	Different compensation technique	Improvement in the distance and data rate is required.
[55]	2022	32	120 km	256 Gbps	Narrow channel spacing	Improve distance and data rate.

Table 2.1: Literature Summarizing. "Tables Continued ".

[56]	2023	50	180 km	2 Tbps	Post-compensation improvement via NRZ coding	Distance improvement
Proposed	2023	80	300 km	2 Tbps	Symmetrical compensation, optimum input power, and optimum modulation format	Continuous improvements to meet future needs

3. METHODOLOGIES

3.1 INTRODUCTION

This chapter will include a demonstration of the methodologies carried out with the proposed 80-channel DWDM RoF system, which will include the clarification of the components and the parts of the proposed system. Describing the significance of each component and the concept of work. Additionally, in this chapter, the demonstration of the parameters that are used to evaluate the performance of the proposed system will be clarified.

3.2 OPTISYSTEM SIMULATOR

High-level advanced demonstrating approaches must be used for the design, testing, and analysis of optical transmission frameworks that are prepared to meet the requirements of 5G correspondence organizations. The Optisystem is one of the most amazing pieces of programming that is currently available when it comes to delivering this capability. A few of the advantages that such programming provides include giving potential customers a global perspective of device results, actively attempting to introduce plan decisions and situations to anticipated clients, enabling simple access to enormous volumes of plan setting of primary, and subsequently changing and improving breadth settings [57].

The Optisystem software has also been extensively used in a wide range of applications because it enables users to configure, create, and confirm proposed devices in both the time and recurrence spaces. This is justified by the fact that the program can complete these tasks simultaneously. This program is responsible for the making of a few significant applications, including FSO, RoF, and Symmetrical Recurrence Division Multiplexing (OFDM), which upholds an expansive assortment of tweak plots and empowers clients to survey gadget yield considering a few determined rules. Among them, FSO and RoF are among the biggest [57].

Subsequently, for the gadget engineering that we have created, which will be explained in more noteworthy depth on the accompanying pages, we will utilize the latest variant of the Optisystem 19.1 programming. The primary sheet of the application is found in Figure 3.1; this sheet makes it a lot less difficult to figure out which tabs are currently dynamic.

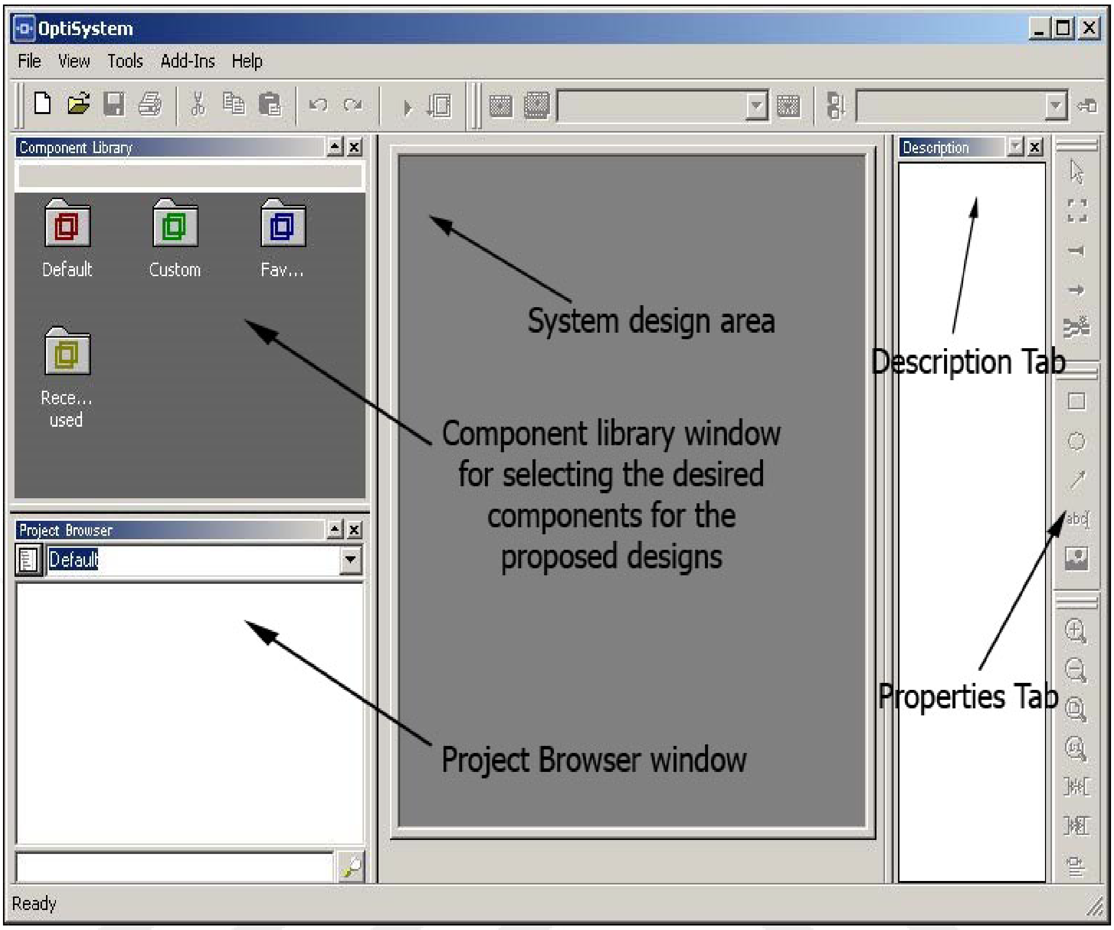

Figure 3.1: The Main Window of the Optisystem Program.

3.3 COMPONENTS AND PARTS OF THE PROPOSED SYSTEM

This section will describe all the components and tools which were used to form the proposed system and its three related parts. These parts are represented by the transmitter part, the medium part, and the receiver part. It is worth mentioning, that Optisystem provides tools and is connected to form the proposed system with all its related components.

3.3.1 Transmitter Part

This part will include the following components:

a. Continuous Wave (CW) Laser

Light Amplification via Stimulated Emission of electromagnetic Radiation is what "laser" stands for in its full acronym form. It is a concentrated kind of light that is produced when the energy levels of electrons change. Laser light is produced like that of light emitted by an incandescent light bulb when electrons in the filament change their energy state because of the flow of electrons caused by electrical energy. Atoms are the starting point for the first fundamental principle. Atoms are in a state of continual motion; they vibrate, move, and spin. These motions are referred to as states of excitation. When energy, like light, heat, or electricity, is given to an atom, this process, known as excitation, occurs. When excitation occurs, the electrons that circle the nucleus of the atom get excited (absorb the energy), which causes them to shift their energy level from "ground" or their equilibrium level to a higher energy state. Excitation may take place in three different forms: light, heat, and electricity. If there is not a prolonged injection of energy, the electrons will eventually settle back down to this more stable ground level. Spontaneous emission—the light portion of "laser"—is photon release. Electrons release photons and generate light in fluorescent lights, gas lanterns, and incandescent bulbs. Even in red-glowing embers, the heated atom's electrons are cooling and releasing red photons [58,59]. Lasers don't spontaneously generate focused light. Needs more. The photon emission procedure can be seen in Figure 3.2.

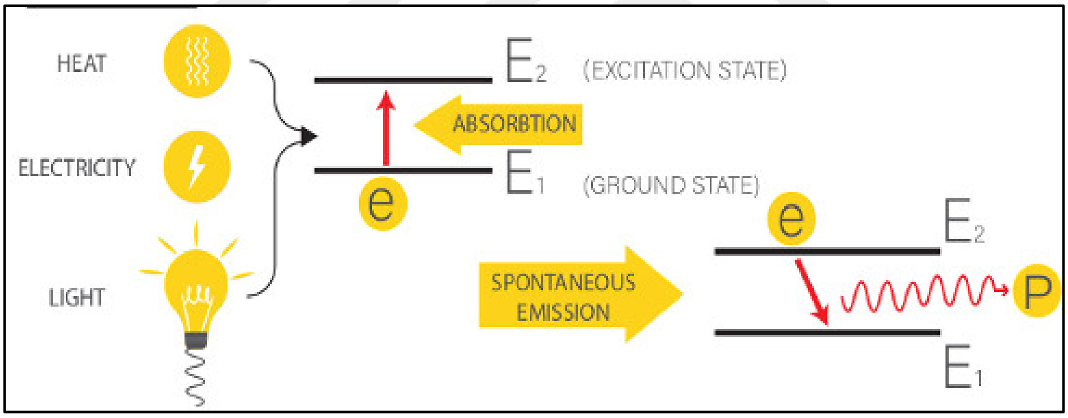

Figure 3.2: Photon Emission Step (Laser Principle).

Excited electrons undergo stimulated emission. Another photon of the same energy level may excite that electron into its ground or stable state. This releases an equal-energy, wavelength second photon. Laser essence. Monochromatic (same wavelength) and coherence (phase and direction) photons are synchronized. "Laser" comes from stimulated emission. No energy level guarantees continued stimulated emission. Enough electrons must emit photons. The second principle of laser can be clarified as seen in Figure 3.3 [60-63].

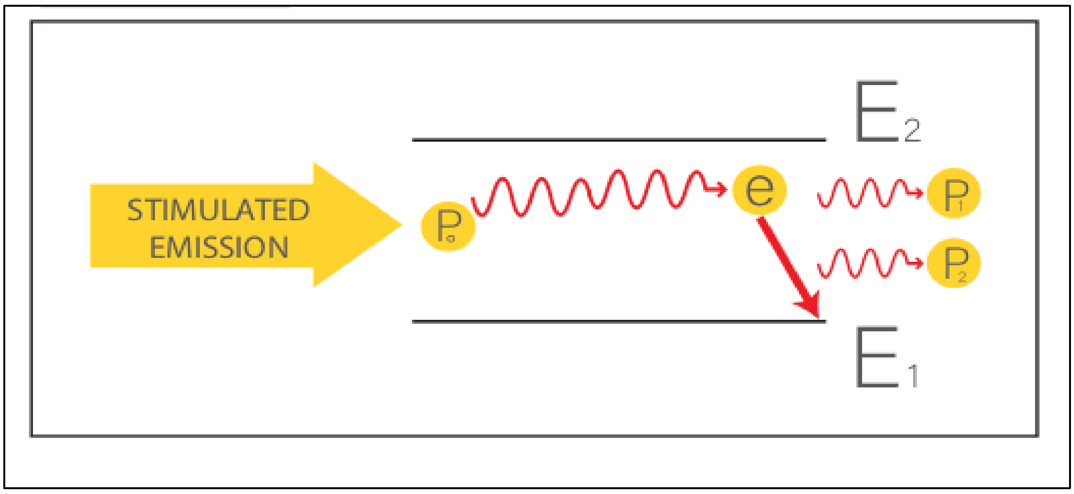

Figure 3.3: Simulated Emission Step (Laser Principle).

Population inversion refers to the total amount of electrons (population) and inversion to a higher energy state of the electron. Electrons are intrinsically grounded. Inverted lasing needs a forcing function. High-energy electrons are needed for effective stimulated emission. More than ground level. Lasing is statistically conceivable only when there are enough stimulated electrons. The degree of population inversion and enhanced emission increase with electron energy. A flash lamp, laser, or electrical charge supplies energy for population inversion. Optical pumping uses this light source with lasers. The procedure performed for the step of inversion population can be clarified as seen in Figure 3.4 [60-63].

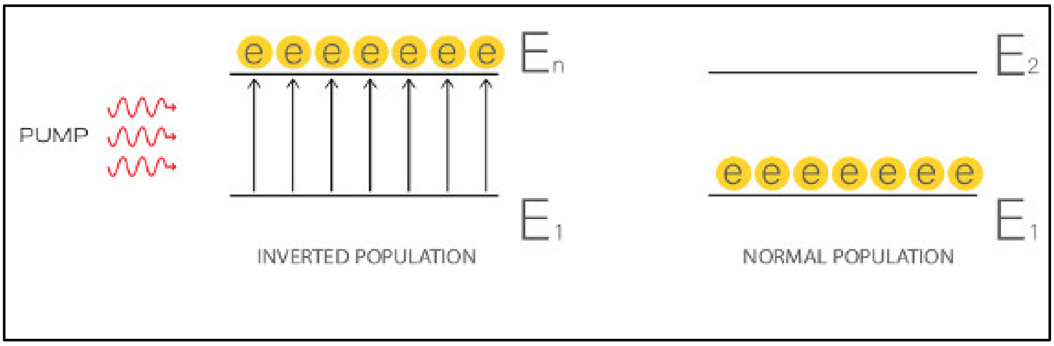

Figure 3.4: Inverse Population Step (Laser Principle).

Population inversion and stimulated emission cause amplification. Stimulated emission surpasses absorption with a population inversion. Because there are more electrons in an excited state of energy that create two photons per input photon. From four photons, 8, 16, and so on are formed. In this circumstance, optical amplification occurs. In a laser, an optical cavity encapsulates electron movement. The gain medium might be a solid, gas, or semiconductor junction. The principle of amplification can be seen in Figure 3.5 [60-63].

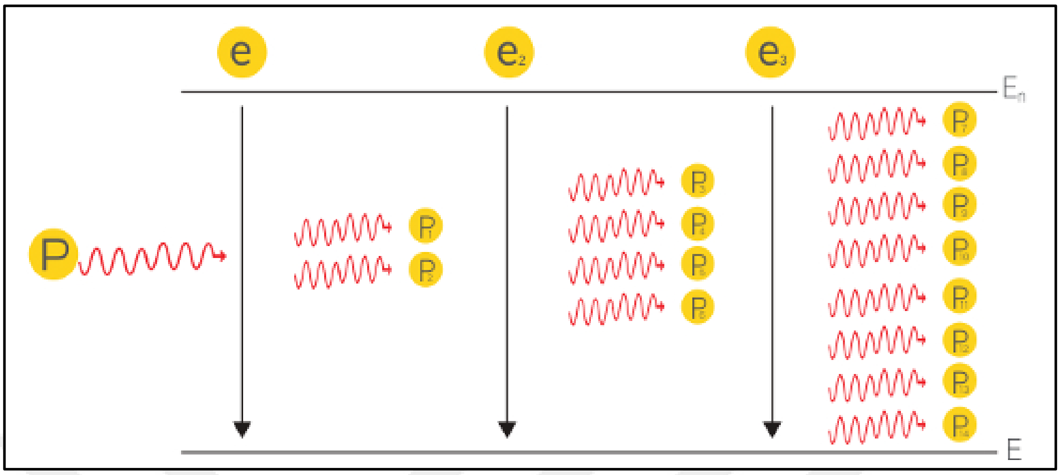

Figure 3.5: Amplification Step (Laser Principle).

However, to do so, following the principle of the conservation of energy, the excited electrons are required to let go of the energy that they received. They do this by emitting an energy particle known as a photon. The recently liberated photon has a highly precise vibrational frequency, which is determined by the degree of energy present at the time of the photon's liberation. There is a correlation between frequency and wavelength. The CW laser, on the other hand, is distinguished from ultrafast or pulsed lasers by the fact that it produces a continuous laser beam rather than a pulsed laser beam [60].

The distinction between a CW and a Pulsed Wave (PW) lies in the fact that the former refers to a beam that is always being released while the latter defines a laser that emits light in discrete bursts [61,62].

Throughout history, CW lasers are better in terms of their stability and power output, whereas brief laser pulses are incapable of sublimating materials with any degree of effectiveness. However, the stability of continuous wave lasers during operation durations ranging from a few microseconds to many weeks still makes them a competitive choice for industrial applications. Chirped Pulse Amplification (CPA) has substantially remedied this problem [62,63].

There are still several CW lasers on the market that employ crystals as gain media. Gain crystals made of titanium-sapphire, also known as Ti: sapphire, and Neodymium-Doped Yttrium Aluminium Garnet, also known as (Nd: YAG), are two of the most common types used in continuous wave systems. However, extensive research and development over many years has also resulted in the production of a multitude of gas and fiber lasers, considerably expanding the applications for continuous wave lasers. The general diagram that clarifies the different types of CW lasers can be seen in Figure 3.6 [60-63].

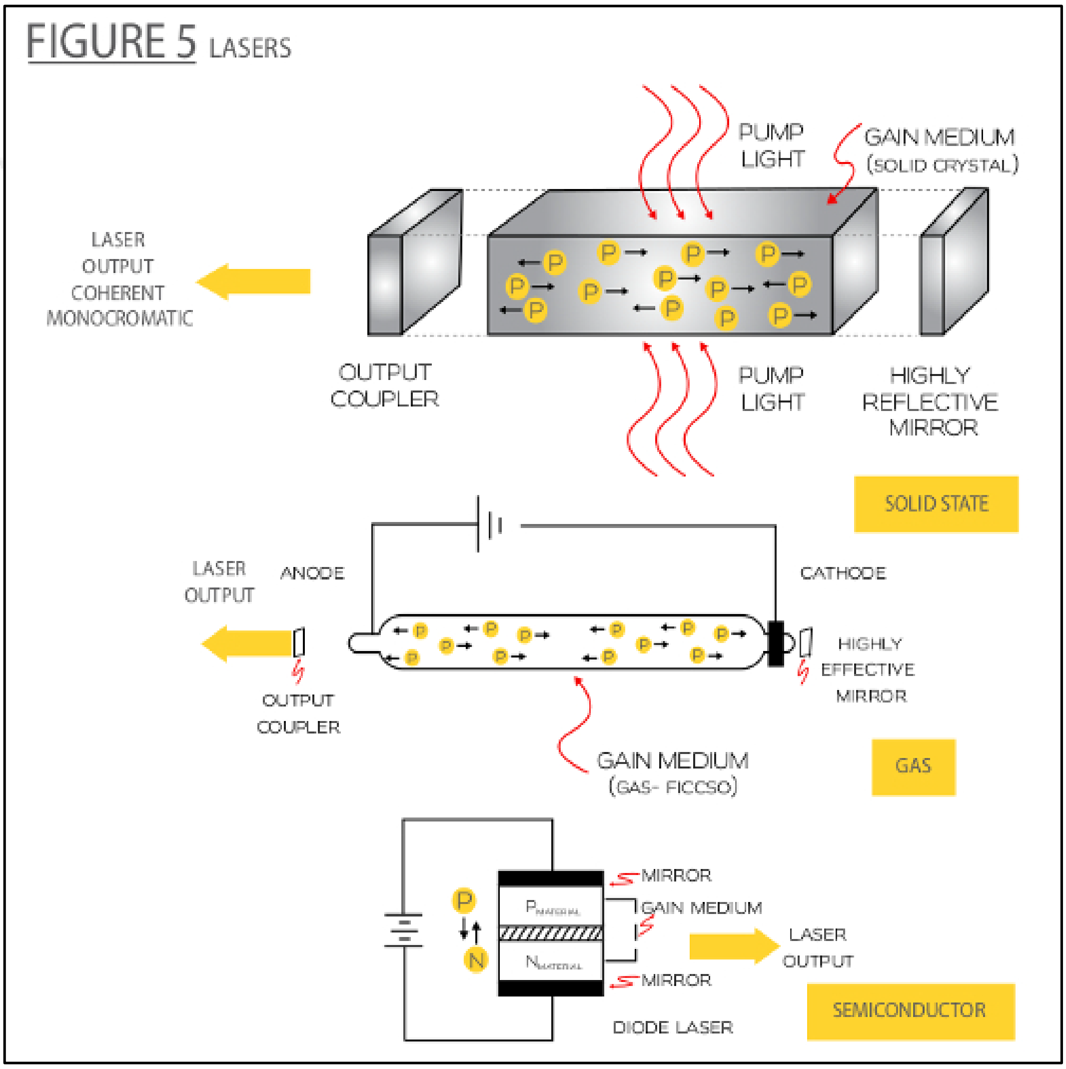

Figure 3.6: Different Types Of CW Laser.

b. Pseudo Random Bit Sequence (PRBS) Generator

A periodic, deterministic signal having features that are comparable to white noise is referred to as a Pseudo-Random Binary Sequence (PRBS). Another name for this signal is Maximal

Length Sequence (MLS). In many cases, a pseudo-random binary sequence may be generated by employing an n-bit shift register in conjunction with feedback provided by an exclusive or (XOR) function. The sequence may seem to be random, but in reality, it repeats itself after every 2n–1 value [66,67].

The pseudo-random binary sequence has certain mathematical benefits that make it appealing as a stimulus signal when applied across a whole period. These advantages make it possible for the sequence to be generated without any discernible pattern. Because of the periodic structure of the signal, differences in response signals between two periods of the stimulus might be attributed to noise. This is because model data is often used to test high-speed serial interface devices to emulate a mission mode. It is a bit stream that has been mathematically randomized, which ensures that the data is adequately neutralized and balanced. In addition to being used in pure digital functional testing, it is also used in mixed-signal functional tests in the capacity of embedded data in a modulation signal. An illustration of the PRBS waveform is shown in Figure 3.7 [66,67].

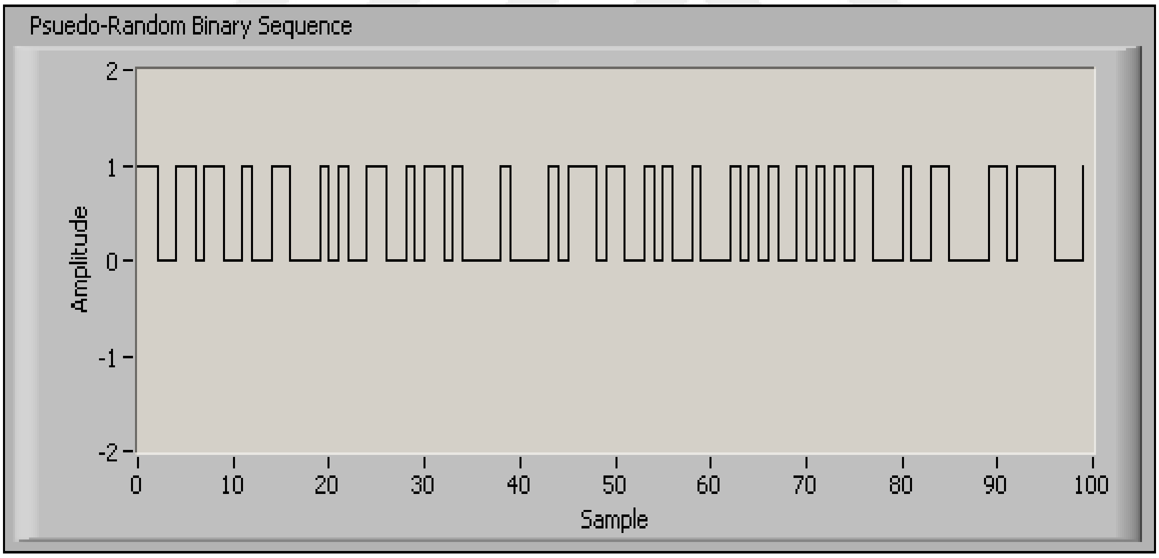

Figure 3.7: Example Of PRBS Waveform.

c. Pulse Generator

Electronic test equipment known as pulse generators are the devices responsible for producing pulses, most often in the form of rectangular pulses. These pulse generators have a broad range of uses, but the one in which they are used most often is as bench test equipment in the process of constructing different kinds of logic circuits. It is possible to utilize the pulse generators to produce pulses that can excite the logic circuit. When choosing pulse generators, it is necessary to know the product specs as well as the parameters. The pulse repetition rate, also known as frequency, is the typical number of pulses that occur during a certain amount of time for each unit of time. Pulse width, also known as pulse length, refers to the amount of time that elapses between the first and final times that the instantaneous amplitude reaches a certain percentage of the peak pulse amplitude [68-71].

The maximum and lowest voltages that a product is capable of producing are referred to, respectively, as pulse generator high-voltage and pulse generator low-voltage. Rise time is the amount of time that has passed since output began to increase from low levels as a result of the peak value. On the other hand, fall time is a measurement of how long it takes for a pulse's trailing edge to fall from a higher reference value to a lower reference value of amplitude. This is done by comparing the amplitude at the higher reference value to the amplitude at the lower reference value. When choosing pulse generators, one of the most crucial characteristics to take into consideration is the delay for both internal and external triggers [68-71].

The block diagram for a pulse generator is shown here in Figure 3.8. A monostable multivibrator, sometimes known as a one-shot oscillator follows a square wave. The frequency of the square wave determines the pace at which the pulse is repeated. A single output pulse was generated for each cycle of input by the one shot, which was triggered on the leading edge of the square wave. The length of time between each output pulse is determined by the one time of the one shot. This duration may be extremely brief, or it can come close to equalling the period of the square wave [71].

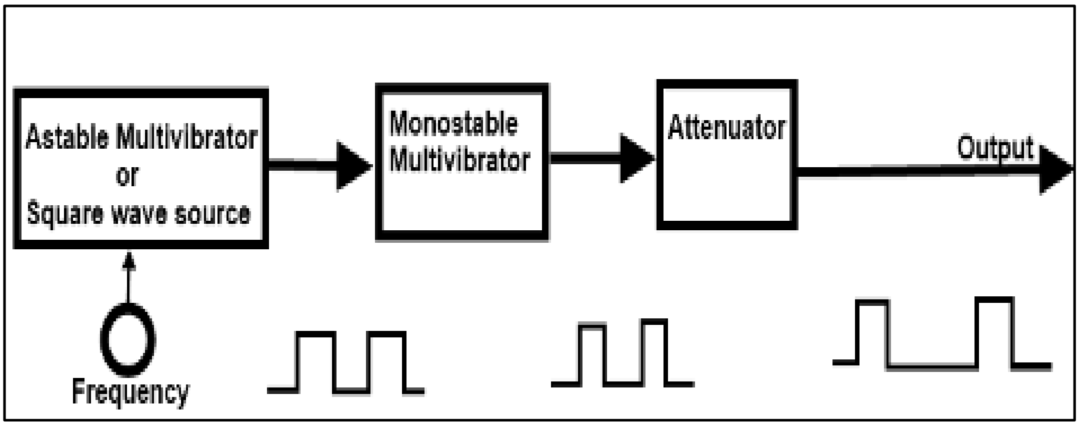

Figure 3.8: Block Diagram Of The Pulse Generator.

d. Mack Zander Modulator (MZM)

it is an interferometric structure that is constructed out of a substance that has a powerful electro-optical effect. 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.

Optical carriers are how 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 optical carriers. In a RoF-based system, the modulation method is the most important step in the process, since it is the one that requires the RF electrical signal to be used to modify the optical carrier signals. 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) [72-75].

Modulation may be broken down into two primary categories, which are [76].

a. Direct Modulation (DM): This DM-based approach, which is also referred to as the Intensity Modulation (IM) technique, directly modulates the amplitude of the laser beam depending on the input RF signal [76].

b. External Modulation (EM): In the EM-based technique, a specific device like MZM is used to modify the phase of the optical carrier. EM stands for external modulation. DM is good for affordable transmitters; however, it resulted in an unwanted chirp for the wavelength, which led to excessive CD at high speeds. Therefore, EM is favored since DM is ideal for inexpensive transmitters [76].

The lithium niobate (LiNbO3) model based MZM is the most attractive modulator for use in optical communication systems. Single Drive MZM (SD-MZM) and Dual Drive MZM (DD-MZM) are the two different types of MZM that are possible. After entering via the input pin, the optical wave is then divided in half and sent to each of the device's other two pins. The DD-MZM has a structure that is comprised of two arms and electrodes. MZM is applied to adjust the amplitude of the optical waves. When the bias is supplied to the two arms of the waveguide interferometer, a phase shift is created in the wave that is traveling through the arm as a result of the applied voltage. The input waveguide then divides into two waveguide interferometer arms. At the output of the MZM, the optical signal would recombine after passing through both arms of the interferometer. The phase difference between the two waves would then be translated into an amplitude-modulated signal [72-73].

Figure 3.9 presents the MZM structure for your viewing pleasure. After being separated into the upper and lower modulator arms, the optical input Ein is then subjected to phase modulation using two-phase shifters that are controlled by the electrical signals V1 and V2 before being recombined as the optical output Eout. Before we get into a more in-depth analysis of the implementation, let's take a look at a few of the MZM structures that have garnered a lot of interest as of late as a result of developments in Data Center Interconnect (DCI) technology and photonic integration. These breakthroughs have made it possible for more data to be transferred between data centers in a shorter amount of time [74].

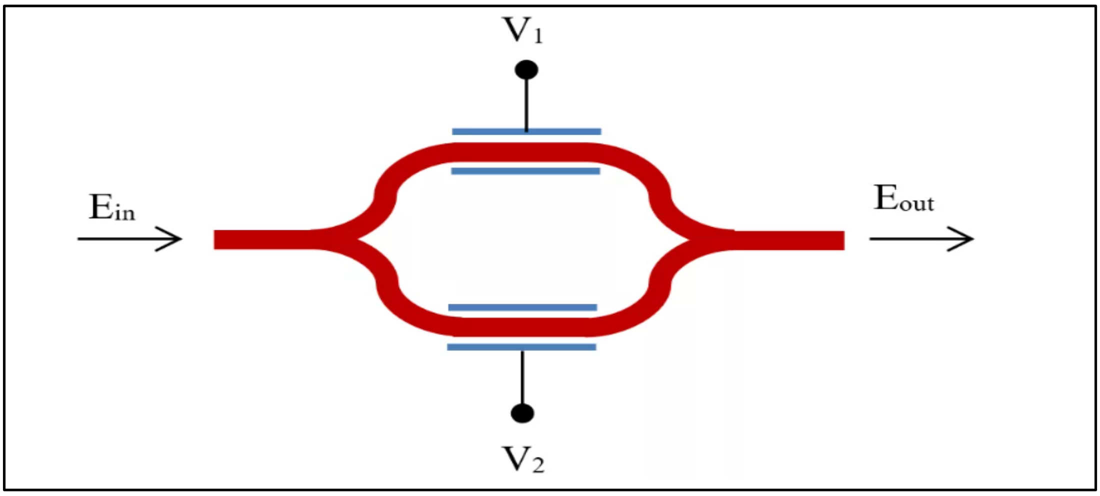

Figure 3.9: MZM Layout Structure.

e. Multiplexer (Mux)

A multiplexer, abbreviated as MUX, is a kind of network equipment that enables several analog or digital input signals to share the same communications transmission channel with other signals of the same type. Multiplexing is a technique that combines and transmits signals across a single common media to improve communication's overall efficiency while simultaneously lowering the total cost of that connection. One of the most exciting new applications of multiplexing is to new communications paradigms like 5G, in which varied hardware and setup capacity offer different forms of signal transport. This application is one of the most fascinating new uses of multiplexing. In the case of waveform multiplexing for 5G, for instance, this sort of multiple signal transmission may be optimized with the use of partial and full connection designs that make use of sub-arrays coupled to radiofrequency chains [77].

The utilization of tiny cell technologies that deliver wideband and multi-gigabyte speeds is described by industry experts as a means of providing support for data-intensive activities such as high-definition television and wireless gaming. They point out that digital beamforming architecture may be beneficial in downlink transmitters as well as other facets of mobile applications [77].

Multiplexing has a bright future in general, and this bright future is closely tied to the forms of connection that will allow for a greater variety of traffic to run on a particular hardware system. For example, Virtual Local Area Networks, often known as VLANs, are configurations that allow a physical Local Area Network (LAN) that is made up of several pieces of hardware to transport more than one bandwidth route through the network. Therefore, signals that are intended for various components are traveling along the same lines, and virtualization techniques are successfully managing their flow [77].

In the same way as multiplexing, demultiplexing creates a form of tunnel system where the multiplexer and the demultiplexer work together to complete each other's functions. This allows data to be transferred more easily between various pairs of equipment. In its most fundamental form, the concept of Mux is inextricably linked to the search for efficiency in telecommunications networks and other systems that share a common "pipeline" for data transmission. The vast improvements in communication technology that have occurred over the last several decades may be attributed to this kind of traffic management. Figure 3.10 shows an example of the Mux device [78].

Figure 3.10: Example Of The Mux Device.

3.3.2 Medium Part

This part will form the medium part of the proposed 80-channel DWDM RoF system which is responsible for performing the transmission over the optical fiber channel and improving such transmission via using the dedicated compensation technique along with using the powerful amplification. This part will include the following components:

a. Fiber Optic Cable

FOs are replacing copper wire organizations as the dominant form of media communication. An extremely thin piece of pure glass called an optical fiber serves as a waveguide for light over very long distances. It makes use of a technique called exhaustive internal reflection. The FO Link is made of two glass layers: the center, which transmits actual light, and the cladding, which is a layer of glass surrounding the center. The refractive index of the cladding is lower than that of the center. As a result, the center experiences intense interior reflection. The majority of filaments are duplex capable, meaning that one fiber is used for sending and the other for receiving. However, it is practical to transmit the two signs along a single strand. Single-mode fiber (SMF) and multi-mode fiber (MMF) are the two primary types of FO links. The size of the center is what matters most fundamentally. The center of MMF is significantly larger, allowing for the spread of a few different modes (or "beams") of light. SMF has a very thin center that permits only one type of light to propagate. Every type of fiber has unique qualities as well as benefits and drawbacks [79, 80].

FO cables are used because they have essentially infinite information capacity, great carrying capacity (extremely wide bandwidth, THz, or Tbits/s), very low transmission losses (0.2 dB/km, cf1 dB/km microwave, 10 dB/km twisted copper pair), and they do not dissipate heat. Other types of cables, such as microwave cables and twisted copper pair cables, do dissipate heat. Lastly, they are resistant to electromagnetic interference as well as crosstalk. Figure 3.11 demonstrate the general view of the FO cable with its internal parts [79,80].

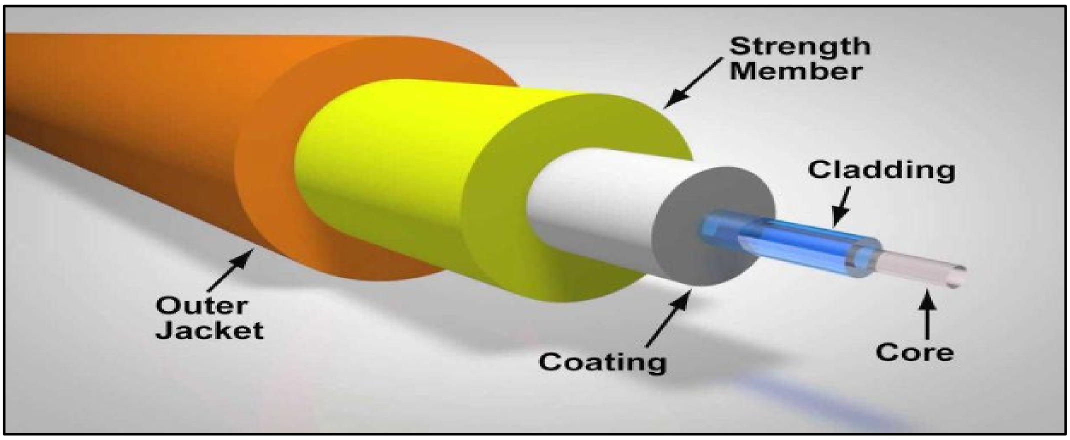

Figure 3.11: Internal Parts Of Fiber Optic Cable.

b. Erbium Doping Fiber Amplifier (EDFA)

Doping the fiber core when it's being manufactured is how one significant category of lumped optical amplifiers get their gain medium from rare-earth elements. This is done during the production process. Doped-fiber amplifiers were first investigated in 1964, but it wasn't until 25 years later that their application became feasible. This was because it took that long for the manufacturing procedures to be mastered. In these types of amplifiers, the dopants are responsible for determining features such as the working wavelength and the gain bandwidth, while silica serves as the function of the host medium. Erbium is the most practicable element among the rare-earth elements to produce fiber amplifiers working in the wavelength area of about 1.5 m. These amplifiers, known as EDFA, have been the subject of a significant amount of research. After 1995, their use in WDM systems brought about a revolution in fiber-optic communications and led to the development of lightwave systems with capacities of more than 1 terabit per second [82,83].

As can be seen in Figure 3.12, EDFAs may be used in an optical transmission line in a variety of roles, including those of a booster, inline amplifier, and preamplifier. To augment the amount of optical power that is sent down the transmission line, the booster amplifier is positioned immediately after the transmitter. The attenuation caused by the optical fiber is counteracted by the insertion of the inline amplifiers, which are located inside the transmission line. The pre-amplifier is positioned directly in front of the receiver to ensure that the receiver receives an adequate amount of optical power. The distance between each of the EDFAs is often measured in tens to hundreds of kilometers [82,83].

Before the development of EDFA, signal regeneration at the end of a lengthy optical fiber transmission line necessitated the use of a complex optical-to-electrical (O-E) and electrical-to-optical (E-O) converter. The need for such O-E and E-O conversion has been removed thanks to the implementation of EDFA, which has resulted in a major simplification of the system. This is particularly helpful in the case of a submarine optical transmission since it is possible that more than one hundred EDFA repeaters would be required to establish a single connection. The TPC-5CN (Trans-Pacific Cable 5 Cable Network), which was the first undersea optical fiber network to use EDFA and began operations in 1996, is also known as the "Cable Network." [82,83].

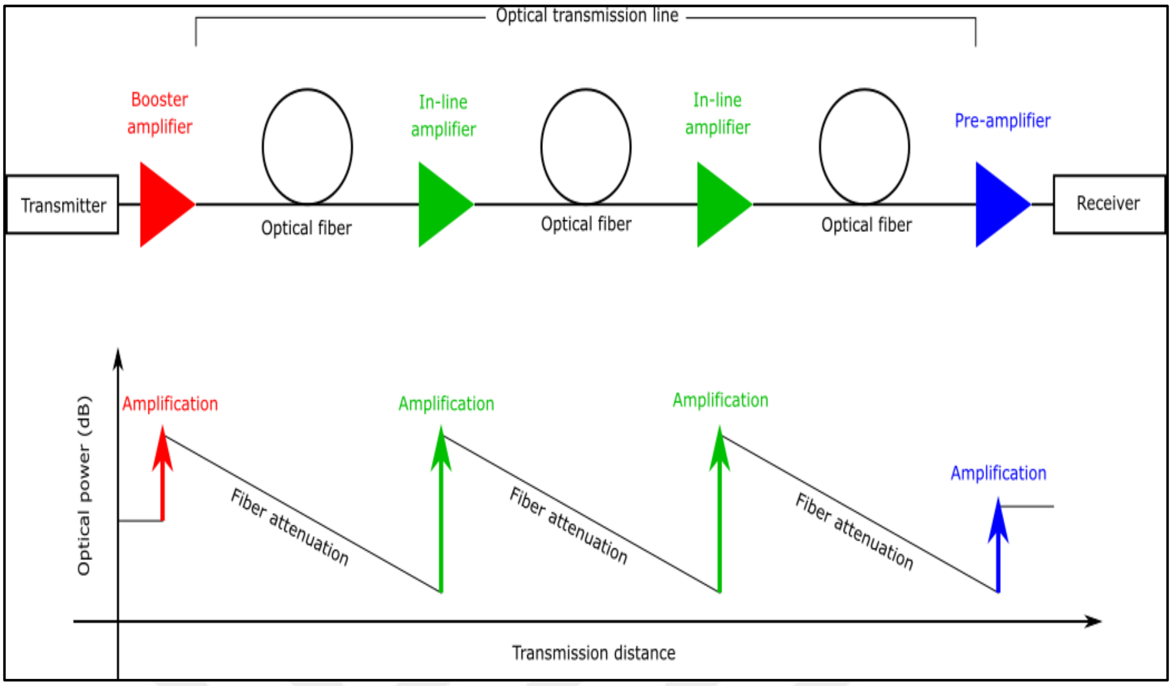

Figure 3.12: Booster, Inline, And Pre-Amplifier Edfas Used ın the Optical Transmission Line.

c. Dispersion Compensation Fiber (DCF)

It is feasible to make use of a fiber that has a significant amount of negative dispersion as part of the DCF strategy. This fiber would be used in combination with a standard fiber. By using a dispersion compensating fiber that has a very high value of the dispersion of the opposite sign in compared to that of normal fiber, it is possible to reduce the quantity of light that is dispersed by a regular fiber, and in certain situations, it may even be possible to eradicate it. The process of dispersion correction will often include the use of one of three methods (fiber-pre, post, or symmetrical), each of which is described in more detail down below. In addition, dispersion-compensating fibers are utilized extensively in the process of upgrading previously existent optical fiber networks that were intended for 1310 nm to be able to operate at 1550nm [85-87].

In a communication system that also includes dispersion compensating fiber, the overall dispersion is equal to zero since the positive dispersion of SMF is balanced out by the negative dispersion value of DCF. As a result, the total dispersion is equal to zero. This guiding principle is the basis for how the DCF does its business as shown in Figure 3.3

clarifying its three major types [86], there are three distinct approaches to considering dispersion within a compensation scheme: pre-compensation, post-compensation, and symmetrical compensation. Each of these approaches has its advantages and disadvantages. It is worth mentioning, that the proposed system of this thesis will consider the hybrid or what is well known as the symmetrical compensation due to many reasons of its effectiveness in handling the CD problems that occur with optical transmission-based data.

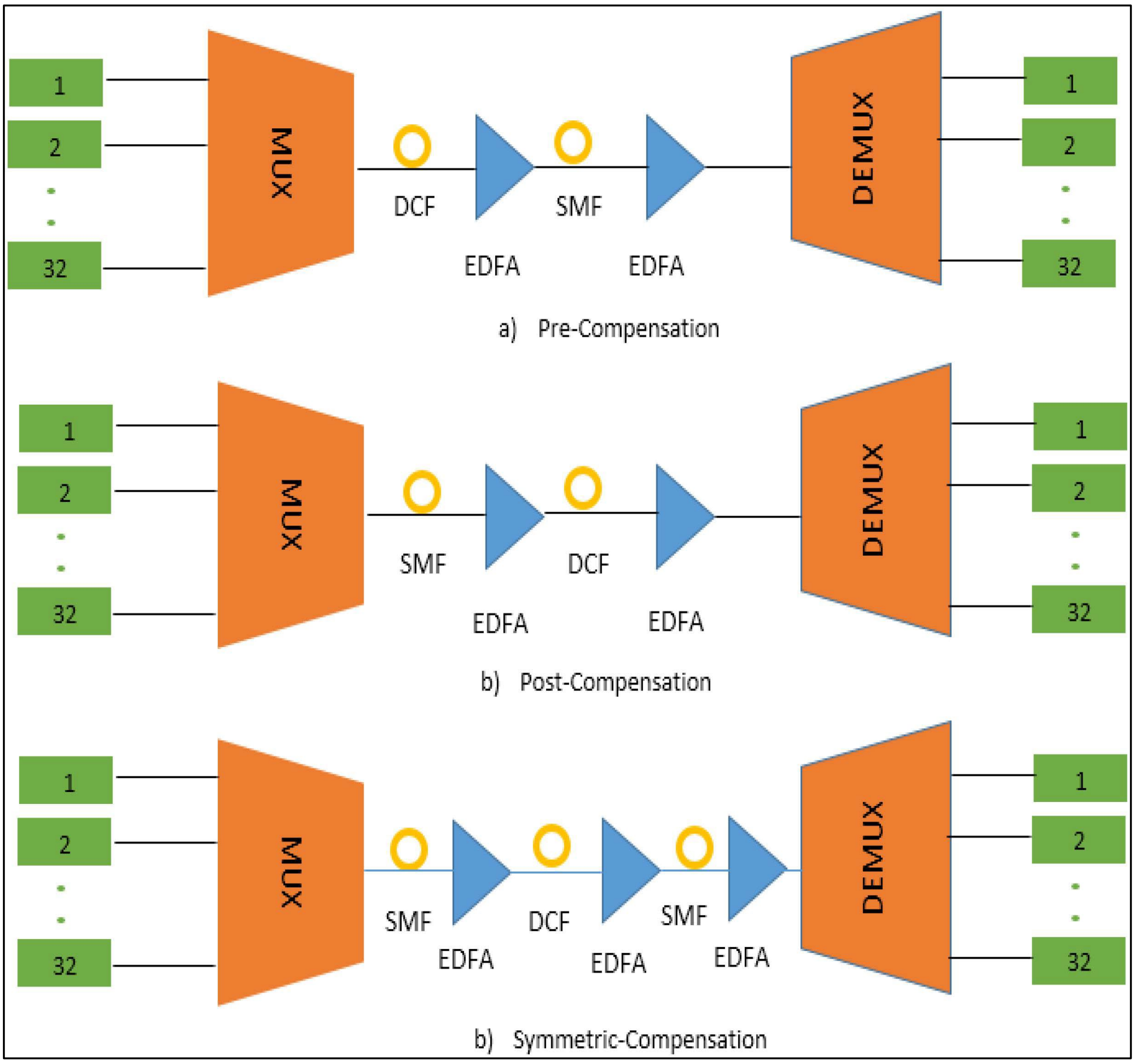

Figure 3.13: Types Of Dispersion Compensation Techniques Using The DCF.

3.3.3 Receiver Part

This part is consisting of the required component to perform the function of receiving the optical signal transmitted and then converting it back to an electrical signal via using the required dedicated tools. Additionally, in this part, all the required tools to analyze the proposed system and evaluate its performance are attached to this part as follows:

a. Demultiplexer (DeMux)

Multiplexers often need a receiving demultiplexer. These mux/demuxers maximize fiber cable consumption and save maintenance costs while carrying several traffic channels between sites. An inverted multiplexer, or demultiplexer, splits data into multiple lower-speed transmission lines. Inverse multiplexers have numerous linked output sources, whereas demultiplexers do not. Unlike a multiplexer, an inverse multiplexer breaks a high-speed connection into several low-speed ones. Demultiplexers merge multiple ISDN networks into a high-speed link. This is beneficial in areas without higher-speed circuits. A three-way inverted multiplexer that exchanges data. Each IP connection may send packets round-robin. Inverse multiplexing across several lines reduces latency, balances load, and simplifies networks. [88]

b. Photodetector (PD)

A photodetector is a kind of computer that works by transforming light into electric impulses. These impulses may then be multiplied and analyzed. The PD of any FO device is very important, just as much so as the optical fiber or light source. The output of a FO networking connection is susceptible to being impacted by PDs. The photodiode, which is based on semiconductors, is the detector that is used the most often in FO systems. Because of a variety of reasons, the most important of which are reduced expenses and a reduced environmental impact. In addition, as can be seen in Figure 3.14, the PIN PD is the kind of semiconductor that is used the vast majority of the time. The quantum performance, responsiveness, response speed, and bandwidth of PIN PD, as well as its Noise Equivalent Power (NEP), are all well-known qualities. [89].

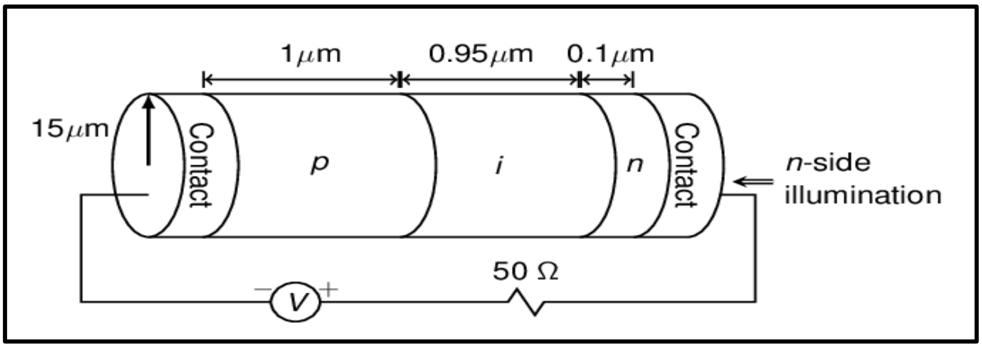

Figure 3.14: PIN Photodetector Type.

c. Filters

A circuit that sends out specific information signals based on their frequencies is known as a repetition-specific circuit. Another name for this kind of circuit is a channel. Depending on the type of channel being used, such recurrence signals may pass through a channel circuit with little to no constriction or some expansion, while other recurrence signals are diminished. In general, there are four different types of channels, as shown in Figure 3.15. The two types of ward branch channels that are most frequently used are optical and electrical branch channels. Additionally, each of these two divisions will have access to a wide variety of structures depending on the type of usage that is growing. Additionally, there are two fundamental categories of channels, known respectively as aloof and dynamic channels. These channels may no longer be grouped. Latent components, such as capacitors, resistors, and inductors, are used in the fundamental cycle of the design, negating the need for an external source of power. The subsequent kind, then again, will comprise both latent and dynamic parts, like semiconductors and functional speakers (Operation Amps) [90].

There is a wide assortment of programming and equipment that might be utilized to build channels. It is feasible to understand a similar exchange capability in more than one way. This suggests that while the channel's numerical characteristics are very similar, its actual characteristics are completely different. Parts in several innovations are frequently directly equivalent to one another and perform the same function in the channels that are clearly defined for each innovation. As an illustration, dampers, masses, and springs are mechanical concepts that are very similar to resistors, inductors, and capacitors found in electrical hardware. Dispersed component channels also include components that connect similarly [90].

One of the most basic uses for channels is in the field of correspondence. The recurrence division multiplexing technique is used by many correspondence frameworks. This technique distributes each data stream to a specific channel by splitting a large recurrence band into numerous smaller recurrence groups known as "spaces" or "channels." The individuals are responsible for designing the channels at each transmitter and recipient work to strike a balance between allowing the desired signal to travel as unambiguously as possible, minimizing interference from and to other cooperating transmitters and noise sources outside the framework, and doing all of this at an affordable cost [91].

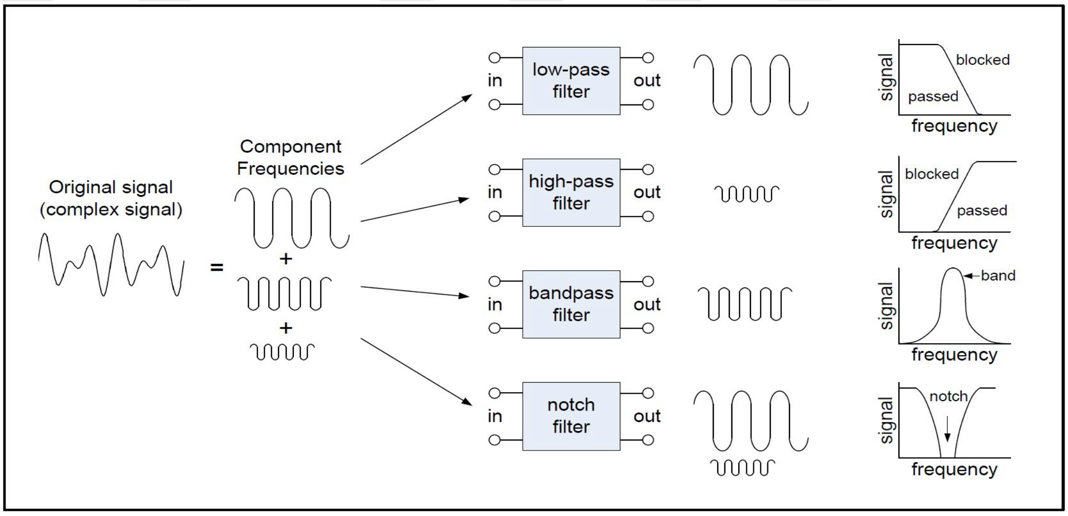

Figure 3.15: The Types Of Filters.

3.4 THE PROPOSED SYSTEM

This section will describe the required components that are used via using the program of Optisystem to form the proposed 80-channel DWDM RoF system as follows:

3.4.1 Transmitter Part

The transmitter part will include the following components, as shown in Figure 3.16:

a. CW laser device, which is used as a laser source and can specify the impact of input power, frequency spacing, and the starting wavelength to be attached to the 80-channel

DWDM RoF system. Notice that the input power is set to 0 dBm to reduce the impact of nonlinearity. Additionally, the channel spacing set for the originally proposed system was 100 GHz due to reasons related to spectrum efficiency and cost-effectiveness.

b. PRBS device, which is used as a binary generator to generate the data stream to be transmitted via the optical fiber communication cable. It is worth mentioning that each channel can transmit 25 Gbps of data, with a total capacity of 2 Tbps for the entire system.

c. pulse generator: which is used to generate the pulse and convert the data coming as a bit stream from the PRBS to a form shape. Note that this thesis has involved the investigation of the NRZ and RZ as modulation methods and a dedicated comparison between the two methods for optimum reliability.

d. MZM device: This is used to combine the two links from the pulse generator (electrical signal form) and the CW laser device (optical signal form). When they are combined, each channel of the 80-channel system will have an optical signal ready to send over the SMF cable. Notice that the impact of the ER plays a significant role in handling the successful combining of the optical and electrical signals, and this value was set to be equal to 30 dB for all the channels of the system.

e. The four mentioned components can be combined in the program of Optisystem via a single component block, known as the WDM transmitter, but when double-clicking on this component, all the required parameters can be found inside it with its dedicated tabs. These tools can be used to perform such a complex system with effectiveness and fewer components for easier layout design via the Optisystem program.

f. Mux device: this is the last device attached to the transmitter side, which occupies the function of combining the optical signals from each channel of the 80-channel system to merge and combine them.

The parameters set in this section with their dedicated values can be listed in Table 3.1.

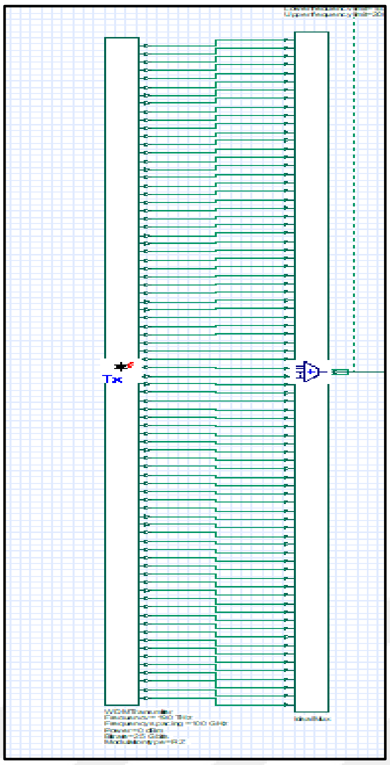

Figure 3.16: The Design Layout Of The Transmitter Part.

Table 3.1: The Values Set For The Transmitter Part.

parameter	value	unit
Number of output ports	80	
Frequency	190	THz
Frequency spacing	100	GHz
Power	0	dBm
Extinction ratio	30	dB
Linewidth	0.1	MHz
Initial phase	0	deg
Bit rate	25	Gbit/s
Modulation type	varied	
Bit rate	2.50E+10	bit/s
Time window	2.56E-09	s
Sample rate	6.40E+12	Hz
Sequence length	64	Bits
Samples per bit	256	
Symbol rate	1.00E+10	symbols/s
Number of samples	16384	
Reference wavelength	1550	nm

3.4.2 Medium Part

As has been mentioned, this part is responsible for the mission of performing optical transmission of the combined data rate from each channel via the Mux device. As a result, in this part, the following components are used, as shown in Figure 3.17:

a. SMF tool: This is used to simulate the function of the optical cable, which can be set for transmission at various distances. Notice that the data gathered from the Mux device in the transmitter part will be transmitted over the SMF cable, the values set for the attenuations can be selected from inside this component. It is worth mentioning that the set distance ranged between 60 and 300 km.

b. DCF tool: is a type of FO cable that can be used as a complementary part of the optical cable and has the major mission of reducing the impact of CD by adding negative dispersion values.

c. EDFA: is a type of amplifier that can be used effectively with the DWDM-based system and has the mission of boosting the transmitted signal. The demonstration set of the three mentioned components formed in this part can be followed based on the dispersion compensation technique, where in this thesis it has been designed based on utilizing the symmetrical type of compensation. The values set for each parameter mentioned in this part can be seen in Table 3.2. Notice that the other parameters that are not mentioned were set to their default values specified by the program of Optisystem v. 19. Finally, it can be noticed that a loop control tool is used to control the transmission distance by varying the number of loops, which will double the transmission distance each time.

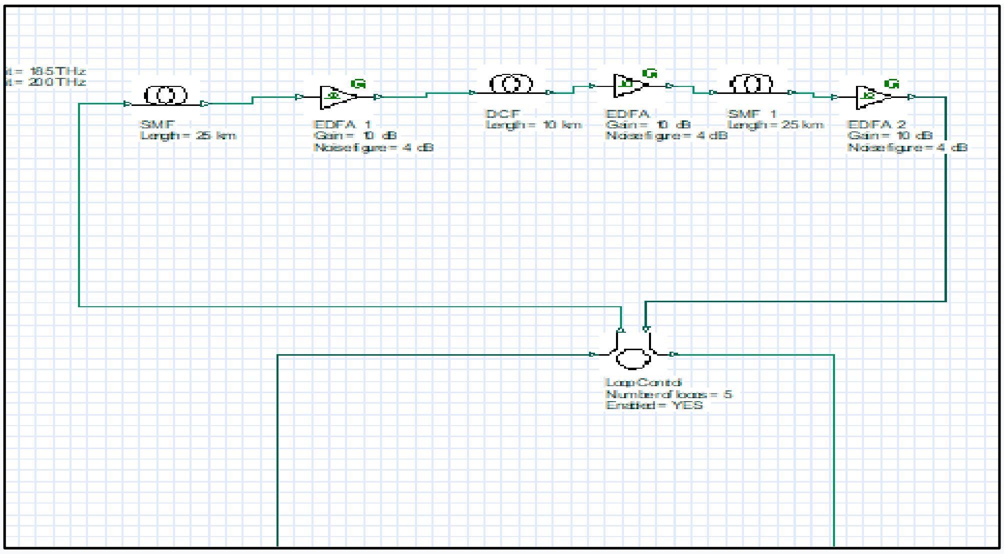

Figure 3.17: The Design Layout Of The Medium Part.

Table 3.2: The Values Set For The Medium Part.

parameter	value	unit
Length SMF	25	km
Attenuation effect	1	
Attenuation data type	Constant	
Attenuation	0.2	dB/km
Group velocity dispersion	1	
Third-order dispersion	1	
Operation mode	Gain Control	
Gain	10	dB
Power	10	dBm
Saturation power	10	dBm
Saturation port	Output	
Include noise	1	
Noise figure	4	dB
Length DCF	10	km
Attenuation effect	0	
Attenuation data type	Constant	
Attenuation	0.5	dB/km

3.4.3 Receiver Part

This part will include the components that are used to receive the transmitted optical signal and then convert it back to an electrical signal via the dedicated photodetector, which is then handled with the dedicated filter to shape it and remove the unwanted part of the signal. Finally, the required analyzer tools are used to evaluate the performance of the proposed DWDM RoF system. The components in the layout of this part can be seen in Figure 3.18. The required components that are used in this part are as follows:

a. A Demux device consists of a 1x80 to handle the 80 channels of the proposed DWDM RoF system. This device aims to handle the separation of the transmitted data and separate it into 80 channels.

b. After separating the channels, each channel will be handled individually, where the first device to be used is the photodetector of type PIN with a gain of 3 dB, which can achieve the mission of converting the optical signal back to an electrical signal. The most important parameter used in this part is specifying the starting frequency attached to the same channel, which should be the same frequency used in the Mux on the transmitter side. Also, the same frequency spacing should be attached to the DeMux. Additionally, the bandwidth is important to be specified in this part, which can play a major role in handling the transmission of the specified data rate.

c. filter: which is used to handle the mission of spacing the signal and cutting the unwanted part of the received signal from each channel. It is worth mentioning that the type of filter used in this mission is the Bessel filter with an order of 2. The parameter values set for these part-based components are listed in Table 3.3.

d. Notice that all three of the components mentioned above can be combined into a single component provided by the recent version of the utilized optical system, which is known as the optical receiver.

e. The final component used in this part is the BER analyzer to serve the mission of handling the evaluation and analyzing the data received based on different metrics of QF, BER, and eye diagrams.

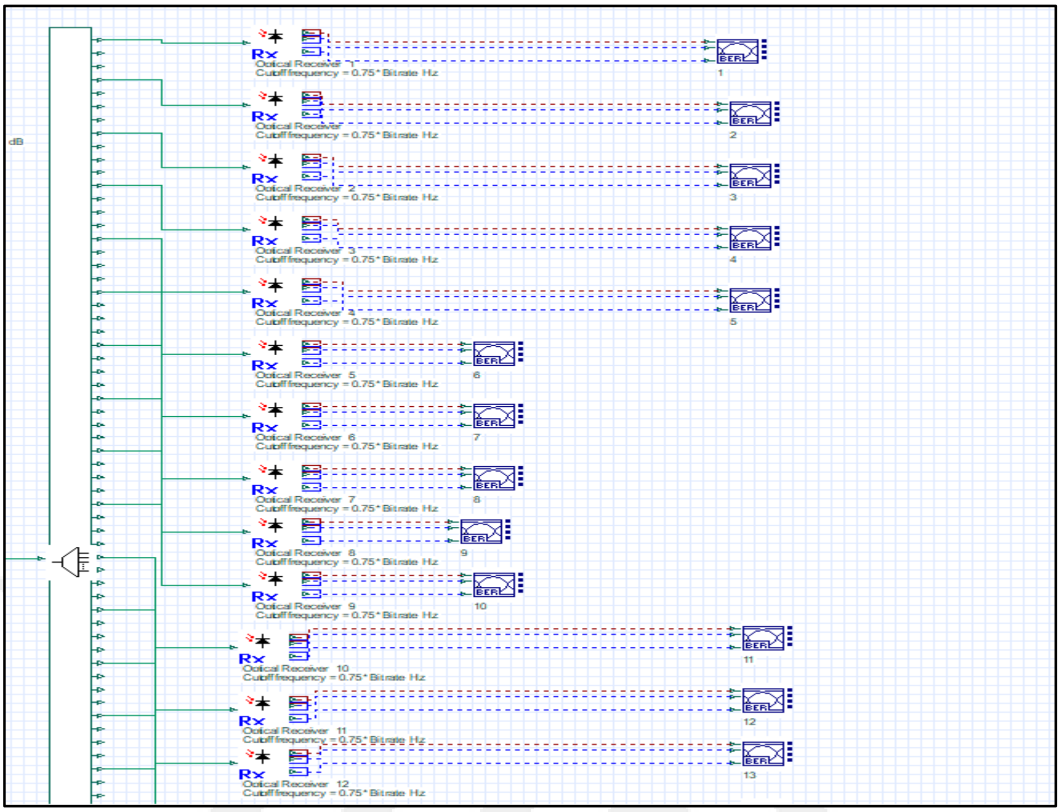

Figure 3.18: The Design Layout Of The Receiver Part.

Table 3.3: The Values Set For The Receiver Part.

parameter	value	unit
Number of output ports	80	-
Frequency	190	THz
Frequency spacing	100	GHz
Bandwidth	80	GHz
Insertion loss	0	dB
Depth	100	dB
Filter type	Bessel	-
Filter order	2	-
Photodiode	PIN	-
Gain	3	-
Responsivity	1	A/W
Dark current	10	nA
Cutoff frequency	0.75 * Bit rate	Hz
Insertion loss	0	dB

The entire system design modeled by using the Optisystem can be seen in Figure 3.19. It is worth mentioning, that 21 channels among the 80-channel system will be selected as a sample for the analysis stage to evaluate the performance of the proposed system.

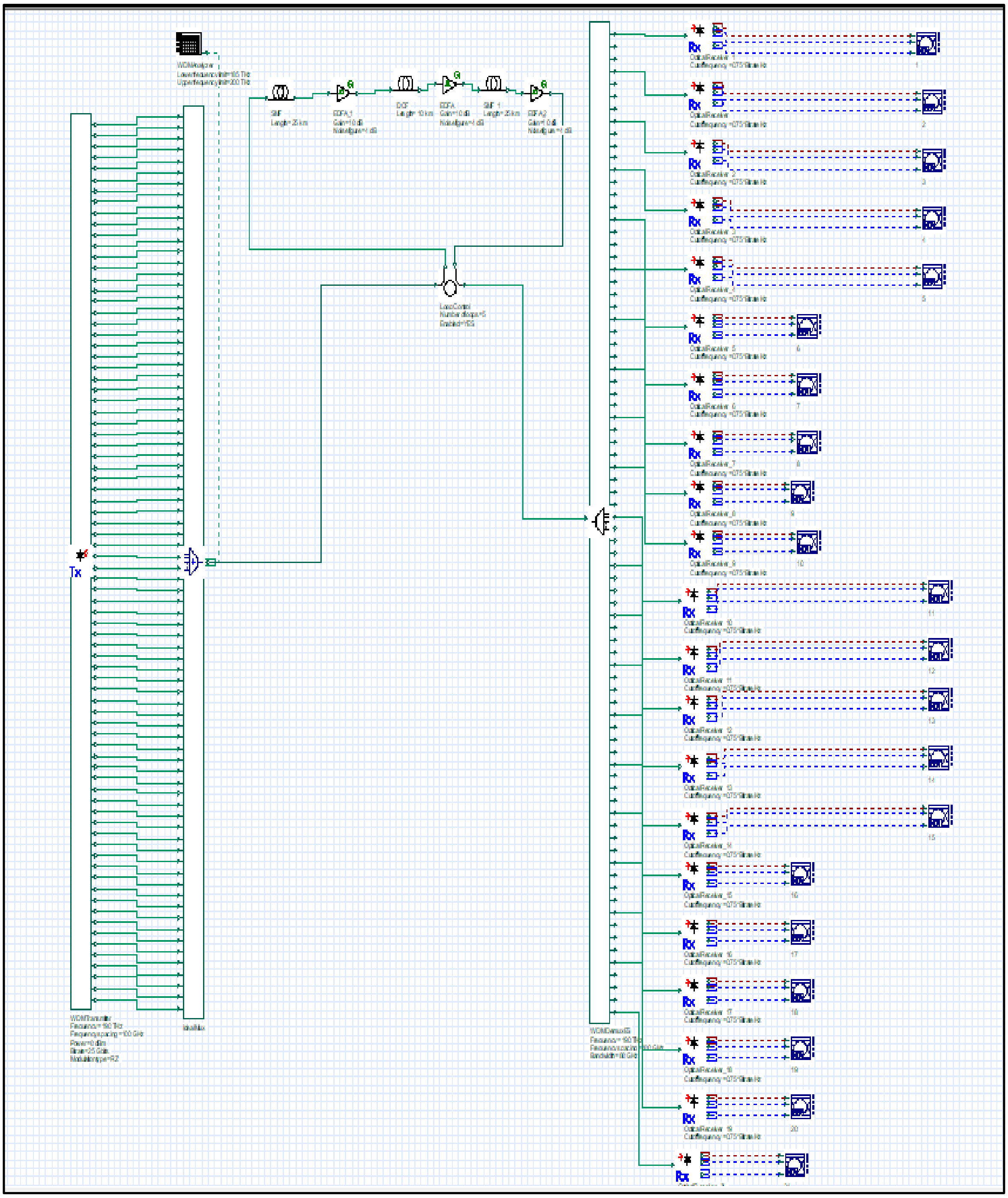

Figure 3.19: The Entire System Design Using The Optisystem Program.

Finally, the methodology carried in this thesis can be clarified in Figure 3.20

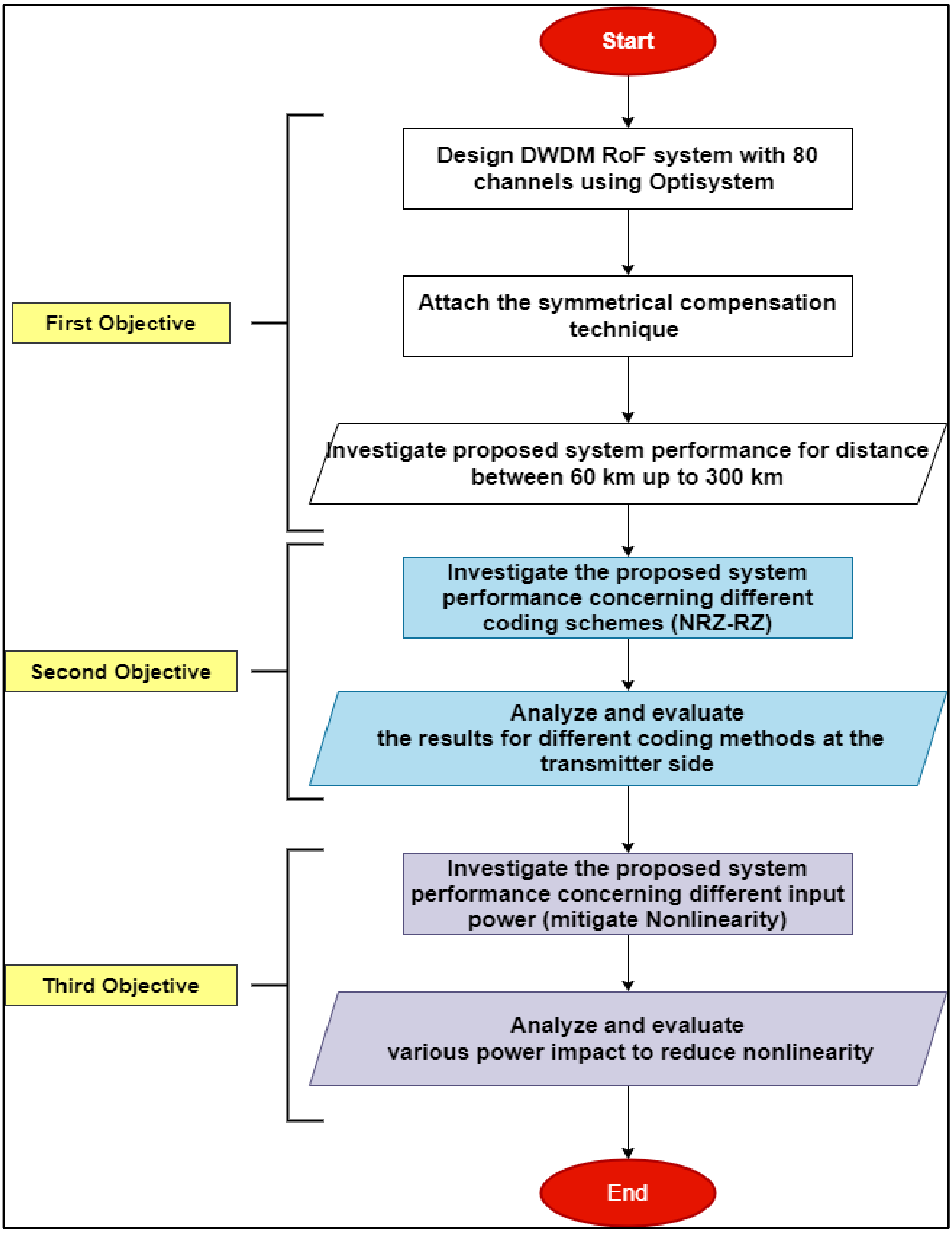

Figure 3.20: The Methodology Of The Proposed System.

3.5 STUDIED PARAMETERS

This section will include the parameters to be utilized to evaluate the performance of the proposed system as follows:

3.5.1 Bit Error Rate (BER)

is a proportion of the trustworthiness of a media transmission signal that depends on the sum or level of pieces that have been moved but have been gotten mistakenly. Fundamentally, the impact on signal quality is relative to the number of mistaken bits that are sent. The digit blunder rate is a helpful proportion of the presentation of the entire start-to-finish framework since it thinks about the collector and the transmitter as well as the medium in the middle between them. Still up in the air by separating the whole number of pieces broadcast within the very measure of time by the number of pieces that were gotten with a blunder. It is broadly agreed that a piece blunder pace of 10–9 is satisfactory for broadcast communications; in any case, a base BER of 10–13 is more qualified for the exchange of information. It is likewise conceivable to depict the rate as a likelihood (Pe) of missteps occurring from now on, given that an adequate degree of certainty is laid out in the rate. A solid piece mistake rate analyzer ought to have the option to do support enactment testing for an assortment of key execution markers (KPIs) [92, 93].

The BER is the proportion of bits that are sent from one active device to another that are sent wrongly relative to the total number of bits sent within a certain amount of time. During BER testing, actual samples of data are sent via the relevant protocol. The BER test will demonstrate the actual performance of the network in real-world scenarios, considering all of the active components. On the other hand, the normal electrical tests that are carried out on the permanent link or channel will offer performance numbers for the cable and the passive components, but they will not include the active equipment. Near-End Crosstalk, Attenuation, Return Loss, and Delay are only a few of the factors that are tested as part of a permanent connection's or channel's typical set of parameters [92,93].

The benefit of doing a test to determine your cable network's bit error rate is that it will demonstrate how well your cable network operates when combined with your active equipment. It is not unheard of for a cable network that barely passes to display bit errors when used in conjunction with active equipment of lesser grade. The electrical margin that is built into cables and communication items that perform better helps to mitigate the effects of issues like these [92,93].

3.5.2 Quality Factor (QF)

The concept of value components might be utilized in a wide assortment of subfields within the fields of material science and design. The letter Q is utilized to address it, and now and again, individuals might allude to it as the QF. The QF is a dimensionless boundary that addresses the energy misfortunes inside a full component, which may be anything from a mechanical pendulum to a component in a mechanical design or even inside an electronic circuit like a resounding circuit. The QF estimates how much energy is lost inside the resounding component [94, 95].

Even though it is connected with misfortunes, the Q variable of a component is straightforwardly associated with the transfer speed of a resonator about its middle recurrence.

The value of Q addresses the amount of energy that has been lost in contrast with the aggregate sum of energy that has been put away in the framework. In this way, a more prominent Q brings about a lower pace of energy misfortune, and as a result, motions will vanish all the more progressively, implying that they will have a low measure of damping and will keep on ringing for a more extended period.

With regards to electrical circuits, the opposition is the guilty party behind any energy misfortunes that happen inside the circuit. Although this can occur somewhere else inside the circuit, the inductor is where most of the opposition is produced [94, 95].

3.5.3 Eye Diagram (ED)

Eye diagrams are an extremely useful tool for swiftly and intuitively evaluating the quality of a digital signal. They have had a great deal of success in this regard. An eye that has been created correctly should include every conceivable bit sequence, ranging from the straightforward 101s and 010s to the solitary ones that come after lengthy runs of zeros consecutively, as well as other difficulty sequences that often reveal flaws in the system's architecture [96].

Eye diagrams provide information on the signal's parameters, including effects arising from physical laws such as the state of the system's bandwidth and so on. It will not indicate any protocol or logical errors; for example, if logic 1 seems to be in good health, the fact that the system intended to communicate a zero will not be revealed by this. If, on the other hand, the physics of the system dictates that a logical one will get so distorted as it is traveling through the system that the receiver at the far end would mistake it for a zero, then this should be illustrated in a proper eye diagram. The eye diagram forming from the bit sequence can be seen in Figure 3.21 [97].

To think about the gadgets that are being tried, standard strategies for characterizing an eye incorporate estimating the ascent times, fall times, jitter at the focal point of the intersection point of the eye, and the overshoot that is available. Other mathematical depictions of eye action may likewise be evaluated. Instruments give mechanized measures, which make the most common way of gathering such estimations simpler and more catalyst.

Although eye diagrams provide a clear and straightforward perspective on parametric performance, in the end, systems are evaluated based on their capacity to transfer bits reliably and successfully without making any errors. The BER, on the other hand, is a ratio that is calculated by dividing the number of bits that were received wrongly (errors) by the total number of bits that were received. This gives an overall score for how well a system is doing, but it doesn't offer much assistance in understanding why performance could be below expectations. It is important to note that the BER test examines logical issues in addition to parametric issues, such as whether the appropriate bit was sent in the first place [97,98].

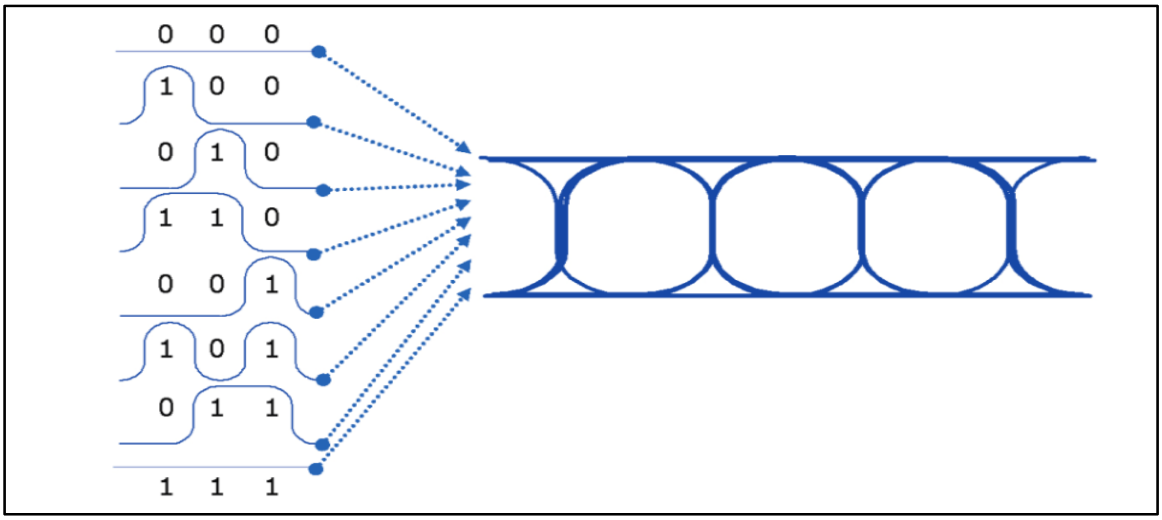

Figure 3.21: Forming The Eye Diagram From Bit Sequence.

4. RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This chapter will include the analysis and evaluation of the obtained results from the Optisystem program for the proposed 80-channel DWDM RoF system with symmetrical compensation. To start with, the results of the originally proposed system will be analyzed and evaluated concerning different parameters of QF, BER, eye diagram, eye closer, eye-opening factor, and eye extinction ratio, which will match the first objective mentioned in the first chapter. After that, an investigation of the utilization of different coding schemes will be carried out to quantify the optimum coding method to be utilized with the proposed system. Such an investigation will meet the second objective of this thesis. Finally, an investigation for the optimum input power will be carried out to evaluate the performance of the proposed system with different power levels to mitigate the impact of nonlinearity effects that might occur when transferring data over FO cables. Such a procedure will meet the third objective of the proposed methodology in this thesis.

4.2 PROPOSED SYSTEM RESULTS

In this section, an evaluation of the proposed 80-channel DWDM RoF system using the technique of symmetrical compensation to handle the problem of CD is carried out. The proposed system is evaluated with different transmission distances up to 300 km and based on different parameters. The selected power for the CW laser was 0 dBm, and the coding scheme set is NRZ. The analysis will be carried out based on the results obtained from the BER analyzer for each of the selected sampled channels, which are 21 channels among the 80-channel system.

4.2.1 QF Results

This parameter is studied concerning the 21 samples of the proposed 80-channel system and based on five cases of distances up to 300 km. The analysis of these parameter results is shown in Table 4.1 and Figure 4.1. The results obtained indicate a reverse relation, as raising the distance will reduce the impact of the signal received quality, and this is due to many reasons related to increasing the impact of attenuation and nonlinearity.

In addition to that, the recorder average QF obtained is 19.9734 dBm, 14.5989 dBm, 13.5643 dBm, 10.4605 dBm, and 9.577 dBm for distances of 60 km, 120 km, 180 km, 240 km, and 300 km, respectively. As a result, indicating reliability in handling successful transmission for 300 km, the averaged obtained results were above the QF threshold of 6 dBm. Furthermore, analyzing the QF per channel of the proposed 80-channel system is demonstrated in Figure 4.2

Table 4.1: QF Results Obtained For Different Distances Using Power 0 Dbm And NRZ Coding.

Channel\ distance	**QF values for different distances (NRZ) coding**				
	60 km	**120 km**	**180 km**	**240 km**	**300 km**
1	24.051	17.7935	15.1635	12.1331	11.5102
4	22.3529	14.691	13.5785	10.5093	10.05942
8	18.6709	14.7754	13.6948	10.5439	9.93699
12	18.8164	13.8276	13.1863	9.7501	9.40157
16	15.8787	14.4742	14.2586	11.0955	10.4104
20	17.8851	12.8325	12.6146	9.51473	9.58682
24	18.672	14.306	14.1312	11.3138	10.6002
28	17.9502	13.1691	13.5649	10.0421	9.1112
32	18.3066	13.7894	12.7889	10.76397	9.5902
36	17.8988	12.5383	10.9606	9.30373	8.43176
40	17.7274	12.691	11.7555	9.0494	8.69415
44	18.1651	14.0287	13.59	11.53154	10.1252
48	17.345	13.5641	12.0441	9.88727	8.02799
52	22.1908	15.1764	13.7151	10.2058	9.68251
56	28.4525	17.5825	15.6585	10.82207	9.9509
60	17.589	13.7544	13.0386	9.58767	8.78063
64	18.3084	14.7542	13.5751	10.82525	9.603
68	23.791	15.3359	13.9815	10.3466	9.2678
72	18.5283	13.9981	13.1699	9.800448	9.091757
76	18.2224	13.7684	13.1143	9.70633	9.12067
80	28.639	19.7264	17.2676	12.9394	10.1484

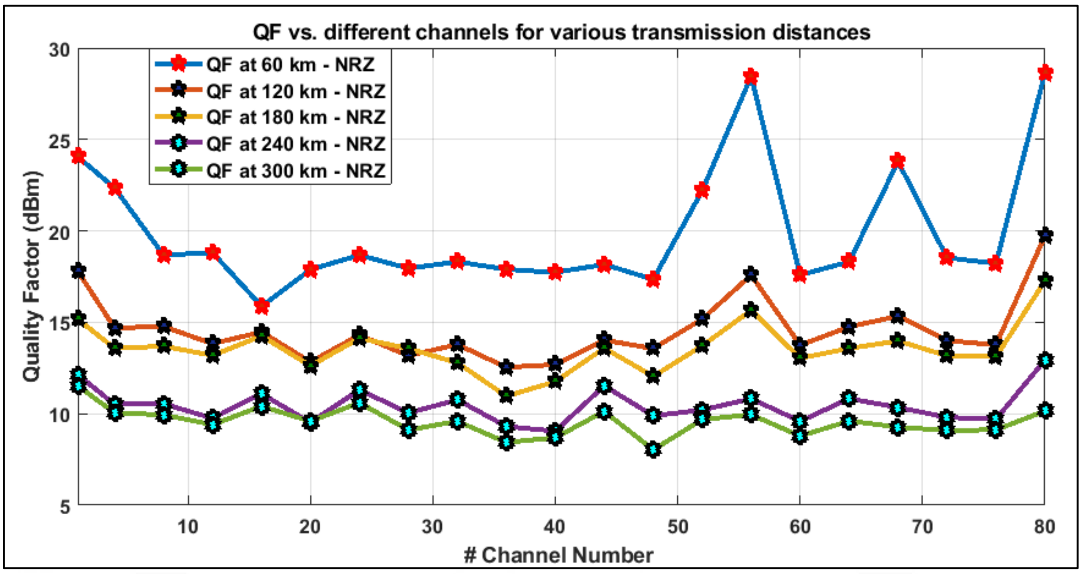

Figure 4.1: QF Vs. Different Distances Using NRZ And Power 0 Dbm.

4.2.2 BER Results

This parameter is studied concerning the same five sets of distances, to show the impact of errored data transmitted under different distances. This parameter is analyzed, and the obtained results were listed in Table 4.2 and drawn in Figure 4.3.

From the analysis of this parameter, it can be noticed a direct relation as raising the distance will increase the error in the transmitted bits due to reasons related to increasing the attenuation and distortion in optical transmission. The averaged BER obtained from the rive set of transmission distances were 2.11E-58, 1.26E-37, 1.40E-29, 7.19E-20, and 2.34E-14 respectively. Additionally, the analysis of BER concerning individual sampled channels can be seen in Figure 4.4 to demonstrate and impact of distances on BER performance for the proposed system.

Table 4.2: BER Results Obtained For Different Distances Using Power 0 Dbm And NRZ Coding.

Channel\ distance	BER values for different distances (NRZ) coding				
	60 km	120 km	180 km	240 km	300 km
1	4.05E-128	3.97E-71	3.04E-52	3.41E-34	5.84E-29
4	5.65E-111	3.49E-49	2.68E-42	3.91E-26	1.58E-22
8	4.25E-78	1.06E-49	5.39E-43	2.70E-26	1.43E-21
12	2.76E-79	8.67E-44	5.24E-40	8.89E-25	2.02E-21
16	4.44E-57	8.76E-48	1.98E-46	6.57E-29	1.10E-25
20	7.68E-72	5.38E-38	8.76E-37	8.74E-27	4.43E-20
24	4.18E-78	1.00E-46	1.22E-45	3.01E-27	1.48E-19
28	2.39E-72	6.60E-40	3.20E-42	4.86E-24	2.43E-19
32	3.66E-75	1.47E-43	9.33E-38	7.85E-30	4.33E-22
36	5.90E-72	2.28E-36	2.93E-28	5.04E-21	1.69E-17
40	1.29E-70	3.24E-37	3.23E-32	7.17E-22	1.75E-18
44	4.84E-74	5.20E-45	2.27E-42	7.64E-29	2.13E-24
48	1.06E-67	3.26E-42	1.03E-33	1.49E-18	4.92E-13
52	2.10E-109	2.41E-52	4.12E-43	9.08E-25	1.76E-22
56	2.27E-178	1.57E-69	1.41E-55	4.46E-28	3.28E-23
60	1.49E-69	2.40E-43	3.64E-39	4.45E-29	6.77E-23
64	3.54E-75	1.44E-49	2.75E-42	4.29E-33	1.43E-26
68	2.07E-72	2.07E-53	1.01E-44	2.13E-28	4.87E-25
72	6.10E-77	8.00E-45	6.51E-40	1.06E-22	8.77E-19
76	1.71E-74	1.97E-43	1.36E-39	1.66E-20	1.45E-20
80	1.09E-180	6.39E-87	4.01E-67	3.62E-28	2.91E-24

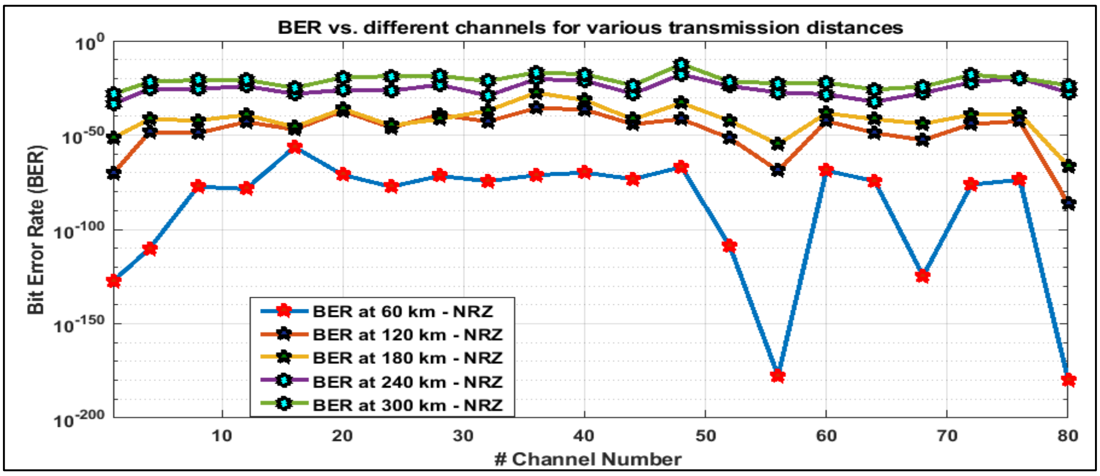

Figure 4.2: BER Vs. Different Distances Using NRZ And Power 0 Dbm.

4.2.3 Eye Closer Results

When attempting to illustrate the performance of the proposed system on a specific channel, it is a very significant parameter to consider. It is good knowledge that dispersion correction, often known as DC, is an effective method for lowering the eye closure penalty in fiber systems that is caused by chromatic dispersion. As a consequence of this, analyzing such a parameter is highly necessary to assess the suggested system. As can be seen in Figure 4.5, this parameter is evaluated over a distance of 300 km.

4.2.4 Eye-Opening Factor Results

It is a very important factor to evaluate the performance of the proposed system in terms of eye height and the opening value which will represent the difference in eye-opening with raising the distance which can be visualized as seen in Figure 4.6. It can be noticed that raising the distance can affect eye-opening which will reduce it and that means increasing the number of bits that are received incorrectly. It is worth mentioning, that this parameter is analyzed concerning the 21 sampled channels of the proposed system.

4.2.5 Eye Extinction Ratio Results

is a ratio that describes the relationship between the one level and the zero level of an eye diagram representing an optical signal. Offsets, including the dark level, that are formed inside the instrument electronics, often after the photodiode, have the potential to impact negatively the accuracy of the extinction ratio measurement. The addition of offsets causes a change in the relative values of the one and zero levels in the incoming signal. This may make the measurement result lower or higher. First, carry out a dark calibration to reduce the amount of extinction ratio measurement errors brought on by offsets. This parameter plays an important role in the assessment of the proposed system, as shown in Figure 4.7.

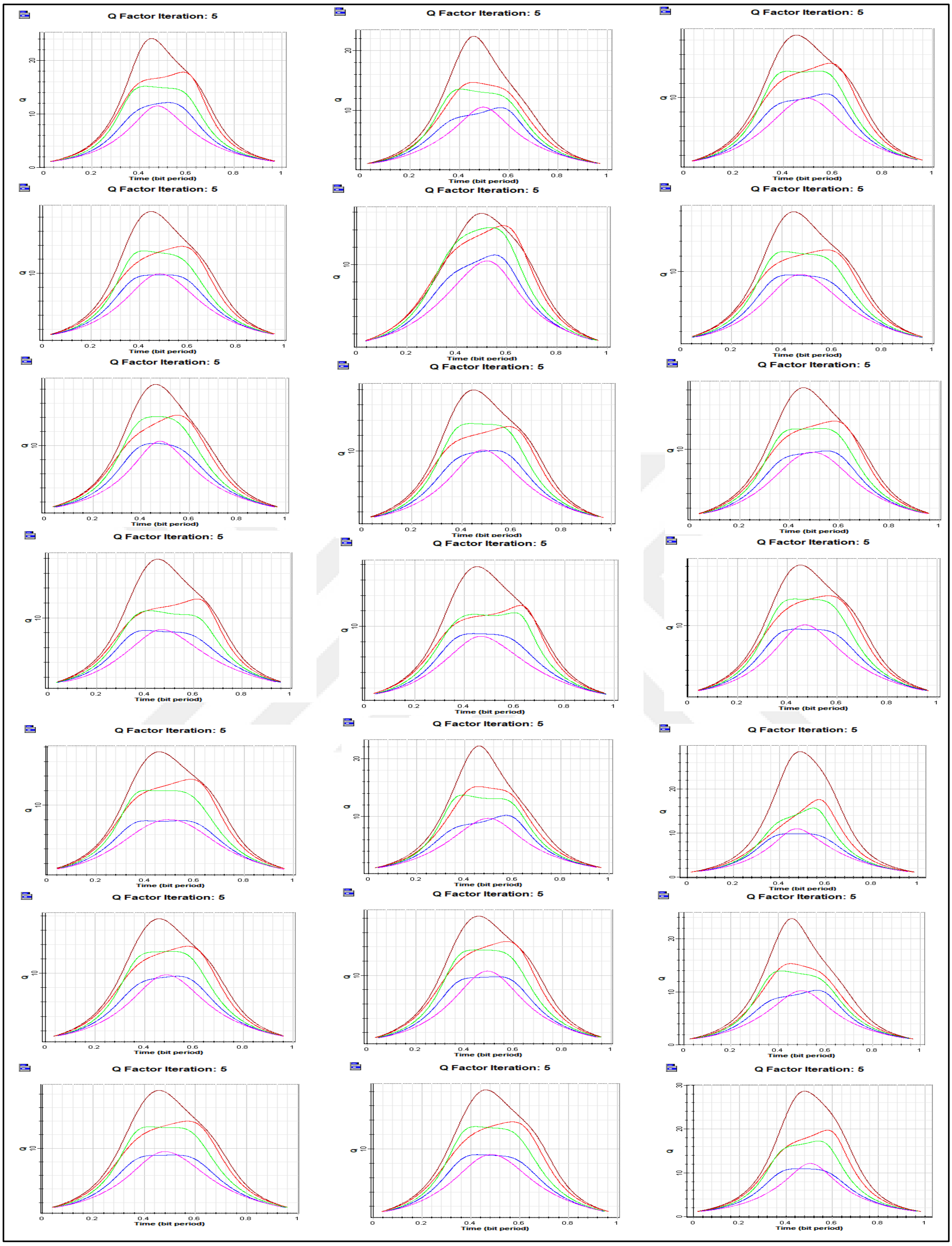

Figure 4.3: QF Vs. Individual Sample Channel At Various Transmission Distances.

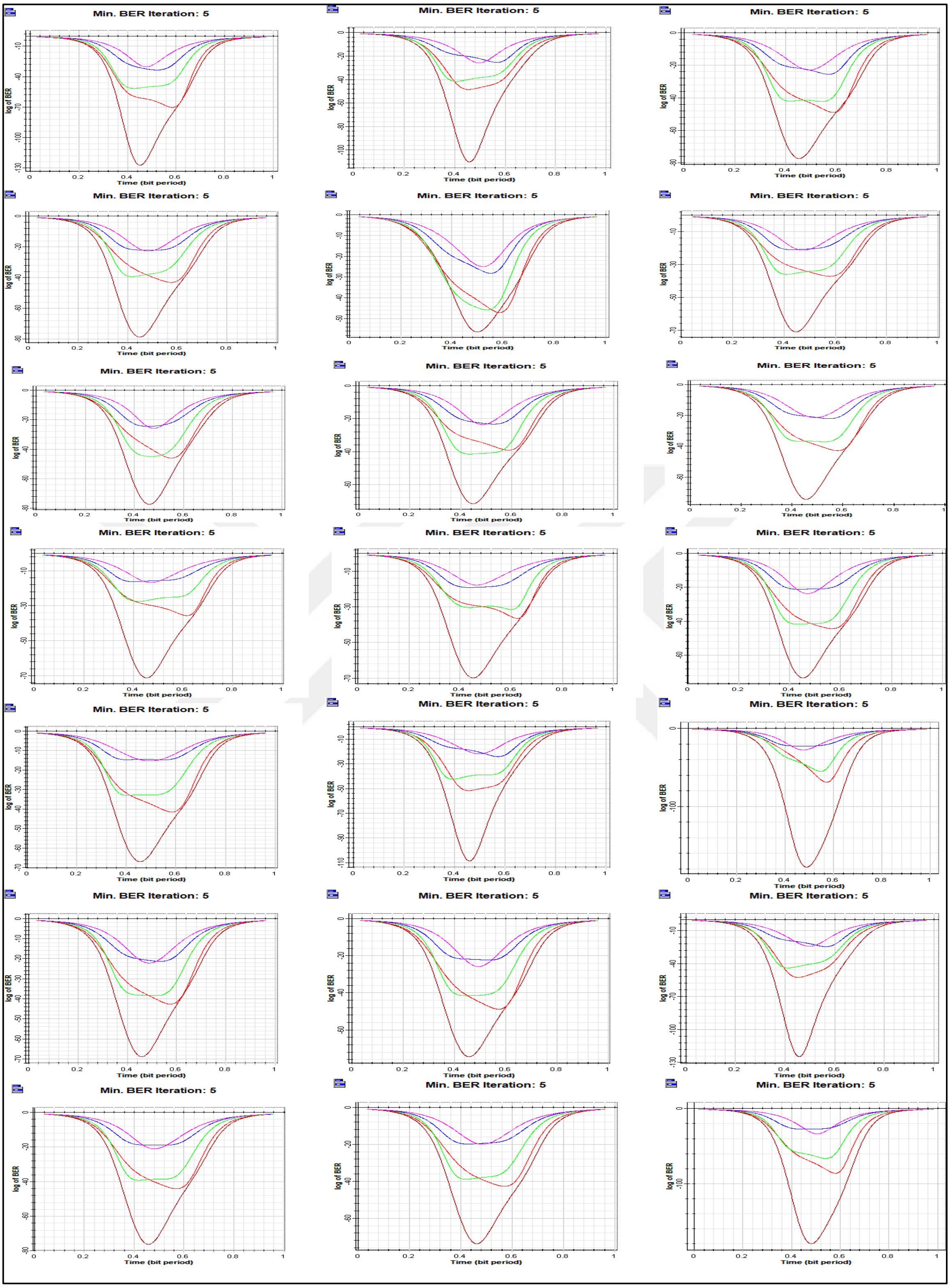

Figure 4.4: BER Vs. Individual Sample Channel At Various Transmission Distances.

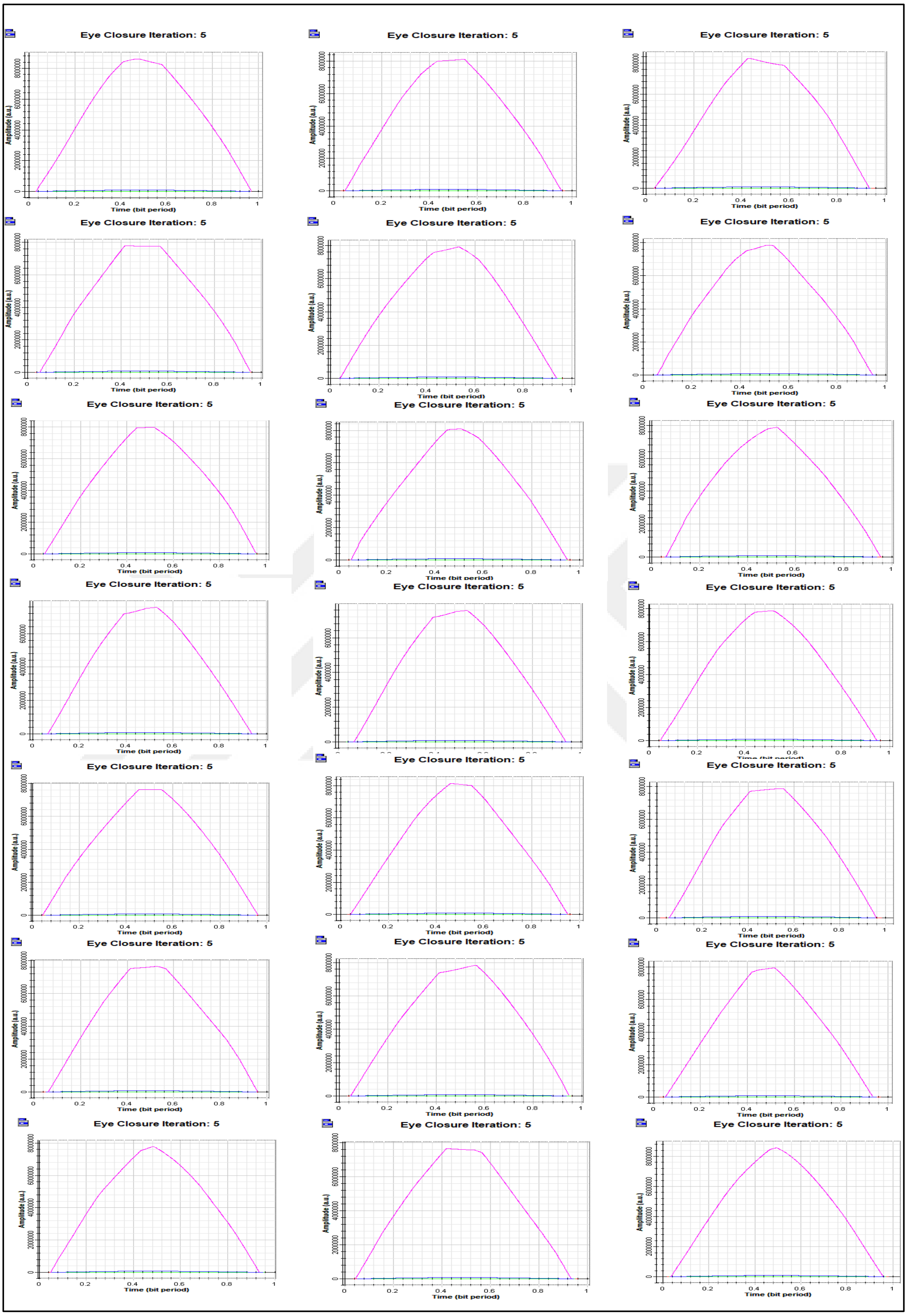

Figure 4.5: Eye Closer Vs. Individual Sample Channel At 300 Km Distance.

4.2.6 Eye Diagram Results

The eye diagram is an additional essential alternative measurement for BER that may be used for binary systems. Amplitude noise and timing jitter are two examples of the sorts of sounds that have the potential to affect system performance. The straightforward BER test is unable to differentiate between the two impacts. The extinction ratio is also measured by the eye diagram, in addition to providing additional information on both time jitter and extinction ratio. Measurement of an eye diagram using traditional methods often entails utilizing a digital oscilloscope and gathering a large amount of data, both of which take a significant amount of time. The InterSymbol Interference (ISI) between data bits may be shown with the use of a simple and practical technique known as an eye diagram. Because of this, an analysis of this parameter is carried out for the 21 channels that were sampled and for a distance of 300 kilometers, which results in an acceptable eye diagram to demonstrate the dependability of the proposed system in managing transmission from 80 channels for 300 kilometers.

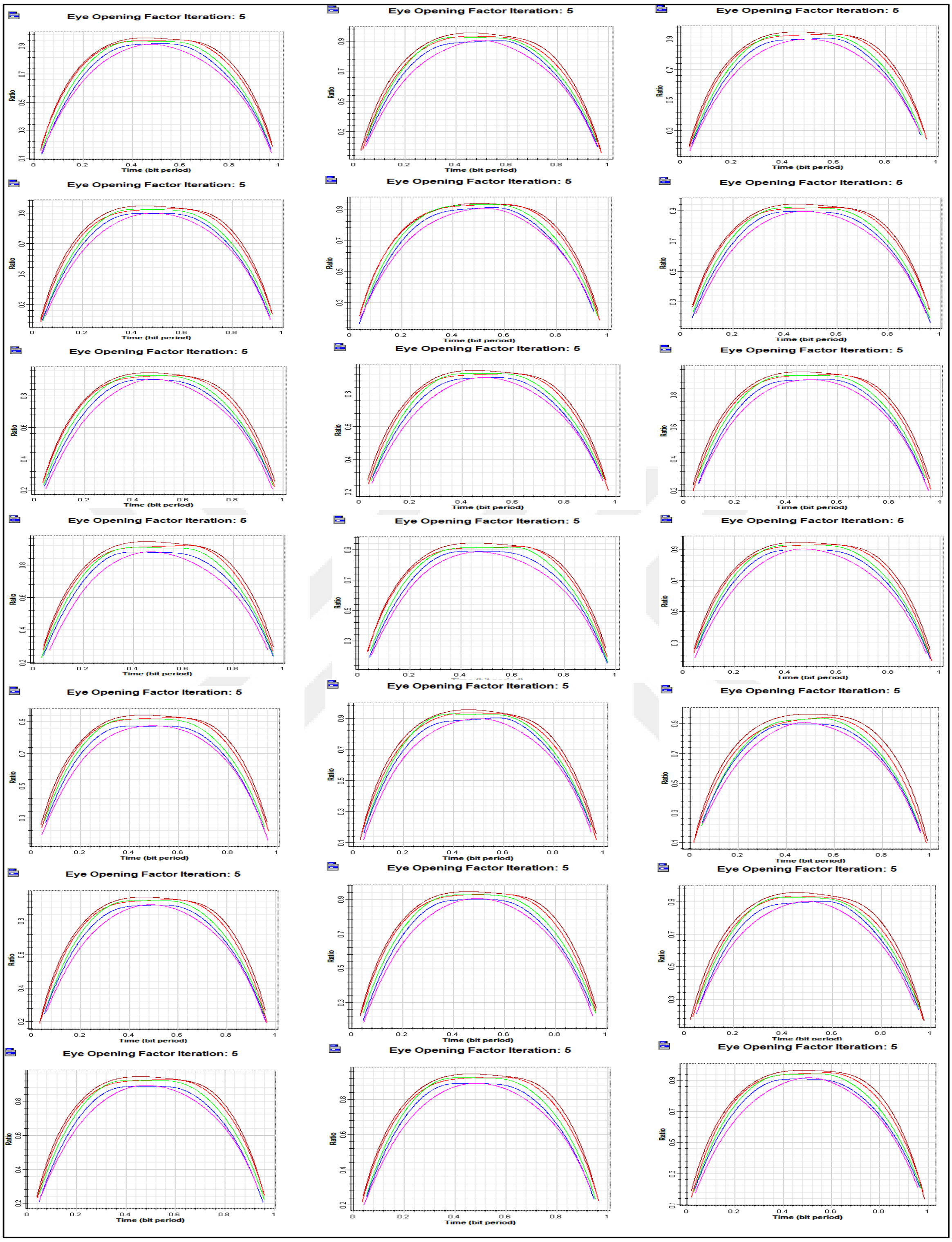

Figure 4.6: Eye Opening Factor Vs. Individual Channel At Different Transmission Distance.

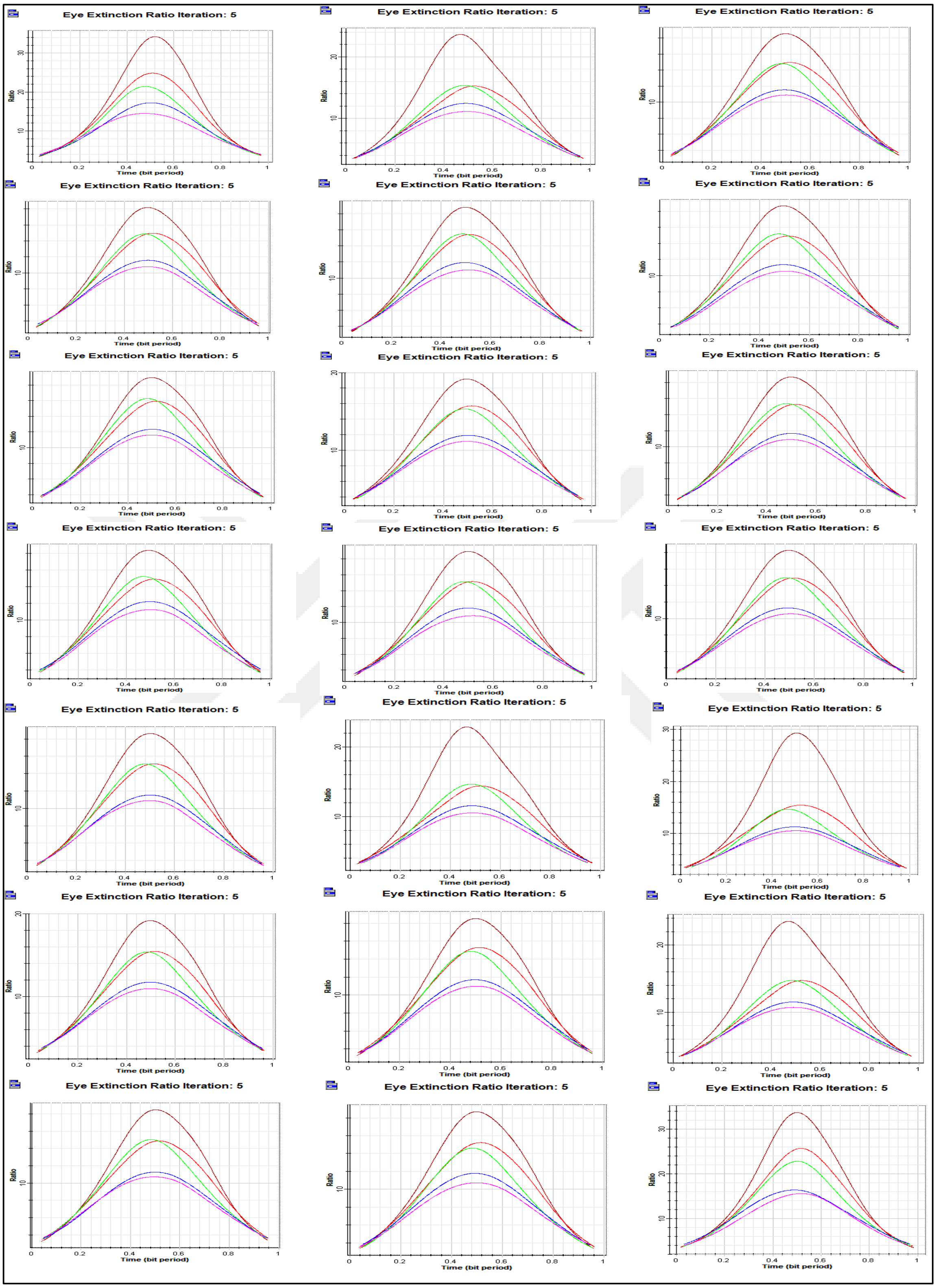

Figure 4.7: Eye Extinction Ratio Vs. Individual Channel At Different Transmission Distances.

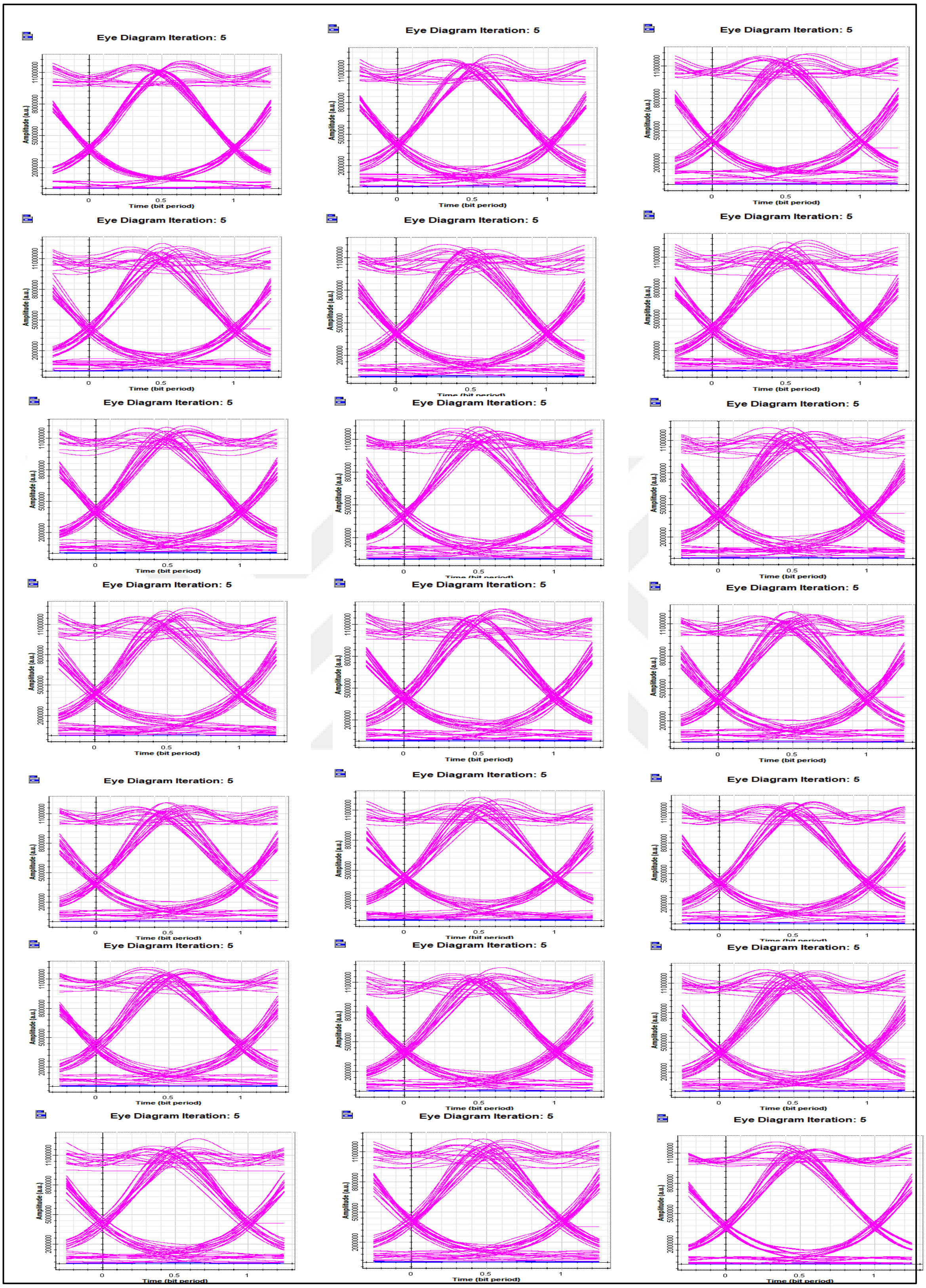

Figure 4.8: Eye Diagram Vs. Vs. Individual Channel At 300 Km Distance.

4.3 CODING SCHEME RESULTS

This section will analyze and investigate the results of the proposed system concerning different coding schemes of RZ and for the set power of 0 dBm. The same five sets of distances were included in the investigation. The analysis of system performance and comparison with the original system carried out using the NRZ is performed based on the studied parameters of QF and BER.

4.3.1 QF Results for Different Coding Methods

The analysis of the QF parameter is evaluated by comparing the results of the proposed system for the modulation method of NRZ and RZ and the same five sets of distances. These results were listed in Table 4.3 and analyzed in Figure 4.9 and indicate the following:

a. For the distance up to 120 km, using the RZ coding for the proposed 80-channel system indicates superior performance with averaged QF of 30.50 dBm while, with using the NRZ coding the averaged QF was 19.9734 dBm. Meanwhile, the average QF in the RZ case was 15.5182 dBm, and for the NRZ case was 14.598 dBm.

b. going for higher distances far from 120 km and up to 180 km utilizing the two techniques of coding resulted in a convergence performance in the obtained averaged QF where the RZ was 13.5163 dBm and for NRZ case the value was 13.5643 dBm for distance 180 km.

c. for the transmission case of distance over 180 km and reaching 300 km, using the NRZ indicate better performance as compared to RZ based method due to reasons related with being requiring less bandwidth and its lower sensitivity towards the laser phase noise. The averaged QF obtained for RZ coding at distances of 240 km and 300 km were 10.46 dBm and 8.831 dBm respectively. While, for the NRZ coding these values were 12.24 dBm and 9.577 dBm for the same set of previous distances. A comparison in averaged QF between the RZ and NRZ-based methods can be seen in Table 4.4. Also, the QF obtained vs. individual sampled channels at different transmission distances can be seen in Figure 4.10, which indicates the QF values varied concerning raising the distance.

Table 4.3: QF Results Obtained For Different Distances Using Power 0 Dbm And RZ Coding.

Channel\ distance	QF values for different distances (RZ) coding				
	60 km	120 km	180 km	240 km	300 km
1	57.7331	18.0009	24.8201	19.1166	10.3736
4	54.5091	16.0945	19.9112	13.4827	9.09546
8	27.9805	15.3421	12.285	11.1946	8.72484
12	26.8427	14.3593	11.7682	12.1102	8.81232
16	27.0369	13.7959	12.3502	10.9663	8.65769
20	25.5277	13.943	12.0031	12.2441	8.68429
24	25.4694	14.3763	12.0377	11.7134	8.23006
28	26.8268	13.7242	12.3719	11.4694	8.46806
32	26.3746	14.0388	12.0095	11.4378	8.34995
36	24.5593	13.4713	11.9911	9.50626	8.94185
40	24.4109	13.0431	12.2295	9.56883	8.35554
44	26.7965	14.7019	12.0254	12.1033	8.68774
48	26.0617	15.1199	12.2417	9.65754	7.8245
52	34.7862	16.8004	12.1877	13.502	8.24949
56	29.0047	14.5526	12.6884	12.4512	8.46352
60	26.4662	14.4021	12.193	11.201	8.46647
64	26.6213	14.4737	11.9151	11.1271	9.71703
68	33.6672	16.053	11.7806	13.4193	8.37424
72	27.5303	13.9969	12.0712	11.495	8.28732
76	27.3258	14.61	11.968	11.7654	8.32432
80	35.0901	30.9838	20.9953	17.6198	11.9969

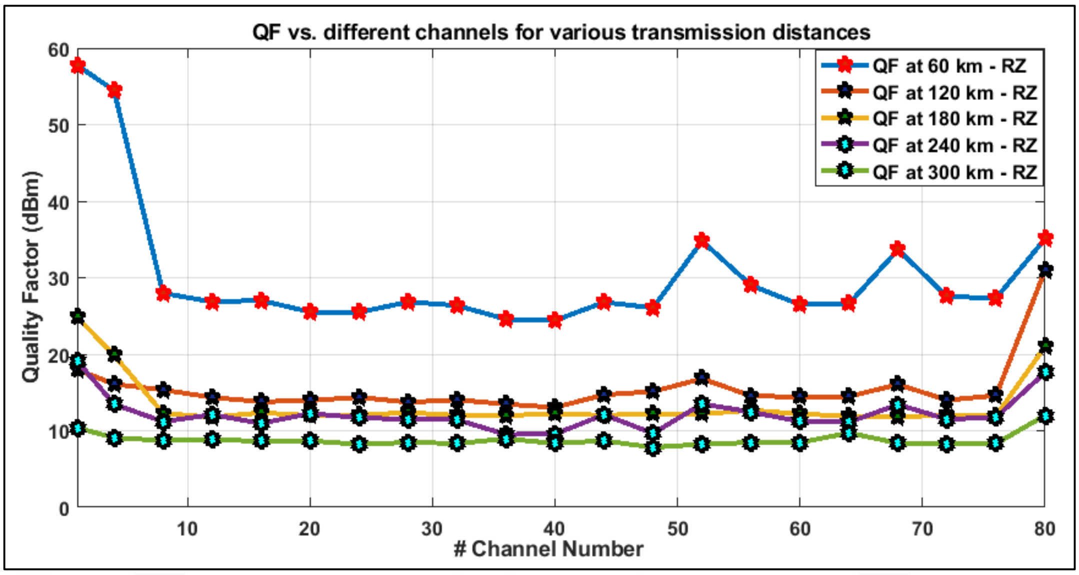

Figure 4.9: QF Vs. Different Distances Using RZ And Power 0 Dbm.

Table 4.4: Averaged QF Obtained From RZ And NRZ-Based Coding Methods.

QF (dBm)	QF values for different distances and coding scheme				
	60 km	**120 km**	**180 km**	**240 km**	**300 km**
NRZ	19.973	14.599	13.564	12.245	9.578
RZ	30.506	15.518	13.516	10.461	8.814

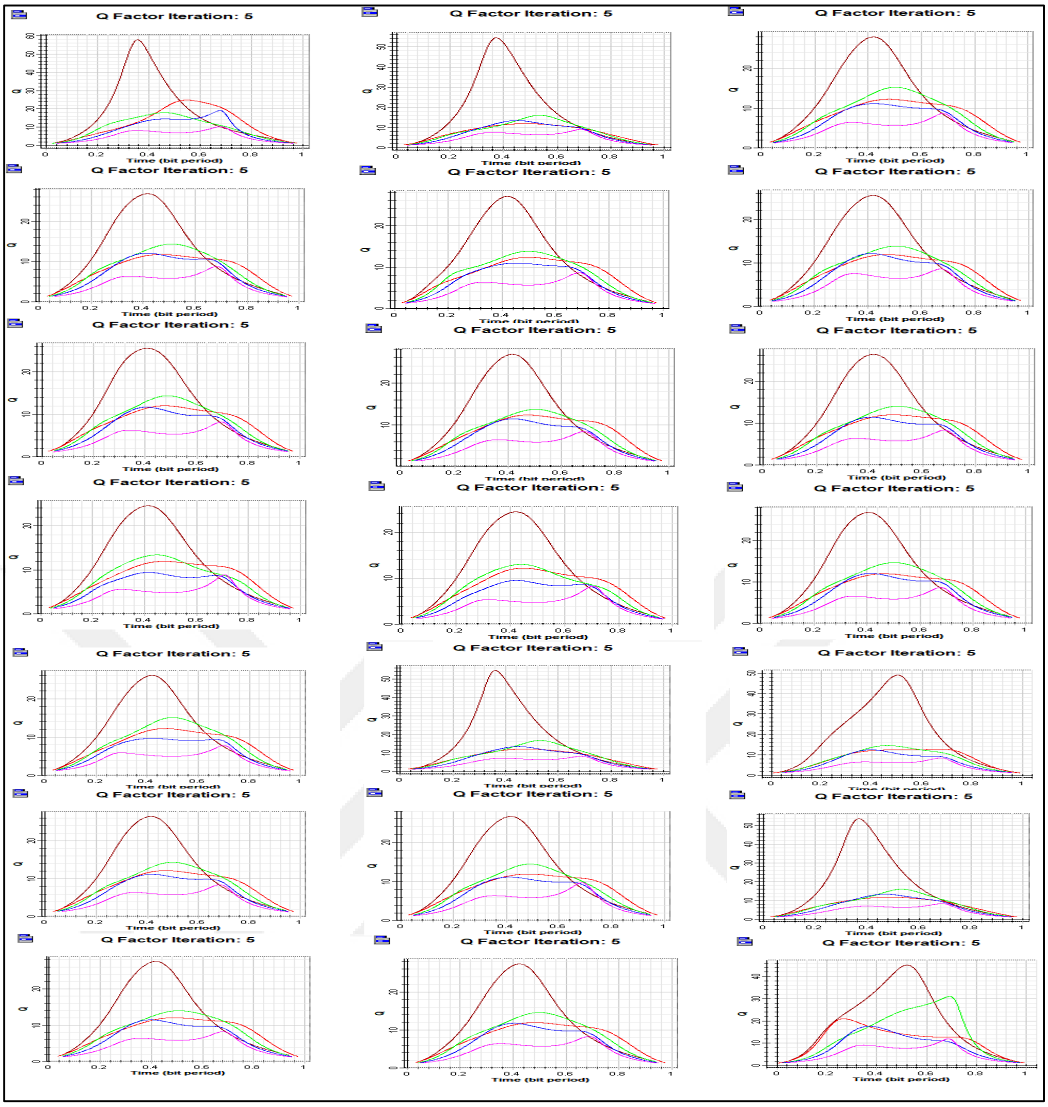

Figure 4.10: QF Vs. Individual Sample Channel At Various Transmission.

4.3.2 BER Results for Different Coding Methods

The BER parameter is studied for the case of using the RZ coding and to be compared with BER values obtained from the case of the NRZ-based method. The same five distances were tested in this part. The results obtained are listed in Table 4.5 and clarified in Figure 4.11. From analyzing these results, it can be noticed that using the RZ-based method gives better performance as compared to the NRZ-based system which means less error occurred during the transmission for distances ranging between 60 km up to 300 km. The averaged BER obtained from the two coding can be seen in Table 4.6. Furthermore, analysis of the BER concerning the individual channel and for the five distances was clarified in Figure 4.12.

where using RZ for 60 km distance recorded a superior performance and the influence is varied from channel to channel due to the various impact of wavelength attached to each channel by the attenuation. Reaching 300 km indicates that using NRZ can achieve fewer BER values and higher QF values.

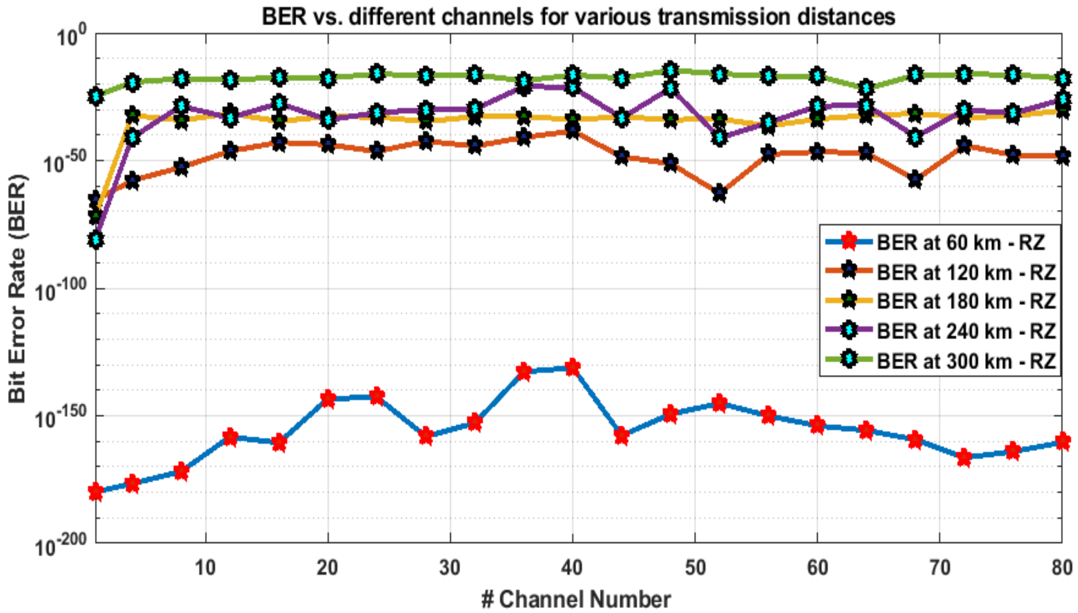

Figure 4.11: BER Vs. Different Distances Using RZ And Power 0 Dbm.

Table 4.5: BER Results Obtained For Different Distances Using Power 0 Dbm And RZ Coding.

Channel\ distance	BER values for different distances (RZ) coding				
	60 km	120 km	180 km	240 km	300 km
1	1.55E-180	2.70E-66	9.46E-73	9.05E-82	1.62E-25
4	2.54E-177	1.39E-58	5.17E-33	9.88E-42	4.42E-20
8	1.36E-172	1.97E-53	5.44E-35	2.07E-29	1.30E-18
12	5.00E-159	4.64E-47	2.85E-32	4.52E-34	6.06E-19
16	2.65E-161	1.33E-43	2.43E-35	2.63E-28	2.39E-18
20	4.69E-144	1.71E-44	1.71E-33	8.62E-35	1.90E-18
24	2.08E-143	3.62E-47	1.12E-33	5.30E-32	9.28E-17
28	7.62E-159	3.57E-43	1.85E-35	8.96E-31	1.24E-17
32	1.30E-153	4.43E-45	1.58E-33	1.30E-30	3.41E-17
36	1.63E-133	1.14E-41	1.97E-33	9.71E-22	1.83E-19
40	6.38E-132	3.43E-39	1.08E-34	5.26E-22	3.12E-17
44	1.73E-158	3.11E-49	1.31E-33	4.97E-34	1.84E-18
48	4.79E-150	5.92E-52	9.29E-35	2.18E-22	2.45E-15
52	7.54E-146	1.21E-63	1.81E-34	7.48E-42	7.86E-17
56	8.54E-151	2.81E-48	3.43E-37	6.83E-36	1.28E-17
60	1.16E-154	2.47E-47	1.69E-34	1.95E-29	1.25E-17
64	1.88E-156	8.77E-48	4.94E-33	4.49E-29	1.26E-22
68	4.35E-160	2.72E-58	2.46E-32	2.28E-41	2.73E-17
72	3.75E-167	8.08E-45	7.49E-34	6.92E-31	5.74E-17
76	1.04E-164	1.20E-48	2.61E-33	2.89E-32	4.21E-17
80	3.80E-161	4.46E-49	3.61E-31	8.57E-27	1.78E-18

Table 4.6: Averaged BER Obtained From RZ And NRZ-Based Coding Methods.

BER	BER values for different distances and coding scheme				
	60 km	120 km	180 km	240 km	300 km
NRZ	2.113E-58	1.265E-37	1.396E-29	7.187E-22	2.341E-16
RZ	3.114E-133	1.639E-40	2.075E-32	8.167E-23	1.361E-14

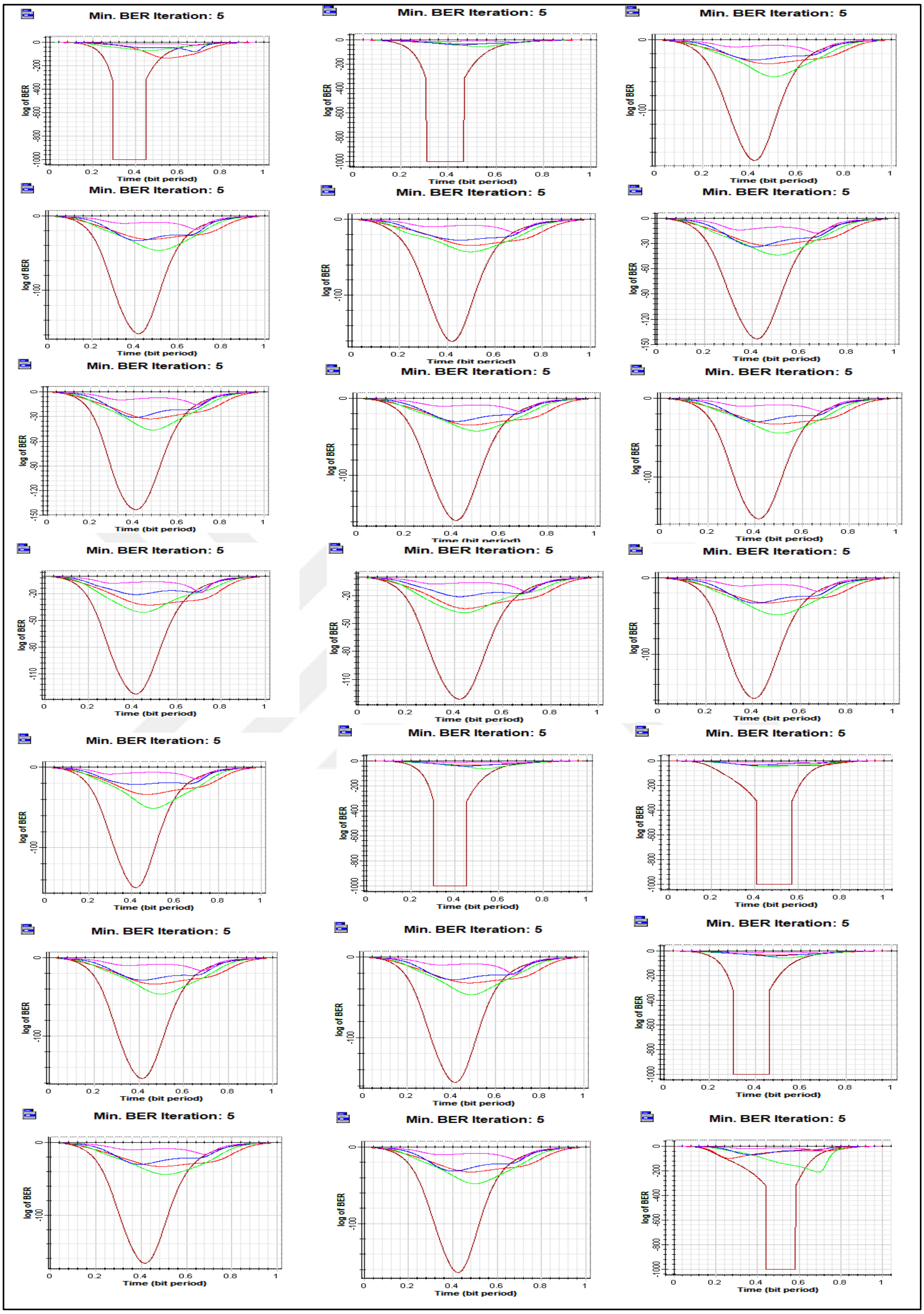

Figure 4.12: BER Vs. Individual Sample Channel At Various Transmission Distances.

4.4 DIFFERENT INPUT POWER RESULTS

In this section, an investigation for various values of input power will be studied besides the original set value of input power which is equal to 0 dBm. The two studied values of input power were -5 dBm and 5 dBm and will be studied for the same range of transmission distances. Also, in this section, the utilization of NRZ and RZ modulation methods will be investigated concerning raising and reducing the input power value to quantify the reliability of the proposed system.

4.4.1 QF-Based Results

QF studied with concerning two input power of -5 and 5 dBm for all the selected sampled and the five cases of distances by using both NRZ and RZ coding. These results were shown in Table 4.7, and Table 4.8 and analyzed in Figure 4.13 and Figure 4.14 for case of NRZ and power of –5 dBm and 5 dBm respectively. Meanwhile, the results of the RZ case are listed in Table 4.9 and Table 4.10 and analyzed in Figure 4.15 and Figure 4.16 for the same investigated input power. The results obtained indicate the following:

a. For 60 km and NRZ coding, varying the input power for ± 5 dBm can have a serious influence in varying the averaged QF by about ± 0.3 dBm. For the RZ case, it can be noticed that reducing the input power to -5 dBm can result in a reduction of the QF with an average value of 1 dBm. Meanwhile, raising the input power to 5 dBm can significantly improve the performance of the proposed system by increasing the averaged QF by about 3 dBm. Confirming the direct relation between the input power and QF values. Keeping in mind increasing the input power can result in a nonlinearity impact that appears during the long-reach transmission.

b. For distances up to 180 km and NRZ coding, varying the input power with ± 5 dBm can have a weak impact on the obtained QF results with averaged QF varied by about ± 0.1 dBm. Meanwhile, when using the RZ coding the variation impact was less than 0.1 dBm.

c. Finally, for the distance up to 300 km, using the power of 0 dBm and NRZ coding indicate the best overall performance as raising power increases the impact of nonlinearity thereby reducing the overall obtained QF values. The averaged QF obtained for both NRZ and RZ and per all studied distances are listed in Table 4.11.

Table 4.7: QF Obtained From Different Transmission Distances Using NRZ And Power Of -5 Dbm.

Channel\ distance	QF values for different distances (NRZ) coding (-5) p				
	60 km	**120 km**	**180 km**	**240 km**	**300 km**
1	24.10	17.81	15.11	12.22	10.52
4	22.55	14.71	13.60	10.51	10.62
8	18.73	14.81	13.65	10.49	9.93
12	18.60	13.53	13.18	9.77	9.87
16	15.27	14.24	14.05	10.85	10.13
20	17.59	12.52	12.48	9.64	9.50
24	18.56	14.24	13.80	10.32	9.65
28	17.75	12.78	13.55	9.97	10.05
32	17.73	13.37	12.51	9.73	9.36
36	16.95	12.24	10.72	8.15	8.31
40	17.21	12.41	11.64	9.21	8.69
44	17.58	13.99	13.57	9.59	10.10
48	16.60	13.34	11.96	7.91	8.09
52	21.58	15.03	13.53	10.23	9.63
56	28.32	17.51	15.75	9.79	10.93
60	17.58	13.83	13.09	9.52	9.75
64	18.28	14.71	13.57	9.85	9.65
68	23.79	15.13	14.00	10.29	10.30
72	18.55	14.04	13.15	8.99	9.57
76	18.28	13.75	13.17	9.19	9.26
80	28.66	19.74	17.39	10.88	11.18

Table 4.8: QF Obtained From Different Transmission Distances Using NRZ And Power Of 5 Dbm.

Channel\ distance	**QF values for different distances (NRZ) coding (5) p**				
	60 km	**120 km**	**180 km**	**240 km**	**300 km**
1	24.0673	17.8107	15.1132	12.2229	11.5244
4	22.6103	14.712	13.5979	10.5109	10.6192
8	18.7105	14.8059	13.6509	10.4892	9.93484
12	18.8396	13.912	13.3298	9.65422	9.9225
16	16.1845	14.6113	14.294	11.2665	10.5631
20	18.0729	12.9873	12.5038	9.49913	9.5736
24	18.6651	14.1633	14.3537	10.277	10.5756
28	18.0437	13.3825	13.5719	10.0668	10.1125
32	18.4068	14.0098	12.7805	9.81829	9.65374
36	18.2444	12.6672	11.1153	8.28704	8.40981
40	17.9008	12.934	11.7515	9.06486	8.65521
44	18.5109	14.143	13.6771	9.60399	10.1362
48	17.8181	13.617	12.0755	7.89845	7.988
52	22.5758	15.2236	13.7465	10.1616	9.65131
56	28.2974	17.5112	15.7508	9.78749	10.9345
60	17.5738	13.8282	13.0894	9.52137	9.74716
64	18.2807	14.7111	13.5751	9.84729	10.6525
68	23.7039	15.1271	13.9976	10.2901	10.3049
72	18.5689	14.0441	13.1532	8.99279	9.56566
76	18.2356	13.7494	13.1662	9.18935	9.26376
80	28.725	19.741	17.3881	10.881	12.1843

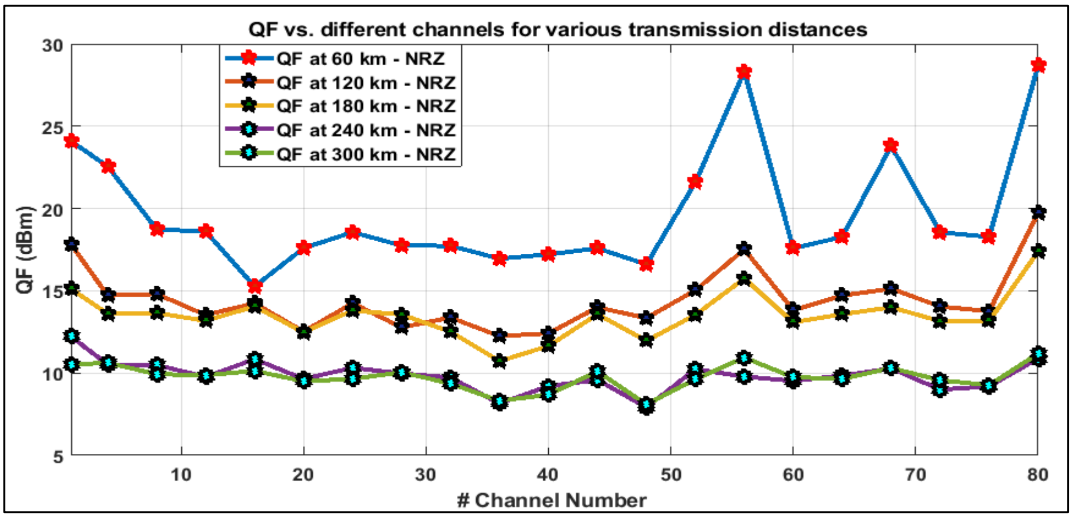

Figure 4.13: QF Vs. Different Transmission Distances At -5 Dbm Input Power And NRZ Coding.

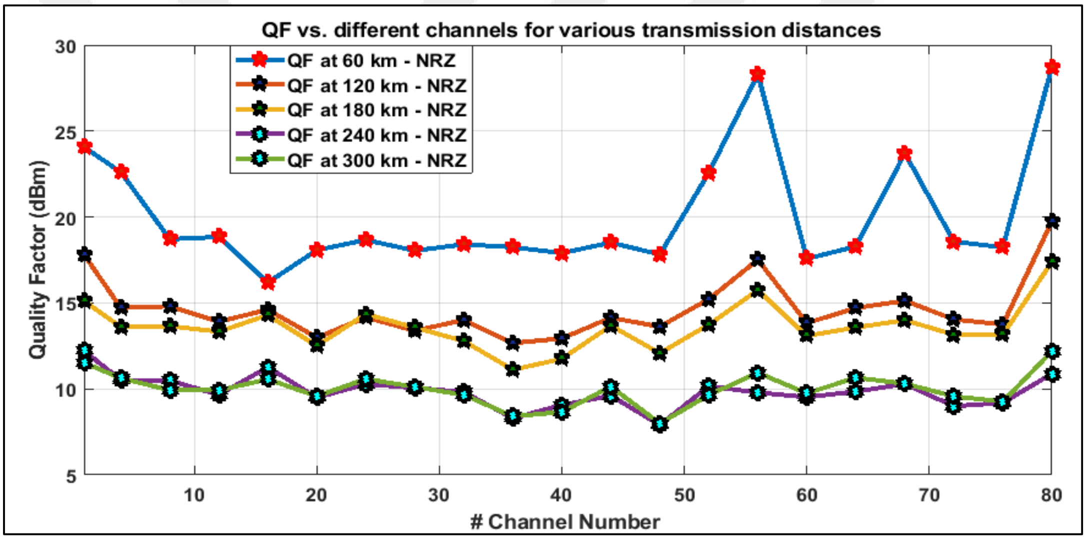

Figure 4.14: QF Vs. Different Transmission Distances At 5 Dbm Input Power And NRZ Coding

Table 4.9: QF Obtained From Different Transmission Distances Using RZ And Power Of -5 Dbm.

Channel\ distance	**QF values for different distances (RZ) coding (-5) p**				
	60 km	**120 km**	**180 km**	**240 km**	**300 km**
1	46.7517	17.8606	25.015	19.0207	10.3545
4	33.5937	16.1663	11.8157	13.3809	9.32257
8	27.2306	15.2812	12.1024	11.157	8.77173
12	25.6686	14.6584	11.5096	12.2705	8.66023
16	24.2464	13.193	12.307	10.8801	8.5243
20	23.7079	13.7644	11.6692	11.7717	8.56568
24	24.4459	14.199	12.063	11.6589	8.29077

Table 4.9: QF Obtained From Different Transmission Distances Using RZ And Power Of -5 Dbm."Tables Continued ".

28	25.1917	13.5673	12.0629	11.1646	8.4261
32	24.2695	13.705	11.6641	11.0702	8.27463
36	22.7499	13.4213	11.7626	9.37752	8.71283
40	22.5846	12.2534	12.018	9.68485	8.27472
44	25.9913	14.8536	11.8798	12.1754	8.66924
48	23.5405	15.179	11.8855	9.46306	7.8464
52	39.0639	16.6896	12.0589	13.2861	8.13589
56	38.4643	14.1571	12.6598	12.6519	8.52825
60	26.5928	14.5001	12.0307	11.2396	8.34006
64	27.4401	14.416	11.9802	11.1626	9.66614
68	44.0352	16.2851	11.8792	13.2566	8.47007
72	27.3021	14.387	12.0487	11.4326	8.33486
76	27.2076	14.5303	12.0054	11.8293	8.11944
80	38.0983	30.4375	20.9935	17.8109	11.9478

Table 4.10: QF Obtained From Different Transmission Distances Using RZ And Power Of 5 Dbm.

Channel\ distance	QF values for different distances (RZ) coding (5) p				
	60 km	120 km	180 km	240 km	300 km
1	46.4553	17.9551	24.9501	18.8925	10.3807
4	53.855	16.137	11.9079	13.4311	9.16878
8	27.4826	15.3831	12.1205	11.1755	8.7329
12	27.0848	14.2376	11.8094	11.9333	8.81233
16	28.3766	13.8781	12.2896	10.9626	8.64107
20	26.4561	14.4332	12.1911	12.4067	8.3771
24	26.3723	14.5096	12.159	11.6084	8.32364
28	26.5915	13.9455	12.4259	11.5394	8.52916
32	26.515	14.211	12.105	11.5195	8.48742
36	25.5906	13.4177	12.1823	9.59388	8.76445
40	25.9143	13.1754	12.5452	9.56888	8.13
44	27.753	14.9943	12.0537	11.9287	8.84461
48	26.4895	14.9154	12.2928	9.71115	7.95537
52	56.1682	16.7728	12.0167	13.5553	8.16533
56	50.8398	14.3722	12.7041	12.4538	8.61995
60	26.416	14.383	12.1413	11.1516	8.57311
64	26.457	14.3885	11.8689	11.1189	9.58114
68	54.0752	15.8278	11.9729	13.3157	8.68508
72	26.7289	14.3008	11.9267	11.373	8.47689

Table 4.10: QF Obtained From Different Transmission Distances Using RZ And Power Of 5 Dbm. "Tables Continued ".

76	26.2249	14.7374	11.8639	11.7355	8.30172
80	46.6271	30.5846	21.0495	17.7786	11.9499

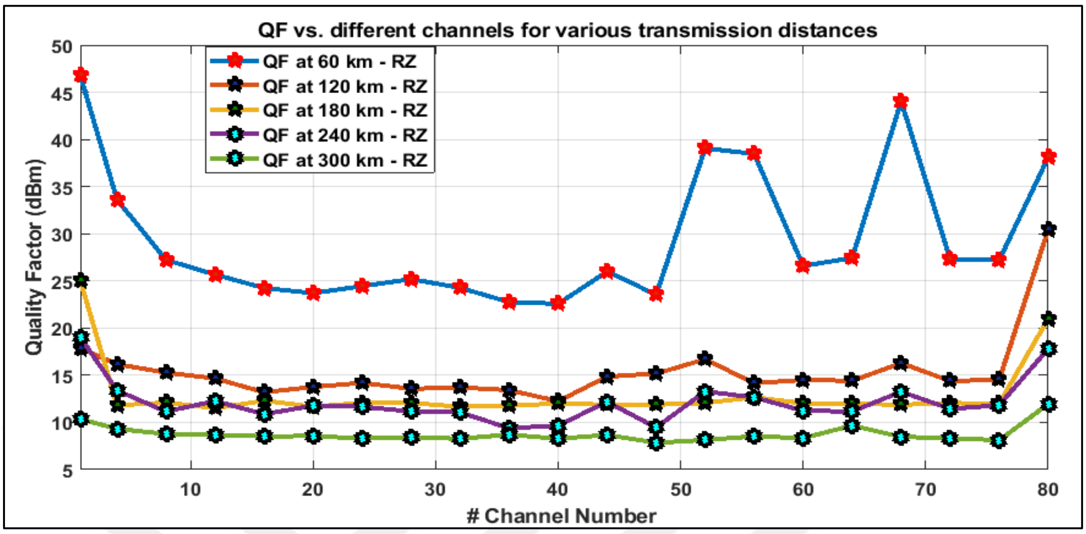

Figure 4.15: QF Vs. Different Transmission Distances At -5 Dbm Input Power And RZ Coding.

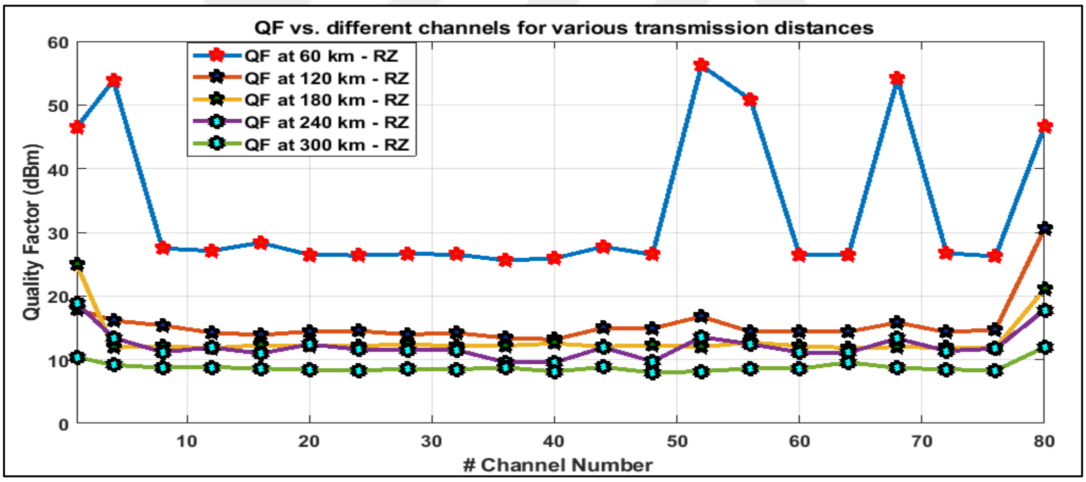

Figure 4.16: QF Vs. Different Transmission Distances At 5 Dbm Input Power And RZ Coding.

Table 4.11: Averaged QF Obtained From Different Input Power And Two Coding Schemes.

Coding with different input power	Averaged QF values at various input power and coding methods				
	60 km	120 km	180 km	240 km	300 km
NRZ (0)	19.9734	14.5989	13.5644	10.4606	9.5777
NRZ (-5)	19.7273	14.4644	13.4992	9.8616	9.7670
NRZ (5)	20.0970	14.6520	13.6039	9.8729	9.9987
RZ (0)	30.5058	15.5183	13.5164	9.2453	8.8136
RZ (-5)	29.4370	15.4050	13.0196	8.1783	8.7732
RZ (5)	33.7368	15.5505	13.1703	10.2264	8.8334

4.4.2 BER-Based Results

BER was investigated concerning two input powers of -5 and 5 dBm for all of the chosen sampling and the five instances of distances by making use of both NRZ and RZ coding. These findings were presented in Table 4.12 and Table 4.13, and their analysis was shown in Figures 4.17 and 4.18 for the case of NRZ and power of –5 dBm and 5 dBm, respectively. In the meanwhile, the findings of the RZ scenario are evaluated in Figure 4.19 and Figure 4.20 for the same explored input power. These results may be found stated in Table 4.14 and Table 4.15. The following may be deduced from the data that was collected:

a. For the case of 60 km transmission and NRZ coding, reducing the input power from 0 dBm to -5 dBm resulted in an overall increase of the BER by about E-4, and when increasing the input power to be equal to 5 dBm, the averaged overall BER reduced by about E-2 which means that increasing the power can significantly reduce the impact of errored bits transmitted.

b. For the distance of 120 km and NRZ coding case, the overall averaged BER influence was in a constant manner where for -5 dBm the averaged BER raised by about E-1, and for the 5 dBm, the averaged BER was reduced also by about E-1. Meanwhile, for the RZ coding the influence was varied as for reducing the input power to be -5 dBm, the variation in averaged BER was about by E-4, and for 5 dBm the variation was in range of E-1.

c. For higher distances reaching the targeted distance of 300 km, the NRZ and RZ-based coding methods indicate a more effective and stable performance as the impact of power reduction and increase almost indicates few changes. Additionally, using the NRZ-based coding method gives better performance as compared to RZ for distances reaching 300 km. Table 4.16 may confirm it

Table 4.12: BER Obtained From Different Distances Using NRZ And Power Of -5 Dbm.

Channel\ distance	BER values for different distances (NRZ) coding (-5) p				
	60 km	120 km	180 km	240 km	300 km
1	1.33E-128	2.82E-71	6.55E-52	1.14E-34	4.95E-31
4	6.41E-113	2.60E-49	2.06E-42	3.85E-26	1.21E-26
8	1.30E-78	6.73E-50	9.87E-43	4.82E-26	1.46E-23
12	1.60E-77	5.08E-42	5.83E-40	7.62E-23	2.85E-23
16	6.11E-53	2.57E-46	3.80E-45	1.03E-27	1.95E-24
20	1.38E-69	2.98E-36	5.01E-36	2.59E-22	1.00E-21
24	3.43E-77	2.44E-46	1.32E-43	2.72E-25	9.05E-27
28	8.90E-71	1.10E-37	3.68E-42	1.02E-23	4.59E-24
32	1.26E-70	4.28E-41	3.13E-36	1.13E-22	3.90E-21
36	8.97E-65	9.10E-35	3.99E-27	1.87E-16	4.67E-17
40	1.08E-66	1.09E-35	1.19E-31	1.68E-20	1.86E-18
44	1.70E-69	8.52E-45	2.91E-42	4.41E-22	2.82E-24
48	3.23E-62	6.35E-41	2.73E-33	1.20E-15	2.95E-16
52	1.28E-71	2.31E-51	5.04E-42	6.90E-25	2.92E-22
56	8.58E-73	5.27E-69	3.30E-56	6.28E-23	3.93E-28
60	1.82E-69	8.89E-44	1.87E-39	8.43E-22	9.42E-23
64	6.47E-75	2.71E-49	2.76E-42	3.44E-23	8.39E-27
68	2.01E-125	4.98E-52	8.10E-45	3.83E-25	3.31E-25
72	3.99E-77	4.25E-45	8.11E-40	1.18E-19	5.52E-22
76	6.48E-75	2.41E-43	6.84E-40	1.95E-20	9.70E-21
80	5.43E-135	4.92E-87	4.94E-68	6.88E-28	1.88E-34

Table 4.13: BER Obtained From Different Distances Using NRZ And Power Of 5 Dbm.

Channel\ distance	BER values for different distances (NRZ) coding (5) p				
	60 km	120 km	180 km	240 km	300 km
1	2.74E-128	2.92E-71	6.53E-52	1.14E-34	4.95E-31
4	1.71E-113	2.55E-49	2.06E-42	3.85E-26	1.21E-26
8	2.02E-78	6.70E-50	9.86E-43	4.82E-26	1.46E-23
12	1.78E-79	2.67E-44	7.73E-41	2.27E-22	1.64E-23
16	3.24E-59	1.18E-48	1.19E-46	9.58E-30	2.19E-26
20	2.60E-73	7.21E-39	3.55E-36	1.02E-21	5.04E-22
24	4.76E-78	7.70E-46	5.04E-47	4.41E-25	1.93E-26
28	4.42E-73	3.83E-41	2.92E-42	3.79E-24	2.40E-24
32	5.79E-76	6.78E-45	1.04E-37	4.59E-23	2.34E-22
36	1.13E-74	4.44E-37	5.26E-29	5.80E-17	2.04E-17
40	5.81E-72	1.41E-38	3.39E-32	6.23E-20	2.46E-18
44	8.39E-77	1.03E-45	6.89E-43	3.80E-22	1.90E-24
48	2.53E-71	1.58E-42	6.89E-34	1.36E-15	6.80E-16
52	3.73E-113	1.17E-52	2.67E-43	1.43E-24	2.38E-22
56	1.86E-176	5.49E-69	3.30E-56	6.28E-23	3.93E-28
60	1.95E-69	8.60E-44	1.87E-39	8.43E-22	9.42E-23
64	5.88E-75	2.73E-49	2.75E-42	3.44E-23	8.39E-27
68	1.64E-124	5.08E-52	8.06E-45	3.83E-25	3.31E-25
72	2.86E-77	4.19E-45	8.11E-40	1.18E-19	5.52E-22
76	1.34E-74	2.56E-43	6.83E-40	1.95E-20	9.70E-21
80	9.24E-182	4.78E-87	4.94E-68	6.89E-28	1.88E-34

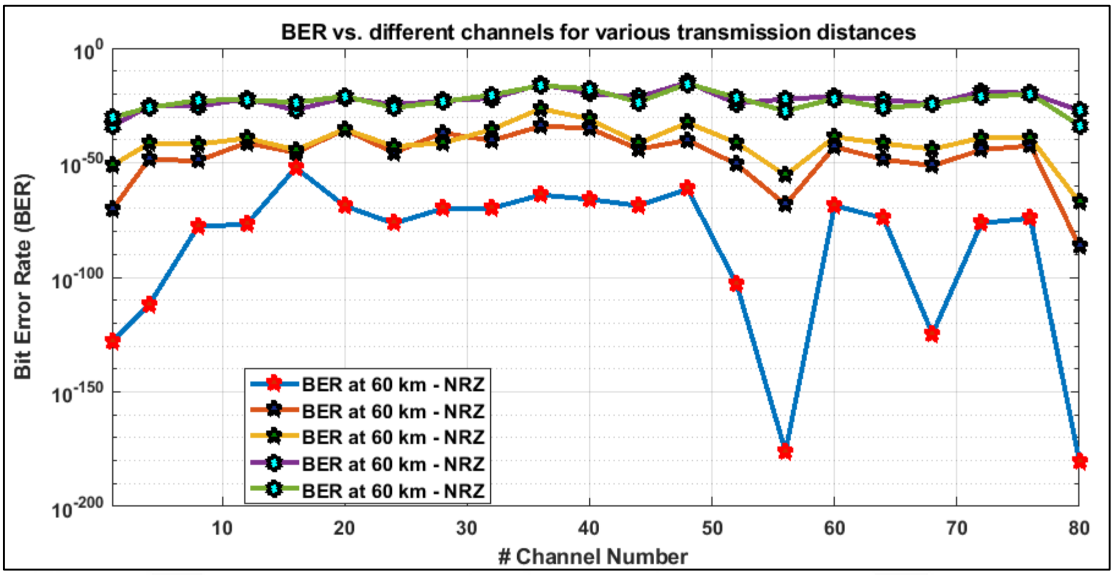

Figure 4.17: BER Vs. Different Transmission Distances At -5 Dbm Input Power And NRZ Coding.

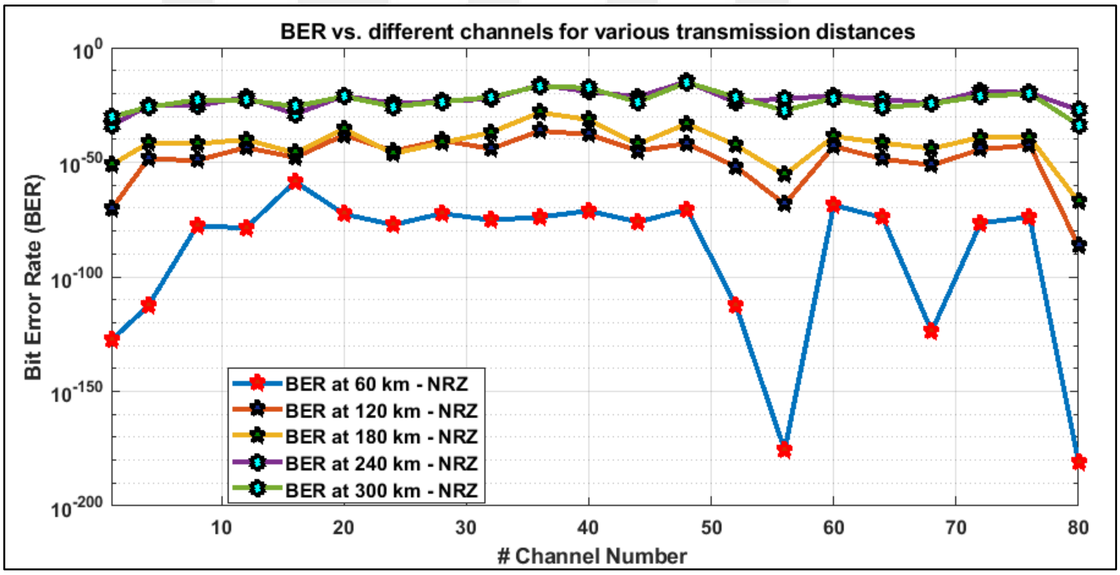

Figure 4.18: BER Vs. Different Transmission Distances At 5 Dbm Input Power And NRZ Coding.

Table 4.14: BER Obtained From Different Distances Using RZ And Power Of -5 Dbm.

Channel\ distance	**BER values for different distances (RZ) coding (-5) p**				
	60 km	**120 km**	**180 km**	**240 km**	**300 km**
1	1.25E-170	1.18E-71	2.08E-138	5.68E-81	1.98E-25
4	2.54E-166	4.36E-59	1.62E-32	3.91E-41	5.33E-21
8	1.36E-163	5.04E-53	5.12E-34	3.16E-29	8.55E-19
12	1.26E-145	5.93E-49	5.90E-31	6.34E-35	2.34E-18
16	3.45E-130	4.69E-40	4.15E-35	6.77E-28	7.67E-18
20	1.42E-124	2.05E-43	9.11E-32	2.58E-32	5.36E-18
24	2.67E-132	4.60E-46	8.28E-34	1.01E-31	5.59E-17
28	2.36E-140	3.06E-42	8.26E-34	2.87E-29	1.78E-17
32	1.95E-130	4.62E-43	9.67E-32	8.38E-29	6.44E-17
36	6.70E-115	2.24E-41	3.03E-32	3.31E-21	1.43E-18
40	2.94E-113	7.87E-35	1.43E-33	1.70E-22	6.19E-17
44	3.00E-149	3.27E-50	7.54E-33	2.06E-34	2.17E-18
48	7.42E-123	2.41E-52	7.02E-33	1.42E-21	2.06E-15
52	5.43E-126	7.78E-63	8.68E-34	1.37E-40	2.02E-16
56	5.43E-140	8.42E-46	4.94E-37	5.42E-37	7.31E-18
60	4.00E-156	5.97E-48	1.22E-33	1.26E-29	3.68E-17
64	4.48E-166	2.02E-47	2.26E-33	3.02E-29	2.08E-22
68	8.54E-155	6.29E-60	7.59E-33	2.02E-40	1.21E-17
72	1.97E-164	3.11E-47	9.83E-34	1.42E-30	3.84E-17
76	2.63E-163	3.87E-48	1.66E-33	1.35E-32	2.32E-16
80	2.44E-150	8.76E-204	3.75E-98	2.88E-71	3.23E-33

Table 4.15: BER Obtained From Different Distances Using RZ And Power Of 5 Dbm.

Channel\ distance	**BER values for different distances (RZ) coding (5) p**				
	60 km	**120 km**	**180 km**	**240 km**	**300 km**
1	1.23E-188	2.16E-72	1.06E-137	6.49E-80	1.50E-25
4	2.54E-163	7.00E-59	5.38E-33	1.99E-41	2.25E-20
8	1.37E-166	1.05E-53	4.10E-34	2.56E-29	1.21E-18
12	7.27E-162	2.66E-46	1.74E-32	3.84E-33	6.06E-19
16	1.93E-177	4.23E-44	5.15E-35	2.74E-28	2.76E-18
20	1.51E-154	1.58E-47	1.73E-34	1.15E-35	2.71E-17
24	1.39E-153	5.23E-48	2.57E-34	1.82E-31	4.23E-17
28	4.12E-156	1.65E-44	9.44E-36	3.99E-31	7.35E-18

Table 4.15: BER Obtained From Different Distances Using RZ And Power Of 5 Dbm. "Tables Continued ".

32	3.15E-155	3.86E-46	4.96E-34	5.07E-31	1.05E-17
36	9.31E-145	2.35E-41	1.93E-34	4.17E-22	9.00E-19
40	2.26E-148	6.01E-40	2.11E-36	5.25E-22	2.07E-16
44	7.84E-170	3.97E-51	9.27E-34	4.11E-33	4.57E-19
48	6.20E-155	1.29E-50	4.95E-35	1.29E-22	8.52E-16
52	8.43E-150	1.93E-63	1.45E-33	3.63E-42	1.58E-16
56	3.43E-144	3.86E-47	2.80E-37	6.61E-36	3.29E-18
60	4.36E-154	3.26E-47	3.19E-34	3.41E-29	4.98E-18
64	1.48E-154	3.01E-47	8.58E-33	4.93E-29	4.76E-22
68	5.32E-151	9.99E-57	2.46E-33	9.17E-41	1.86E-18
72	1.06E-157	1.08E-46	4.29E-33	2.82E-30	1.14E-17
76	6.85E-152	1.84E-49	9.11E-33	4.12E-32	5.09E-17
80	5.83E-150	9.80E-55	1.15E-38	5.12E-29	3.14E-19

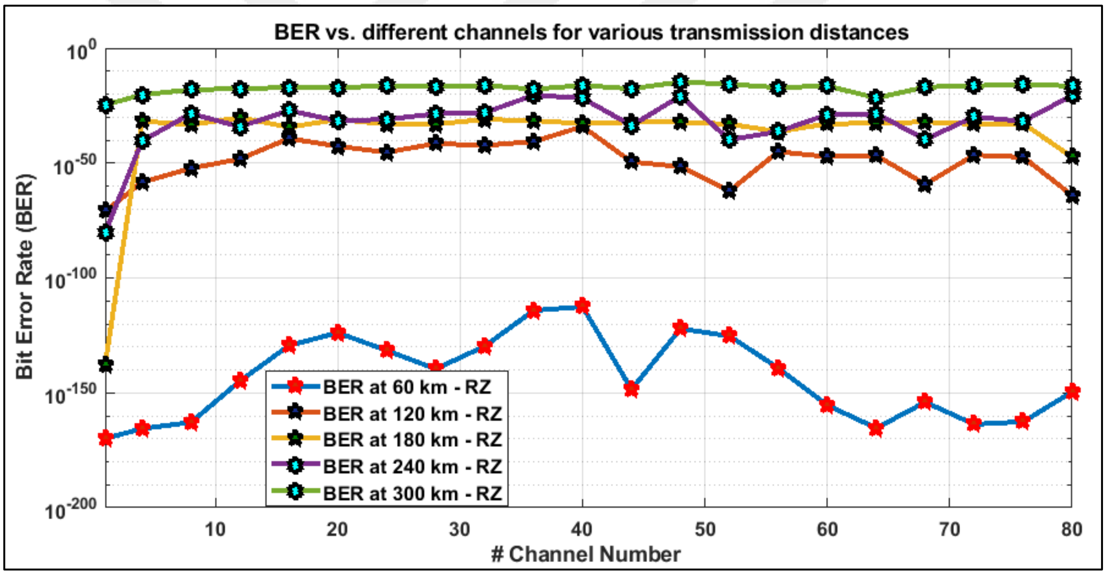

Figure 4.19: BER Vs. Different Transmission Distances At -5 Dbm Input Power And RZ Coding.

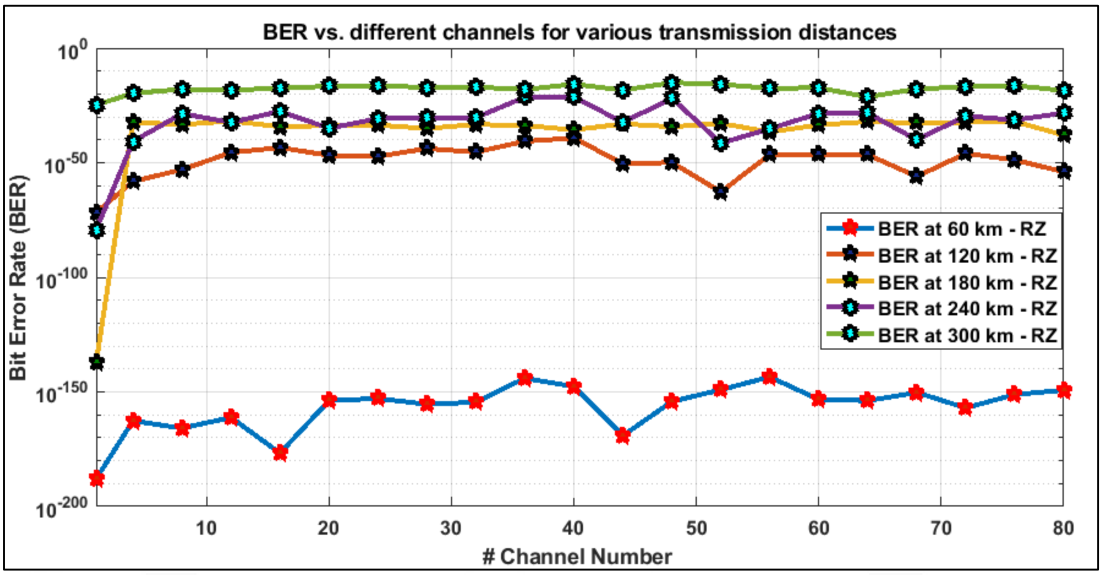

Figure 4.20: BER Vs. Different Transmission Distances At 5 Dbm Input Power And RZ Coding.

Table 4.16: Averaged BER Obtained From Different Input Power And Two Coding Schemes For Five Cases Of Distances.

coding with different input power	**Averaged BER values at various input power and coding methods**				
	60 km	**120 km**	**180 km**	**240 km**	**300 km**
NRZ (0)	2.11E-58	1.26E-37	1.40E-29	7.19E-20	2.34E-17
NRZ (-5)	2.91E-54	5.00E-36	1.90E-28	6.61E-17	1.64E-17
NRZ (5)	1.54E-60	2.22E-38	2.50E-30	6.74E-17	3.35E-17
RZ (0)	3.11E-133	1.64E-40	2.08E-32	8.17E-23	1.36E-16
RZ (-5)	1.43E-114	3.75E-36	4.08E-32	2.34E-22	1.34E-16
RZ (5)	2.08E-145	2.97E-41	2.46E-33	5.10E-23	6.59E-17

4.5 COMPARISON WITH LITERATURE

In this section, a dedicated comparison will be carried out concerning the recent studies that proposed a system with the capability to handle the connection of 80 channels for the RoF technique. This comparison will be formed based on different parameters as withdrawn in Table 4. From this table, it can be concluded that the proposed system along with using the dedicated input power, channel spacing, and the required modulation method can significantly improve the proposed system in handling the transmission of large data rates and for long distances.

Table 4.17: Comparison With Different Literature.

Parameter	**Proposed system**	**Ref. [52]**	**Ref. [54]**
No. of channels	80	80	80
Spacing (GHz)	100	100	100
Data rate	2 Tbps	960 Gbps	960 Gbps
Distance	300 km	Not specified	120 km
Compensation method	Symmetrical	Not specified	Pre-post
Modulation technique	NRZ-RZ	RZ	NRZ
No. of samples	21	8	20
Input power	(-5 to 5)	Not specified	(-10 to 5)

5. CONCLUSIONS

5.1 CONCLUSIONS

The conclusion carried from the proposed system in this thesis can be summarized below:

a. This thesis design and implements a novel 80-channel DWDM RoF system vis using the power of symmetrical compensation as a method of compensation technique to handle the CD effects. The proposed system was designed with low input power equal to 0 dBm and channel spacing of 100 GHz and tested for distances ranging between 60 km to 300 km. An NRZ-based coding scheme was set for the proposed system of this thesis.

b. For the first objective conclusion, the proposed system indicates reliable performance in handling successful transmission for the targeted distance where the averaged QF obtained from the sampled channels were 19.9734, 14.5989, 13.5643, 10.4605, and 9.577 dBm, and the averaged BER were 2.11E-58, 1.26E-37, 1.40E-29, 7.19E-20, and 2.34E-14 for the distance of 60, 120, 180, 240, and 300 km respectively.

c. For the second objective conclusion, using the RZ gives better performance for distances up to 120 km, while going for higher distances towards 300 km using the NRZ can achieve the best overall results in improving the QF and reducing the BER at the receiver side. NRZ outperforms RZ due to reasons related to its less bandwidth requirement and low distortion by laser noise.

d. For the third objective conclusion, using NRZ with ± 5 dBm input power variation resulted in an averaged influence varied of about ± 0.3 dBm in the obtained QF values and an overall increase of the BER by about E-4, and when increasing the input power to be equal to 5 dBm, the averaged overall BER reduced by about E-2 which means that increasing the power can significantly reduce the impact of errored bits transmitted.

e. For the third objective conclusion, using RZ with ± 5 dBm input power variation resulted in reducing the input power to -5 dBm can result in a reduction of the QF with an average value of 1 dBm. Meanwhile, raising the input power to 5 dBm can significantly improve the performance of the proposed system by increasing the averaged QF by about 3 dBm. Confirming the direct relation between the input power and QF values. Keeping in mind increasing the input power can result in a nonlinearity impact that appears during the long-reach transmission. For the BER values, the impact of variation in BER was raised to be between E-10 to E-20.

f. Also, for the third objective-based conclusions and the distances up to 180 km and NRZ coding, varying the input power with ± 5 dBm can have a weak impact on the obtained QF results with averaged QF varied by about ± 0.1 dBm. Meanwhile, when using the RZ coding the variation impact was less than 0.1 dBm.

g. Finally, for the distance up to 300 km, using the power of 0 dBm and NRZ coding indicate the best overall performance as raising power increases the impact of nonlinearity thereby reducing the overall obtained QF and BER values. Hence, using the NRZ-based coding method gives better performance as compared to RZ for distances reaching 300 km.

5.2 SUGGESTIONS FOR FUTURE

In the future, several points may be covered such as:

a. Investigating the impact of various channel spacing via using the symmetrical compensation technique and the influence of channel spacing variation on the system performance.

b. Using alternative dedicated methods of direct detection-based advanced modulation and using polarization mode division-based techniques.

c. Propose an ultra-dense system that can handle effectively more channels above 100 channels by using the required dedicated methods and techniques.

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