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Enhanced Modulation Strategies for High-Speed Optical Communication Networks

Kunal Patil[1], Dr. Vinod Kumar Suman[2], Dr. Sangita Rajput[3]
[1]*Research Scholar, Department of Electronics & Telecommunication*
[2]*Professor, Department of Electronics & Telecommunication, Sunrise University, Alwar*
[3]*Professor, Department of Electronics, SSVPS Engineering Dhule*

Abstract: In the rapidly evolving landscape of high-capacity optical communication systems, the quest for increased data rates has become paramount. As the demand for seamless and high-speed data transmission continues to surge, researchers and engineers are delving into innovative approaches to enhance the efficiency and performance of optical communication systems. Advanced modulation techniques have emerged as a pivotal area of exploration, offering the promise of unlocking higher data rates and greater bandwidth utilization. These techniques leverage the inherent capabilities of light to carry data, pushing the boundaries of what is achievable in the realm of optical communication. In this context, this exploration delves into the fascinating realm of advanced modulation techniques, shedding light on their significance, applications, and the transformative potential they hold for the future of high-capacity optical communication systems.

Objectives: High-capacity optical communication systems are being developed to meet the increasing demand for seamless and high-speed data transmission. Advanced modulation techniques, such as Quadrature Amplitude Modulation (QAM), Orthogonal Frequency Division Multiplexing (OFDM), Frequency Shift Keying (FSK), Phase Shift Keying (PSK), and MIMO, are being explored to unlock higher data rates and greater bandwidth utilization. These techniques leverage the inherent capabilities of light to carry data, pushing the boundaries of what is achievable in the realm of optical communication. Optical communication systems have emerged as a cornerstone technology in meeting the escalating data rate demands of the modern digital age. With advancements like wavelength division multiplexing (WDM), optical systems can achieve multi-terabit-per-second data rates, making them pivotal in global communication networks. As 5G networks roll out and 6G promises are on the horizon, optical communication systems will play an indispensable role in backhaul and fronthaul connections, supporting low latency and high data rates needed for the next generation of wireless communications.

Methods: Nonlinearity induced impairments such as FWM and XPM in a traditional optical communication link may be compensated for by either allowing the residual local dispersion of the fiber to persist or by appropriately increasing the channel spacing.

Since dispersion is a linear process, dispersion correction may be applied at the receiver end or sporadically across the connection to balance the buildup of dispersion along the transmission fiber.

However, this makes the system more difficult than those that use optical fibers with lower dispersion values to avoid the need for dispersion control. Results: Modelling the creation, propagation, and receipt of the sent signal is a part of the signal simulation process in an optical fiber transmission system. Every simulation involves a trade-off between time and accuracy. Research, development, testing, and refining of the intricate models needed to construct an optical system simulator usually take time and resources. Because the Opti system 10.0 simulator is available in commercial optical system simulators that offer affordable prices, sophisticated simulation algorithms, and user-friendly graphical user interfaces, it was selected to assess the transmission capabilities of a wide range of phase modulation formats. With simulation modules for active and passive photonic components, several fiber types, integrated digital signal processing modules, time domain and frequency domain analyzers, electrical signal sources, filters, and other relevant sub-systems, it is a widely acknowledged standard simulator. Additionally, by using other programming languages, such Matlab®, to communicate with this simulator, users may develop, construct, and integrate new modules with Optisystem.

Conclusions: In order to model, develop, and simulate the ideal circumstances for a long-haul optical communication connection in order to obtain an optimum propagation length, this thesis covers the theoretical examination and analysis of the optical channel characteristics. Using the analytical model and numerical simulation analysis of this fiber transmission channel, the designer may choose a design plan and an appropriate solution for different modulation formats within the specified operational limits.

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Examining the effects of linear and non-linear phase impairments that happen during pulse propagation in the fiber medium on the design of long-haul fiber optic communication systems is the main goal of the thesis. This chapter outlines possible future expansions of the intended study and summarises the results and contributions of the current work.
Keywords: High-Capacity Communications, Energy-Efficient Optical Fiber, Signal Processing Innovations.

I. INTRODUCTION

In the rapidly evolving landscape of high-capacity optical communication systems, the quest for increased data rates has become paramount. As the demand for seamless and high-speed data transmission continues to surge, researchers and engineers are delving into innovative approaches to enhance the efficiency and performance of optical communication systems. Advanced modulation techniques have emerged as a pivotal area of exploration, offering the promise of unlocking higher data rates and greater bandwidth utilization. These techniques leverage the inherent capabilities of light to carry data, pushing the boundaries of what is achievable in the realm of optical communication. In this context, this exploration delves into the fascinating realm of advanced modulation techniques, shedding light on their significance, applications, and the transformative potential they hold for the future of high-capacity optical communication systems.

1.1 Advanced Modulation Techniques: Advanced modulation techniques play a pivotal role in modern communication systems, enabling the efficient transmission of data over various channels and under different conditions. One such technique is Quadrature Amplitude Modulation, which combines amplitude and phase modulation to convey multiple bits of information per symbol. Higher-order QAM schemes, such as 16-QAM or 64-QAM, allow for even greater data rates, making them crucial in high-speed data transmission like digital television and broadband internet.

Another advanced modulation technique is Orthogonal Frequency Division Multiplexing, which divides the data stream into multiple subcarriers, each with its own modulation scheme. OFDM is highly resilient to multipath interference and can mitigate the effects of fading in wireless channels, making it the foundation of many wireless communication standards, including Wi-Fi and 4G LTE.

Furthermore, Frequency Shift Keying (FSK) and Phase Shift Keying (PSK) are advanced modulation techniques that modulate the carrier signal's frequency or phase, respectively, to represent digital data. These techniques are essential in applications like radio frequency identification and satellite communications.

MIMO is another advanced technology that employs spatial diversity by using multiple antennas at both the transmitter and receiver. MIMO leverages various modulation techniques to improve data rates and signal reliability in wireless communication systems. It is a fundamental technology in 5G and emerging 6G networks.

In the context of optical communication, techniques like Quadrature Phase Shift Keying (QPSK) and Coherent Optical Modulation are used to transmit high-capacity data over optical fibers. These advanced modulation schemes are vital for long-haul and high-speed optical communication systems that underpin the internet's backbone.

1.2 Optical Communication Systems and Data Rate Demands: Optical communication systems have emerged as a cornerstone technology in meeting the escalating data rate demands of our modern digital age. These systems utilize light, typically in the form of laser-generated optical signals, to transmit data over long distances through optical fibers. The appeal of optical communication lies in its ability to offer exceptional bandwidth and data-carrying capacity, surpassing traditional copper-based systems.

The exponential growth of data-intensive applications, such as high-definition video streaming, cloud computing, and the Internet of Things (IoT), has fueled an insatiable appetite for higher data rates. Optical communication systems have risen to this challenge, supporting data rates that were once deemed unimaginable. With advancements like wavelength division multiplexing (WDM), which allows multiple data streams to be transmitted simultaneously over different wavelengths of light, optical systems can now achieve multi-terabit-per-second data rates, making them pivotal in the backbone of global communication networks.

Furthermore, as 5G networks continue to roll out and promises of 6G on the horizon, optical communication systems will play an indispensable role in backhaul and fronthaul connections, supporting the low latency and high data rates needed to sustain the next generation of wireless communications. In data centers, optical interconnects have become essential, facilitating rapid data transfer and reducing latency to ensure seamless operation of cloud services and data storage facilities.

1.3 Benefits of Advanced Modulation Techniques: Advanced modulation techniques, such as Quadrature Amplitude Modulation (QAM) and Orthogonal Frequency Division Multiplexing (OFDM), have revolutionized the field of telecommunications and digital data transmission. These techniques offer a multitude of benefits that enhance the efficiency, capacity, and reliability of modern communication systems.[1]

One key advantage of advanced modulation techniques is their ability to transmit more data in a given bandwidth compared to traditional modulation schemes. QAM, for instance, can represent multiple bits of information in a single symbol, allowing for higher data rates over the same channel. This increased spectral efficiency is crucial in the era of growing data demands and limited available frequency spectrums.

Furthermore, advanced modulation techniques provide improved resistance to noise and interference. By spreading the data across multiple carriers or symbols, these techniques make it possible to recover lost or corrupted data more effectively. This robustness is essential for maintaining communication quality in noisy environments or over long distances.

In addition to their resilience to noise, these modulation techniques enable adaptive modulation and coding schemes. This means that communication systems can dynamically adjust their modulation and error correction codes based on the current channel conditions. When the channel is clear and the signal-to-noise ratio is high, the system can use higher-order modulation for increased data rates. Conversely, in adverse conditions, it can switch to more robust modulation schemes to maintain a reliable connection.

Advanced modulation techniques also contribute to the flexibility and versatility of modern communication systems. OFDM, for example, is well-suited for broadband communications because it can efficiently divide the available spectrum into numerous subcarriers. This makes it possible to transmit data over a wide range of frequencies, facilitating applications like Wi-Fi, 4G/5G cellular networks, and digital television broadcasting.

1.4 Polarization-Multiplexed Modulation: Polarization-multiplexed modulation is a sophisticated technique used in optical communication systems to enhance data transmission rates and capacity. This technique leverages the polarization properties of light to transmit multiple independent data streams simultaneously over a single optical fiber, effectively multiplying the information-carrying capacity of the medium.

In polarization-multiplexed modulation, two orthogonal polarization states of light (typically referred to as the vertical and horizontal polarizations) are used to encode different data channels. Each polarization state can carry its unique data stream, effectively doubling the transmission capacity compared to traditional single-polarization systems. This method is particularly valuable in long-distance optical fiber communication where spectral efficiency and bandwidth utilization are critical.

One of the key advantages of polarization-multiplexed modulation is its ability to mitigate polarization mode dispersion (PMD), a phenomenon in optical fibers that can distort and degrade the quality of transmitted signals over long distances. By using multiple polarization states, the impact of PMD can be minimized, resulting in more reliable and higher-capacity optical communication links.[2]

However, polarization-multiplexed modulation also presents its own set of challenges. Maintaining the orthogonal polarization states throughout the optical path requires precise alignment and control of optical components, which can be technically demanding. Additionally, polarization-dependent losses and impairments can affect signal quality and require compensation techniques.

1.5 Optical Code Division Multiple Access (Ocdma): Optical Code Division Multiple Access is an advanced and innovative technology in the field of optical communication systems. Unlike traditional optical networks that rely on time-division or wavelength-division multiplexing, OCDMA leverages unique codes to enable multiple users to access the network simultaneously. This technology has gained significant attention due to its potential to address the increasing demands for high-speed and secure data transmission in modern telecommunications.

OCDMA systems use a technique known as optical encoding, where each user is assigned a specific code, typically in the form of optical pulses or sequences. These codes are carefully designed to be orthogonal, meaning they have minimal interference with each other. When multiple users transmit data over the same optical fiber simultaneously, the receiver uses its corresponding code to extract its intended signal while suppressing interference from other users. This inherent security feature makes OCDMA particularly attractive for applications requiring robust data privacy and security.[3]

Moreover, OCDMA offers advantages in terms of network efficiency and scalability. Unlike time-division multiplexing (TDM), where users must contend for time slots, or wavelength-division multiplexing (WDM), which requires multiple dedicated wavelengths, OCDMA allows for a more flexible and efficient use of the available bandwidth. New users can be easily accommodated by assigning them unique codes, making OCDMA networks highly scalable to meet growing communication demands.

However, OCDMA is not without its challenges. One significant issue is the need for precise synchronization among users to ensure that their codes align correctly at the receiver. Additionally, optical components capable of generating and processing these unique codes can be complex and expensive, which may limit widespread adoption.

II. OBJECTIVES

Alan E. Willner et al (2017) highlight the most recent advancements in the application of OAM multiplexing for high-capacity free-space optical and millimeter-wave communications. He tackle a diverse array of technical obstacles, such as atmospheric turbulence and crosstalk, and he also explore potential strategies to mitigate the detrimental consequences.[16]

Naazira Badar et al (2017) predicated on a WDM-FSO system. The performance of an 8-channel WDM-based FSO system under mild, moderate, and intense turbulence conditions is to be assessed using widely accepted modulation schemes. The Gamma–Gamma fading model is employed to execute atmospheric turbulence modelling. The system is simulated on OptiSystem 14.0.[17]

Ahmed Nabih Zaki Rashed et al (2018) The objective of this investigation is to optimise the performance of optical fiber communication systems by examining modulation algorithms for radio over fiber communication systems. In order to achieve this objective, the modulation alternatives that have been suggested typically implement a variety of conventional modulation technologies. The proposed modulation technologies integrate a variety of modulation techniques, including differential phase shift keying amplitude modulation, offset quadrature phase shift keying amplitude modulation, frequency phase modulation, and pulse amplitude frequency modulation, to be applied to various optical communication system models. [18]

Harpreet Kaur Gill et al (2019) This research offers a high-capacity intersatellite optical wireless system that is based on mode division multiplexing (MDM). 64 linearly polarized modes are integrated into the system to enhance its performance. The proposed MDM Inter-Satellite Optical Wireless Communication system has been constructed at various distances of 750–3750 km with data rates of 10, 20, and 40 Gbps, utilizing a variety of modulation algorithms, such as Manchester, DPSK, and DQPSK. The results have been compared using Q-factor, eye diagrams, and minimal bit error rate. [19]

D. Anandkumar et al (2020) This paper investigates a variety of atmospheric effects, such as absorption, scintillation, fog, and turbulence. The initial section of the paper analyses the channel models, while the latter section summarises the various modulation and diversity techniques, as well as the comparative study of the (SNR) and (BER) under a variety of atmospheric factors in the FSO system. This survey provides a thorough examination of the essential information required to establish a low-cost, high-capacity FSO link. [20]

S. Magidi et al (2021) This article investigates the hybrid modulation schemes and FSO channel models that have been recently implemented to optimise FSO performance. The FSO modulation schemes that are employed most frequently are presented with their conditional probability of error. Additionally, the bit error expressions for the hybrid modulation schemes are furnished.[21]

Abu Jahid et al (2022) This survey offers a thorough examination of a variety of critical technologies, as well as the significance, demonstration, recent development, and implications of state-of-the-art criteria in the fields of spectrum reuse, classification, architecture, physical layer security, and future applications. Among a variety of enticing optical wireless technologies, it is intended to simplify the understanding of FSO systems. Furthermore, the successful deployment of FSO systems is demonstrated by the implementation of adaptive modulation, channel modelling schemes, relay-aided transmission, cooperative diversity, prospective challenges, and a diverse array of mitigation techniques. Additionally, prospects for the immediate future are underscored.[22]

Deepak Garg (2023) provides a basic overview of the aforementioned technologies and subsequently summarises the most recent strategies for improving the system's performance. To achieve this, the literature on fiber communication and its integration with the next generation networks, which are primarily based on Radio over Fiber (RoF), Fiber to the Home (FTTH), and Free Space Optics (FSO), is analysed to identify the antecedent limitations and their respective enhancement measures. [23]

Vishal Jain et al (2024) offers in this paper a concise summary of the fiber nonlinearity effect and a thorough analysis of a diverse array of fiber nonlinearity compensation methods.[24]

III. METHODS

Nonlinearity induced impairments such as FWM and XPM in a traditional optical communication link may be compensated for by either allowing the residual local dispersion of the fiber to persist or by appropriately increasing the channel spacing.

Since dispersion is a linear process, dispersion correction may be applied at the receiver end or sporadically across the connection to balance the buildup of dispersion along the transmission fiber.

However, this makes the system more difficult than those that use optical fibers with lower dispersion values to avoid the need for dispersion control.

A. *Mach–Zehnder Modulators*

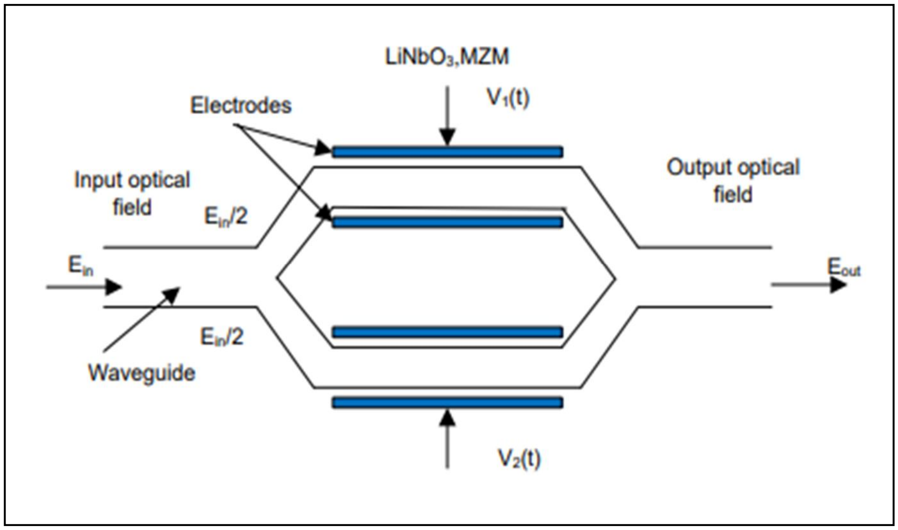
The concept of interference drives Mach-Zehnder modulators, as opposed to electro-absorption modulators.

There is an input coupler separating the two incoming light beams.

A phase modulator is used on one route to accomplish the regulation of the phase difference between the two optical beams by the applied voltages V1, 2.

Depending on the phase difference that is produced, this applied electrical voltage may produce either constructive or destructive interference, a phenomenon called as intensity modulation.

Fig.1: Optical intensity modulator based on Mach-Zehnder interferometric structure[15]



B. *Modulation Formats under investigation*

To choose the best modulation format, a number of factors need to be taken into account, such as power margin, tolerance against GVD, SPM, XPM, FWM, and SRS, as well as spectrum efficiency and tolerance against fiber nonlinear effects. Because the NRZ format is so simple to create, detect, and analyze, it is the most basic format that has been widely utilized in IMDD systems to date. In light of the fact that optical systems are integrating DWDM and optical amplifiers to accommodate larger data rates, the NRZ modulation format may not be the best option for big capacity optical systems in the recent past [25,26]. However, because of its historical domination, wide field deployment, and simplicity, NRZ would be a useful benchmark.

C. *Non Return to Zero (NRZ) Format*

The NRZ format is now the most extensively utilised in commercial goods due to its simplicity. Compared to phase shift keying, it is less vulnerable to laser phase noise, has a smaller electrical bandwidth for transmitters and receivers, and has the simplest transmitter and receiver setup. Fig. 2 displays the NRZ coding format.

Fig.2: Representation of the NRZ code.

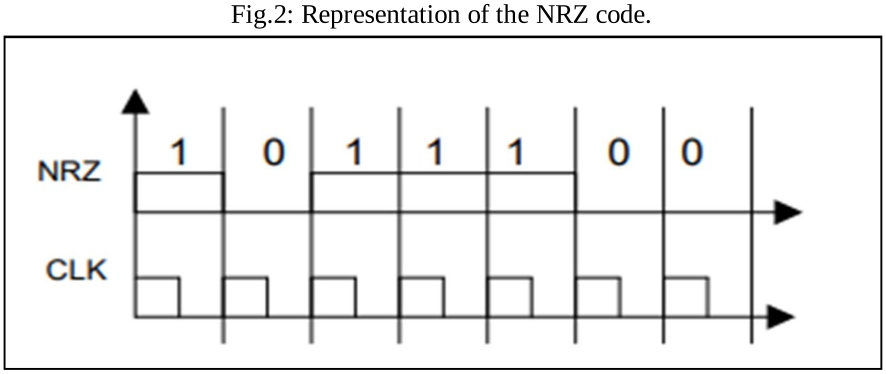


Fig.3: Block diagram of NRZ transmitter

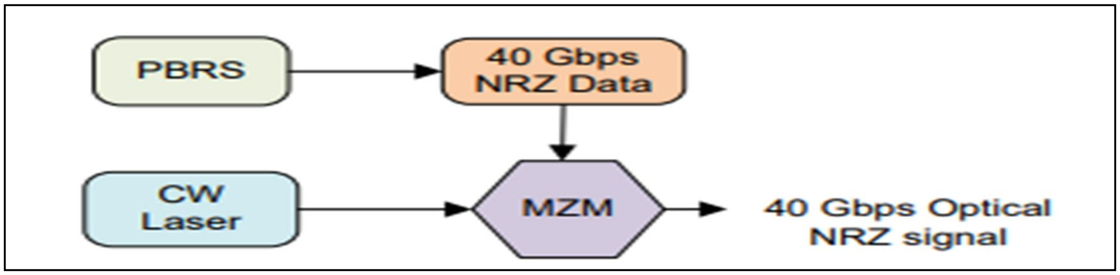


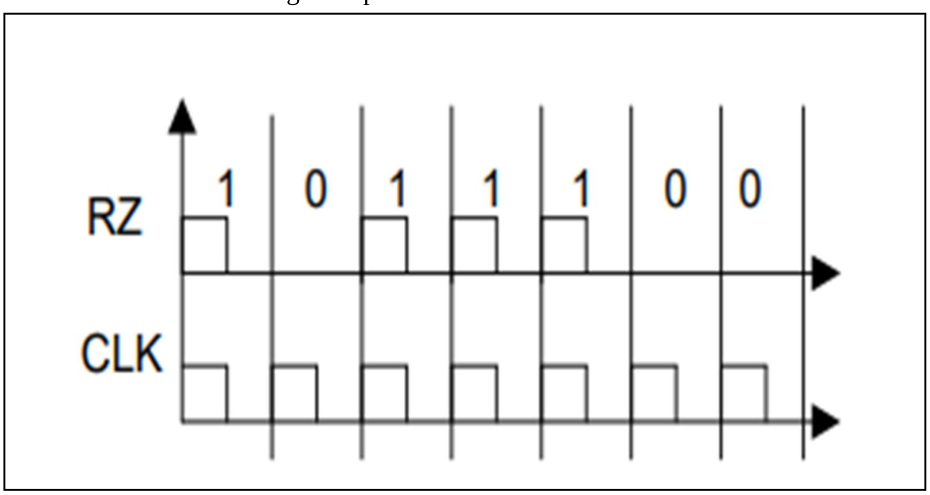
Fig. 3 shows the schematic block design for the 40 Gbps NRZ transmitter. A 40 GHz NRZ data stream powers the MZM by ON/OFF keying an optical signal produced by the continuous-wave (CW) laser source. The applied electric field, whose voltage varies according to a preset function, modulates the intensity of the carrier light wave. An electrical NRZ signal is used to drive the MZM at the quadrature point of the modulator power transfer function. NRZ optical transmissions are detected by a simple photodiode at the receiver, which transforms the optical power of the signal into an electrical current. The term "direct detection" describes this. In this thesis, other modulation kinds are also detected using the same direct detection approach, as long as they are not indicated explicitly.

The decreased on-off transitions cause the NRZ pulses to have a limited optical spectrum. Improved dispersion tolerance and enhanced spectral efficiency are made possible by the narrower spectral width; still, ISI occurs in between the pulses. Since an NRZ modulated optical signal is less resistant to the fiber nonlinear effect than its RZ equivalent, more study is being done on the RZ format [27].

D. Return-to-Zero (RZ) Format

Higher data rates, such 40 Gbps, have a greater influence on non-linearity, and the RZ signal format performs better than the NRZ signal format. As shown in Fig. 4, the power level in RZ format is 0 for the 0 bit continually. After half the duration, it returns to 0 for the logical 1 bit.

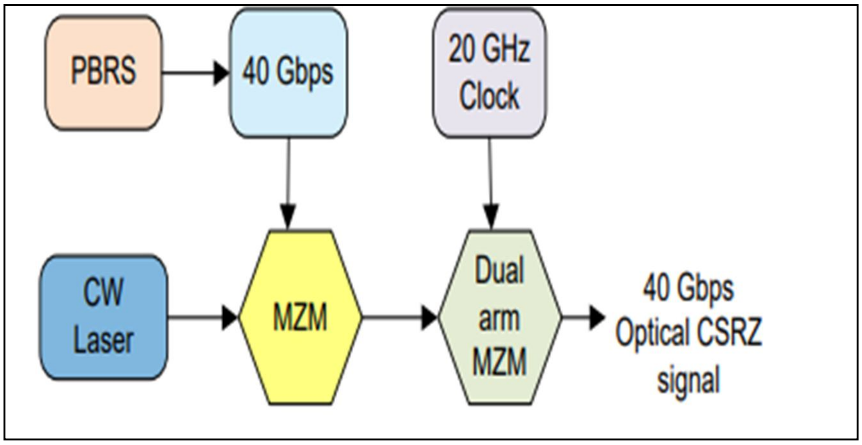
Fig.4: Representation of the RZ code.



E. Transmitter Design for Carrier Suppressed Return-to-Zero (CSRZ) Format

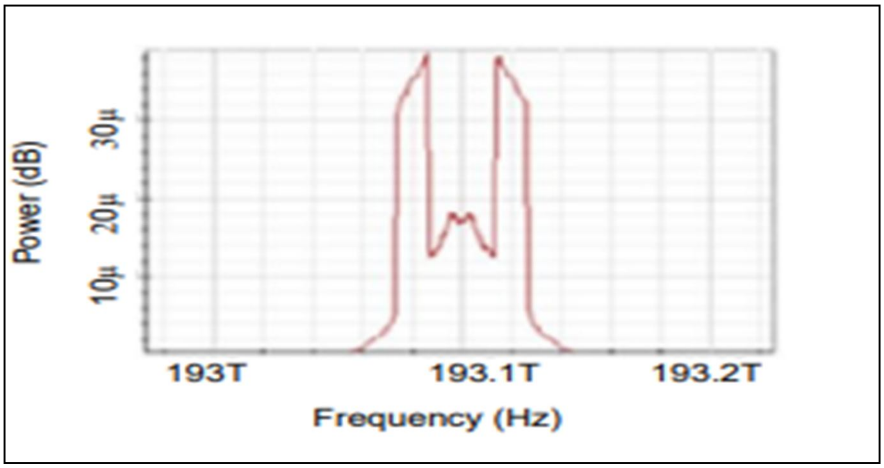
Many transmission experiments have used the CSRZ format, which is a modification of the RZ format and has a smaller pedestal shape of the optical spectrum than the original RZ format [27]. It is also very resistant to the combined effects of SPM and GVD. The π phase shift that occurs between successive data points sets the CSRZ signal apart from ordinary RZ. Unlike correlative coding schemes, like duobinary, the sign reversals happen at every bit transition and are independent of the signal's information-carrying part. When successive bit locations alternate, the fundamental frequency components are lowered to half of the data rate. For CSRZ, there is no carrier component as a consequence of this phase shift in the optical domain [28, 29].

Fig.5: Block diagram of CSRZ transmitter



Due to its lower optical power needs, CSRZ can accommodate more multiplexed channels during transmission and can withstand chromatic dispersion more well. Furthermore, carrier suppression in WDM systems lowers the efficiency of FWM [29]. The CSRZ transmitter setup that is being analysed is shown in Fig. 5 Two MZMs may be concatenated to create a CSRZ optical signal. The first MZM uses 40 Gbps NRZ data to control light intensity coming from a CW laser source. The resulting NRZ optical signal is then modulated by the second MZ modulator, which is driven by a clock operating at half bit-rate (20 GHz in this example). An optical signal with CSRZ is produced as a consequence of this technique.

Fig.6: Spectrum of CSRZ signal



At the transmission minimum, the optical field transfer function of the MZM changes sign, resulting in phase inversions between neighboring bits. As seen in Fig. 6, this causes a pi phase shift to be created between any two consecutive bits. As a result, the carrier frequency center peak is suppressed and the spectrum is altered.

F. Opti System

Research and development activities make considerable use of Opti System 10.0, a powerful optical communication system design simulation tool that examines and simulates an optical link [31–33]. It has been used in the present thesis to build and simulate optical communication systems to assess their performance while taking the proper properties of system components into account. The fair modelling accuracy and ease of use of this program make it suitable with both Windows and UNIX platforms. Each block in the picture represents a subsystem or component of the optical communication system; the system is shown as a connected collection of blocks. Similar to how actual signals are exchanged in a real-world communication system, the Opti System simulation transfers "signal" data between component models.

It offers a range of simulation engines together with corresponding simulation approaches. This allows for the most flexibility in the modelling and simulation of systems, such as large metro networks with feedback loops and EDFA transients due to the addition and removal of channels, ultra-long-haul DWDM telecom systems, and short-distance data communication links. The data post-processing and display capabilities of Optisytem provide a flexible and easy-to-use graphical measurement interface that may be used as a virtual laboratory instrument set. Among the interactive and post-processing features that allow for the simulation of a project once and the subsequent analysis of the results are graph superimposition, correlation graphs, interactive cursor read-out data, peak search, eye-diagram measurements, and BER/Q evaluation. These features help to save time during the design process.

1) Simulation Set-Up for CSRZ format

This thesis has constructed three different dispersion compensation systems (pre-, post-, and symmetrical compensation) to adjust for the accumulated dispersion. In the pre-compensating situation, DCF acts as a pre-compensating factor for the accumulated dispersion of the transmission fiber. The gain G of the amplifier, which compensates for the fiber loss in the DCF, may be found after the DCF by:

$$G = \alpha_{DCF} L_{DCF} \quad \ldots (3.1)$$

where L is the DCF's length and ATC is the dispersion compensating fiber's attenuation coefficient. A similar equation applies to the gain of the amplifier that comes after the transmission fiber, where αTF is the transmission fiber's attenuation coefficient.

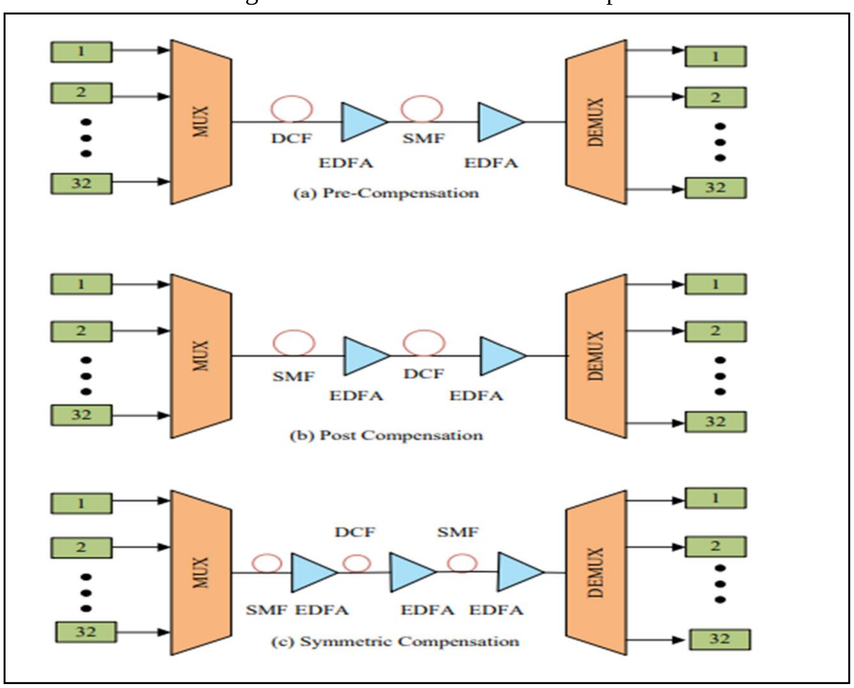
$$G = \alpha_{TF} L_{TF} \quad (3.2)$$

To account for the dispersion of the transmission fiber, the following factors should be considered when choosing the linear dispersive compensation length, or LDCF:

$$L_{DCF} = \frac{L_{TF} D_{TF}}{-D_{DCF}} \quad (3.3)$$

where L is the transmission fiber’s length, H is the transmission fiber’s dispersion, and D is the DCF's dispersion. The DCF post makes up for the transmission fiber’s dispersion in a post-compensating situation. In a symmetrical compensation scenario, the sequence of placement of fibers is transmission fiber, DCF, and transmission fiber [34]. The proposed 32-channel DWDM system, consisting of the transmitter section, optical receivers, and fiber, is shown in Figure 7. 193.1 THz is the first channel's central frequency. Table 1 provides specifics on the implemented simulation parameters.

Fig. 7: Schematic of simulation setups



Pre-compensation, post-compensation, and symmetrical compensation schemes are the three types of compensation schemes.
By mixing fibers with normal and anomalous GVD to create a dispersion map, the transmission link's design maintains a low average GVD while permitting a high local GVD across the link's length [35]. This technique is known as periodic dispersion management. To put it another way, the DCF and SMF parameters are selected so as to guarantee that the first-order dispersion is accurately compensated (D= 0), where D is the associated fiber's first-order dispersion parameter [ps/nm/km] and L is the total length of the SMF or DCF per span.

Table 1: Simulation parameters

Bit rate	40 Gbps
Sequence length	64
Samples/bit	256
DWDM channel spacing	50 GHz
Central frequency of the 1st channel	193.1 THz
Capacity	32-channel 40-Gbps
Distance	30 Km X N Spans
Input Power	-10 dBm

2) Transmitter section

The WDM transmitter is made up of an optical multiplexer, data modulators, filters, pseudo random bit sequence (PRBS) generator, and CW lasers. The PRBS generator generates bit sequences of 27–1 bits at a 40 Gbps rate. The 193.1–194.65 THz frequency range is covered by the equally scattered frequencies emitted by the CW laser, with a 50 GHz frequency separation between neighbouring channels. MZM has an extinguishing ratio of 30 dB. Each CW laser's output port has a CSRZ transmitter linked to it, as shown in Fig. 3.7. An optical multiplexer receives optical signals from 32 of these data modulators at its 32 input terminals. To ensure linear cross-talk reduction in the frequency domain, each channel is optically filtered using a narrow transmission optical filter prior to multiplexing [28]. In this regard, consideration has been given to a 50 GHz bandwidth second-order Gaussian filter. The channel spacing and operational wavelengths comply with ITU-T regulations.

3) Fiber section

The SMF gets the combined optical signal. Kerr-nonlinearity, dispersion, induced and spontaneous Raman scattering, and unidirectional signal flow are all included in the OptiSystem model. The characteristics of the fiber are shown in Table 2. The purpose of the gain that the EDFA inserts after every row is to make up for the losses from the row before it. The amplifiers have a fixed noise figure of 6 dB. To stop PMD, the scalar model of both femtosecond fibers was used. Subsequently, the signal is broadcast across N 30-kilometer-long spans of SMF. Pre, post, and symmetrical dispersion correction techniques for the proposed DWDM system have been simulated.

Table 2: Fiber parameters

Fiber Type	Attenuation (dB/Km)	Dispersion (ps/km-nm)	Dispersion Slope	Mode EffectiveArea	Non linear refractive index
SMF	0.22	17	0.08	80	2.6×10^{-20}
DCF	0.5	-85	-0.45	30	2.6×10^{-20}

4) Receiver section

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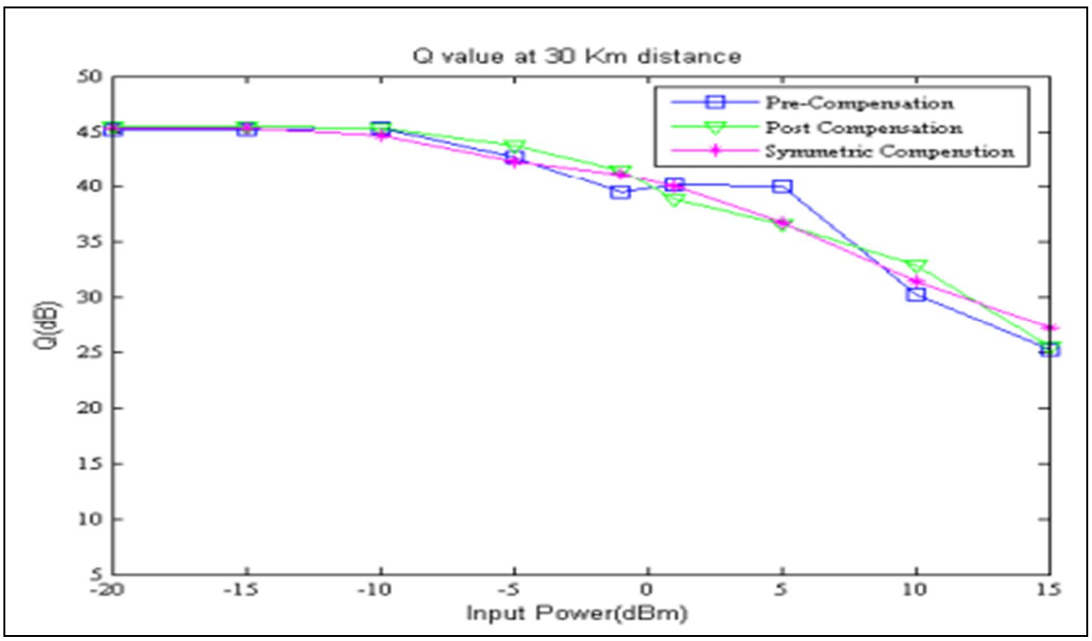
The signal is first demultiplexed in the receiver, then it is routed via the filter and 3R regenerator after being picked up by a PIN detector. The 32 output connectors of the used optical demultiplexer are used. Filter settings for Bessel band pass filters: With a depth of 100 dB, a filter order of 4, and a 3 dB cut-off frequency of 65 GHz, the channels at the corresponding wavelengths were divided. To get the best result, the filter's settings have been tuned. A PIN photodiode with a reference frequency of 193.1–194.65 THz, response [A/W] of 1, and dark current of 0.1 nA is then used to transmit the optical signal from each port. An electrical low pass Bessel filter, whose cut-off frequency is dictated by the modulation used and is optimum at 40 GHz with order 3, follows the PIN photodiode. Then, an electrical signal is produced by the 3R regenerator and linked straight to the BER analyzer. To create graphs and findings, such as eye diagrams, BER, Q values, and eye openings, the BER analyzer is used as a visualizer.

5) Investigation and Discussions of CSRZ format

The effectiveness of the CSRZ modulation format has been examined for pre, post, and symmetrical dispersion correction systems in a 1.28 Tbps DWDM system, with respect to received maximum Q value and eye opening. Because the first channel's findings are the most severe, they were included for system analysis. In this simulation, SMF and DCF fibers that are appropriate for mitigating GVD are used in order to create a 30 km span. Transmission spans were then cascaded in sequence to attain multiples of thirty kilometers in length. As a function of signal input power for spans 1 through 4, the Q value is graphically shown for pre, post, and symmetrical-compensation methods in Fig. 8 (a)–(d).

Fig. 8: Q value as a function of signal input power for a) span 1 (30 Km) (b) span 2 (60 Km) (c) span 3 (90 km) and (d) span 4 (120 km) for various dispersion compensation schemes

Fig. 8(a)



In a high data rate WDM system, it is preferable to minimise non-linear effects by making sure that the input power is as low as practical. The input power has been changed from -20 dBm to 15 dBm in light of this. Although it is normally not advised to operate at a power level above 5 dBm, the developed system works efficiently at a power level of 10 dBm. Only for the 4th Span, the power Q values at 15 dBm are, however, lower than the minimum necessary 15.6 dB. It is also clear that for all dispersion correction techniques, the Q value is initially maintained until -10 dBm, after which it starts to drop. The fact that the DWDM system has little non-linear effects at low powers clarifies this. However, the increasing dominance of non-linear effects, such FWM and XPM, brought on by the optical Kerr effect lowers the Q value and causes the pulses to overlap at higher energies. This discovery is in excellent accord with the previously published findings [27, 29].

Fig. 8(b)

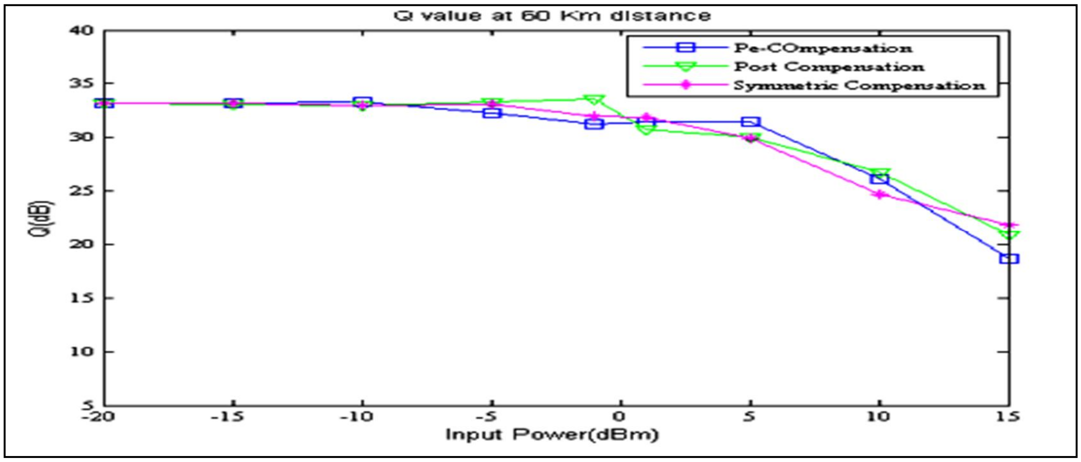


Fig. 8(c)

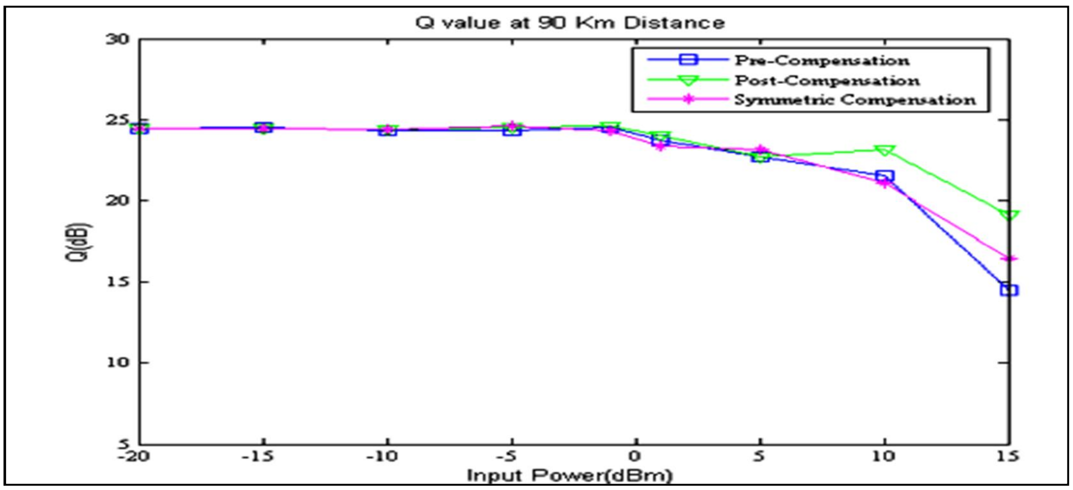
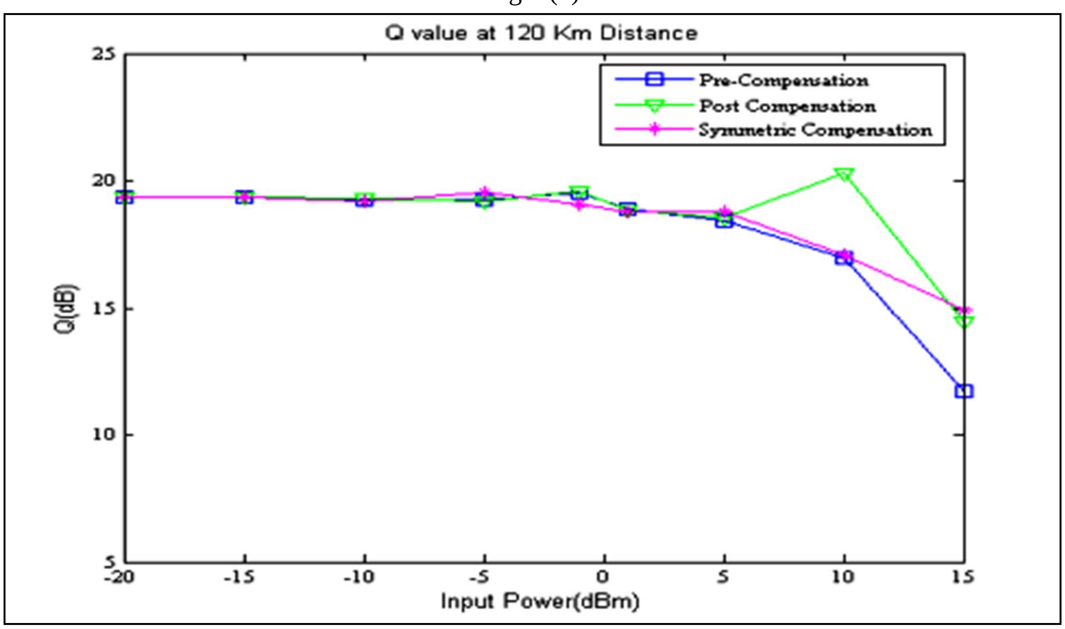
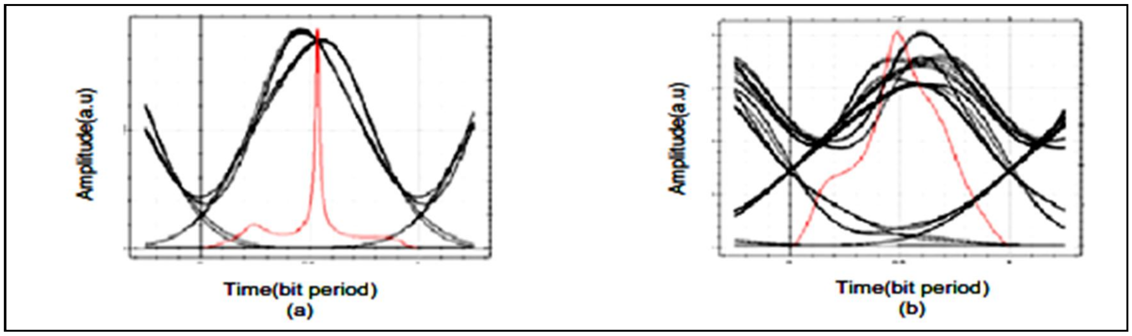


Fig. 8(d)



It has been shown that when the input signal strength rises for all three approaches, the Q value is initially maintained up to –10 dBm. Beyond this, however, it starts to decline due to the predominance of non-linear optical Kerr's effects. It has also been observed that the pre-compensation strategy performs the least well. However, there is a significant association between symmetric compensation systems and post compensation schemes, with post providing better performance at 15 dBm of input power.

Fig. 9: Eye diagrams of CSRZ modulation format at Pin= -10 dBm for post compensation schemeat a distance of (a) 30 Km (b) 120 Km



When the input power is -20 dBm, the post-compensation system produces the greatest Q value of 45.46 dB at a distance of 30 km. At a distance of 120 kilometres, the Q value drops to 19.35 dB, nevertheless. Because of its better performance, we have studied the post-compensation method in greater detail to forecast the eye diagrams at the receiver, as shown in Fig. 9. Both the eye's shape and aperture size diminish with distance.

As a result, compared to the pre and symmetrical dispersion compensation methods, it has been shown that the post compensation scheme performs better in terms of eye opening and Q value. Due to inter-channel XPM and FWM brought on by spectral widening, DWDM transmission still causes significant deterioration even though the CSRZ format is immune to GVD and SPM effects because of its limited spectral width. Wave frequencies interact with one another via frequency division multiplexing (FWM) to generate sum and difference frequencies, which in turn interact with one another to enhance bandwidth. The CSRZ format causes the filter bandwidth to be chosen three times in order to fit the extended pulse bandwidth, which causes the optical spectra to grow and the Q value to decrease at long distances. Moreover, carrier suppression reduces the effectiveness of four wave-mixing in WDM systems. As a result, it may be said that the conventional NRZ/RZ format is less appropriate for DWDM systems than the CSRZ format.

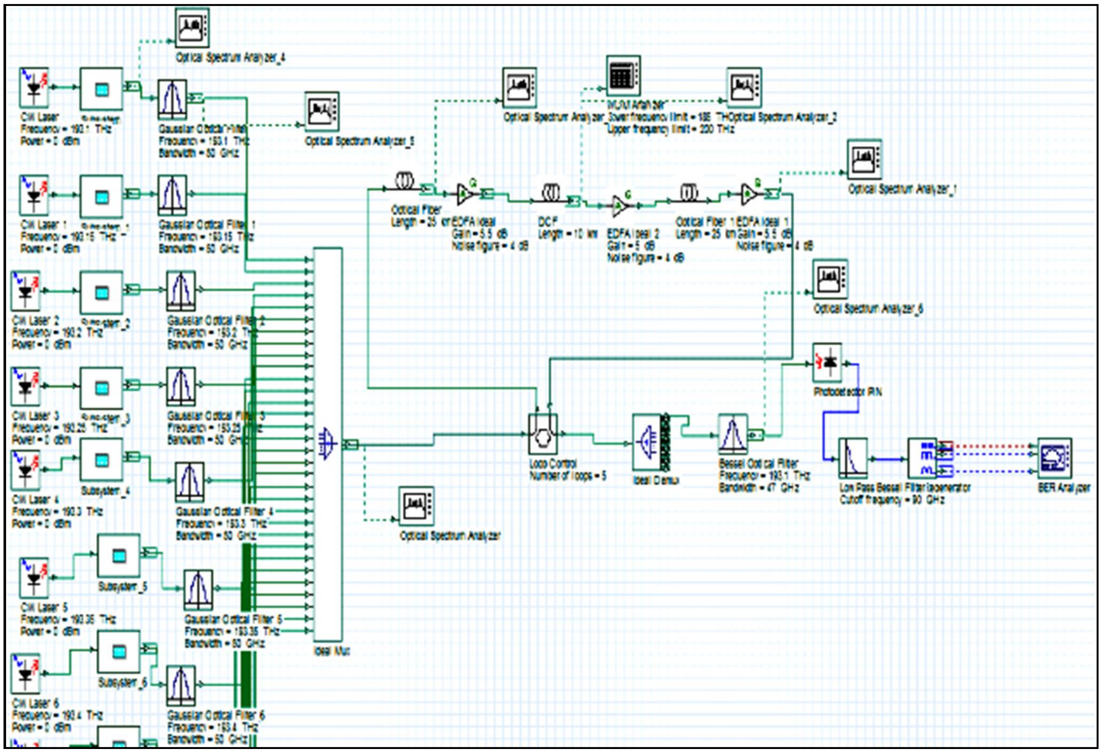
IV. RESULTS

Modelling the creation, propagation, and receipt of the sent signal is a part of the signal simulation process in an optical fiber transmission system. Every simulation involves a trade-off between time and accuracy. Research, development, testing, and refining of the intricate models needed to construct an optical system simulator usually take time and resources. Because the Opti system 10.0 simulator is available in commercial optical system simulators that offer affordable prices, sophisticated simulation algorithms, and user-friendly graphical user interfaces, it was selected to assess the transmission capabilities of a wide range of phase modulation formats. With simulation modules for active and passive photonic components, several fiber types, integrated digital signal processing modules, time domain and frequency domain analyzers, electrical signal sources, filters, and other relevant sub-systems, it is a widely acknowledged standard simulator. Additionally, by using other programming languages, such Matlab®, to communicate with this simulator, users may develop, construct, and integrate new modules with Optisystem.

Initially, DPSK and DQPSK formats were used to maximise performance on a 40 Gbps single-channel optical connection. The channel numbers were gradually expanded to 32 with a channel spacing of 50 GHz in order to reach an aggregate capacity of 1.28 Tb/s. For a range of fiber types, the simulation study was carried out in the C-band (1530 nm – 1565 nm) to assess the system's effectiveness for the proposed modulation settings. 193.1 THz is the center frequency of the first channel in the 32-channel DWDM system diagram shown in Fig. 10. These formats have been studied in the literature with a lower transmission data rate or with fewer channels at a 50 GHz channel spacing. Both formats are examined in this study under different dispersion compensating schemes. This suggested design's non-linear mitigation performance has been examined via an analysis of pre-, post-, and symmetric compensation arrangements. To account for dispersion and non-linearities, a DCF of 10 km is used in the pre-compensation system before the 50 km-long SMF. The gain of the EDFAs used in the connection is 5 dB and 11 dB, respectively. The post-compensation technique employs a DCF of 10 km to mitigate the dispersion buildup that happens after a 50 km SMF.

In the symmetrical-compensation system, a 10 km DCF is introduced between the 50 km SMF, as shown in Fig.10. Three in-line EDFAs with gains of 5.5 dB, 5 dB, and 5.5 dB are used in this experiment. Consistent with the results of the literature, the post compensation approach was shown to provide the best performance for both the DPSK and DQPSK forms [38]. This tactic was therefore used in the continuing enquiry. The findings are examined in a particular instance utilising the Q value and are startling over several transmission lengths up to 1600 km.

Fig. 10. Schematic of simulation setup



N spans of 60 km each are used to convey the signal once the input voltage has been adjusted. The optical multiplexer, data modulators, filters, CW lasers, and PRBS generator make up the WDM transmitter. CW lasers have uniformly spaced emission frequencies ranging from 193.1 to 194.65 THz, separated by a 50 GHz channel. It is shown that MZMs have an extinction ratio of 30 dB. A data modulator is used to drive each CW laser, as shown in Figs. 10 and 11 for DQPSK and DPSK, respectively. An optical multiplexer's 32 input terminals receive the modulated optical signal.

In DWDM systems, the reciprocal interaction of the signals and the accumulated ASE noise leads to the inevitable impairments of linear and nonlinear crosstalk. Therefore, it is essential to perform an accurate comparison between the two modulation schemes by optimising the optical and electrical filtering on both the transmitter and receiver sides [39]. Because of this, we have used receiver sensitivity to assess the filter's efficacy in terms of the received Q value. The 'elevated cosine' transfer function, whose center is the signal carrier frequency, was used to represent the optical filters of the multiplexer and de-multiplexer.

Table 3: Multiplexer Filter optimization

Filter Order	No of loops	Q value With Bessel Filter	Q value with Gaussian Filter	Q value with Rectangular
3	1	23.56	24.29	18.85
	5	23.17	21.74	18.48
	10	21.4	19.02	17.81
	15	19.99	16.84	17.06

	20	17.71	15.41	15.66
	25	16.49	14.2	14.32
4	1	23.36	24.04	18.85
	5	22.82	21.93	18.48
	10	21.84	18.72	17.8
	15	19.61	16.95	17.06
	20	17.92	15.31	15.43

The chart clearly shows that even with the same beginning Q value as the Gaussian filter, the Bessel filter may achieve a longer transmission reach. As such, the Bessel filter has been included into our design. Because the starting Q value is too tiny for the rectangular case, the proposed connection will not be particularly stable. Furthermore, we evaluated the ideal electrical and optical filter bandwidth required for effective signal transmission. Our results suggest that shorter channel spacing requires a wider electrical bandwidth. Before multiplexing, each channel is optically filtered using a third-order Gaussian filter (bandwidth of 50 GHz for DPSK format and a fourth-order Bessel filter (bandwidth of 50 GHz for DQPSK format) to avoid crosstalk between neighboring channels. This is taken into consideration. When the combined optical signal is sent to the SMF, consideration is given to the dispersion, stimulated Raman scattering, unidirectional signal flow, and Kerr-nonlinearity. The usage of a scalar model for both fiber segments has served to lessen the impact of PMD. The following parameters have been considered: dispersion slope (S) of 0.08 ps/nm2/km at 1550 nm, attenuation (α) of 0.22 dB/km, D of 17 ps/km-nm, and nonlinear refractive index (n2) of 2.6×10^{-20} m2/W. The DCF segment used in each span at 1550 nm has the following characteristics: α = 0.5 dB/km, D = -85 ps/km-nm, S = -0.45 ps/nm2/km, n2 = 2.6×10^{-20} m2/W, and Aeff = 30 μm2. The receiver is made up of the de-multiplexer, demodulators, filters, and 3R regenerator. To evaluate required filter settings, a simulation of the 32-port demultiplexer's output has been performed. When using a third order Gaussian filter with a bandwidth of 50 GHz for DPSK, the design performs optimally; when using a second order Bessel band pass filter with a 3 dB bandwidth of 50 GHz for DQPSK, the design performs optimally. The 3R regenerator, which generates graphs and results including eye diagrams, BER, Q value, and eye opening, is then linked to the BER analyser.

V. DISCUSSION

In order to model, develop, and simulate the ideal circumstances for a long-haul optical communication connection in order to obtain an optimum propagation length, this thesis covers the theoretical examination and analysis of the optical channel characteristics. Using the analytical model and numerical simulation analysis of this fiber transmission channel, the designer may choose a design plan and an appropriate solution for different modulation formats within the specified operational limits. Examining the effects of linear and non-linear phase impairments that happen during pulse propagation in the fiber medium on the design of long-haul fiber optic communication systems is the main goal of the thesis. This chapter outlines possible future expansions of the intended study and summarises the results and contributions of the current work.

Enhancing the transport capacity and transmission distance of DWDM systems while lowering the cost per carried information bit has become very desirable due to the growing demand for bandwidth. It is clear that new approaches to binary data encoding over the optical carrier have been developed as a result of the constraints placed on DWDM transmission and the development of optical communication systems. This thesis focused on the difficulties these modulation methods provide throughout various stages of implementation. Generally speaking, the kind of fiber, the pace at which data is sent across the channel, and the wavelength spacing all play a role in determining which optical modulation scheme is best. Service providers may save costs by using most of the current systems with the best modulation formats and innovating their current light wave network without having to completely update.

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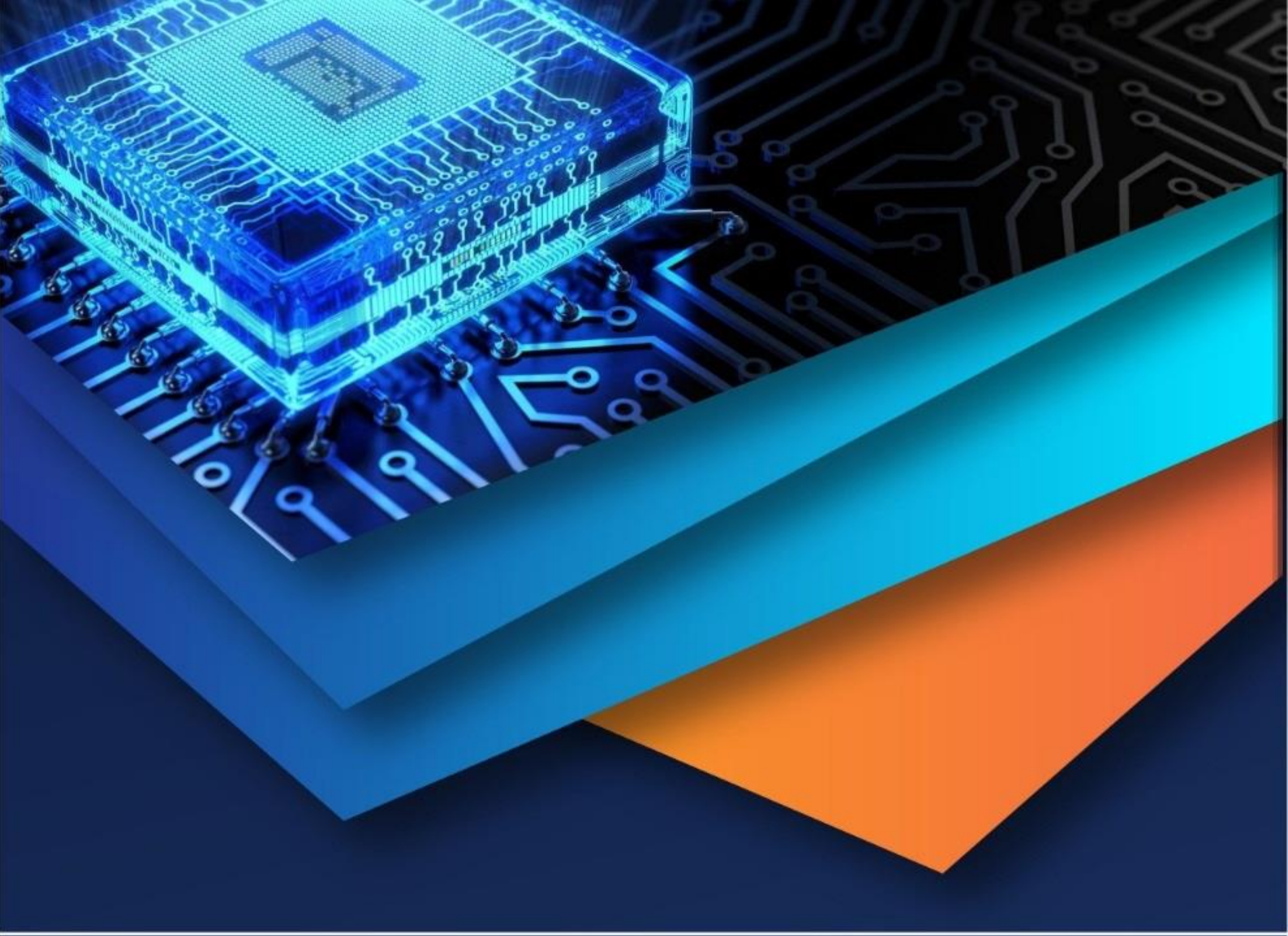

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