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Modulation techniques for increasing data rates in high capacity optical communication systems

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Abstract – *Dense Wavelength Division Multiplexing (DWDM) has emerged as a practical solution in fiber-optic communication systems due to the exponential growth in channel capacity requirements for long-haul, high-speed transmission. As a result, designing optimized system solutions that account for channel characteristics has become a crucial area of research, aiming to maximize the performance of optical networks. The capacity of optical channels is generally influenced by several factors, including the dispersive and nonlinear properties of the fiber medium, signal structure, and interference from various sources. In multichannel optical systems, these impairments can be significantly more detrimental—especially at high data rates where fiber nonlinearities become pronounced.*
Therefore, comprehensive understanding, modeling, and characterization of optical channel behavior under diverse operating conditions are essential for leveraging the maximum transmission capacity while minimizing performance degradation. This system examines how spectrally efficient modulation schemes in optical communication can mitigate both linear and nonlinear impairments associated with high-speed data transmission. Given the stringent limitations imposed by the properties of the optical channel, DWDM systems must carefully select both the modulation format and pulse shape to achieve optimal performance. Intensity and phase modulation formats are among the viable technologies that enable the design of high-performance optical networks. This dissertation delves into the theoretical foundations of various models used to analyze and simulate high-speed optical communication systems. It investigates the impact of system components and modulation formats on overall performance through theoretical analysis, mathematical modeling, and computer simulations. The study considers five modulation formats: Carrier-Suppressed Return-to-Zero (CSRZ), Modified Duobinary, Differential Phase Shift Keying (DPSK), and Differential Quadrature Phase Shift Keying (DQPSK).

Keywords- *Carrier Suppressed Return to Zero, Modified Duobinary, Differential Phase Shift Keying, Differential Quadrature Phase Shift Keyin.*

I INTRODUCTION

In the rapidly evolving landscape of high-capacity optical communication systems, the pursuit of increased data rates has become a fundamental objective. As the demand for seamless, high-speed data transmission continues to grow, researchers and engineers are increasingly turning to innovative methods to enhance the efficiency, reliability, and overall performance of optical networks. Among these advancements, advanced modulation techniques have emerged as a critical focus area, offering the potential to significantly improve

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bandwidth utilization and elevate achievable data rates. By exploiting the unique properties of light as a carrier of information, these techniques are pushing the boundaries of optical communication capabilities. This exploration delves into the domain of advanced modulation techniques, highlighting their significance, practical applications, and the transformative potential they hold for the future of optical communications. Techniques such as Quadrature Amplitude Modulation (QAM) and Orthogonal Frequency Division Multiplexing (OFDM) have revolutionized digital data transmission across various communication platforms. These methods enhance spectral efficiency, increase transmission capacity, and improve the robustness of modern communication systems [1]. Another pivotal development is polarization-multiplexed modulation, a sophisticated approach that leverages the polarization properties of light to transmit multiple independent data streams over a single optical fiber. This technique utilizes two orthogonal polarization states—typically horizontal and vertical—to carry separate data channels. As a result, the transmission capacity can be effectively doubled compared to traditional single-polarization systems. This method is particularly advantageous in long-haul communication scenarios where bandwidth efficiency and channel capacity are paramount.

A key benefit of polarization-multiplexed modulation lies in its ability to mitigate polarization mode dispersion (PMD)—a detrimental effect in optical fibers that can lead to signal distortion and degradation over extended distances. By using multiple polarization states, the impact of PMD is reduced, resulting in more stable and higher-performance communication links [2]. Furthermore, Optical Code Division Multiple Access (OCDMA) represents an innovative leap in optical networking technologies. Unlike conventional multiplexing methods such as Time-Division Multiplexing (TDM) or Wavelength-Division Multiplexing (WDM), OCDMA utilizes unique optical codes to allow multiple users to access the network simultaneously. This technique has garnered significant interest due to its inherent ability to support high-speed, secure, and flexible data transmission, making it a promising solution for next-generation optical networks [3].

II LITERATURE REVIEW

A variety of recent studies have explored innovative approaches to enhancing the capacity, performance, and reliability of optical wireless communication systems. Harpreet Kaur Gill et al. (2019) proposed a high-capacity Inter-Satellite Optical Wireless Communication (ISOWC) system utilizing Mode Division Multiplexing (MDM). The system integrates 64 linearly polarized modes to significantly boost performance across distances ranging from 750 km to 3750 km, supporting data rates of 10, 20, and 40 Gbps. Multiple modulation schemes—Manchester, Differential Phase Shift Keying (DPSK), and Differential Quadrature Phase Shift Keying (DQPSK)—were implemented and evaluated. The system's effectiveness was assessed using metrics such as Q-factor, eye diagrams, and bit error rate (BER), demonstrating substantial improvements in performance [4]. D. Anandkumar et al. (2020) conducted an extensive study on Free Space Optical (FSO) systems, focusing on various atmospheric impairments including absorption, scintillation, fog, and turbulence. The first part of their work delves into channel modeling under these atmospheric effects, while the second part offers a comparative analysis of Signal-to-Noise Ratio (SNR) and BER performance across different modulation and diversity techniques. Their findings provide key insights for designing low-cost, high-capacity FSO links [5].

S. Magidi et al. (2021) investigated hybrid modulation schemes and FSO channel models aimed at optimizing system performance. The study presents the conditional probability of error for commonly used FSO modulation schemes and provides bit error expressions for various hybrid techniques. This work contributes significantly to the understanding and selection of optimal modulation formats in varying channel conditions [6]. Abu Jahid et al. (2022) offered a comprehensive review of current technologies and developments within the field of optical wireless communication. The survey covers a wide spectrum of topics including spectrum reuse, system architecture, physical layer security, and adaptive modulation. The study emphasizes the deployment of advanced techniques such as relay-aided transmission, cooperative diversity, and sophisticated channel modeling, outlining both the present challenges and future directions for successful FSO system implementation [7].

Deepak Garg (2023) provided an overview of recent strategies for enhancing the performance of fiber-optic communication systems, especially within the context of next-generation networks. The study explores the integration of fiber technology with systems like Radio over Fiber (RoF), Fiber to the Home (FTTH), and FSO, identifying key limitations and suggesting improvements for future deployment. This review highlights the

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convergence of technologies as a critical factor in advancing high-speed optical communications [8]. 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.[9]

III METHODOLOGY

Nonlinearity-induced impairments, such as Four-Wave Mixing (FWM) and Cross-Phase Modulation (XPM)**,** can significantly degrade performance in traditional optical communication links. These impairments may be mitigated by either maintaining residual local dispersion within the fiber or by increasing channel spacing between adjacent wavelength channels. Since dispersion is a linear phenomenon**,** its effects can be effectively compensated either at the receiver end or at intermediate points along the transmission path. This compensation strategy helps counteract the cumulative dispersion that builds up during signal propagation. However, incorporating dispersion compensation mechanisms increases system complexity compared to architectures that utilize optical fibers with inherently low dispersion**,** which can reduce or even eliminate the need for active dispersion management.

Mach–Zehnder Modulators- Unlike electro-absorption modulators, which rely on absorption characteristics to control light intensity, Mach-Zehnder Modulators (MZMs) operate based on the principle of optical interference. An input coupler initially splits the incoming light into two separate paths or arms. One or both arms are equipped with phase modulators, which apply voltage signals V1V_1V1 and V2V_2V2 to induce a controlled phase shift between the two optical signals. By precisely adjusting the phase difference between the two paths, the modulator can produce either constructive or destructive interference when the beams are recombined at the output coupler. This interference directly translates into a modulation of the output light versatile and widely used component in high-speed optical communication systems.intensity, a mechanism known as intensity modulation. The ability to control light output through phase manipulation makes the MZM a

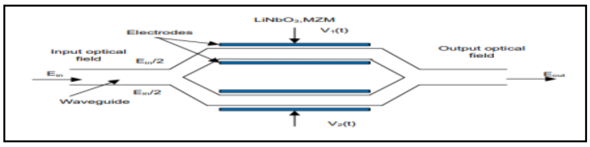

Fig.3.1: Optical intensity modulator based on Mach-Zehnder interferometric structure.

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 fibre 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 [10,11]. However, because of its historical domination, wide field deployment, and simplicity, NRZ would be a useful benchmark.

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. 3.2 displays the NRZ coding format.

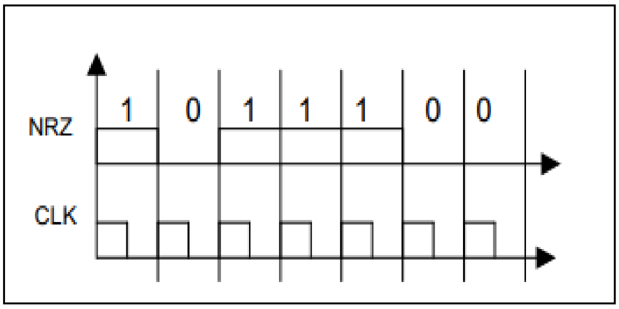

Fig.3.2: Representation of the NRZ code

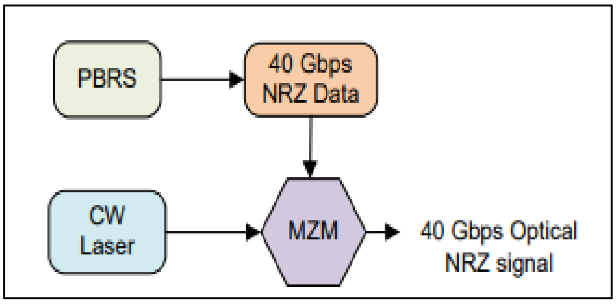

Fig.3.3: Block diagram of NRZ transmitter

Fig. 3.3 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.

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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 fibre nonlinear effect than its RZ equivalent, more study is being done on the RZ format [12].

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. 3.4, 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.

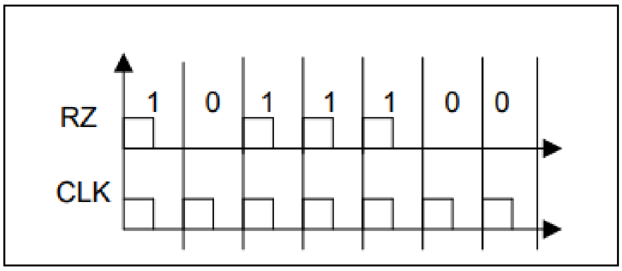

Fig.3.4: Representation of the RZ code.

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 [13]. 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.

Receiver section- 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 analyser. To create graphs and findings, such as eye diagrams, BER, Q values, and eye openings, the BER analyser is used as a visualizer.

IV. RESULT & DISCUSSION

Numerical Simulation Model and System Description

The simulation of an optical fiber transmission system involves modeling the generation, propagation, and reception of optical signals, all of which are critical to evaluating system performance. Every simulation process presents a trade-off between computational time and accuracy. The development and refinement of accurate models for optical systems require substantial research effort and resources.

To conduct the simulation study in this work, OptiSystem 10.0 was selected due to its widespread acceptance, cost-effectiveness, advanced simulation algorithms, and user-friendly graphical interface. This commercial optical system simulator provides a comprehensive library of modules, including both active and passive photonic components, various fiber types, digital signal processing (DSP) elements, and analytical tools for both time-domain and frequency-domain analysis. Furthermore, OptiSystem supports integration with external programming platforms, such as MATLAB®, enabling users to design and embed custom modules for specialized simulations.

The simulation study initially focused on evaluating Differential Phase Shift Keying (DPSK) and Differential

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Quadrature Phase Shift Keying (DQPSK) formats for a 40 Gbps single-channel optical link. The system was then scaled up to a 32-channel DWDM configuration, with a channel spacing of 50 GHz, resulting in a total aggregate capacity of 1.28 Tbps. Simulations were conducted within the C-band spectrum (1530–1565 nm), across different fiber types, to assess system performance under varying channel and transmission conditions. The central frequency of the first channel in the 32-channel DWDM system was set to 193.1 THz, forming the reference point for adjacent channel allocations.

V. CONCLUSION

This paper presents a theoretical investigation and simulation-based analysis of optical channel characteristics aimed at modeling and optimizing long-haul optical communication links. The objective is to determine the optimal propagation distance under realistic transmission conditions. By employing both analytical modeling and numerical simulation of the fiber transmission channel, designers can evaluate various modulation formats and select appropriate design strategies within defined operational constraints.

The core focus of this work is to analyze the influence of linear and nonlinear phase impairments—such as chromatic dispersion and nonlinear effects like self-phase modulation and cross-phase modulation—that affect signal integrity during pulse propagation in optical fibers. These impairments are critical in determining the feasibility and performance of long-haul fiber optic communication systems.

As the demand for bandwidth continues to rise, enhancing both the transmission capacity and reach of Dense Wavelength Division Multiplexing (DWDM) systems, while simultaneously reducing the cost per transmitted bit, has become a major objective in optical network design. The growing complexity and limitations of DWDM-based transmission have spurred the development of advanced binary encoding schemes and spectrally efficient modulation formats, which are essential for meeting the performance demands of next-generation optical communication infrastructures.

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