Performance Studies and Comparative Analysis of FSO Links using CSRZ, RZ, NRZ, PPM and QPSK Modulation Schemes

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Abstract—**Free space optical (FSO) communication stands as a cutting-edge wireless technology facilitating data exchange via precisely directed beams of light. Its utilization of unlicensed optical wavelengths grants ample bandwidth capacity while ensuring immunity to electromagnetic interference, addressing EMI/EMC concerns effectively. FSO's deployment establishes secure communication channels with minimal latency, leveraging Earth's atmosphere as a transmission medium. However, its availability can be hindered by local weather conditions like rain, fog, snow, and wind. This study focuses on assessing modulation techniques—RZ, NRZ, CSRZ, PPM, and QPSK—and their performance, particularly in terms of the Q-factor. The evaluation accounts for variations in distance, bit rates, and input laser power, employing eye diagrams for a thorough analysis of their efficacy.**

Index Terms—**free space optic, modulation schemes, Q-factor, received signals power, Bit sequence generator, RZ pulse generator, and NRZ pulse generator, as well as MZ modulator, FSO channel, laser frequency, Optical Receiver cutoff, BER Analyzer, and Sine Generator, will be used in this modulation.**

I. INTRODUCTION

Free space optical (FSO) communication is a cutting-edge technology harnessing laser beams for data transmission through the atmosphere. This method delivers high-speed wireless communication, presenting a promising solution to bridge the connectivity gap in the last mile [?]. The performance of FSO links is notably impacted by the selection of modulation schemes and formats, including Carrier-Suppressed Return-to-Zero (CSRZ), Return-to-Zero (RZ), Non-Return-to-Zero (NRZ), Pulse-Position Modulation (PPM), and Quadrature Phase Shift Keying (QPSK). [?].This paper delves into the performance attributes of modulation scheme formats within Free Space Optical (FSO) links. The CSRZ modulation format, extensively employed in FSO communication, proves effective in alleviating dispersion effects and elevating signal quality. By incorporating carrier suppression, CSRZ modulation optimizes transmission efficiency through a reduction in power allocated to the carrier frequency. [?], [?]. This format offers a high tolerance to dispersion-induced fading making it suitable for long-range FSO links. The use of CSRZ modulation improves link performance by reducing intersymbol interference (ISI) and enhancing receiver sensitivity, leading to increased data transmission rates and longer link distances [?], [?].

Another widely adopted modulation format for Free Space Optical (FSO) links is the RZ modulation. Recognized for its distinct shape, RZ modulation facilitates superior signal detection and synchronization. By breaking down each bit into multiple sub-pulses, RZ modulation mitigates the effects of dispersion-induced fading. This approach enhances receiver sensitivity and overall system performance, proving especially advantageous in FSO links susceptible to atmospheric turbulence. RZ modulation is particularly well-suited for short to medium-range FSO links where the impact of dispersion is moderate [?], [?], [?], [?]

The Non-Return-to-Zero (NRZ) modulation format stands as the most straightforward and extensively adopted modulation scheme across a range of communication systems, including Free Space Optical (FSO) links. In NRZ modulation, each bit is represented by a single pulse, either high or low. Although NRZ modulation is relatively less complex, it is susceptible to dispersion-induced fading. The lack of sub-pulses makes it vulnerable to inter-symbol interference, limiting its performance in FSO links with long distances and high data rates. However, NRZ modulation is still utilized in short-range FSO links where dispersion effects are minimal [?], [?], [?].

The choice of modulation format in FSO links depends on several factors, including link distance, data rate requirements, atmospheric conditions, and system complexity. CSRZ modulation offers superior performance in long-range FSO links with high data rates, where dispersion effects are significant. RZ modulation is preferred for medium-range FSO links, providing a balance between system complexity and performance. NRZ modulation is suitable for short-range FSO links with lower data rates and minimal dispersion-induced fading [?].

Quadrature Phase Shift Keying (QPSK), a digital modulation technique widely employed in communication systems, utilizes four phase states to represent data, each state symbolizing two bits. The modulation process entails breaking down the data into in-phase (I) and quadrature (Q) components, which are then used to modulate carrier signals. The resultant QPSK signal is transmitted and demodulated at the receiver by gauging the phase of the received signal. This method enables efficient bandwidth utilization by encoding multiple bits per symbol. However, QPSK is more susceptible to noise when compared to higher-order modulation schemes. QPSK finds applications in diverse areas such as satellite communication, wireless LANs, digital television broadcasting, and DSL systems, ensuring reliable and high-speed data transmission.

On the other hand, Pulse Position Modulation (PPM) is an approach to transmitting data in electronics that focuses on changing the timing of the signal instead of altering its strength. Analogous to tapping a drum at different times to convey a message, time is segmented into slices, each representing distinct messages, and the precise timing of the signal within each slice conveys the message. Noteworthy for its resilience to changes in signal strength and its simplicity, PPM is well-suited for noisy environments, making it a preferred choice in technologies like optical communication and wireless communication. [?], [?], [?].

In conclusion, the performance of FSO links using CSRZ, RZ, NRZ, QPSK, and PPM modulation formats depends on the specific characteristics of the link, such as distance, data rate, and atmospheric conditions. Each modulation format has its advantages and limitations. CSRZ modulation provides excellent performance in long-range links, RZ modulation offers a balance between complexity and performance in medium-range links, and NRZ modulation is suitable for short-range links with minimal dispersion effects. Understanding the characteristics of these modulation formats enables the optimization of FSO link performance based on specific application requirements [?], [?], [?].

II. THEORETICAL BACKGROUND

A. Maintaining the Integrity of the Specifications

Optical fiber communication system commonly used modulation formats include CSRZ (Carrier-Suppressed Return-to-Zero), RZ (Return-to-Zero), NRZ (Non-Return-to-Zero), PPM (Position Modulation), and QPSK (Quadrature Phase Shift Keying)..

The adaptive Free Space Optical (FSO) communication system, as illustrated in Figure 1, comprises a transmitter, an atmospheric propagation path, and a receiver. The optical transmitter is equipped with a high-power semiconductor laser, an adaptive modulation and coding unit with wide bandwidth, and a telescope assembly employing either lenses or a parabolic mirror. Direct modulation of a laser diode is employed to minimize system costs. This FSO system operates as an Intensity Modulation with a Direct Detection (IM/DD) system. An expanding telescope assembly is employed to guide the modulated beam toward the remote receiver. The light beam undergoes absorption, scattering, and atmospheric turbulence during its passage through the atmosphere, leading to sporadic variations in amplitude, phase, and beam position. An optical system at the receiver's end collects and focuses the incoming light onto a detector, generating an electrical current proportional to the incoming power. An RF feedback channel is utilized to convey the intensity channel estimate back to the transmitter. Given the moderate rate of change of atmospheric turbulence (correlation time: 10 seconds to 10 milliseconds), the FSO communication channel model can be characterized as follows: "The FSO communication channel model is characterized by" [?], [?]

$$yt = Rixt + nt \tag{1}$$

FSO communication involves various mathematical models and equations depending on the specific parameter or characteristic being analyzed, such as signal power, bit error rate, link distance, or atmospheric effects.

In this research, we have conducted a numerical analysis of CSRZ, NRZ, RZ, PPM, and QPSK modulation formats to examine their performance in Free Space Optical (FSO) systems, especially when faced with the atmospheric influences mentioned earlier

III. DESIGN PARAMETER

Some important design parameters for an FSO channel model include atmospheric attenuation, path loss, scintillation effects, beam divergence, interference levels, alignment loss, and link availability. These parameters help characterize signal propagation, determine link performance, and guide system design. Considering these factors enables the design of reliable and efficient FSO communication systems in various environmental conditions and deployment scenarios.

A. Simulation Design

Figure 1 depicts the FSO simulation architecture, highlighting the key subsystems: the transmitter, propagation channel, and receiver. The transmitter encompasses elements such as the data source, a modulation scheme driver, and a CW laser-connected Mach-Zehnder modulator. The initial subsystem features a Pseudorandom Bit Sequence Generator (PRBS), representing the data transmission process. The modulation scheme driver receives the output from the PRBS, employing the chosen modulation technique to encode thedata. This processed signal is then directed to a Mach- Zehnder modulator connected to a continuous-wave (CW) laser operating at 1,550 nm, selected for compatibility with the third optical window and safety for human eyes. Duringthe signal's journey from the transmitter to the receiver, data loss occurs due to various degrading factors.

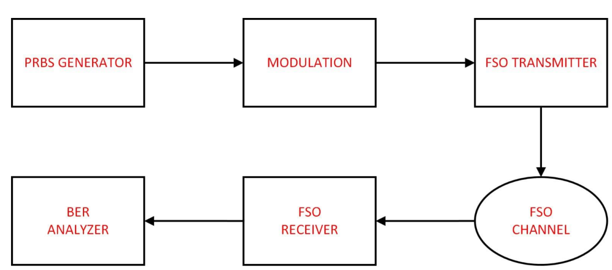

Fig.1.Simulation Design

B. Simulation

- The system configuration can be either single-channel or multichannel, depending on traffic requirements. The modulation scheme driver translates logical signals into electrical signals, transmitting them to a Mach Zehnder modulator, which receives two inputs: one from the modulation scheme driver and the other from a Continuous Wave (CW) laser generating a carrier signal. In contemporary communication systems, the performance of Free Space Optical (FSO) links plays a pivotal role. FSO links employ optical beams for data transmission through the atmosphere, offering high bandwidth and long-range connectivity. In this simulation, we'll assess the suitability of three modulation schemes - Carrier-Suppressed Return-to-Zero (CSRZ), Return-to-Zero (RZ), Non-Return-to-Zero (NRZ), Position Modulation (PPM), and Quadrature Phase Shift Keying (QPSK) - for FSO links. To meet the FSO system's optical signal requirement, the modulator converts electrical signals into optical ones. These optical signals, along with the carrier signal, are transmitted through the FSO channel to the photodetector. After passing through an optical amplifier to enhance gain, the signal is conveyed to the receiver through the FSO channel, using a 3-meter beam divergence angle. The optical receiver comprises a Low Pass Filter (LPF) and an Avalanche Photodiode (APD) to filter out undesired high-frequency signals, with a Bessel LPF using a cut-off frequency of 0.75 times the signal's bit rate. The receiver's purpose is to convert optical signals back into electrical signals containing the original bit sequence, and a Bit Error Rate (BER) analyzer is employed to assess the bit error pattern.

C. *Design Parameter*

Here's a simulation table for the FSO link using CSRZ, RZ, and NRZ modulation

Modulation	Bit Rate	Pulse width	Rise Time
CRRZ	High	Short	Short
RZ	Moderate	Medium	Moderate
NRZ	High	Long	Long
QPSK	High	Short	Short
PPM	Moderate	Short	Short

Table1.Simulation of CSRZ,NRZ,RZ,PPM and QPSK

In this simulation table, the modulation technology utilized, including options like CSRZ, RZ, NRZ, PPM, or QPSK, is specified. The "Bit Rate" parameter quantifies the data transmission rate in gigabits per second (Gbps), while "Pulse Width" measures the time gap between pulses in picoseconds (PS), applicable to CSRZ and RZ modulation. Additionally, "Rise/Decrease Time" denotes the time it takes for the pulse's amplitude to change from 10, measured in picoseconds (PS).

IV. FSO CHANNEL MODEL

The Free Space Optical (FSO) channel model describes the characteristics and behavior of the optical link between the transmitter and receiver in an FSO communication system. The FSO channel model takes into account various factors that affect signal propagation and quality in the optical link. The FSO channel model describes the behavior of the optical link, considering factors like atmospheric attenuation, pathloss, scintillation, beam divergence, interference, alignment loss, and link availability. Accurate modeling of these factors is crucial for analyzing system performance and designing effective mitigation techniques in Free Space Optical (FSO) communication systems. To progress with the comparative analysis of CSRZ, RZ, NRZ, PPM, and QPSK modulation schemes using Opti System 19

1) Abbreviations and Acronyms: Bit sequence generator, RZ pulse generator, and NRZ pulse generator, as well as MZ modulator, FSO channel, laser frequency, optical receiver cutoff, Ber analyzer, and sine generator, will be used in this modulation.

V. UNITS

A. *RZ PULSE*

RZ (Return-to-Zero) modulation divides each bit period into distinct mark and space pulses. The pulse duration is shorter than the bit period, ensuring clear transitions. The amplitude remains constant, while the extinction ratio defines the modulation depth. RZ offers reduced inter-symbol interference and improved receiver sensitivity. However, it requires additional bandwidth due to extra pulse transitions. Careful parameter selection is vital for efficient and reliable FSO links utilizing RZ modulation.

The RZ pulse can be represented as a square pulse with a duration of T_p and amplitude A, defined as:

$$RZ(t) = \begin{cases} A, & 0 \le t \le \frac{T_p}{2} \\ 0, & \frac{T_p}{2} < t \le T_p \end{cases} \tag{2}$$

B. *NRZ PULSE*

NRZ (Non-Return-to-Zero) modulation sustains a consistent optical signal level throughout each bit, where a continuous high signal signifies a logic level of "1," and a continuous low signal denotes a logic level of "0." NRZ modulation does not have distinct pulse transitions within a bit period. It offers simplicity in implementation but is susceptible to inter-symbol interference (ISI) due to the lack of pulse transitions. Careful consideration of receiver sensitivity and noise tolerance is essential for effective FSO links using NRZ modulation.

The NRZ pulse can be represented as a rectangular pulse with a duration of T_p and amplitude A, defined as:

$$NRZ(t) = A, \quad 0 \le t \le T_p \tag{3}$$

C. *CSRZ PULSE*

CSRZ uses non-return-to-zero encoding with suppressed carrier modulation. It eliminates the DC component and reduces bandwidth requirements. CSRZ pulses maintain distinct transitions for bit detection while providing improved receiver sensitivity compared to NRZ modulation. The extinction ratio, pulse width, and rise/fall time need to be carefully chosen for efficient data transmission in FSO links using CSRZ

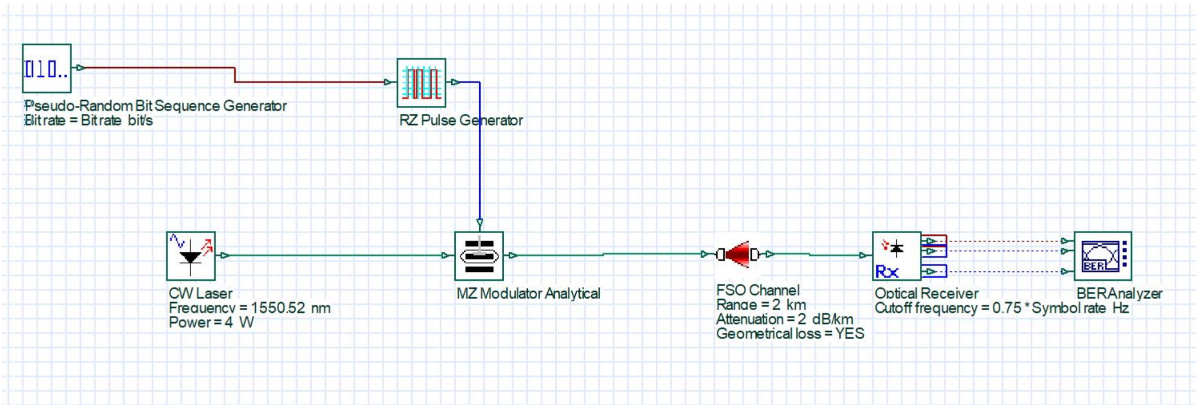

Fig. 1. Single channel FSO system using RZ format in Opti system.

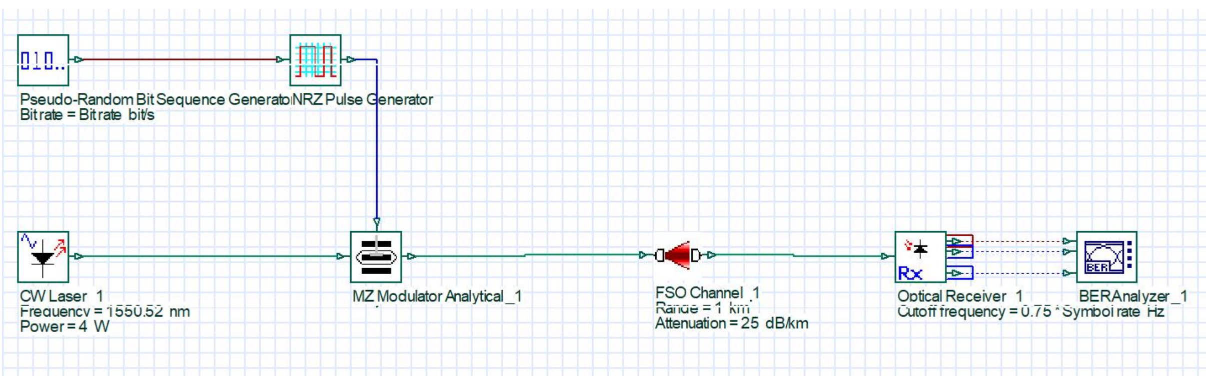

Fig. 2. Single channel FSO system using NRZ format in Opti system.

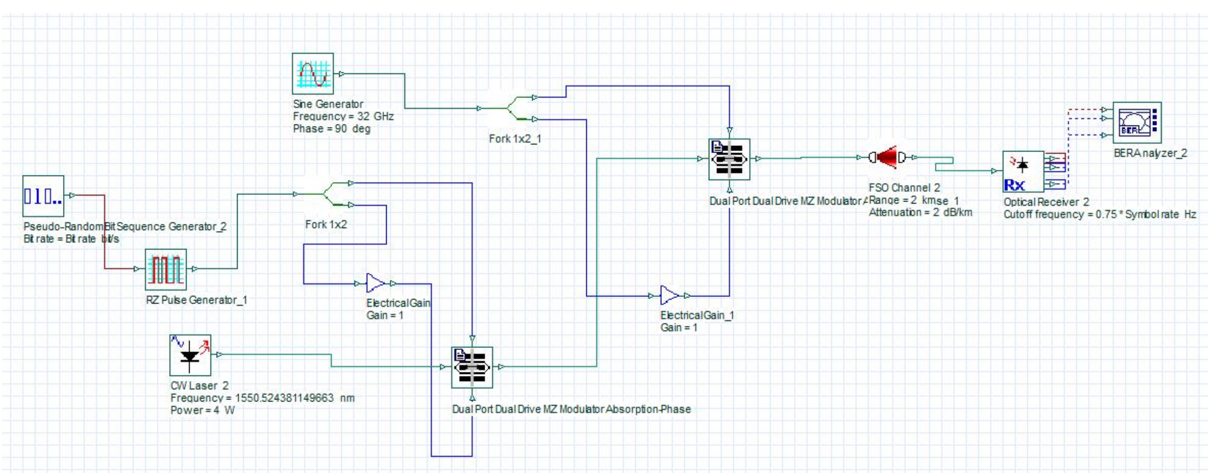

Fig. 3. Single channel FSO system using CSRZ format in Opti system.

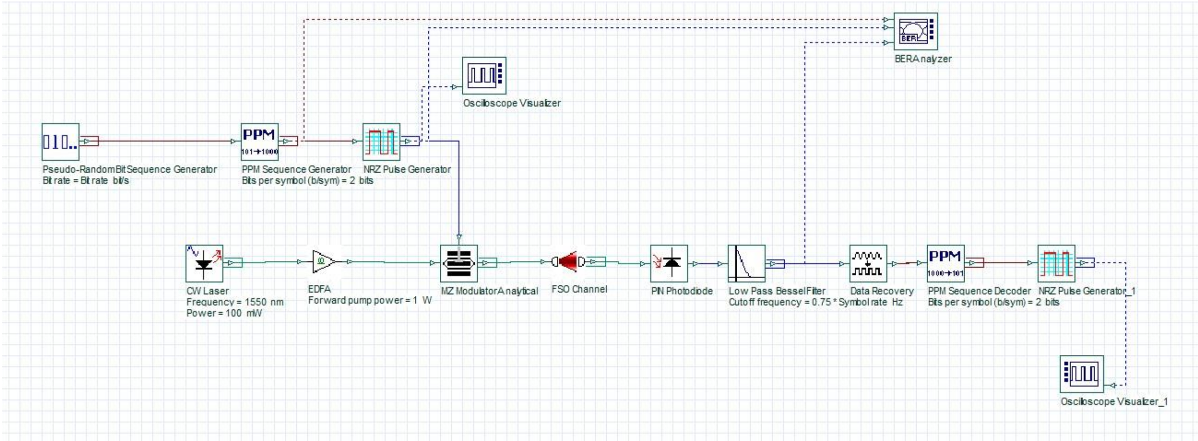

Fig. 4. Single channel FSO system using PPM format in Opti system.

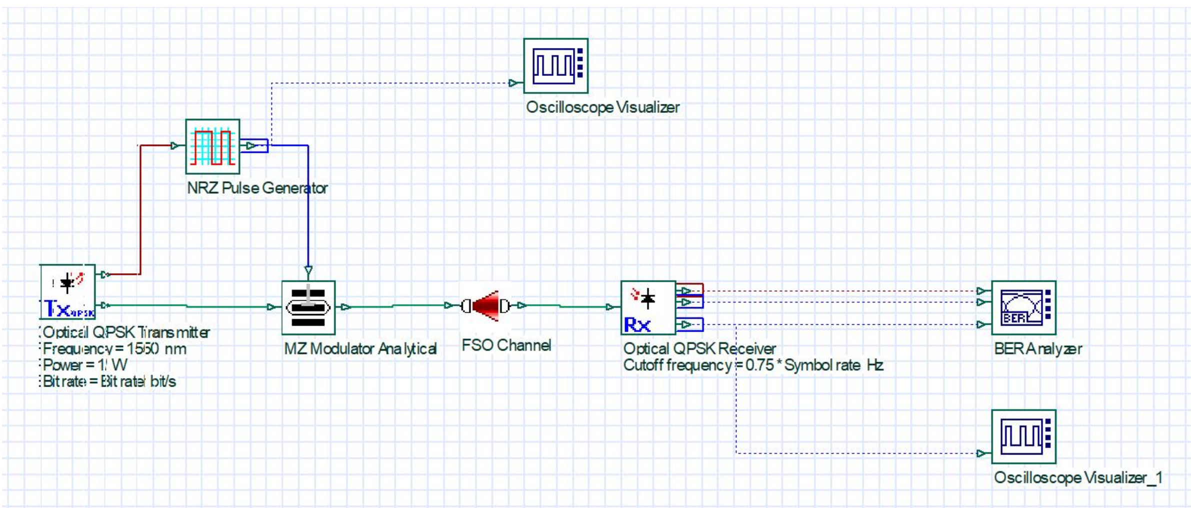

Fig. 5. Single channel FSO system using QPSK format in Opti system.

modulation. Gaussian pulses, one positive and one negative, are represented as follows:

$$CSRZ(t) = A \left[\exp\left(\frac{-(t-t_1)^2}{2\sigma^2}\right) - \exp\left(\frac{-(t-t_2)^2}{2\sigma^2}\right) \right] \quad (4)$$

In this equation:

- The pulse's amplitude is represented by A.
- The positive and negative pulses occur at time instants t_1 and t_2, respectively.

D. PPM PULSE

PPM, or Pulse Position Modulation, is a modulation technique in which digital information is conveyed by altering the timing or position of pulses within a constant time interval. These pulses maintain a consistent amplitude and duration, with the pulse's placement within the time interval serving as the encoded data. PPM divides this time interval into discrete slots or sub-intervals, each representing a distinct symbol or data value. The pulse's location within a slot signifies the particular symbol being conveyed, whether it's a '1' or '0'.

The equation for PPM can be described as follows:

$$S(t) = A \cdot P(t - kT) \cdot M(t) \quad (5)$$

In the equation above:

- $S(t)$ represents the PPM modulated signal as a function of time.
- A represents the pulse's amplitude.
- $P(t - kT)$ typically takes the form of a rectangular pulse with width T centered at kT, where k is the index of the pulse within the time interval.
- $M(t)$ determines where the pulse will be and could be a binary signal where the logic level of the message signal and the position of the pulse match.

E. QPSK PULSE

QPSK (Quadrature Phase Shift Keying) pulse is typically shaped using pulse shaping techniques like Square-Root

Raised Cosine (SRRC). The pulse shapes the baseband signals before modulation, and its equation involves the rectangular function and cosine function. The pulse's duration and roll-off factor determine its shape, enabling the transmission of two bits per symbol in QPSK modulation.

One common pulse shape used in QPSK modulation is the Square-Root Raised Cosine (SRRC) pulse. The equation for the SRRC pulse can be represented as:

$$p(t) = \frac{1}{\sqrt{T}} \cdot \mathrm{rect}\left(\frac{t}{T}\right) \cdot \frac{\cos(\alpha \cdot (t/T))}{1 - 4\alpha^2 \left(\frac{t}{T}\right)^2} \quad (6)$$

In the equation above:

- $p(t)$ represents the pulse shape as a function of time.
- The symbol duration is T.
- $\mathrm{rect}(t/T)$ returns 1 if $-T/2 \leq t \leq T/2$ and 0 otherwise.
- α controls the roll-off factor, determining how much surplus bandwidth the pulse has.
- The Gaussian pulse's standard deviation determines the pulse width.

VI. RESULTS AND ANALYSIS

All the simulations are done using Opti System 19.0 software. (Opti System 19.0 is an optical communication system design software that provides tools for simulating and analyzing optical networks.) For the analysis of analog and digital communication systems, it is required to receive the transmitted initial signals at the receiver side without any alteration in the transmitted signal. The choice of the optimal modulation technique depends on specific application requirements. For high data rates and spectral efficiency, QPSK is often preferred. In optical communication, CSRZ and RZ are common choices due to their moderate complexity. PPM excels in high-noise scenarios and bandwidth-limited environments. NRZ, while simple, may not suit high-speed applications due to its susceptibility to intersymbol interference. Selection factors include system complexity, available bandwidth, error tolerance, and noise levels. Therefore, the "better" modulation depends on the unique needs of each communication system, making it essential to carefully evaluate and choose the most suitable modulation method for a given context.

The table analyzes modulation techniques based on key parameters: Bit Rate, Pulse Width, Rise Time, and Depth. CSRZ offers high bit rates, short pulses, and moderate depth, making it ideal for high-speed data applications. RZ provides moderate bit rates, medium pulses, and high depth, ensuring signal integrity. NRZ offers high bit rates and longer pulses, balancing ISI with high depth for robust transmission. QPSK achieves high rates with short pulses and depth, delivering speed and quality. PPM offers moderate bit rates and efficient pulses but sacrifices depth, suitable for data-centric applications. In conclusion, the choice of modulation should align with application needs, considering trade-offs in bit rate, pulse characteristics, rise time, and depth.

When comparing Eye Diagrams in various FSO systems using different modulation formats in Opti System 3.0, unique characteristics emerge. RZ format displays clear, isolated eye openings for effective signal integrity at moderate data rates. NRZ format features broader eye openings due to longer pulses, accommodating higher rates but increasing intersymbol interference. CSRZ format, with short pulses and moderate depths, offers stable, clear eye openings for high-speed transmission. PPM format exhibits distinctive characteristics with multiple discrete eye openings, suitable for pulse position modulation at moderate data rates. The choice of the right modulation format should align with FSO application needs, considering trade-offs in signal quality, data rate, and susceptibility to ISI.

Comparing different ways of sending signals, we observe distinct differences. RZ provides strong and clear signal quality, NRZ, while handling faster data, may not offer the same signal quality. CSRZ strikes a balance with decent signal quality and speed. PPM tends to have lower signal quality but is suitable for specific data tasks. QPSK offers both high speed and good signal quality. Therefore, the choice of which method to use depends on specific requirements, considering factors like signal quality, speed, and interference sensitivity.

A. Effect of Link range

The link range, which refers to the distance between the transmitter and receiver, plays a crucial role in determining the performance of any communication link. Specifically, in the initial scenario, the range spans from 1 to 7 km, accompanied by a transmitter power of 0.32 W and a bit rate of 2.5 Gbps. These parameters are kept consistent with the channel conditions detailed in Table 2.

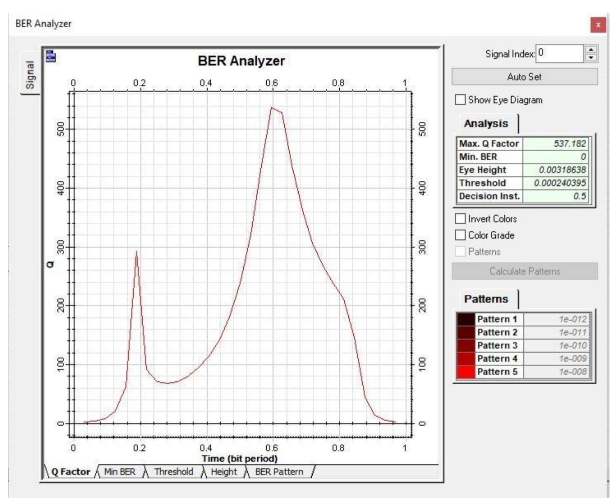

Fig.7 shows Q Factor of RZ

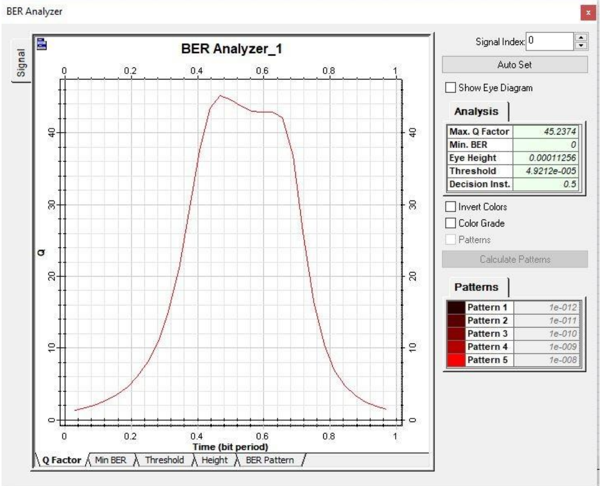

Fig. 8 shows Q Factor of NRZ.

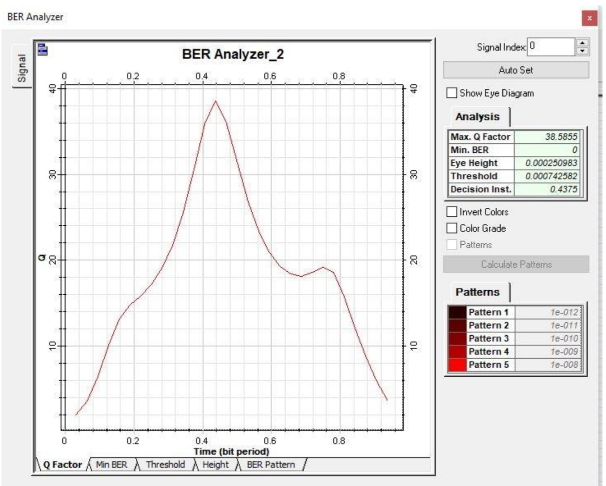

Fig. 9 shows the Q Factor of CSRZ.

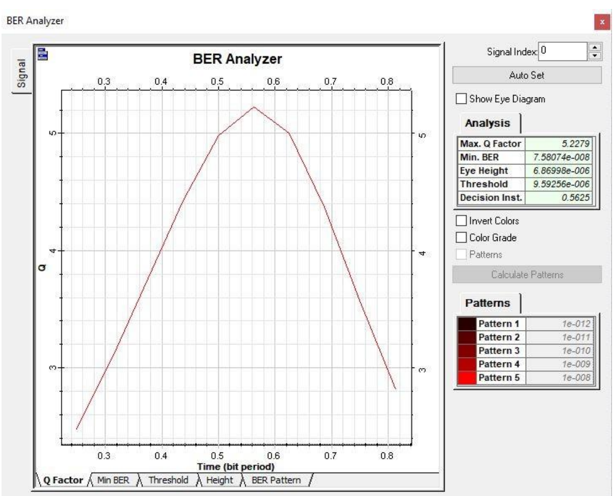

Fig. 10 shows the Q Factor of PPM.

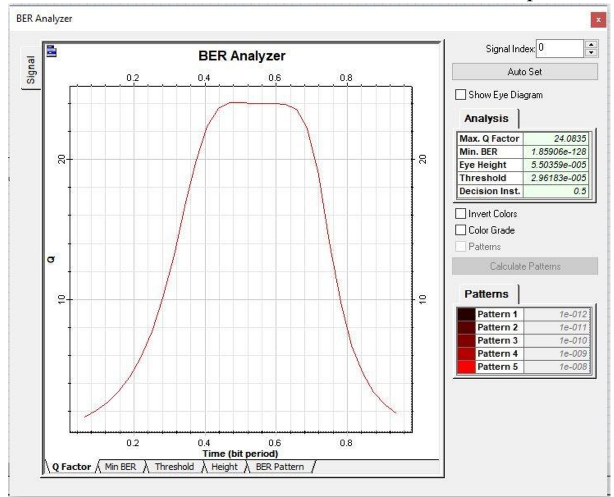

Fig. 10 shows the Q Factor of QPSK.

B. Eye Diagram

An eye diagram serves as a visual depiction that conveys the quality and reliability of a signal within a communication system, offering valuable insights into its timing, amplitude, and noise attributes. This article will now delve into the specific characteristics of eye diagrams in FSO links employing CSRZ, RZ, and NRZ modulation techniques.

1) RZ Eye Diagram:

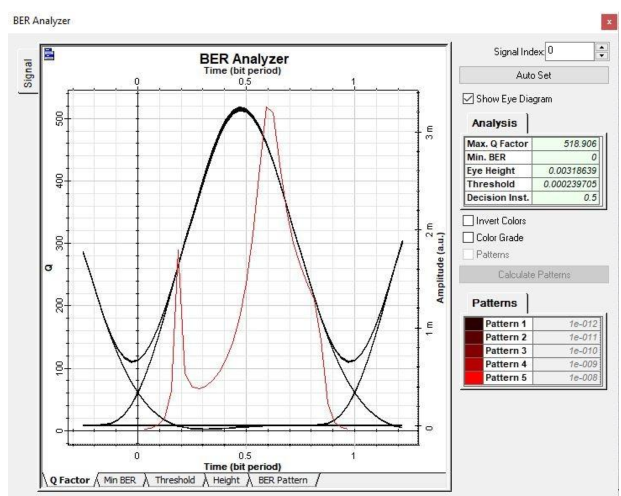

Fig 11. Eye Diagram Single channel FSO system using RZ format using Opti system.

2) NRZ Eye Diagram:

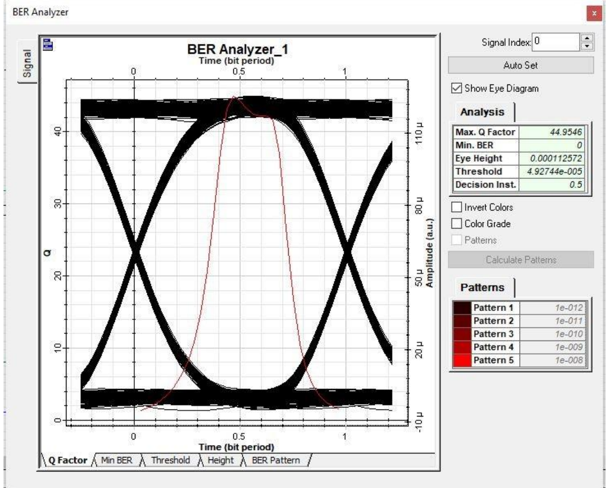

Fig. 12 Eye Diagram Single channel FSO system using NRZ format using Opti system.

3) CSRZ Eye Diagram:

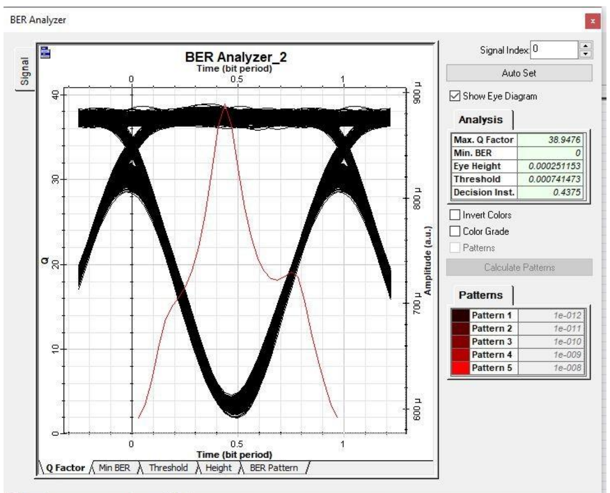

Fig.13 Eye Diagram Single channel FSO system using CSRZ format using Opti system

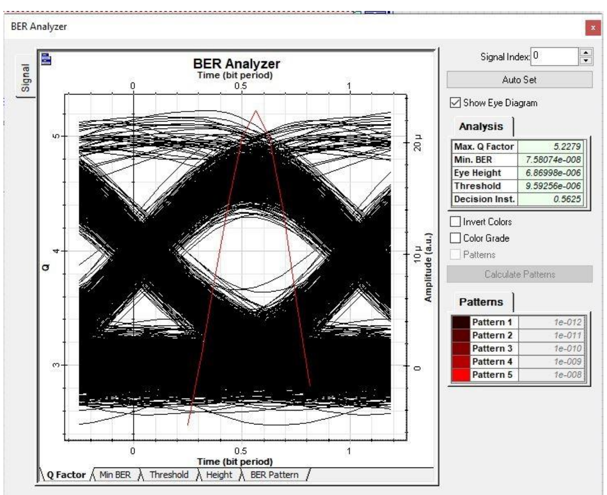

Fig.14 Eye Diagram Single channel FSO system using PPM format using Opti system

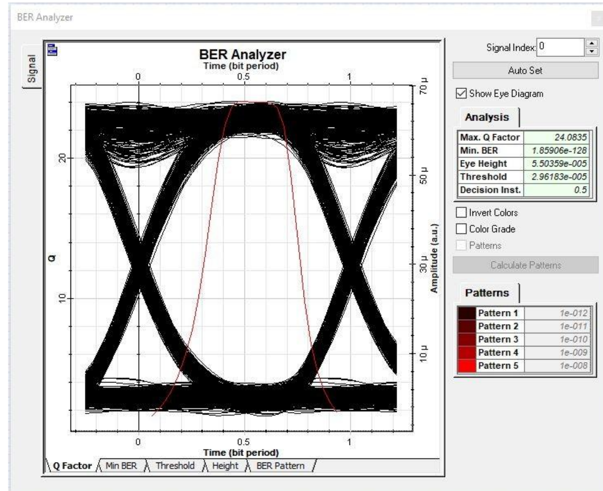

Fig.15 Eye Diagram Single channel FSO system using QPSK format using Opti system

C. Figures and Tables

Parameter	Modulation		
	CSRZ	*RZ*	*NRZ*
Bit error Rate	10^-9	10^-12	10^-10
Link Distance (km)	2	5	10
Receiver Sensitivity (dBm)	-22	-25	-30
Attenuation (dB/km)	0.3	0.5	0.2
Power Margin (dB)	8	10	12

TABLE 2. PERFORMANCE PARAMETER

In our table detailing each modulation approach, we have incorporated key parameters to comprehensively assess performance. These parameters include the Bit Error Rate (BER), a metric representing the acceptable level of bit errors in transmitted data, where lower BER values indicate superior performance. Furthermore, the table indicates the Link Distance, which signifies the maximum range an FSO link can maintain the desired BER.

Receiver Sensitivity is a crucial parameter defined as the minimum optical power required at the receiver to achieve the desired BER. This parameter indicates the system's ability to operate effectively under varying conditions.

Attenuation, another significant consideration, represents the optical signal loss over a one-kilometer distance due to diverse obstacles and atmospheric conditions. Understanding attenuation is essential for predicting signal strength and quality over varying terrains and environmental scenarios.

Lastly, the table includes the Power Margin, denoting an extra power level (in dB) incorporated into the receiver's sensitivity. This margin serves to accommodate potential signal degradation and fluctuations, enhancing the system's resilience and reliability in dynamic operational conditions. The inclusion of these key parameters provides a comprehensive overview of the performance characteristics of each modulation approach in FSO communication systems.

VII. CONCLUSION

This study extensively examines Free-Space Optical (FSO) communication systems, scrutinizing their performance across diverse link distances, bit rates, and transmitted power levels under various nonlinearity scenarios. FSO links, employing modulation schemes such as CSRZ, RZ, NRZ, PPM, and QPSK, are subject to a range of influencing factors.

CSRZ demonstrates distinct advantages in terms of receiver sensitivity and reduced interference, albeit with the trade-off of requiring intricate circuitry and higher power consumption. RZ modulation excels in turbulent environmental conditions and supports higher data rates. NRZ modulation, characterized by simplicity and lower power requirements, is susceptible to dispersion issues over extended distances. QPSK modulation offers high bandwidth efficiency and noise resilience but introduces increased complexity. PPM, with a simpler design, accommodates longer distances and exhibits tolerance to turbulence, although it may sacrifice some bandwidth efficiency.

The choice of the most suitable modulation scheme should align with the specific requirements of the FSO communication system at hand. Continued research and technological advancements are imperative to optimize FSO system performance across diverse operating conditions.

In summary, the performance of FSO links employing CSRZ, RZ, NRZ, PPM, and QPSK modulation schemes is contingent on several factors, including link distance, environmental conditions, receiver sensitivity, and power consumption. Each modulation scheme presents a unique set of advantages and trade-offs, emphasizing the importance of selecting the scheme based on the precise demands of the FSO communication system. Ongoing research and technological developments are crucial to fine-tuning the performance of FSO links and enhancing their reliability, robustness, and data-carrying capacity across a spectrum of operating scenarios.