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Impact of Design Parameters on FSO System under Rain Conditions

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Abstract

In wireless communication, FSO promises to provide high-speed communication under extremely vulnerable atmospheric conditions. This study evaluates the effect of system design parameters for moderate rain conditions by simulating the proposed model using Optisystem 22.0. In this work, the divergence angle and the aperture diameter were varied, and their effects on the system were observed in terms of the signal quality, Bits in error, and the receiver's optical power. The findings show that increasing the divergence angle degrades system performance, whereas an increase in the receiver's aperture diameter improves the signal quality at the receiver side. The observed eye diagram reveals that the received signal quality is improved as it has less Inter-Symbol Interference.

Keywords: Free Space Optical Communication, Beam Divergence, Optical Power, Photodetector, Q-Factor.

1. Introduction

Free-Space Optical (FSO) communication has emerged as a promising technique for achieving extremely high bandwidth in gigahertz transmission channels, particularly for Line-of-Sight (LoS) applications. Its key advantages include high security, freedom from licensing requirements, large bandwidth capacity, and inherent immunity to electromagnetic interference (EMI) [1], [2].

Despite these benefits, the performance of FSO systems is susceptible to limitations arising from both system design parameters and external environmental conditions. System design parameters such as aperture diameter and beam divergence angle significantly impact

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link performance [3], [4]. Environmental factors like dust, rain, fog, atmospheric turbulence, multipath fading, and scintillation also introduce challenges [3].

Beam divergence, which describes the spread of the transmitted optical beam [4], is an important parameter, especially in long-distance communication. Increased beam divergence leads to a wider beam spread, consequently reducing the power density at the receiver, increasing signal losses, and diminishing overall link efficiency [5]. Interestingly, one study exploring divergence angles ranging from 0.4 to 6 mrad observed improved performance over extended link lengths [6]. Another study indicated that link length has a more significant impact on beam divergence than source power. Specifically, a six-fold increase in link length resulted in an eight-fold decrease in divergence, whereas reducing optical power by five times only led to a four-fold decrease in divergence [7]. This highlights the complex interplay between system parameters and link distance.

The aperture diameter at both the transmitter and receiver also plays an important role in FSO system performance. Atmospheric turbulence, for instance, is known to degrade link performance; however, research suggests that increasing the receiver aperture diameter can effectively enhance the Bit-Error-Rate (BER) and Quality-Factor (Q-Factor) of the received signal [9]. In certain FSO deployment scenarios, such as ground-to-air communication, large transmitter apertures and relatively smaller receiver apertures might be necessary. In such cases, beam divergence can cause significant variations in the recovered signal power. Furthermore, with smaller aperture diameters, beam truncation of a fundamental Gaussian beam could negatively impact transmission quality [10].

Several simulation studies have analyzed the effect of aperture diameters on system performance. One such study, which varied the transmitter aperture diameter from 1 to 5 cm and the receiver aperture diameter from 2 to 12 cm, found the best Q-Factor (51.8873) was achieved with a 5 cm transmitter aperture and a 12 cm receiver aperture. This study corroborates that larger receiver apertures generally improve performance by maximizing received optical power and reducing signal dispersion [11]. Experimental evaluations of aperture-averaging factors further support this, demonstrating that larger apertures help mitigate the scintillation effects caused by atmospheric turbulence. Analysis of BER under varying Signal-to-Noise Ratios (SNR) and turbulence conditions illustrated that aperture averaging can enhance FSO link performance in the presence of strong turbulence. However, excessively large receiver apertures offer only marginal improvements against intensity scintillation, suggesting the need for optimization to balance system efficiency and cost [12].

Increasing transmission power is another method to extend the achievable length of an FSO system [13]. Furthermore, the operational wavelength can also influence performance. A study examining an FSO system at wavelengths of 850, 950, and 1550 nm over a 1 km link in foggy and humid conditions revealed that while smaller divergence angles yielded better performance overall, larger aperture diameters improved performance in terms of reduced BER, improved Q-factor, enhanced SNR, data rate, and received optical power [14].

For the efficient operation of FSO systems, the careful optimization of key system design parameters, particularly the beam divergence angle and the aperture diameters at both the transmitter and receiver, is crucial. Furthermore, understanding their interplay under various environmental conditions, such as rain-affected environments, necessitates detailed quantitative analysis [8]. In this study, an FSO system under light atmospheric conditions is examined by varying the divergence angle and the aperture diameter using a Single Photon Detector (SPD) for sensitive reception of the signal. The aim of this research is to enhance the Q factor of the receiver's signal, reduce BER, and minimize the latency under light rain conditions. The motivation of this research lies in the requirement to provide insights that help design a robust FSO system that can sustain in adverse weather conditions.

2. Mathematical Model

While propagating in space, the optical beam gets attenuated as per the Beer-Lambert equation

$$\zeta = \frac{P_r}{P_t} = e^{[-Al]} \tag{1}$$

Where ζ represents the transmittance at an FSO link of l km with P_t (mW) transmitted power under A (dB/km) attenuation due to light rain, and P_r as received power [15].

The received power in FSO communication systems not only depends upon the atmospheric attenuation and link length, but also depends upon the aperture diameter and the beam divergence angle as in equation (2)

$$P_r = P_t \frac{a_2^2}{[a_1+(D\times R)]^2} \times 10^{(-A\times l/10)} \quad (2)$$

Here the received power Pr is expressed in terms of transmitted power Pt, aperture diameters a1 and a2 in m, and the beam divergence angle in mrad [16].

Table 1. Types of Rain Intensity and Scale of Rain Rate

Rain Intensity	**Drizzle**	**Light Rain**	**Medium Rain**	**Heavy Rain**	**Cloud Burst**
Rates (mm/hr)	0.25	2.5	12.5	25	100

The rain intensity can be classified into five categories depending upon the rainfall rate in mm/hr as mentioned in Table 1 [17]. The proposed FSO system is examined under light rain. The attenuation caused by rain relies upon the rain-rate and the specific constant k and a as in equation (3)

$$A= k*(R^{a}) \quad (3)$$

Here R is rain rate in milimeter per hour and the coefficients k and a are calculated from the ITU-R P.838-3 recommendation [18], [19]. For current work the values of k and a were chosen as k= 1.076 and a= 0.67 [20] i.e.

$$A= 1.076*(R^{0.67}) \quad (4)$$

The Q-factor plays a vital role in analysing the FSO system performance. In the received pulse, the noise level can be estimated with the knowledge of the Q-factor. The minimal value of the Optical Signal-to-Noise ratio could be specified by the Q-factor to achieve a specified BER. The amount of signal distorted by noise is specified by SNR. The SNR could be calculated with the knowledge of received signal and noise power as in equation (5)

$$SNR = 10\ log_{10}(\frac{P_{signal}}{P_{noise}}) \quad (5)$$

The equation (6) indicates the importance of SNR for the calculation of the Q-factor of signal received.

$$Q = \frac{SNR\sqrt{2NB}}{1+\sqrt{1+2SNR}} \tag{6}$$

Here N represents bit time and B the bandwidth of the optical signal. The BER represents the errouneous bits at receiver side. The Q-factor can be used to calculate the BER as in equation (7) [21], [22]

$$BER = \frac{1}{2} erfc\left(\frac{Q}{2}\right) \tag{7}$$

3. Simulation Model Design

This system simulates an FSO communication link with a Single Photon Detector (SPD) under light rain weather conditions. It follows a step-by-step process, from data generation to optical transmission and reception as illustrated in Figure. 1. The transmitter generates, modulates, and transmits optical signals through free space. The Pseudo-Random Bit Sequence (PRBS) generates a sequence of random bits. The NRZ Pulse Generator converts this into an electrical NRZ signal (0s and 1s). The system utilizes NRZ among many available pulse generators as it can contribute to improving system performance by 23% compared to RZ [23][24]. The Continuous Wave Laser Source emits an optical carrier wave of 193 THz and Power = 30 dBm. The laser alone cannot carry data; it needs to be modulated. The MZ Modulator modulates the CW laser light with the NRZ signal. It functions as an external modulator to modulate the digital signal onto the high-frequency carrier [25]. The modulated optical signal carries the digital information. An Optical Power Meter is used after the modulator to measure the transmitted power [8]. The Free Space is utilized as the medium. The modulated signal travels through the FSO channel. The input parameters for the simulation design are chosen with the best results obtained from the literature [26], are described in Table 1. The novelty of the research lies in choosing the SPD for detection and the values of the beam divergence angle and receiver aperture diameter.

Table 2. Input Simulation Parameters

Input Parameter	Value
CW Laser Power	30 dBm
Date Rate	10 Gbps
Weather Condition	Light Rain

Frequency	193 THz
Rain Attenuation	8.17 dB/ km
Link length	2 km
Modulation Format	NRZ
Beam Divergence angle	1-25 mrad
Receiver aperture diameter	1-25 cm
SPD Gain	10
Responsivity	1.2 A/W

Due to rain attenuation and beam divergence, the signal loses its strength. An Optical Power Meter at the receiver end measures the received power. This section detects, processes, and regenerates the optical signal. The Single Photon Detector (SPD) converts optical power into an electrical signal. SPD is highly sensitive, making it effective for weak signals in high-attenuation conditions [21].

The Filter is used to eliminate undesirable noise due to high-frequency components in the detected signal. The 3R Regenerator is used to re-amplify the weak signal, reshape the waveform to restore its original form, and re-time the signal to correct jitter effects. The processed signal is sent to an analyzer to check the signal clarity, BER estimation, and jitter and noise levels in the received signal [27].

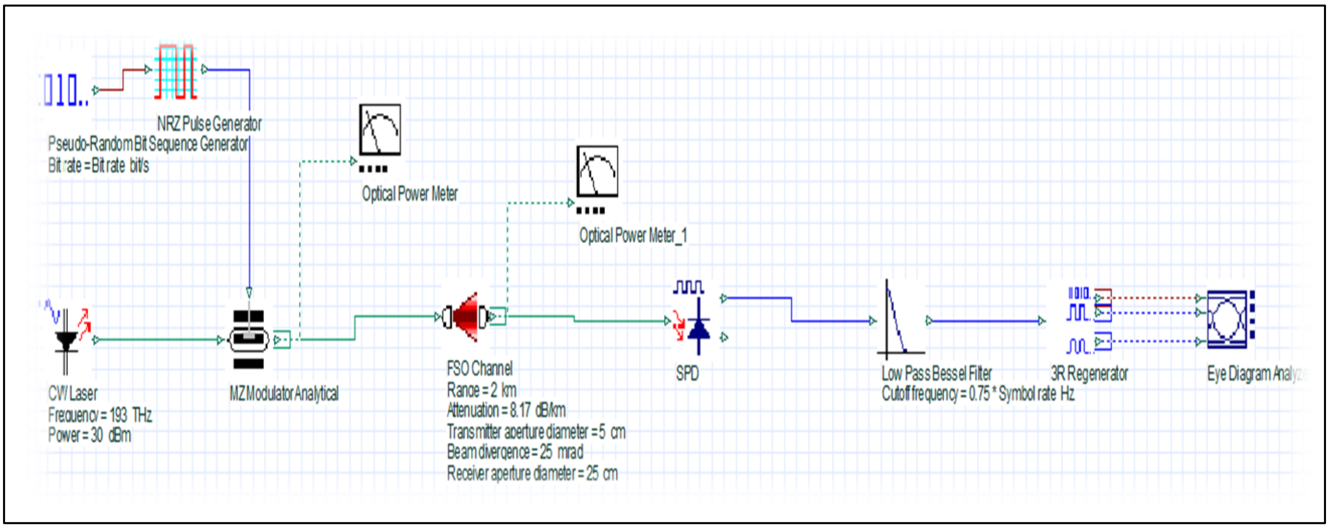

Figure 1. Simulation Model Design Using Optisystem 22.0

3.1 Performance under Light Rain Conditions

Problem Identification is the first step of the process, and it points out the limitations of Free Space Optical (FSO) systems in unfavourable weather, especially rain. Particular attention is paid to the beam divergence and aperture diameter. The authors in the Simulation Design Setup use Optisystem 22.0 to design a simulation of an FSO system using a 30 dBm CW laser and a Mach-Zehnder modulator transmitting in light rain conditions over a 2 km link. A high-sensitivity Single Photon Detector (SPD) is selected.

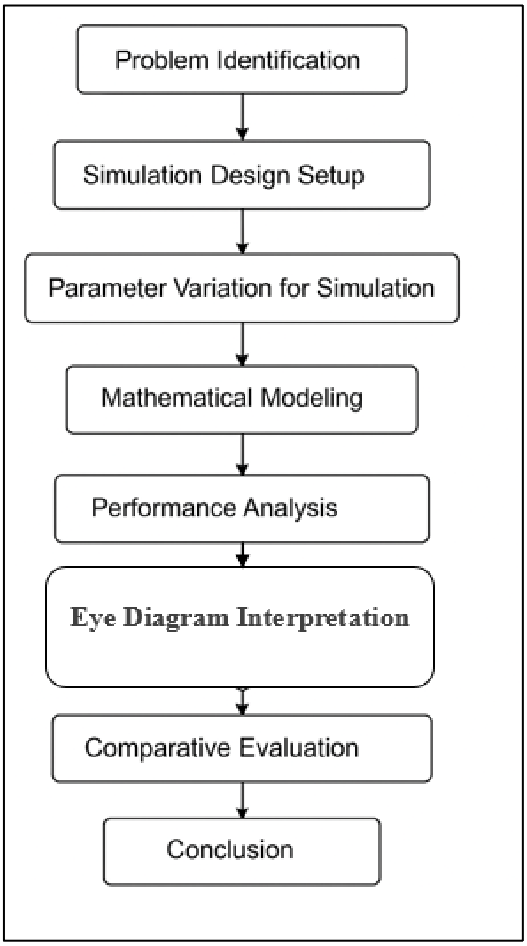

Figure 2. Methodological Framework for Evaluating FSO System

The next step is the Parameter variation in which divergence angle (1–25 mrad) as well as receiver aperture diameter (1–25 cm) is varied to note their effect. Mathematical Modeling applies Beer-Lambert Law and ITU-R P.838-3 standards to estimate attenuation and received power, including Q-factor, BER, and SNR. Performance Analysis translates into reading that larger aperture diameters enhance signal quality, but increased divergence worsens performance. The Eye Diagram Interpretation measures signal integrity as lowered ISI and jitter is observed in optimum settings. Comparative Evaluation emphasizes the proposed SPD configuration to be better than the traditional detectors. The study ends up with optimized parameters: Best results can be obtained using 5 mrad divergence and 20 cm aperture. Figure 2 depicts the methodological framework for evaluating FSO system.

4. Results and Discussions

An FSO system is implemented to observe the impact of design parameters on the Q-factor, BER, and received optical power to find the optimum values of divergence angle and aperture diameter.

4.1 Effect of Beam Divergence Angle

Studies have shown that increasing the beam divergence angle leads to an exponential reduction in received power. In an experiment, it was shown that FSO systems with smaller divergence angles exhibit better performance, provided that accurate beam tracking is maintained [28].

Figure. 3 illustrates the variation in the quality of signal with Divergence Angle in an FSO communication system. The important factor of FSO performance indication is the Q-Factor, which is related to the BER. The more the Q-factor better the signal quality. It was observed in the results that the divergence angle is strongly inverse relative to the Q-Factor because as the beam divergence increases, the Q-Factor declines significantly, indicating a deterioration in signal quality. It was observed that there is a Steep Decline at Small Divergence Angles, meaning the Q-factor drops rapidly when the divergence angle increases from 1 mrad to around 5 mrad. This suggests that small divergence angles allow for higher optical power concentration, leading to better signal quality. After 5 mrad, there was a Gradual Decrease Beyond 5 mrad, this suggests that beyond a certain divergence, the beam spreading effect dominates, reducing the received optical power. At a divergence angle of around 25 mrad, the Q-Factor approaches very low values, possibly near the threshold where signal detection becomes unreliable. This indicates severe signal degradation due to excessive beam spreading, leading to higher BER and potential link failure.

As observed in Figure. 4, from 0 to around 10 mrad, the BER remains nearly zero, indicating minimal signal degradation. At around 11 mrad, BER starts increasing, suggesting a noticeable impact on signal quality. Beyond 13 mrad, BER rises sharply, reaching a peak at 15 mrad. This indicates severe signal degradation or possible loss of communication.

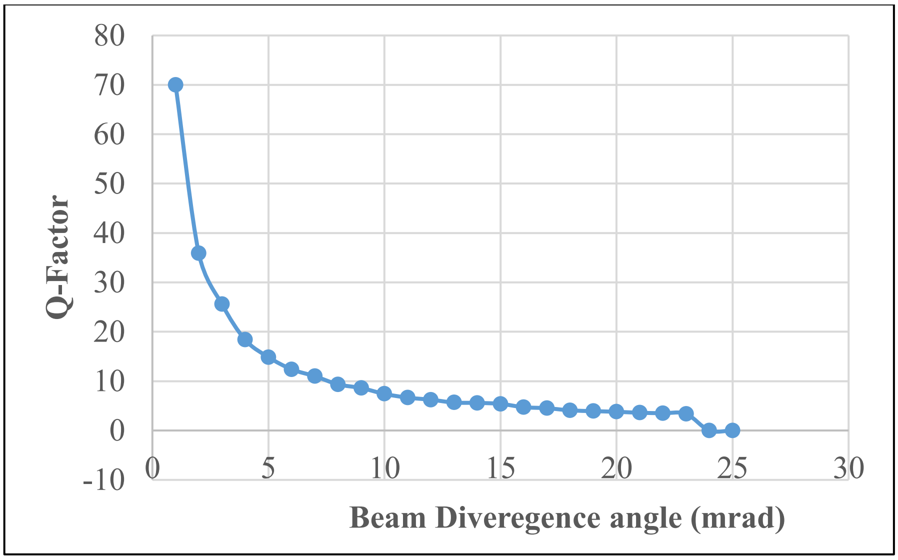

Figure 3. Effect of Beam Divergence Angle on Q-Factor

The increase in beam divergence spreads the transmitted signal beyond the receiver's effective aperture, reducing received power. A wider divergence spreads the optical power over a larger area, lowering the power received per unit area, and making detection more error-prone. In real-world Free Space Optical (FSO) systems, environmental factors like dust, turbulence, and scattering further contribute to increased BER at higher divergence angles.

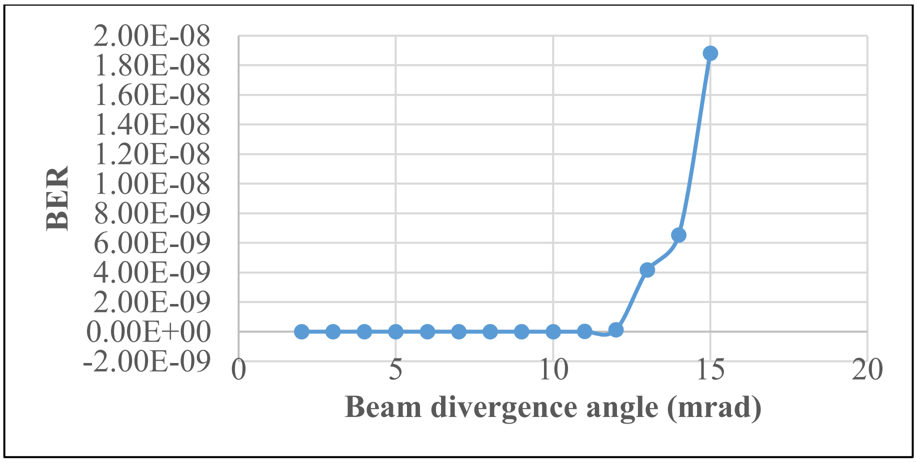

Figure 4. Effect of Beam Divergence Angle on BER

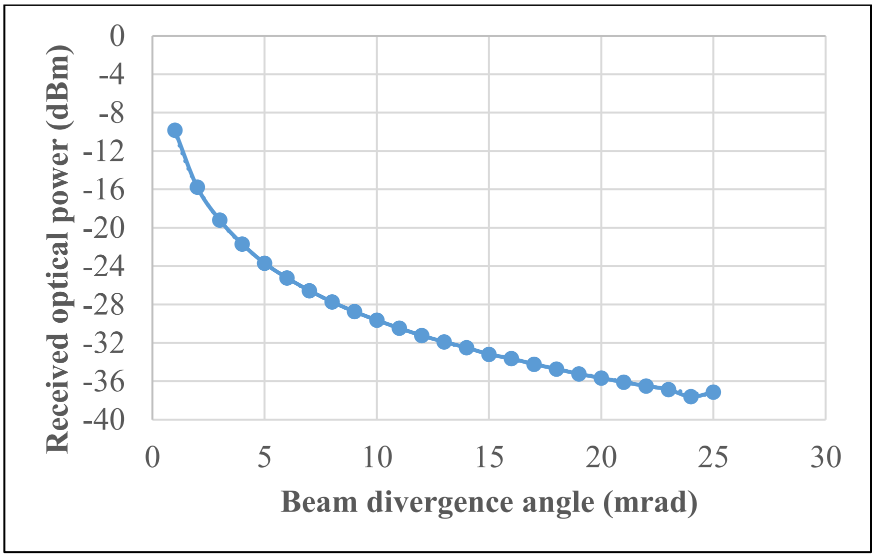

Figure 5. Effect of Beam Divergence Angle on Received Optical Power

Figure. 5 illustrates that for small divergence angles (0 to ~5 degrees), the received power decreases rapidly. As the beam divergence continues to increase, the rate of power loss slows, but the overall received power continues to decline. Beyond 25 degrees, the received power reaches a very low level, approaching -40 dBm, unable to detect the signal. As the divergence angle increases, the transmitted beam spreads over a larger area, reducing the optical power density at the receiver. A wider beam means that less of the transmitted signal will be seized by the receiver aperture, leading to significant power loss. In free-space optical communication, power density reduces approximately as the inverse square of the divergence angle, explaining the sharp initial drop followed by a more gradual decrease.

4.2 Effect of Receiver's Aperture Diameter

In FSO communication, the receiver aperture diameter plays an important role in deciding the optical power collected at the receiver. A larger aperture improves the system's ability to capture optical signals, especially in the existence of beam divergence and atmospheric turbulence. A larger receiver aperture captures more photons, improving signal strength and reducing noise. Improved photon collection enhances SNR, leading to better signal quality and a higher Q-Factor. A larger aperture reduces the impact of minor beam misalignments, ensuring more stable reception. Beyond a certain point, increasing aperture size may have limited benefits due to factors like optical system limitations, background noise, and diminishing signal gains [2].

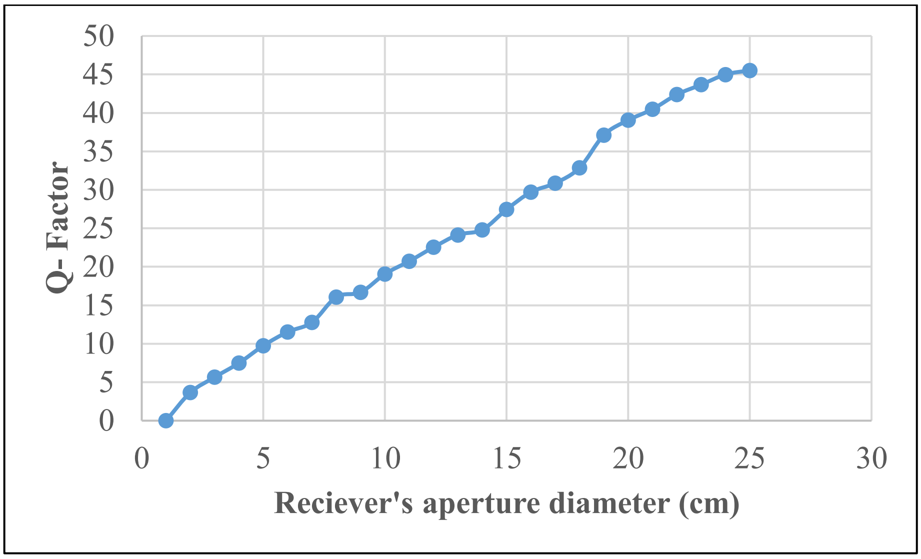

Figure 6. Effect of Receiver Aperture Diameter on Q-Factor

Figure. 6 illustrates a graphical relation between the Receiver aperture diameter and the Q-factor. It is clearly observed that the Q-Factor increases as the receiver aperture diameter increases, showing an approximately linear relationship with slight variations. Hence, showing a Positive Correlation between receiver aperture diameter and Q-factor. For small aperture sizes (0 to ~10 cm), the Q-Factor increases steadily, and the Q-Factor is low, indicating poor signal quality and a higher bit error rate (BER).

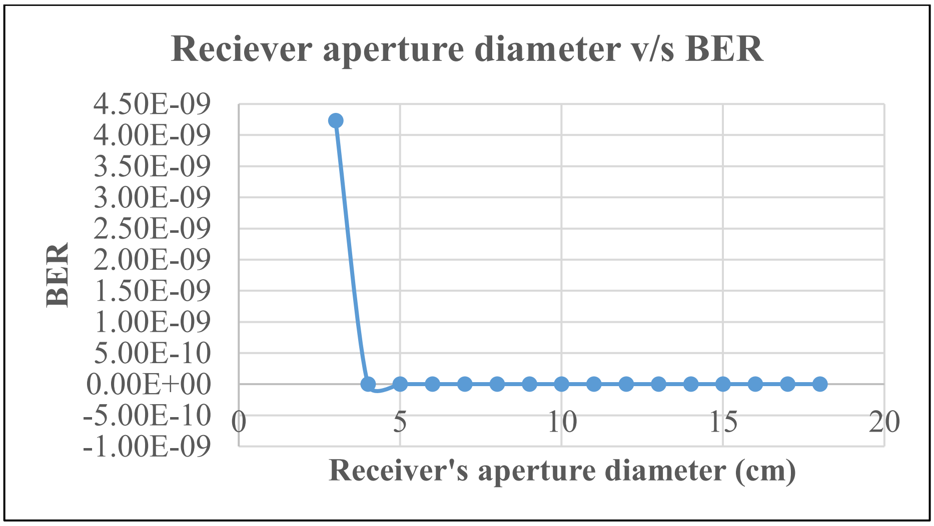

Figure 7. Effect of Receiver Aperture Diameter on BER

The growth remains consistent, but the Q-factor increases gradually. From medium aperture range (10-20 cm) Q-factor improves significantly, making this range ideal for most applications. Diminishing returns in Q-Factor improvement, meaning further increases in aperture size may not justify the added cost or complexity. Initially, at a low receiver aperture diameter of around 2-3 cm, the BER is significantly high, as illustrated in Figure 7. on increasing receiver aperture diameter, the BER rapidly drops to almost zero at around 4-5 cm. Beyond this point, increasing the aperture diameter further does not cause significant changes in BER, which remains approximately zero. A small aperture captures less optical power, leading to increased signal attenuation and higher BER. As the aperture size increases, it collects more optical power, improving the SNR and reducing BER significantly. This result helps optimize system design by selecting a sufficiently large aperture without unnecessary increases in hardware size and cost.

Initially, at a small aperture diameter, the received optical power is very low around -40 dBm as illustrated in Figure. 8. As the aperture diameter increases, the received power increases non-linearly, showing a rapid initial rise, followed by a gradual increase beyond 20 cm. A larger aperture collects more light, leading to improved received optical power. Initially, small increases in aperture size significantly improve power reception, as more signal photons are captured. A minimum aperture size is required to achieve an acceptable received power level. Increasing the aperture beyond 20 mm provides diminishing returns, meaning an optimal trade-off must be considered between size, cost, and system complexity. Larger apertures reduce beam divergence effects but might introduce alignment and handling challenges.

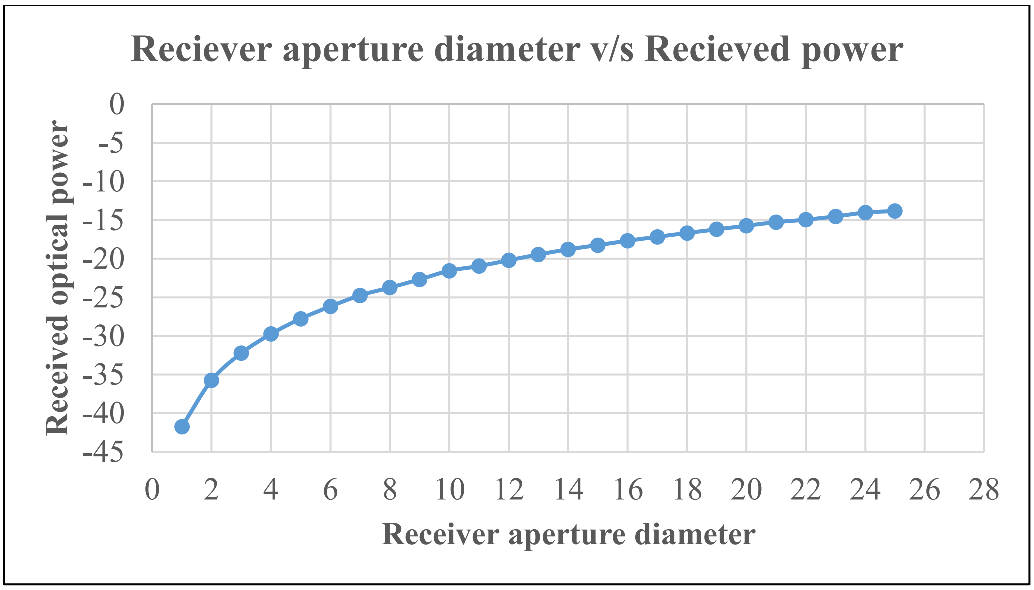

Figure 8. Effect of Receiver Aperture Diameter on Received Optical Power

In many literatures similar kind of work has been carried out but with different types of recivers or photo detectors. On comparing the proposed work with the existing literature it was found that the combination of receiver aperture diameter as 20 cm, beam divergence angle of 5 mrad and by using SPD as photo detector the best results has been obtained in terms of Q-factor and BER as illustrated in Table 3.

Table 3. Comparison of the Results of the Proposed Work with Existing Literature

Reference Study	Receiver Aperture Diameter	Beam Divergence angle	Q-Factor	BER	Receiver/ Detector
[29]	20 cm	5 mrad	6.22	$10^{-9.}$	PIN
[30]	20 cm	1 µrad	2.3	10^{-6}	CPDM-256-QAM receiver
[31]	20 cm	--	4.7	--	DPSK receiver
[8]	20 cm	2.5 mrad	34.7	--	APD
Proposed work	20 cm	5 mrad	39.05	2.5×10^{-302}	SPD

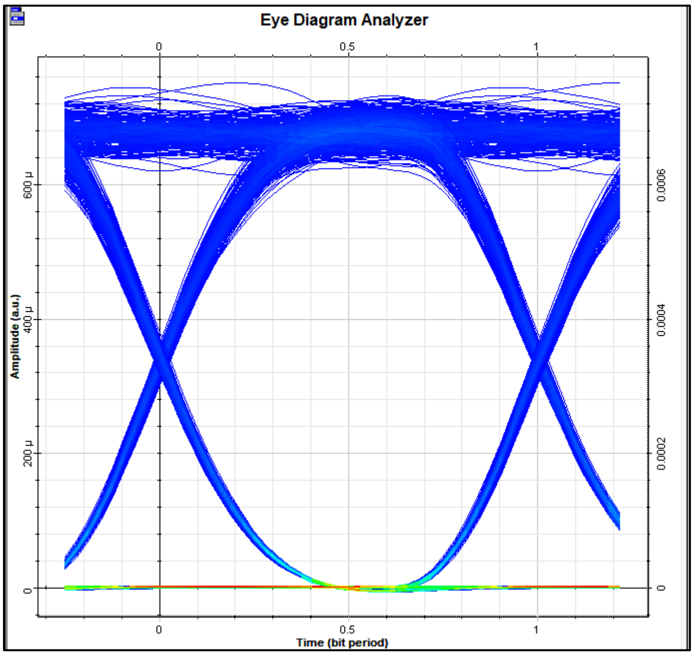

Figure 9. Eye Pattern of Received Signal

4.3 Eye Diagram Analysis

The eye diagram was observed for the FSO system with input parameters as defined in Table 1, also the values of Beam divergence angle and aperture diameter were kept 2 mrad and 20 cm respectively. The Eye diagram illustrated in Figure. 9 provides critical performance metrics for the FSO communication system. The eye diagram exhibits a well-defined open eye, which signifies good signal integrity and minimal inter symbol interference (ISI) preventing cross-talk. The minimum spread in signal transitions suggests lower jitter enhancing data reliability. A larger eye opening corresponds to higher SNR and lower BER. The high Q-Factor (37.1296) and good eye height suggest a high-quality signal, as it indicates a strong distinction between logic "0" and logic "1". Since the received BER is very low, it indicates that only a few bits were erroneous, concluding excellent transmission performance.

5. Conclusion

In this study, the FSO system under light rain conditions was examined for varying divergence angles and receiver aperture diameter. The study illustrated that when the beam divergence angle was varied between 0-5 mrad, the Q-factor and received optical power reduced abruptly, and the BER remained in an acceptable range later on, the quality of the signal reduced gradually, hence keeping the beam divergence angle as low as possible will give better performance. Whereas, on changing the receiver aperture diameter between 0-20cm, the Q-factor and received optical power increases abruptly and beyond this range it moves towards saturation. Hence increasing the aperture diameter beyond 20 cm will only increase the system cost system while not improving the performance of the system.

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