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Performance Evaluation of Free Space Optical Links with NRZ and RZ Line Codes Using APD and PIN Receivers under Diverse Weather Conditions

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***Abstract*— In this paper, we evaluate the performance of a free space optics (FSO) link operating at a wavelength of 1550 nm using non-return-to-zero (NRZ) and return-to-zero (RZ) line codes, as well as avalanche photodiode (APD) and positive-intrinsic-negative (PIN) receivers, under various weather conditions. The study analyzes pointing error and received signal attenuation across different scenarios, including clear air, haze, and fog. Results indicate that the pointing error for NRZ-APD is 11.62 µrad, slightly higher than the 11.22 µrad observed for RZ-APD. However, RZ-APD experienced greater signal attenuation across all weather conditions compared to NRZ-APD. For PIN receivers, the study shows maximum pointing errors of 10.55 µrad and 10.42 µrad for NRZ-PIN and RZ-PIN configurations, respectively, in foggy conditions. These findings suggest that a wavelength of 1550 nm offers optimal performance for FSO links across all weather conditions, with NRZ-APD and RZ-PIN showing advantages in terms of pointing accuracy. This paper provides valuable insights for the design and implementation of robust and efficient FSO communication systems in diverse atmospheric environments.*

I. INTRODUCTION

Free space optics (FSO) has gained substantial attention in recent years as a viable alternative to radio frequency communication for high-speed wireless data transmission. It offers numerous advantages such as high bandwidth capacity, immunity to electromagnetic interference, and the potential for cost-effective, rapid deployment. However, FSO systems face significant challenges related to atmospheric attenuation due to scattering effects under varying weather conditions, as well as pointing errors and fluctuations in received signal power [1-4]. One of the primary challenges in FSO communication is the impact of atmospheric attenuation caused by environmental factors such as fog, rain, snow, haze, and turbulence. Fog, in particular, poses a severe challenge to FSO links due to the dense concentration of water droplets in the air, leading to significant scattering and absorption of the optical signal. Studies such as those by Author et al. [5] have quantified the attenuation caused by different types of fog and have proposed models to predict FSO performance under foggy conditions. Rain and snow also contribute to signal attenuation, although their impact is generally less severe than that of fog. In heavy rain, the optical signal is scattered and absorbed by raindrops, while snowflakes can cause scattering and attenuation. Research by Author et al. [6] has shown that the impact of rain and snow on FSO links depends on the intensity and duration of the precipitation. Haze and dust can also impact FSO systems by scattering and absorbing optical signals. The presence of particulate matter in the atmosphere can significantly reduce signal quality, particularly in regions with high levels of air pollution. Author et al. [7] have investigated the effects of haze on FSO links and have highlighted the importance of considering local environmental conditions when designing FSO systems. Another critical factor affecting FSO communication is pointing errors, which occur when the transmitting and receiving antennas are misaligned. FSO systems typically use narrow beams of light, and even small misalignments can lead to significant signal loss. Precision in beam alignment and stabilization is essential for maintaining high-quality communication links. The effects of pointing errors can be mitigated through various techniques, such as active tracking and auto-alignment systems. For example, Author et al. [8] proposed an adaptive beam-tracking method that uses feedback from the received signal to adjust the alignment of the transmitting and receiving antennas dynamically. This approach has shown promising results in maintaining link stability and minimizing signal loss. Beam divergence is another factor that affects FSO system performance. As the optical beam travels through the atmosphere, it spreads out, causing a reduction in signal intensity. Author et al. [9] have studied the effects of beam divergence on FSO links and have proposed methods to optimize beam shaping and focusing to enhance system performance.

The quality of the received signal in FSO systems is influenced by several factors, including atmospheric conditions, pointing accuracy, and beam divergence. Fluctuations in received signal power, also known as scintillation, can occur due to atmospheric turbulence, leading to variations in signal quality. Research by Author et al. [10] has explored the impact of atmospheric turbulence on received signal power and has suggested the use of advanced modulation and coding techniques to improve system resilience. For example, techniques such as adaptive modulation and forward error correction (FEC) can help maintain reliable communication even in challenging conditions.

FSO systems can benefit from the use of advanced modulation techniques to enhance link performance. Common modulation schemes include on-off keying (OOK), pulse position modulation (PPM), and quadrature amplitude modulation (QAM). Each of these techniques offers different advantages and trade-offs in terms of data rate, power efficiency, and resilience to atmospheric effects [11-14].

Author et al. [15] conducted a comprehensive analysis of various modulation techniques in FSO systems and found that PPM provides higher power efficiency, while QAM offers better spectral efficiency. The choice of modulation technique depends on the specific requirements of the communication link and the expected environmental conditions.

In summary, the recent literature on free space optics highlights the importance of understanding and addressing challenges related to atmospheric attenuation, pointing errors, and received signal power in FSO system design. Advanced techniques such as adaptive beam tracking, optimized modulation schemes, and error correction methods are essential for ensuring reliable and high-performance FSO communication links. Future research should continue to explore innovative approaches to overcome these challenges and further enhance the viability of FSO as a robust communication technology.

In this paper, we examine the impact of atmospheric attenuation due to scattering effects across various weather conditions, as well as evaluate pointing errors and variations in received signal power under these conditions.

II. SIMULATION RESULTS AND DISCUSSIONS

Atmospheric weather conditions significantly influence the performance of FSO links. The impact of varying weather conditions is linked to the size distribution of scattering particles, denoted as q, and visibility, denoted as V. The specific attenuation in decibels per kilometer (dB/km) for the Kim and Kruse model is calculated using the following equation:

$$\alpha = \frac{3.91}{V(km)}\left(\frac{\lambda}{\lambda_0}\right)^{-q}$$

Where,

V (km) = visibility

λ (nm) = wavelength

λ_0 = visibility reference wavelength

Size distribution of scattering particles for Kruse Model [16]

$$q = \begin{cases} 1.6 \; if \; V > 50km \\ 1.3 \; if \; 6km < V < 50 \; km, \\ 0.585 \; \; if \; V < 6km \end{cases}$$

The impact of atmospheric attenuation on FSO link performance under different weather conditions is presented in Table 1. Figure 1 illustrates how changes in visibility affect the attenuation experienced by the FSO link.

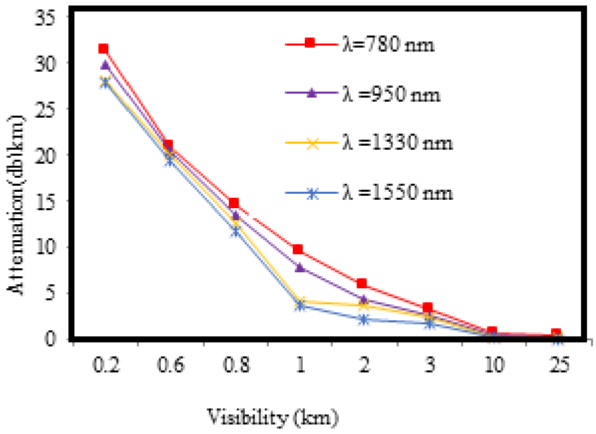

Fig.1. Atmospheric Attenuation Vs Visibility at different weather condition for Different wavelengths

Table 1: Atmospheric Attenuation at Different Weather Conditions for Different Wavelengths

Weather Condition	Visibility (km)	Attenuation (dB/km)			
		λ=780 nm	λ =950 nm	λ =1330 nm	λ =1550 nm
Clear air	25	0.4	0.3	0.2	0.1
	10	0.7	0.5	0.3	0.2
Haze	3	3.2	2.7	2.3	1.8
	2	5.8	4.3	3.8	2.1
	1	9.7	7.9	4.2	3.7
Fog	0.8	14.7	13.5	12.7	11.8
	0.6	20.9	20.5	20.1	19.5
	0.2	31.3	29.8	28.2	27.9

In clear air conditions with high visibility (V = 10 km, 25 km), atmospheric effects on signal power levels are minimal across all wavelengths. However, the situation shifts under haze and fog conditions. In haze scenarios (V = 1 km, 2 km, 3 km) and fog scenarios (V = 0.2 km, 0.6 km, 0.8 km), visibility diminishes, and the impact of scattering particles becomes pronounced. Observations indicate that a wavelength of 1550 nm experiences the lowest attenuation, making it the optimal choice for FSO-based data transmission.

III. PERFORMANCE ANALYSIS FOR FSO LINK AT 1550 NM

The performance evaluation of the proposed FSO link operating at a wavelength of 1550 nm, using non-return-to-zero (NRZ) line codes and APD-PIN receivers, under various weather conditions is presented in the figure 2, 3 and 4. Figure 2 state that as visibility decreases due to weather conditions such as haze or fog, pointing error becomes a more significant concern for FSO links. Poor visibility can lead to increased beam divergence and misalignment between the transmitter and receiver. This misalignment, in turn, can result in a higher pointing error, reducing link quality and increasing the bit error rate (BER). Adaptive beam steering and tracking techniques may be necessary to maintain optimal link performance under these challenging conditions [17-19].

The received signal power at 1550 nm is closely related to visibility. As visibility decreases due to scattering and absorption by atmospheric particles, received power levels are significantly impacted. This reduction in received power can lead to signal degradation and increased BER. Using power control techniques, such as adaptive power adjustment, can help maintain stable signal levels despite varying weather conditions.

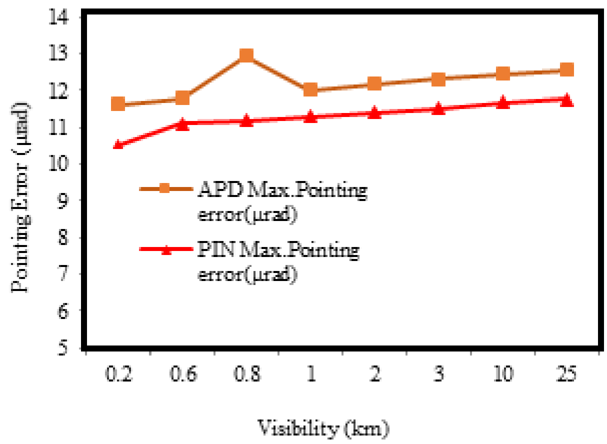

Fig.2. Visibility Vs Pointing Error at 1550 nm for a NRZ line codes

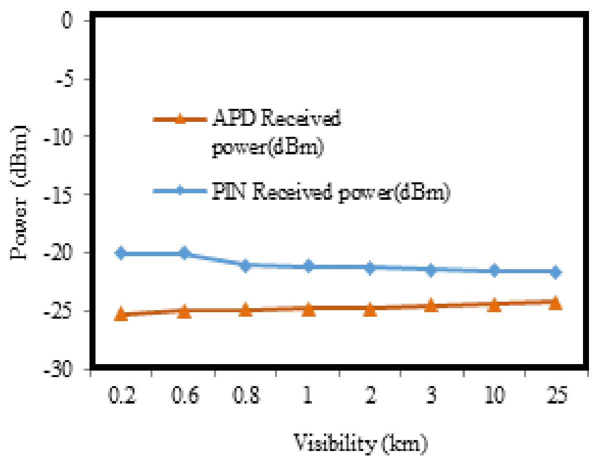

Fig.3. Visibility Vs receiving Power at 1550 nm for a NRZ line codes

The eye diagram is a critical tool for assessing signal quality in FSO links. An open eye pattern indicates a clear, low-noise signal with minimal intersymbol interference (ISI). As weather conditions deteriorate and visibility decreases, the eye diagram may start to show signs of closure due to increased noise and distortion. This closure can lead to higher BER and reduced communication reliability. By optimizing the system's parameters, such as adjusting line codes or employing signal processing techniques, it is possible to mitigate these effects and maintain a well-defined eye diagram.

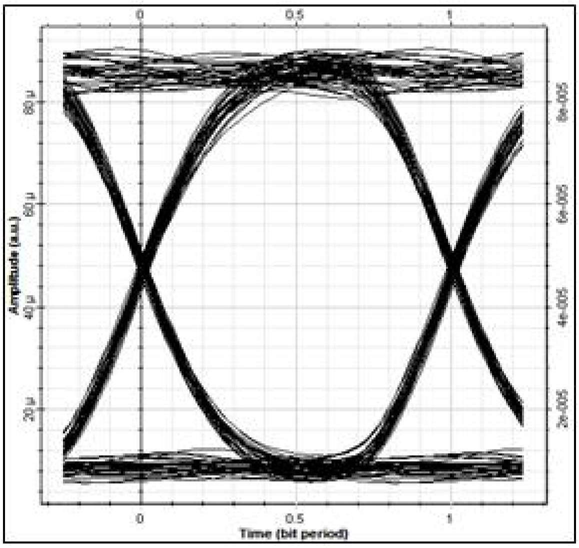

*Fig.4. Eye diagram for NRZ line code at 1550 n**m***

The performance evaluation of the proposed FSO link operating at a wavelength of 1550 nm, using return-to-zero (RZ) line codes and APD-PIN receivers, under various weather visibility is presented in the figure 5, 6 and 7

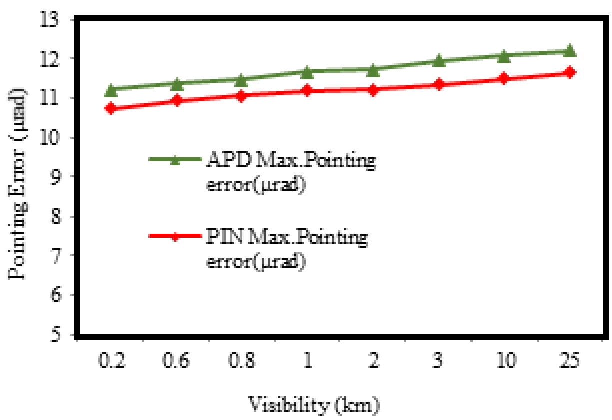

Fig .5. Visibility Vs Pointing Error at 1550 nm for a RZ line codes

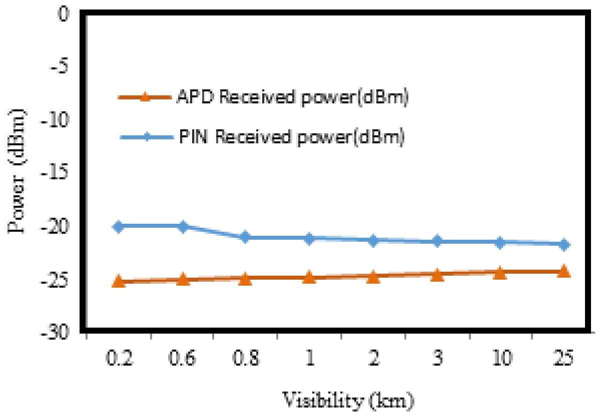

Fig 6. Visibility Vs receiving Power at 1550 nm for a RZ line codes

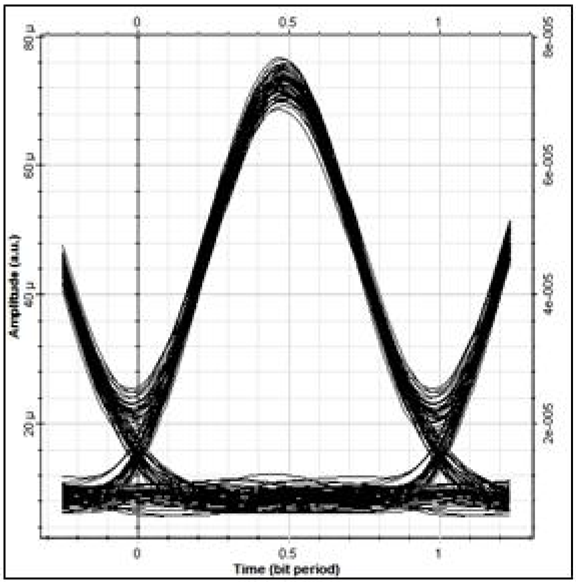

Fig.7. Eye diagram for RZ line code at 1550 nm

Both APD and PIN receivers are affected by pointing error; however, the higher sensitivity of APD receivers makes them slightly more resilient in maintaining link performance under challenging conditions compared to PIN receivers. Employing adaptive beam steering and tracking techniques is crucial to ensure optimal performance for both types of receivers.

The received signal power at 1550 nm is closely related to visibility. As visibility decreases due to scattering and absorption by atmospheric particles, received power levels are significantly impacted. This reduction in received power can lead to signal degradation and increased BER. APD receivers generally exhibit higher sensitivity compared to PIN receivers, making them better suited for environments with low visibility where received power is substantially reduced. Nonetheless, using power control techniques, such as adaptive power adjustment, can help maintain stable signal levels despite varying weather conditions for both APD and PIN receivers.

APD receivers may offer better eye patterns in adverse conditions due to their higher sensitivity and faster response times compared to PIN receivers. By optimizing system parameters, such as adjusting line codes or employing signal processing techniques, it is possible to mitigate these effects and maintain a well-defined eye diagram with both APD and PIN receivers.

Table 2: Maximum Pointing Errors and Received Signal Power at Different visibility for RZ Line Codes and APD-PIN Receivers (λ=1550 nm).

Modulation Technique		RZ			
Receiver Type		APD		PIN	
	Visibility	Max. Pointing error (µrad)	Received power (dBm)	Max. Pointing error (µrad)	Received power (dBm)
Clear air	25	12.20	-25.01	11.65	-22.46
	10	12.07	-25.21	11.50	-22.57
Haze	3	11.95	-25.32	11.33	-22.62
	2	11.73	-25.46	11.21	-22.75
	1	11.68	-25.57	11.18	-22.91
Fog	0.8	11.47	-25.68	11.07	-23.02
	0.6	11.36	-25.82	10.92	-23.20
	0.2	11.22	-25.91	10.42	-23.31

IV. CONCLUSION

The findings from this study contribute valuable insights into the performance of the proposed FSO link at 1550 nm with NRZ and RZ line codes, as well as the use of APD and PIN receivers under various weather conditions.

For the NRZ-APD configuration, the pointing error was measured at 11.62 µrad, which is slightly higher than the 11.22 µrad observed for the RZ-APD configuration. This suggests that while both configurations perform similarly in terms of pointing accuracy, RZ-APD offers a marginal improvement in this regard. However, the study also indicates that RZ-APD experienced greater attenuation of the received signal across all weather conditions compared to NRZ-APD. This increased attenuation may impact the overall performance and reliability of the link, suggesting that NRZ-APD may be the preferred configuration for minimizing signal degradation. In the case of PIN receivers, the performance study revealed that, in the presence of fog, the maximum pointing error for NRZ-PIN and RZ-PIN was 10.55 µrad and 10.42 µrad, respectively. Similar to the APD configurations, RZ-PIN exhibits a slight advantage in pointing error over NRZ-PIN. Based on these findings, the wavelength of 1550 nm emerges as the most suitable choice for FSO links across different weather conditions. This wavelength demonstrates lower attenuation and greater stability in adverse weather conditions, making it a favorable option for reliable data transmission. Overall, the analysis provides a clearer understanding of how different configurations impact link performance, enabling more informed decisions in the design and implementation of FSO systems. These insights can guide future research and development efforts to optimize FSO technology further, ensuring robust and efficient wireless communication systems in diverse and challenging atmospheric environments.

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