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Comparative Performance Evaluation of FSO Links Using NRZ and RZ Line Codes with APD and PIN Receivers in Different Weather Environments

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Abstract— *This paper presents a comparative performance analysis of Free Space Optical (FSO) communication links operating at a wavelength of 1550 nm using Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ) line coding techniques in combination with Avalanche Photodiode (APD) and Positive-Intrinsic-Negative (PIN) receivers under different atmospheric conditions. The performance of the FSO system is evaluated in terms of pointing error and received signal attenuation in clear air, haze, and fog environments. The obtained results reveal that the NRZ-APD configuration exhibits a pointing error of 11.62 µrad, which is slightly higher than the 11.22 µrad observed for the RZ-APD configuration. However, the RZ-APD setup experiences comparatively higher signal attenuation under all considered weather conditions. In the case of PIN receivers, maximum pointing errors of 10.55 µrad and 10.42 µrad are observed for NRZ-PIN and RZ-PIN schemes, respectively, particularly under foggy atmospheric conditions. The analysis demonstrates that the 1550 nm operating wavelength provides reliable and efficient performance for FSO communication links in varying weather environments. Furthermore, NRZ-APD and RZ-PIN configurations show improved performance in terms of pointing accuracy and system reliability. The findings of this study offer useful insights for the development and optimization of robust high-speed FSO communication systems operating under adverse atmospheric conditions.*

Keywords— ***Free Space optics (FSO), photo diode, pointing error.***

I. INTRODUCTION

Free Space Optical (FSO) communication has emerged as an attractive and rapidly developing wireless communication technology capable of providing high-speed data transmission with large bandwidth, improved security, and cost-effective deployment. The increasing demand for broadband communication services, high data rates, and reliable wireless connectivity has significantly enhanced the importance of FSO systems in modern communication networks. Unlike conventional radio frequency (RF) communication systems, FSO communication employs optical signals transmitted through the atmosphere to establish line-of-sight (LOS) communication links. Due to the utilization of optical carriers, FSO systems can achieve data rates ranging from several Mbps to multi-Gbps while operating in an unlicensed optical spectrum [1].

FSO communication offers numerous advantages over RF communication systems, including higher bandwidth availability, immunity to electromagnetic interference, compact transceiver size, low power consumption, rapid deployment, and enhanced communication security due to the narrow optical beam divergence [2]. These characteristics make FSO systems highly suitable for applications such as satellite communication, military communication, last-mile connectivity, inter-building communication, disaster recovery systems, cellular backhaul networks, and next-generation 5G/6G communication infrastructures [3].

Despite these advantages, the performance and reliability of FSO communication systems are strongly affected by atmospheric conditions and environmental impairments. Since optical signals propagate through the atmosphere, they experience attenuation due to absorption and scattering caused by atmospheric particles such as fog, haze, rain, dust, and snow [4]. Among all atmospheric conditions, fog is considered the most severe impairment because the size of fog particles is comparable to the optical wavelength, resulting in significant attenuation and degradation of the received signal power [5]. Additionally, atmospheric turbulence and pointing errors caused by building sway, thermal expansion, and mechanical vibrations further deteriorate the quality and stability of FSO links [6].

To improve the performance of FSO systems under varying atmospheric conditions, researchers have focused on optimizing modulation techniques, receiver configurations, and operating wavelengths. Among the commonly employed line coding schemes, Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ) modulation techniques are widely used due to their simple implementation and effective transmission characteristics. NRZ modulation provides better bandwidth efficiency and lower spectral requirements, whereas RZ modulation offers improved synchronization capability and reduced inter-symbol interference [7]. Therefore, a comparative analysis of NRZ and RZ line coding schemes under adverse weather conditions is essential for identifying the most suitable modulation format for reliable FSO communication.

The performance of an FSO system also depends significantly on the type of optical receiver used for signal detection. Avalanche Photodiode (APD) and Positive-Intrinsic-Negative (PIN) photodiodes are the most commonly utilized receivers in optical wireless communication systems. APD receivers provide higher sensitivity and internal gain, making them suitable for long-distance optical communication links operating under low received power conditions. However, APDs require higher bias voltages and introduce additional noise due to avalanche multiplication. In contrast, PIN photodiodes offer simpler design, lower cost, reduced noise characteristics, and faster response time, although their sensitivity is lower compared to APD receivers [8]. Consequently, the selection of an appropriate receiver configuration plays a crucial role in enhancing the performance and reliability of FSO systems.

Another important design parameter in FSO communication is the operating wavelength. Optical wavelengths such as 850 nm, 1310 nm, and 1550 nm are commonly used in optical wireless systems. Among these wavelengths, 1550 nm is widely preferred because it provides lower atmospheric attenuation, improved eye safety, and compatibility with existing optical fiber communication components [9]. Moreover, the 1550 nm wavelength demonstrates superior performance under foggy and hazy weather conditions compared to lower operating wavelengths [10].

Several researchers have investigated the performance of FSO communication systems using different modulation schemes, receiver types, and atmospheric models. Mohammed et al. analyzed the performance of FSO links using NRZ and RZ line coding techniques with APD and PIN receivers under various weather conditions in the presence of pointing errors [11]. Their study revealed that the NRZ-APD configuration operating at 1550 nm provided superior performance in terms of received signal power and Bit Error Rate (BER) compared to other receiver and modulation combinations. The authors also reported that atmospheric attenuation and pointing errors significantly degrade system performance, particularly under dense fog conditions.

Kaur and Soni performed a comparative analysis of FSO communication systems using different modulation formats and wavelengths [12]. Their study compared

NRZ and RZ modulation techniques operating at 1310 nm and 1550 nm wavelengths with APD and PIN photodetectors. Simulation results demonstrated that the NRZ modulation scheme with APD receiver at 1550 nm achieved the highest Q-factor and improved communication performance. The authors concluded that higher operating wavelengths improve the transmission reliability of FSO systems under adverse atmospheric conditions.

Hadisiswoyo et al. presented a simulation-based comparison of NRZ and RZ pulse modulation techniques for FSO systems under different weather environments such as sunny and rainy conditions [13]. The study evaluated parameters including received optical power, photocurrent, eye height, and optical spectrum. Their results showed that NRZ modulation achieved better received signal power and improved eye diagram performance compared to RZ modulation under varying atmospheric conditions.

Ali investigated the performance of NRZ and RZ-On-Off Keying (OOK) modulation formats for FSO communication systems operating under foggy weather conditions [14]. The study analyzed BER performance using different fog models at 850 nm and 1550 nm wavelengths with PIN photodiode receivers. The results indicated that the 1550 nm operating wavelength offered lower BER and superior communication reliability under dense fog conditions.

A comparative analysis of different optical transmission windows for FSO systems under adverse atmospheric conditions was presented in Procedia Computer Science [15]. The authors investigated the performance of 850 nm, 1310 nm, and 1550 nm wavelengths under varying atmospheric attenuation levels. Their findings confirmed that the 1550 nm wavelength achieved improved transmission efficiency and longer communication range compared to lower optical wavelengths.

El Arif et al. investigated the performance of different NRZ-based modulation techniques, including non-chirped NRZ, chirped NRZ, and alternate-chirped NRZ schemes for FSO systems operating at high data rates [16]. The study demonstrated that NRZ-based modulation formats provided stable communication performance and enhanced Q-factor under moderate atmospheric attenuation conditions.

Borwankar and Shah studied the influence of weather conditions such as fog and rain on FSO link performance using OptiSystem simulations [17]. Their research highlighted that fog causes severe attenuation and substantial reduction in received optical power, thereby limiting the communication range of FSO systems. The authors emphasized the importance of selecting suitable modulation schemes and receiver configurations to improve system reliability.

Recently, Pottoo et al. experimentally investigated the performance of 1550 nm FSO communication links under Arctic weather conditions, including snowfall, humidity variations, and atmospheric turbulence [18]. Their experimental observations demonstrated that environmental conditions significantly affect attenuation characteristics and system performance. The study recommended adaptive compensation techniques and efficient receiver designs to improve communication reliability in harsh atmospheric environments.

Although significant research has been conducted on FSO communication systems using different modulation techniques, receiver types, and operating wavelengths, limited work has focused on the combined comparative analysis of NRZ and RZ line coding techniques using both APD and PIN receivers under multiple atmospheric conditions with detailed pointing error evaluation. Therefore, this paper presents a comparative performance evaluation of FSO links operating at 1550 nm wavelength using NRZ and RZ line coding techniques with APD and PIN receivers under clear air, haze, and fog conditions. The analysis focuses on important performance parameters such as pointing error and received signal attenuation to identify the most efficient receiver and modulation configuration for reliable optical wireless communication systems operating in diverse atmospheric environments.

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.

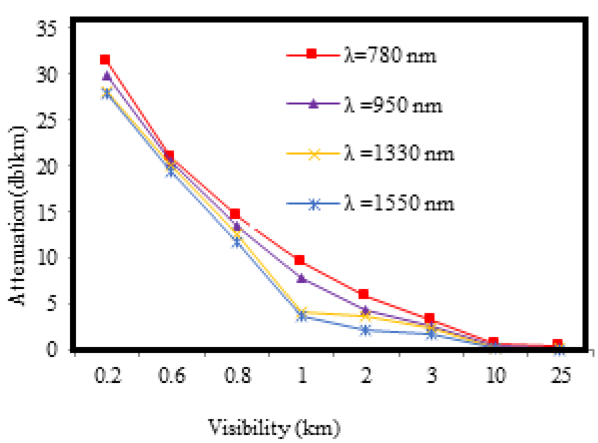

Fig.1. Atmospheric Attenuation Vs Visibility at different weather condition for Different wavelengths

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.

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. 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.

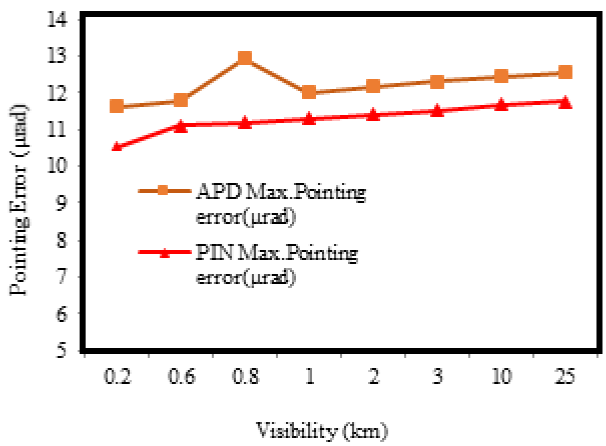

Fig.2. Visibility Vs Pointing Error at 1550 nm for a NRZ line codes

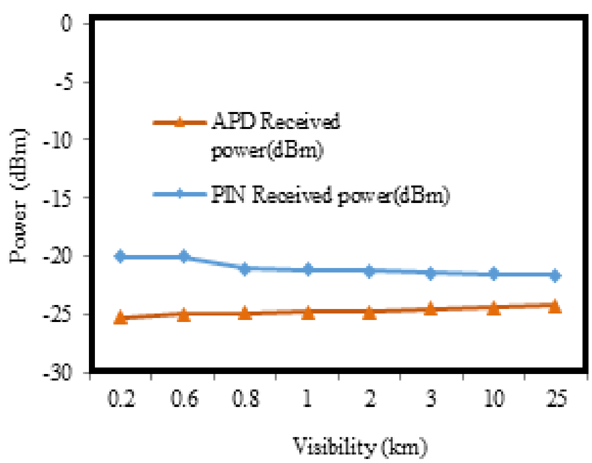

Fig.3. Visibility Vs receiving Power at 1550 nm for a NRZ line codes

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.

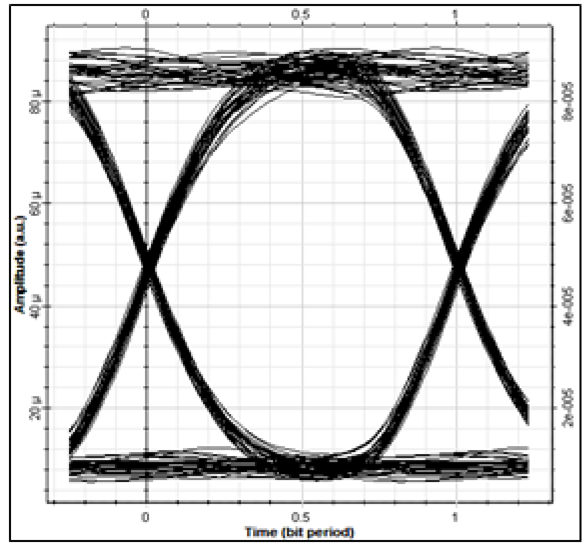

Fig.4. Eye diagram for NRZ line code at 1550 nm

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

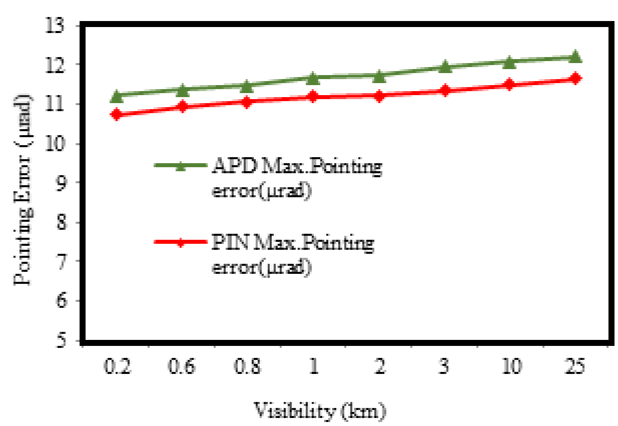

Fig .5. Visibility Vs Pointing Error at 1550 nm for a RZ line codes

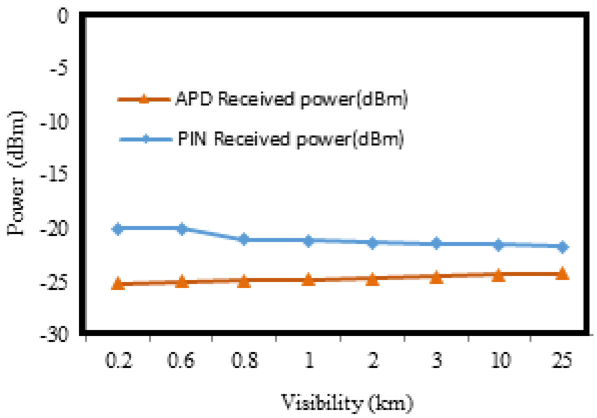

Fig 6. Visibility Vs receiving Power at 1550 nm for a RZ line codes

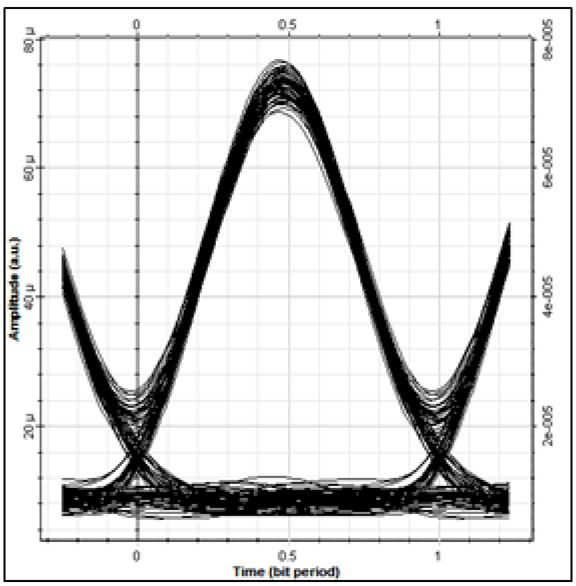

Fig.7. Eye diagram for RZ line code at 1550 nm

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

III. CONCLUSION

This study presents a comparative performance evaluation of Free Space Optical (FSO) communication links operating at a wavelength of 1550 nm using NRZ and RZ line coding techniques with APD and PIN receivers under different atmospheric conditions, including clear air, haze, and fog. The analysis provides important insights into the impact of modulation formats and receiver configurations on pointing error and received signal attenuation in adverse weather environments.

The obtained results indicate that the NRZ-APD configuration exhibits a pointing error of 11.62 µrad, which is slightly higher than the 11.22 µrad observed for the RZ-APD configuration. Although the RZ-APD setup demonstrates marginally better pointing accuracy, it experiences comparatively higher received signal attenuation under all considered weather conditions. This suggests that the NRZ-APD configuration offers improved overall transmission performance and greater signal stability for FSO communication links.

For PIN receiver-based configurations, the maximum pointing errors observed under fog conditions are 10.55 µrad for NRZ-PIN and 10.42 µrad for RZ-PIN. Similar to the APD-based systems, the RZ-PIN configuration shows a slight improvement in pointing accuracy compared to NRZ-PIN. However, the overall system performance analysis indicates that receiver sensitivity and atmospheric attenuation significantly influence communication reliability in challenging weather conditions.

The study further demonstrates that the 1550 nm operating wavelength provides superior performance for FSO communication systems under varying atmospheric environments due to its lower attenuation characteristics and enhanced transmission stability. Consequently, the 1550 nm wavelength is identified as the most suitable choice for reliable and high-speed optical wireless communication links.

Overall, the comparative analysis presented in this work offers a better understanding of the influence of line coding techniques and photodetector configurations on FSO system performance. The findings of this research can assist researchers and system designers in selecting appropriate modulation formats and receiver types for the development of robust, efficient, and reliable FSO communication systems capable of operating effectively under diverse and adverse weather conditions. Furthermore, the results may serve as a foundation for future research focused on improving FSO system performance through advanced modulation schemes, adaptive receiver techniques, and atmospheric compensation methods.

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