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Harnessing Polarization Diversity for Enhanced Reliability in Free Space Optical Communications

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ABSTRACT: This article delves into the strategic application of polarization diversity in Free-Space Optical (FSO) communication systems. With the overarching aim of optimizing data transmission and bolstering reliability, the paper explores the utilization of diverse polarization orientations to navigate the challenges posed by varying atmospheric conditions. By transmitting identical data streams through different polarization states, the impact of atmospheric turbulence is effectively mitigated, leading to enhanced signal quality and system dependability. This article sheds light on the theoretical underpinnings and simulation modeling of harnessing polarization diversity in FSO communication. The simulations conducted in this study using OptiSystem software ver. 17 demonstrate the effectiveness of this approach in mitigating the adverse impacts of atmospheric turbulence. Notably, the results consistently indicate that the integration of polarization diversity leads to lower Bit Error Rates (BERs) across a spectrum of turbulence conditions. Furthermore, the proposed FSO system exhibits a remarkable ability to sustain robust communication capabilities over extended distances, outperforming the conventional system. Significantly, the proposed FSO system under weak, moderate, and strong turbulence conditions achieves operational distances of approximately 4250, 3750, and 3200 meters, respectively compared to conventional system, which achieves distances of 3750, 3250, and 2250 meters, respectively. This significant performance disparity underscores the potency of the proposed FSO system in overcoming the challenges of atmospheric turbulence and extending the reach of optical communication.

1. INTRODUCTION

In response to the ever-increasing requirements for high-speed telecommunications, the realm of Free Space Optic (FSO) communications is swiftly gaining prominence as an efficient alternative to traditional Radio Frequency (RF) links and optical cable networks [1, 2]. At its core, FSO harnesses the propagation of light beams to transmit data through the atmosphere, offering a host of advantages particularly in situations where laying physical cables or fiber optics is not feasible or cost-effective, such as in urban environments with limited infrastructure or disaster-stricken areas needing rapid connectivity restoration [3, 4]. Operating using unlicensed spectrum with specific wavelengths of light, typically in the near-infrared (NIR) range, FSO technology can attain remarkable high data rates akin to fiber optics with low latency and enhanced security [5, 6].

Despite these advantages, FSO also faces challenges related to weather conditions like rain, fog, snow, and dust, limited range and line of sight (LoS) constraints. These challenges can temporarily degrade the quality of the optical signal and affect the reliability of communication, especially during adverse weather conditions [7, 11].

Several mitigation techniques and strategies are introduced to address the challenges posed by weather conditions and atmospheric effects in FSO communication systems, such as adaptive optics, error correction coding and diversity techniques (multimode and multi-aperture diversity reception, ...) [12, 13]. Additionally, careful site selection, frequency planning, and link budget calculations are essential to the design of FSO systems that can operate effectively in various weather conditions and atmospheric environments [14, 15]. It is important to note that the mentioned mitigation strategies can enhance the robustness and reliability of FSO systems in a wide range of atmospheric conditions but might not completely eliminate the effects of all adverse weather conditions. Indeed, each technique addresses specific challenges associated with atmospheric effects, such as turbulence, scattering, and absorption. However, some extreme weather conditions, such as heavy rain, dense fog, or severe turbulence, can still pose challenges that might lead to temporary disruptions in FSO communication.

Furthermore, among the aforementioned approaches, diversity techniques, including polarization diversity, stand out as an exceptionally effective method for countering the atmospheric scintillation effects and enhancing the resilience and reliability of FSO links. Atmospheric scintillation, also known as optical scintillation or twinkling, refers to the rapid fluctuations in the intensity and phase of an optical signal caused by atmospheric turbulence making it difficult to maintain a stable communication link [16]. Polarization diversity involves transmitting the optical signal using different polarization states (e.g., vertical and horizontal polarizations) simultaneously. By exploiting the fact that atmospheric turbulence affects different polarization states differently, the probability rises that some beams

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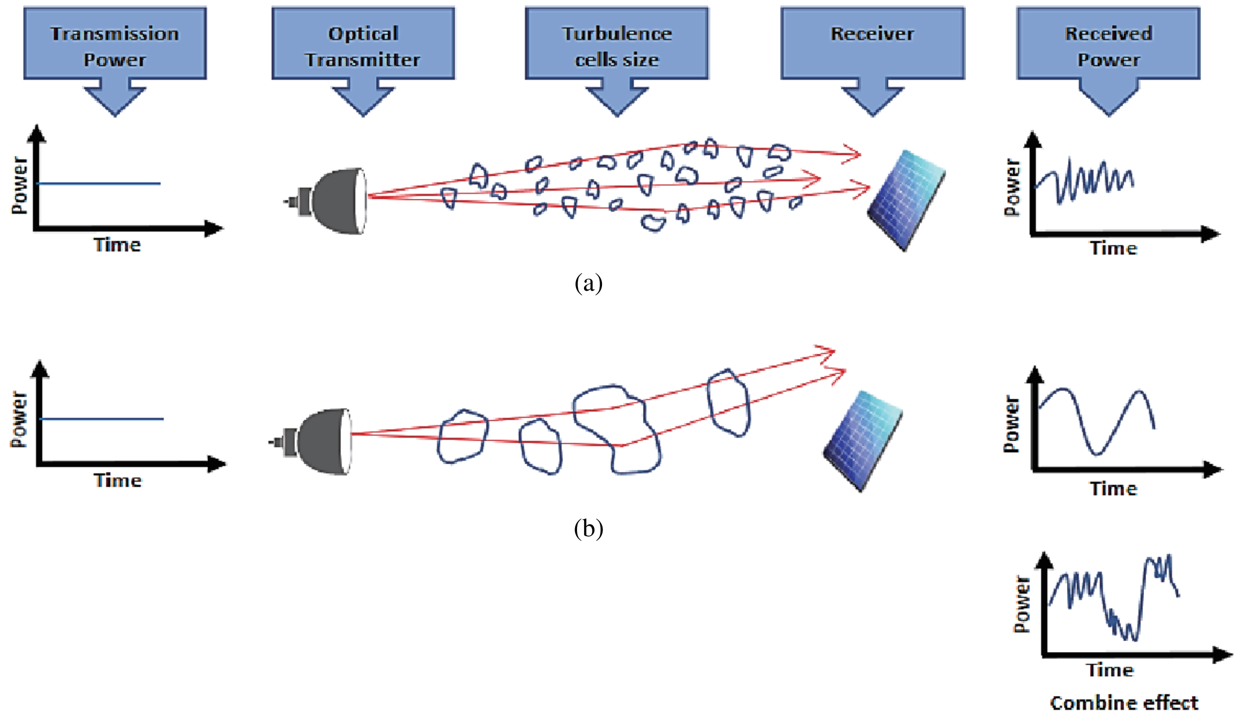

FIGURE 1. The atmospheric turbulence effect on the optical signal depending on the size of the turbulence cell (a) smaller than the laser beam diameter (b) larger than the laser beam diameter [22].

might elude the impacts of atmospheric turbulence. At the receiver's end, the collected signals from multiple polarization states can be combined to effectively counteract the adverse impacts of scintillation and signal degradation, further augmenting the overall quality of the received signal [17, 18].

Depending on the specific requirements of the communication scenario and the goals of the system design, polarization diversity in FSO links can be harnessed in two distinct manners: either transmitting different data at different polarizations or transmitting the same data using different polarizations. In the first approach, distinct sets of data are simultaneously transmitted using different polarization states. This approach essentially increases the effective data rate of the system. By exploiting the orthogonal nature of polarization states, multiple independent data streams can be transmitted on the same carrier frequency without interfering with each other. However, this method requires careful signal processing techniques at the receiver to separate and recover the different data streams correctly. Alternatively, the same data can be duplicated and transmitted using different polarization states, such as horizontal and vertical polarizations. This strategy serves to mitigate the effects of scintillation and other atmospheric effects, consequently enhancing elevating both the overall quality and the reliability of the FSO communication link [19–21].

The primary goal of the paper is to harness polarization diversity for the purpose of optimizing data transmission through varying atmospheric conditions while concurrently bolstering reliability. This is achieved by transmitting identical data streams using diverse polarization orientations, thereby effectively mitigating the impact of atmospheric turbulence and its adverse effects. In Section 2, we will delve into the atmospheric turbulence that influences FSO communication. Section 3 will discuss the concept and benefits of polarization diversity. Section 4 will explore the methodology of transmitting identical data with diverse polarizations and present case study of FSO transmission with real-world scenarios using OptiSystem ver.17 software. Following this, Section 5, will present the simulation results, which serve as a testament to the efficacy of our proposed FSO system in mitigating the adverse impacts of atmospheric turbulence. Finally, Section 6 will conclude our study, summarizing the key insights and implications drawn from our research.

2. OVERVIEW OF ATMOSPHERIC TURBULENCE

The transmission of optical signals through the expanse of free space is inherently influenced by the complex interplay of atmospheric conditions. These atmospheric effects can significantly impact the propagation of light and, consequently, the reliability and quality of Free-Space Optical (FSO) communication.

Atmospheric turbulence, characterized by the irregular motion of air masses, is a formidable adversary in FSO communication. As light traverses the atmosphere, random variations in the refractive index due to turbulence cause fluctuations in the intensity and phase of the optical signal. This phenomenon is known as scintillation. The result is a shimmering or flickering effect that can lead to signal fading and even momentary sig-

TABLE 1. Refractive index structure coefficients for the different turbulent channels [25, 26].

Turbulence regime	C_n^2
Weak	$5 \times 10^{-17}\,\mathrm{m}^{-2/3}$
Moderate	$5 \times 10^{-15}\,\mathrm{m}^{-2/3}$
Strong	$5 \times 10^{-13}\,\mathrm{m}^{-2/3}$

nal loss. The severity of scintillation is influenced by factors such as temperature gradients, wind speeds, and the distance the light travels through the atmosphere. Figure 1 showcases the relationship between the size of the turbulence cell within the atmosphere and the consequential effects it imposes on the received optical signal [22].

In cases where turbulence cells' diameters prove smaller than that of the laser beam (Figure 1(a)), intricate interactions occur between the turbulence and light wavefront. The irregular motion of air masses leads to rapid changes in the refractive index of the air, causing the light rays to bend and distort. Slight variations in the arrival times of different elements constituting the beam's wavefront lead to a complex interplay of constructive and destructive interference. As a result, the intensity of the laser beam arriving at the receiver undergoes temporal rhythmic fluctuations — a phenomenon commonly referred to as scintillation [16, 22].

On the other hand, larger cells physically bend the beam's path, leading to deflection from the expected trajectory. As illustrated in Figure 1(b), the laser beams emitted from the source experience deflection as they traverse through the larger turbulence cell. Instead of following the anticipated on-axis trajectory, the beams arrive off-axis due to the bending introduced by the expansive turbulence cell. This off-axis arrival deviates from the beam's trajectory in a turbulence-free environment, emphasizing the atmospheric turbulence's capacity to alter the trajectory of light [22, 23]. These effects highlight the intricate dynamics of atmospheric turbulence on optical signals and underscore the challenges that must be addressed in FSO communication systems.

Indeed, the classification of atmospheric turbulence is essential in understanding its varying impact on optical signals. The turbulence can be categorized into distinct regimes — weak, moderate, strong, and saturated — depending on the extent of variation in the refractive index and inhomogeneity across the atmosphere. Mathematical models are integral in capturing the essence of these turbulence regimes. Various models have been developed to represent each turbulence regime accurately. For instance, the Log-normal, Gamma-Gamma, double Gamma-Gamma, negative exponential and M-distribution models correspondingly portray weak, weak-to-strong, moderate-to-strong, saturated and generalized turbulences [24]. Each model offers a mathematical framework to characterize the specific turbulence conditions accurately. These atmospheric turbulence models play a critical role in shedding light on the statistical characteristics of the irradiance fluctuation. By describing the Probability Density Function (PDF) statistics of these fluctuations, these models facilitate the prediction and analysis of the impact of turbulence on optical signals. This, in turn, aids in designing robust communication systems capable of mitigating the effects of varying turbulence regimes, ensuring more dependable and efficient Free-Space Optical communication.

Hence, in this article, we consider the Gamma-Gamma fading channel model to describe weak-to-strong turbulence, where the PDF of Gamma-Gamma distribution of a given signal intensity I is given as [25–28]:

$$p\left(I\right)=\frac{2\cdot\left(\alpha\cdot\beta\right)^{(\alpha+\beta)/2}}{\Gamma\left(\alpha\right)\cdot\Gamma(\beta)}\cdot I^{\frac{\alpha+\beta}{2}-1}k_{\alpha-\beta}\left(2\sqrt{\alpha\cdot\beta\cdot I}\right),\ I>0 \tag{1}$$

where $\Gamma(\cdot)$ represents the Gamma function; $k_{\alpha-\beta}(\cdot)$ is the $\alpha-\beta^{\text{th}}$ order modified Bessel function of the second kind; and α, β are the scintillation parameters specified as functions of the Rytov variance σ_R^2 as follows [29]:

$$\alpha = \left\{\exp\left[\frac{0,49\cdot\sigma_R^2}{\left(1+1,11\cdot\sigma_R^{12/5}\right)^{5/6}}\right]-1\right\}^{-1};$$

$$\beta = \left\{\exp\left[\frac{0,51\cdot\sigma_R^2}{\left(1+0,69\cdot\sigma_R^{12/5}\right)^{5/6}}\right]-1\right\}^{-1}$$

The Rytov variance σ_R^2 can be calculated according to [29]:

$$\sigma_R^2 = 1,23\cdot C_n^2 k^{7/6}\cdot L^{11/6} \tag{2}$$

where C_n^2 represents the index refraction structure parameter with value varying from $10^{-13}\,\mathrm{m}^{-2/3}$ for strong turbulence to $10^{-17}\,\mathrm{m}^{-2/3}$ for weak turbulence [30]; $k = 2\pi/\lambda$ is the wave number; and L is the propagation distance. When $\sigma_R^2 \ll 1$, it indicates that the turbulence is weak. Otherwise the turbulence is strong as depicting in Table 1.

3. POLARIZATION DIVERSITY

Polarization diversity represents a pivotal concept within the realm of FSO communication, harnessing the unique properties of light polarization to enhance signal resilience. This section delves into the foundational aspects of polarization diversity, elucidating how diverse polarization orientations can be ingeniously utilized to counteract the impact of atmospheric challenges. By exploring the intricate interplay between polarization states and atmospheric effects, we gain a comprehensive understanding of how this technique enhances the robustness of FSO systems.

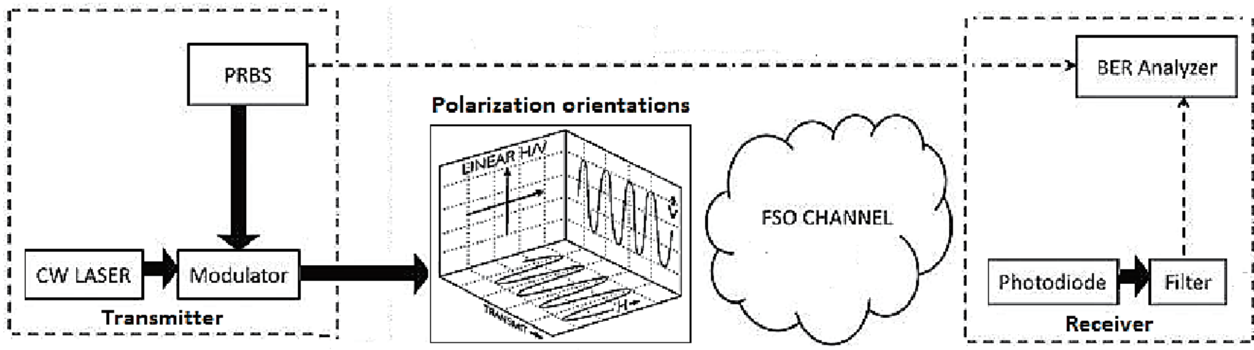

FIGURE 2. Design of FSO communication system leveraging polarization diversity.

By capitalizing on the orthogonal nature of polarization states, FSO systems can simultaneously transmit independent data streams on the same carrier frequency without interfering with each other. This approach significantly augments the system's capacity and data rates, effectively multiplying the effective data transmission capacity. Furthermore, by harnessing the distinctive behavior of polarized light in the presence of atmospheric turbulence, polarization diversity enables enhanced resistance to scintillation, signal fading, and other atmospheric-induced degradations, thus elevating the reliability and overall performance of FSO communication [20, 21].

Atmospheric turbulence, as previously discussed, induces dynamic changes in the refractive index, leading to fluctuations in the intensity and phase of the optical signal — scintillation. These fluctuations result from the interaction of light with varying turbulence conditions along its propagation path. However, when polarized light encounters turbulence, each polarization state experiences distinct phase shifts, thus affecting their paths differentially. This intricate behavior is the cornerstone of polarization diversity's effectiveness. By simultaneously transmitting identical data streams through different polarization orientations (Figure 2), the adverse impacts of turbulence on one polarization can be offset by the relatively unaltered state of another. Essentially, while one polarization state may experience significant scintillation-induced fading, another polarization state might remain comparatively unaffected. At the receiver's end, these diverse polarization-oriented signals can be synergistically combined [31].

The received optical power in a polarization diversity system can be expressed as a combination of the powers received in the individual polarization states. Assuming two orthogonal polarizations (Horizontal and Vertical), the total received power (P_r) can be written as

$$P_r = P_{r\_H} + P_{r\_V} \tag{3}$$

where P_{r_H} is the received power in the horizontal polarization state, and P_{r_V} is the received power in the vertical polarization state.

By doing so, the adverse effects of scintillation-induced signal degradation can be mitigated, resulting in improvement in signal quality ($SNR = SNR_H + SNR_V$) and more stable and reliable optical communication in dynamic environmental conditions.

4. PROPOSED POLARIZED FSO SYSTEM MODEL

The proposed system model employed for simulation in OptiSystem ver.17 is depicted in Figure 3. The optical transmitter includes a Pseudo Random Bit Sequence (PRBS) generator, a Non-Return to Zero (NRZ) pulse generator, a Mach-Zehnder Modulator (MZM), a continuous Wave (CW) Laser source and a Polarization Diversity Component (PDC). The binary sequence of pseudo-random bits generated using the PRBS generator is fed into the NRZ pulse generator, where it undergoes a transformation into electrical pulses. The obtained electrical pulses and a CW laser signal, generated by Laser source, are combined and modulated within the MZM modulator. This modulation process results in an optical signal with variable intensity, which closely follows the characteristics of the input electrical signal. The modulated signal is conveyed through the free space in two orthogonal polarizations through the utilization of the Polarization Diversity Component. As illustrated in Figure 3, the PDC consists of three components:

- Fork 1×2 used to duplicate the input optical signal, resulting in the creation of two identical output signals. This replication process ensures redundancy and facilitates further polarization control.
- Polarization Rotator (PRo) employed to change the polarization state of the incoming optical signal.
- Polarization Combiner (PC) utilized for merging the optical signals with different polarization states into a single output signal.

The receiving end of the proposed polarized FSO link, as illustrated in Figure 4, consists of a series of essential components to process and analyze the received optical signal. These components include a polarization splitter (PS), two photodiodes (PINs), an electrical combiner (2×1), a Low-Pass Bessel Filter (LPBF), a 3R regenerator, and a Bit Error Rate (BER) analyzer. Upon reaching the receiver in the FSO communication system, the incoming optical signal undergoes a series of cru-

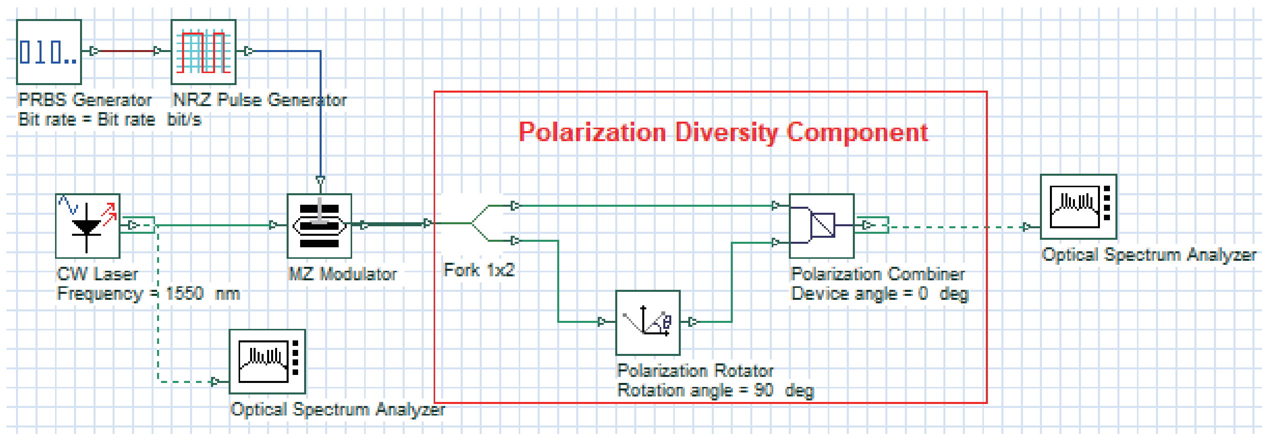

FIGURE 3. Simulation schematic layout of the polarized FSO system: Transmitting units.

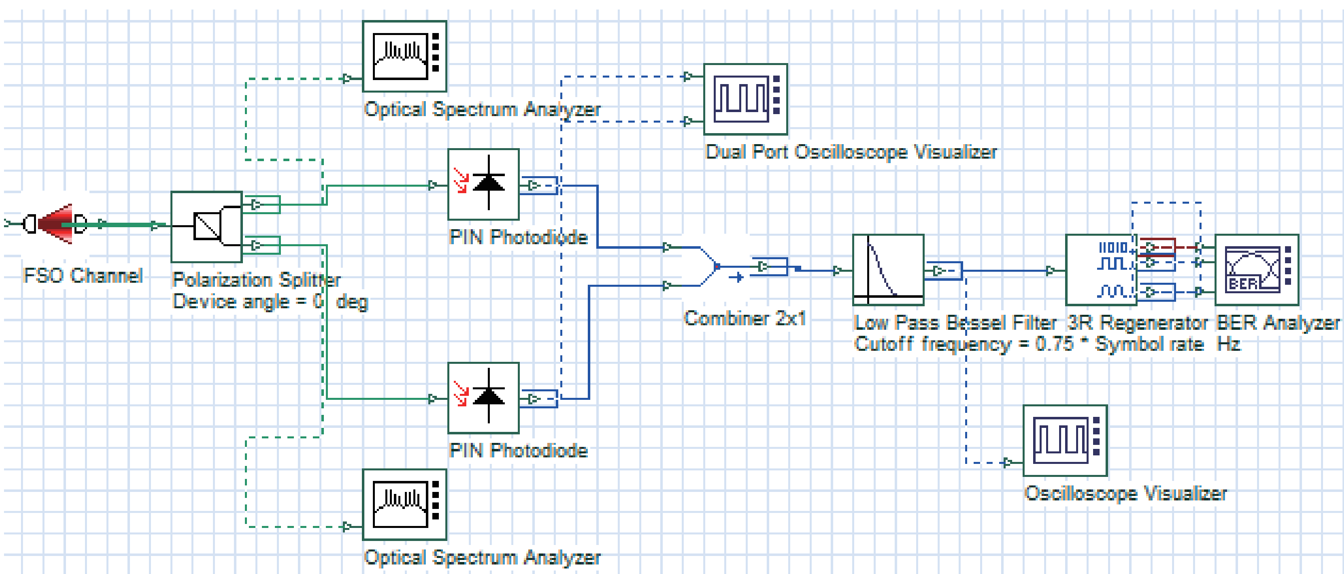

FIGURE 4. Simulation schematic layout of the polarized FSO system: Receiving units.

cial processing steps. The initial step involves passing the signal through a PS component, which serves to decompose the incoming optical signal into two orthogonal components of equal amplitude. This decomposition is fundamental for subsequent analysis and further processing of the received signal.

Following their separation, the two distinct optical signals are independently detected by two photodetectors. Subsequently, these photodetector outputs are combined through an electrical combiner. This combining step is vital as it allows for the integration of the information carried by both polarization components into a unified electrical signal. Moreover, to enhance the quality of the received signal, an LPBF with cutoff frequency set at 75% of the bit rate is employed to effectively attenuate the noise component. Subsequently, 3R regenerator plays a pivotal role in the signal processing chain. It meticulously restores and regenerates the electrical signal, ensuring that it faithfully reproduces the original bit sequence. Ultimately, the performance and quality of the received signal are meticulously assessed through the utilization of a BER analyzer. The proposed FSO system simulation was conducted using parameter values as detailed in Table 2.

5. SIMULATION RESULTS

The study involves a performance evaluation of the proposed FSO system model, incorporating polarization diversity. In order to assess the proposed system's efficacy, a comparative analysis is conducted in two scenarios with and without polarization diversity. Using the same simulation parameters shown in Table 2, the key performance metric under scrutiny is the BER, and the comparison was conducted over varying link distances for diverse turbulence conditions. The findings of this comparative study are visually presented in Figures 5, 6, and 7, offering valuable insights into the impact of polarization diversity on system performance across different atmospheric turbulence conditions.

Figure 5 provides an insightful evaluation of the system's performance by conducting a comparative analysis in terms of

TABLE 2. Simulation parameters.

Parameters	Values
Data bit rate	2.5 Gbps
Sequence length	1024 bits
Samples per bit	32
Optical frequency	1550 nm
CW laser power	10 dBm
Beam divergence	2 mrad
Transmitter aperture diameter	5 cm
Receiver aperture diameter	20 cm
Turbulence model	Gamma-Gamma
Atmospheric attenuation	0.23 dB/Km (Clear weather)
Link range	250–4500 m
PIN Responsivity	0.85 A/W
Dark Courrent	10 nA
Thermal noise	1.8×10^{-23} W/Hz
Shot noise	Considered

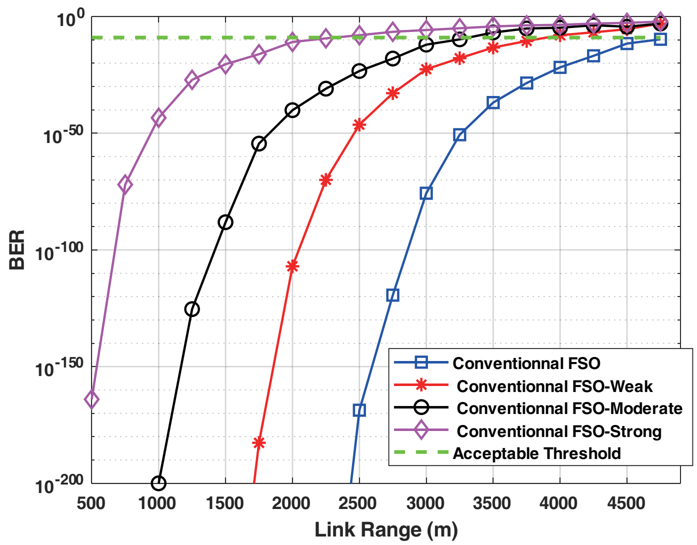

FIGURE 5. Comparative performance analysis of conventional FSO system in various atmospheric turbulence scenarios.

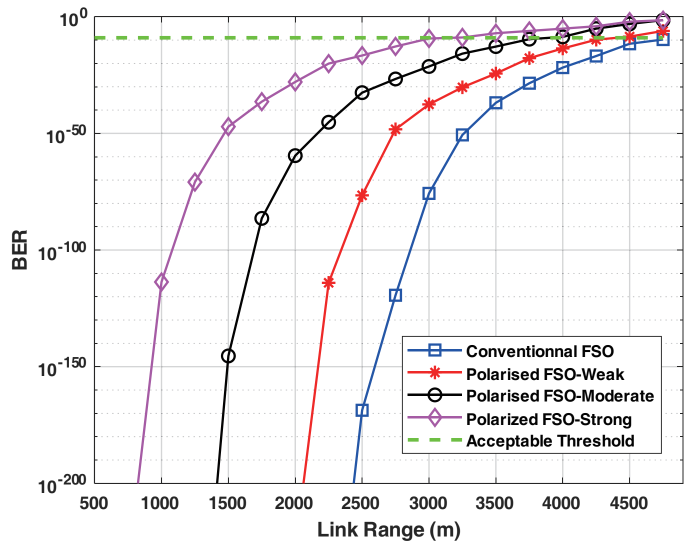

FIGURE 6. Comparative performance analysis of proposed FSO system in various atmospheric turbulence scenarios.

BER of the conventional FSO system (without polarization diversity) with and without considering atmospheric turbulence, under clear weather condition alongside the aforementioned system considering three different atmospheric turbulence scenarios referred as weak, moderate, and strong.

By scrutinizing the findings within Figure 5, we gain valuable insights into how atmospheric turbulence, spanning the spectrum from weak to moderate and strong conditions, impacts the performance of the FSO system. This impact is most prominently observed in the BER vs. link distance relationship, which exhibits distinctive error rate variations as a direct consequence of changes in the transmission distance. These variations underscore the dynamic nature of FSO system performance in response to atmospheric turbulence levels.

As illustrated in Figure 5, weak turbulence has a minor impact, resulting in lower error rates over different link distances resulting in a minimal impact on the signal quality. Moderate turbulence conditions typically result in a moderate level of scintillation. In this scenario, the refractive index fluctuations become more pronounced, causing noticeable fluctuations in the optical signal, leading to an increase in BER with increasing link distance. The BER curve shows a more noticeable rise, especially at longer distances. Likewise, strong turbulence conditions indicate a high level of atmospheric turbulence, with significant fluctuations in refractive index. Under strong turbulence, the optical signal experiences pronounced scintillation, causing significant degradation of the signal quality and a steep increase in BER as the link distance increases. The BER curve

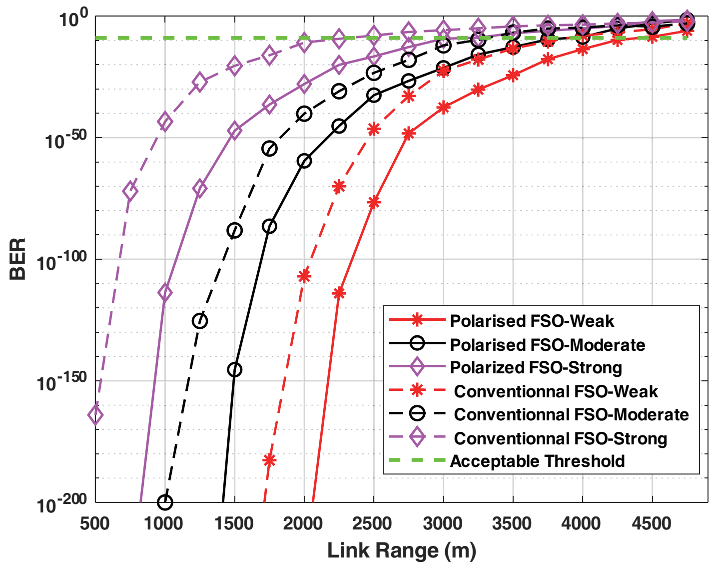

FIGURE 7. Performance Comparison of the proposed FSO System vs. Conventional System under Varied Turbulence Conditions.

becomes steep, indicating a substantial deterioration in system performance with distance.

Based on these observations, we can determine the maximum permissible distance for each atmospheric turbulence scenario while adhering to an acceptable BER threshold of 10^{-9}. In comparison to the conventional FSO system without turbulence, which demonstrates reliable operate at distances exceeding 4750 meters, the FSO system under weak, moderate, and strong turbulence conditions maintains its performance over distances of up to approximately 3750, 3250, and 2250 meters, respectively. These outcomes underscore the pivotal influence of turbulence conditions on shaping the performance of FSO systems, emphasizing the imperative need for adaptive strategies like polarization diversity to effectively mitigate turbulence induced impairments.

To this end, we will now examine the polarization diversity's effectiveness in mitigation the turbulence's impacts, as depicted in Figure 6 which depicts a comparison between the conventional FSO system without turbulence consideration and the proposed system with polarization diversity operating under various turbulence conditions. The results of the comparison clearly demonstrate enhanced signal quality, as indicated by lower BER, emphasizing the system's capability for reliable communication over extended distances even in turbulent conditions.

To gain deeper insights into the effectiveness of our approach, Figure 7 provides a comparative analysis between the conventional and the proposed FSO system under various turbulence conditions, as follows:

- The results indicate that the proposed FSO system, incorporating polarization diversity, consistently achieves a lower BER than the conventional system across various turbulence conditions.

- The findings strongly suggest that the proposed system excels in maintaining robust communication capabilities over prolonged distances, even when being confronted with turbulent conditions, surpassing the performance of the conventional system.

- The proposed FSO system sustains its performance across weak, moderate, and strong turbulence conditions, achieving operational distances of approximately 4250, 3750, and 3200 meters, respectively.

- The proposed FSO system under moderate conditions can achieve an equivalent level of performance in terms of maximum link distance compared to the conventional FSO system operating under weak conditions.

- The proposed FSO system under strong conditions can achieve a maximum link distance that is nearly identical to that of the conventional FSO system operating under moderate conditions.

6. CONCLUSION

The turbulence conditions are crucial considerations when the performance of FSO communication systems is modeled and analyzed, as they have a substantial impact on signal quality and system reliability. The presented findings underscore the pivotal role of polarization diversity in fortifying the resilience and performance of FSO communication systems. The comprehensive analysis showcased in this study reveals that the integration of polarization diversity leads to lower BER, even in the face of challenging atmospheric turbulence conditions. Furthermore, the proposed FSO system exhibits a remarkable ability to sustain robust communication capabilities over extended distances, outperforming the conventional FSO system across weak, moderate, and strong turbulence conditions. In particular, the obtained results illustrate that the proposed FSO system can rival or even surpass the performance of the conventional system under weak, moderate, and strong turbulent conditions, achieving operational distances of approximately 4250, 3750, and 3200 meters, respectively. These outcomes affirm the effectiveness of polarization diversity as a strategic enhancement, promising to elevate the reliability and reach of FSO communication in adverse environmental conditions.

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