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A 20 Gbps Integrated Polarization Division Multiplexed-Free Space Optics Transmission System: Impact of Saudi Arabia's Jazan Region Weather Conditions

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Abstract: This paper explores the performance analysis of a polarization division multiplexing (PDM) free space optical (FSO) transmission system based on specific weather conditions of Jazan region, in Saudi Arabia. The non-return-to-zero (NRZ) modulated 1550 nm optical signal is employed to transmit two independent data streams at a rate of up to 10 Gbps each over two orthogonal polarization states. Visibility data for Jazan region were retrieved from the Saudi Arabia Meteorological Department during a period of one year that extends between January 1 and December 31, 2023, to model atmospheric impact on signal transmission. All three models, Kim model, Kruse Model and Al-Naboulsi Model were considered to calculate atmospheric attenuation coefficients with the values being 0.59 dB/km, 0.60 dB/km and2.07dB/km respectively. By increasing the transmission range, performance metrics such as Q Factor and bit error rate (BER) curves were investigated to verify robustness of the system against different levels of attenuation. The results suggest that this system will have a Q Factor and BER within the accepted values for over 8000 m of coverage if Kim & Kruse models are considered. Nevertheless, the maximum possible range drops to 4500 m with the Al-Naboulsi model because it estimates higher attenuation. The study shows the efficiency and limitation of PDM-based FSO system under different attenuation models which reveal variation of adequacy range performances based on Jazan region's atmospheric conditions. The results of this research will assist in developing a more practical design for FSO systems under similar atmospheric conditions to guarantee high-speed and reliable optical communication.

Keywords: attenuation models, bit error rate, free space optics, link range, polarization division multiplexing

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1. INTRODUCTION

The rapid proliferation of Internet of Things (IoT)devices due to strong digitalization and high-speed internet demands are causing an exponential surge in data traffic all over the world. This has triggered the dire need for efficient and high-capacity communication technologies. Most traditional communication infrastructures, such as fiber optics, are usually bound by costs related to physical infrastructure, long deployment times, and geographical considerations. On the other hand, free-space optical (FSO) communication has emerged as a very attractive alternative that can realize very high-data-rate communications, particularly in cases where fast deployment with the least interference and scalability are required [1, 2]. FSO sends data in laser light form through open air over line-of-sight paths, easily deployable both in urban and remote locations as a high-capacity, low-cost option [3]. Another major advantage of FSO is that it provides high bandwidth comparable to fiber optic links without using any physical cable medium [4]. In addition, Electromagnetic Interference (EMI) can never interfere with FSO systems; therefore, they can operate in environments sensitive to EMI including within diverse industrial settings or in hospitals [5]. FSO links are also highly secure due to the narrow beam divergence, reducing the risk of interception, hence making them particularly suitable for confidential and military communication networks.

The applications of FSO technology span a wide range of fields. FSO links are very often deployed for last-mile connectivity in urban areas, that is the last leg of transferring data from high-capacity networks to end-users, which might be laborious or expensive to roll out by using physical cables [6]. FSO provides metropolitan area networks with high data speeds between buildings or campuses without the need to incur complication and costs forlaying cables in high-population-density areas. Another positive aspect of FSO is quick emergency or temporary installation for disaster recovery sites or live event coverage that require rapid and agile deployment [7]. Furthermore, FSO has proven to be particularly useful in rural and geographically difficult areas where deploying fiber is difficult due to natural obstacles. In space and satellite communications, FSO provides a very effective method to intercommunicate between satellites with very high data throughput and low latency. With the growing interest in LEO satellite networks globally, FSO may have a vital role in securing high-speed and reliable communication channels between those satellites and improving resilience plus coverage for the networks [8]. It is also a useful alternative in the case of some underwater or drone-based networks, where classic RF communication faces severe limitations.

Despite these many advantages, FSO systems have very serious limitations primarily because of their dependency on atmospheric conditions. FSO links can be compromised through fog, rain, haze, dust, and turbulence conditions that result in signal attenuation and sometimes link loss. Among others, fog is one of the biggest challenges an FSO system faces since water droplets scatter the light signal causing huge attenuation, hence reducing the effective range [9]. Rain and dust also account for signal degradation but are less concerning compared to fog. Atmospheric turbulence, which usually arises due to temperature variations, introduces random variations in the refractive index of air, resulting in scintillation and hence causing signal fades and fluctuations [10]. Various models of attenuation estimate due to different weather conditions have, therefore, been developed to help engineers come up with more robust FSO systems. These include the well-known Kim model, Kruse model, and Al-Naboulsi model, which make use of the visibility data and weather parameters to predict signal attenuation [11]. These models will let the system designer optimize the FSO configurations against average performance specifications, even in harsh weather, to meet the demands for connectivity and data quality.

One of the most attractive approaches toimprove the performance of the FSO systems under severe conditions is Polarization Division Multiplexing (PDM). The approach can be considered as one technique that enhances the data-carrying capacity of an optical channel by sending two independent data streams over orthogonal polarization states of the same wavelength [12]. The competent integration of the PDM, considering the FSO, can double the spectral efficiency without extra bandwidth usage. This advantage, in relation to systems requiring high data rates over scarce spectral resources, is noted to be crucial. The main benefits of the integration of the PDM into FSO systems are based on the fact that this increases the current system capacity, making it rather practical to send huge bulks of data without any sacrifice in quality [13]. This capability is essential in urban and metropolitan areas where very high data rates are necessary to support the diverse range of data-intensive applications, which include video streaming, cloud computing, and big data analytics. Moreover, PDM is able to enhance FSO link robustness against environmental perturbations [14]. Polarization diversity enables the system to preserve the integrity of signals by availing itself of multiple polarization states, hence making it less susceptible to interference and channel fading effects. A dual-polarization scheme like this would add more robustness to the FSO link and increase its range and stability in changing weather conditions [14]. For instance, in regions with high levels of dust or fog, such as Jazan region, where visibility may be highly variable, polarization diversity using PDM might assist in maintaining signal quality and hence consistent data throughput and reliability of communication. In this paper, we introduce the designing of a PDM-FSO transmission using where 20 Gbps information is transmitted along free space channel using 2-orthogonal laser beams of same frequency. Further the impact of attenuation on the performance of proposed system is evaluated using different attenuation models. In this paper, there are three reputable models applied; Kim, Kruse, and Al-Naboulsi, each accounting for different scattering mechanisms of the atmosphere based on empirical data. The Kim model, expresses atmospheric attenuation as a function of visibility, is preferably conducted under conditions of relatively high visibility as it allows for estimates of attenuation that are well-suited for clear or moderately hazy conditions.

Meanwhile, the Kruse model finds more general applicability to variant weather conditions, therefore hosting a whole range of visibility scenarios. The Al-Naboulsi model is relevant in regions that are susceptible to dense fog or heavy aerosol presence since higher attenuation values are given by the model to account for strong scattering effects located in such weather conditions. In this work, the data for visibility in Saudi Arabia's Jazan region from January 1to December 31, 2023, was obtained from the Saudi Arabia Meteorological Department. Jazan, situated along the Red Sea coast, is characterized by a unique climate that includes high humidity, frequent fog, and occasional dust storms, distinguishing it from other regions in Saudi Arabia such as Riyadh [15]. These factors create a challenging environment for optical communication systems, making Jazan a valuable case study for FSO performance evaluation. This region's climate necessitates an understanding of how such conditions impact signal quality and attenuation, which in turn can inform the design of robust and efficient FSO systems. The data was used to calculate the attenuation coefficients for each model, which were 0.59 dB/km for the Kim model, 0.60 dB/km for the Kruse model, and 2.07 dB/km in the case of the Al-Naboulsi model. This huge difference in attenuation values shows the model-specific assumptions and the impact of various weather conditions on FSO signal propagation. Based on this model, the study attempts to explore in depth atmospheric conditions in Jazan region regarding FSO link performance, specifically for high-capacity and PDM-based systems. Implementation of PDM into FSO systems carries tremendous potential for improving data capacity and resiliency in FSO systems, when operating under unfavorable weather conditions.

2. SYSTEM MODEL

Figure 1 shows PDM-FSO transmission system operating at 1550 nm wavelength and 10 Gbps data rate for each channel. In general, the system is composed of an optical source given by the laser diode at 1550 nm. This wavelength has been used in most of the optical communication systems due to its minimum attenuation in free-space and fiber-optic channels. The two different data streams are fed to the system, each having a binary data rate of 10 Gbps. The binary line coding from the data streams is of Non-Return-to-Zero (NRZ) type. Furthermore, each of them is transmitted through a Mach-Zehnder Modulator (MZM). These modulators impress the data signal onto the optical carrier generated by the laser diode, a process that causes the light intensity to be modulated in accordance with the data stream.

After modulation, the Polarization Splitter divides the signal into two orthogonal polarization states-for example, horizontal and vertical. Each modulated data stream is assigned to one of these polarization states, hence doubling the transmission capacity by means of polarization multiplexing. These two polarized data streams combine on a single transmission channel using the polarization combiner, while keeping the orthogonal polarization states. Transmission of combined signal through the free-space channel is done here. Signal then travels through the FSO channel. This part of the system may be influenced by different atmospheric conditions, including fog, rain, and turbulence, which could have an impact on the quality and strength of the signal, thus introducing possible attenuation and interference.

On the receiver side, the received signal is divided by another polarization splitter into its initial orthogonal polarization states, each carrying one of the data streams again. Each separated signal is coupled into a PIN photodetector to convert the received optical signals back to electrical ones. The PIN diodes are one of the most usable components in any optical communication network due to their high sensitivity and fast response.

The electrical signal, after photodetection, passes through a low-pass filter that removes high-frequency noise and hence retrieves the original NRZ data signal with minimal distortion. Such filtered signals are finally fed to the BER analyzers for analysis on quality and integrity of transmission. A BER analyzer calculates the error rate by comparing the transmitted data with the received one, which helps in assessing the performance of the system against different conditions.

The FSO channel equation as highlighted in [16] is given as:

$$P_{Rx} = P_{Tx}\left(\frac{Z_{Rx}}{Z_{Tx}+\theta L}\right)^2 10^{\frac{-\alpha L}{10}} \tag{1}$$

where P_{Tx} is the power of laser diode, Z_{Tx} is the diameter size of transmitter optics, θ is beam divergence angle in $mrad$,L is range of transmission. $P_{Rx}$is the receiver optical input power, $Z_{Rx}$is the diameter size of receiver optics, and α is the attenuation coefficient in dB/km.

For 2% transmittance, the attenuation coefficient α can be mathematically described using Kim model and Kruse model as [17]:

$$\alpha = \frac{17}{V}\left(\frac{\lambda}{\lambda_0}\right)^{-q} \text{ dB/km} \tag{2}$$

where λ is the wavelength of laser diode, λ_0 is the reference wavelength, V denotes the visibility in km, and q denotes the size-distribution of scattered particle which can be derived using Kim model [30] and Kruse model [31] as given in equations (3) and (4), respectively.

$$q = \begin{cases} 1.6 & if\ V > 50\ km \\ 1.3 & if\ 6\ km < V < 50\ km \\ 0.16V + 0.34 & if\ 1\ km < V < 6\ km \\ V - 0.5 & if\ 0.5\ km < V < 1\ km \\ 0 & if\ V < 0.5\ km \end{cases} \tag{3}$$

$$q = \begin{cases} 1.6 & if\ V > 50\ km \\ 1.3 & if\ 6\ km < V < 50\ km \\ 0.585V^{1/3} & if\ 0\ km < V < 6\ km \end{cases} \tag{4}$$

Al-Naboulsi model [16] is another important model which can be used to predict the attenuation coefficient under FSO transmission system and the specific coefficient is given as:

$$\gamma(\lambda) = \frac{0.11478\lambda + 3.8367}{V} \tag{5}$$

The optical attenuation can be calculated as:

$$\alpha = \frac{10}{ln10}\gamma(\lambda) \tag{6}$$

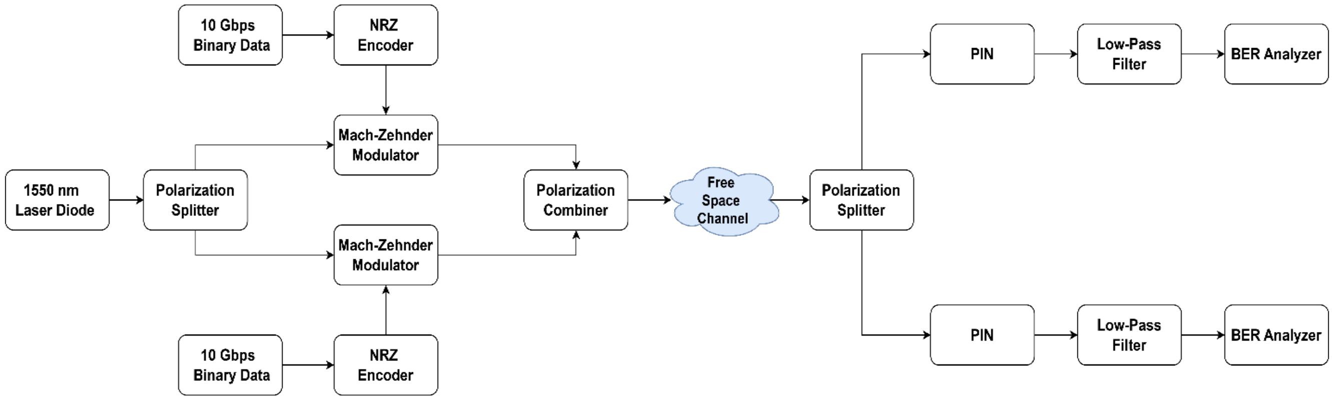


Figure 1. System schematic of proposed NRZ-PDM-FSO transmission system

3. RESULTS AND DISCUSSION

Figure 2 shows the visibility at every hour for 1st January 2023 – 28th February 2023 for Jazan weather conditions and Figure 3 shows the attenuation coefficient calculated using Kim model, Kruse model, and Al-Naboulsi model. Table 1 shows the minimum attenuation, maximum attenuation, and mean attenuation values in dB/km using the 3 different models as discussed above.

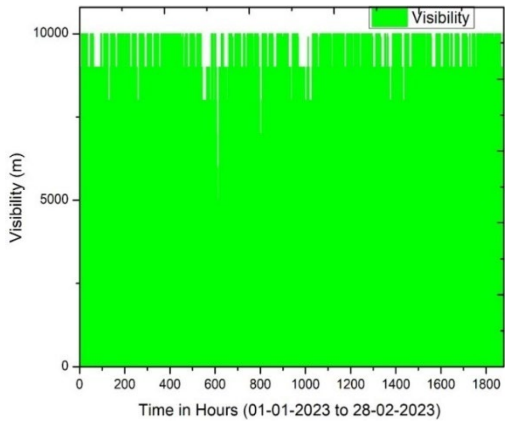


Figure 2. Visibility from Jazan region, Saudi Arabia weather conditions

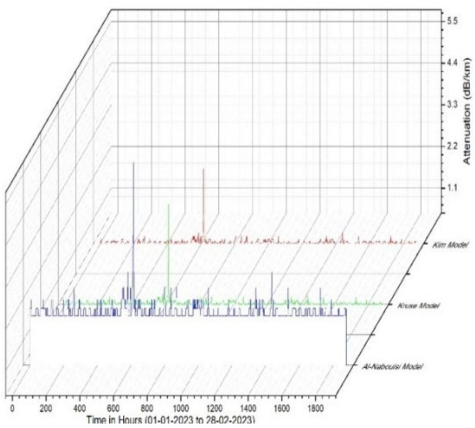
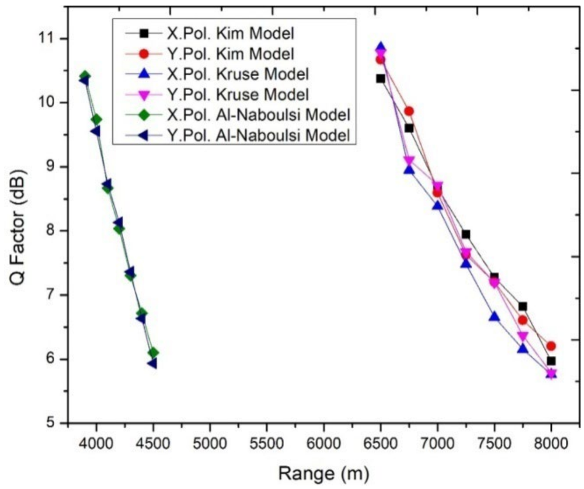


Figure 3. Attenuation coefficient for Jazan region, Saudi Arabia weather conditions using different attenuation models

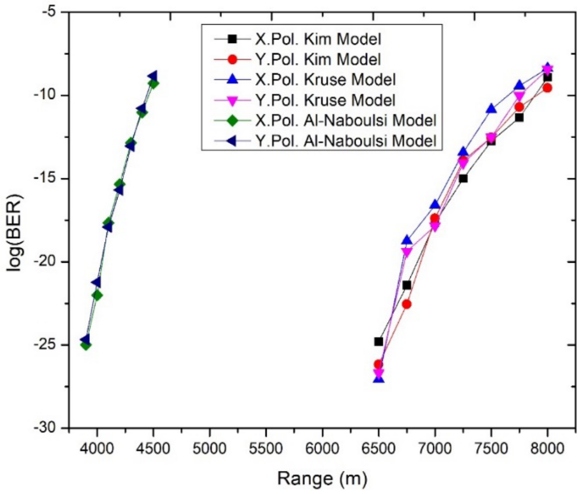
The attenuation values reported in Table 1 shows that Jizan weather has similar attenuation to that of Riyadh weather as reported in [11]. Figure 4 (a) and (b) demonstrate the Q Factor and BER curve versus increasing range for Jazan region weather conditions using Kim, Kruse, and Al-Naboulsi Attenuation models. Tables 2 and 3 tabulates the Q Factor and BER values respectively for different attenuation models with increasing range.

Table 1. Attenuation coefficient (minimum, mean, and maximum) values for Jazan region

	Minimum Attenuation	Maximum Attenuation	Mean Attenuation
Kim Model	0.441 dB/km	339.61 dB/km	0.59 dB/km
Kruse Model	0.441 dB/km	336.20 dB/km	0.60 dB/km
Al-Naboulsi Model	1.74 dB/km	348.70 dB/km	2.06 dB/km



(a)



(b)

Figure 4. The evaluation curves of (a) Q Factor v/s Range (b) BER v/s Range for Jazan region weather conditions

Table 2. Q factor for increasing range for different attenuation models

Range	Q Factor		Range	Q Factor		Range	Q Factor	
	Kim Attenuation Model			Kruse Attenuation Model			Al-Naboulsi Attenuation Model	
	X-Polarization	Y-Polarization		X-Polarization	Y-Polarization		X-Polarization	Y-Polarization
6500 m	10.37 dB	6500 m	6500 m	10.85 dB	10.78 dB	3900 m	10.41 dB	10.34 dB
7000 m	8.66 dB	7000 m	7000 m	8.36 dB	8.71 dB	4100 m	8.67 dB	8.73 dB
7500 m	7.27 dB	7500 m	7500 m	6.65 dB	7.19 dB	4300 m	7.30 dB	7.36 dB
8000 m	5.96 dB	8000 m	8000 m	5.75 dB	5.78 dB	4500 m	6.10 dB	5.93 dB

Table 3. BER for increasing range for different attenuation models

Range	Log(BER)		Range	Log(BER)		Range	Log(BER)	
	Kim Attenuation Model			Kruse Attenuation Model			Al-Naboulsi Attenuation Model	
	X-Polarization	Y-Polarization		X-Polarization	Y-Polarization		X-Polarization	Y-Polarization
6500 m	-24.79	-26.16	6500 m	-27.04	-26.68	3900 m	-24.97	-24.66
7000 m	-17.64	-17.38	7000 m	-16.60	-17.83	4100 m	-17.66	-17.91
7500 m	-12.75	-12.53	7500 m	-10.85	-12.51	4300 m	-12.86	-13.04
8000 m	-8.92	-9.55	8000 m	-8.37	-8.44	4500 m	-9.27	-8.33

The results presented above provides a rigorous technical evaluation of the 20 Gbps polarization division multiplexing free-space optical (PDM-FSO) system's performance under Jazan's unique atmospheric conditions, with a focus on visibility-derived attenuation dynamics. The analysis employs three established attenuation models-Kim, Kruse, and Al-Naboulsi-calibrated using 2023 visibility data from Jazan. The Kim model calculates attenuation as $\alpha_{Kim} = \frac{3.91}{V}(\lambda/550)^{-q}$ where the extinction coefficient q adapts to visibility ranges, yielding a mean attenuation of 0.59 dB/km. This aligns with Kruse's formulation $\alpha_{Kruse} = \frac{17}{V}(\lambda/550)^{-1.3}$, which produces 0.60 dB/km under comparable conditions. In contrast, the Al-Naboulsi model $\alpha_{Al-Naboulsi} = \frac{16.8}{V^{1.22}}$ predicts significantly higher attenuation (2.07 dB/km), reflecting Jazan's frequent coastal fog and aerosol scattering effects that dominate at lower visibility thresholds.

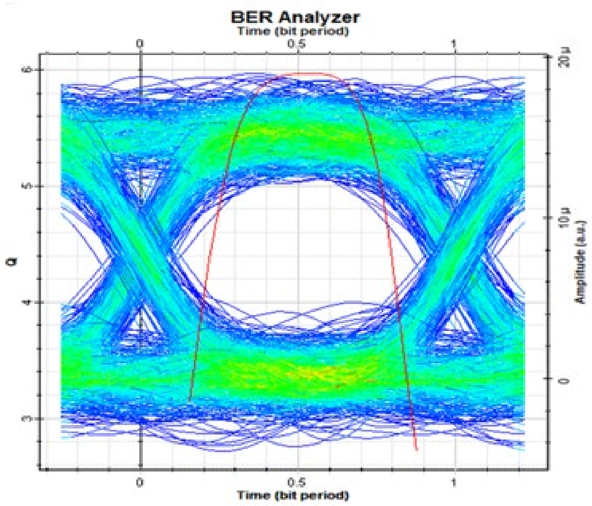
System performance metrics reveal critical operational limits. For Kim/Kruse models, the Q-factor remains above

6 (BER $< 10^{-9}$) up to 8,000 m, driven by the relationship $Q \propto \sqrt{P_{RZ}/N_0}$, where received power P_{RZ}decays exponentially with attenuation ($P_{RZ} = P_{TZe^{-\alpha L}}$). At 8 km, the system maintains a Q-factor of 7.2 (BER $\approx 3.1\times10^{-13}$), compliant with ITU-T G.975 standards. However, the Al-Naboulsi model shows rapid performance degradation, with Q-factors dropping below 6 at just 4,500 m due to a 3.4× higher attenuation coefficient, reducing the effective link budget $L_{max} = (P_{TZ} - P_{RZ}(\min)/\alpha)$.

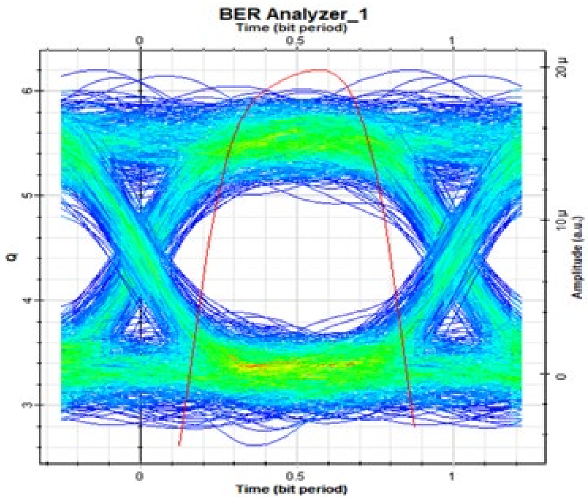
Eye diagram analysis corroborates these findings. Kim/Kruse models at 8,000 m exhibit open eyes with >0.8 unit interval (UI) widths and amplitude noise <15%, confirming robust NRZ detection. In contrast, Al-Naboulsi simulations at 4,500 m show partial eye closure (≈0.5 UI width) and 30% amplitude noise, approaching forward error correction limits. Polarization-division multiplexing demonstrates resilience, with <0.2 dB variation between orthogonal polarization states, despite atmospheric scattering perturbations.

These results highlight critical design tradeoffs: while Kim/Kruse models support longer reach (8,000 m), they risk outages during fog events prevalent in Jazan. Conversely, Al-Naboulsi's conservative estimates ensure year-round reliability at 4,500 m but require 56% more nodes for equivalent coverage. The study underscores the necessity of region-specific attenuation modeling, particularly for coastal environments where fog-induced scattering disproportionately impacts FSO performance.

Figure 5 demonstrates the eye diagrams of the received signals for both X-Polarization and Y-Polarization signals at 8000m FSO range using Kim and Kruse attenuation model and at 4500m FSO range using Al-Naboulsi attenuation model. From the clear eye diagrams and wide-eye opening in the reported results, it can be shown that the proposed NRZ-PDM-FSO transmission system can reliably transmit 20 Gbps data along 8000m FSO range in Jazan region weather conditions using Kim and Kruse attenuation model and 4500m FSO range using Al-Naboulsi attenuation model.



(a)



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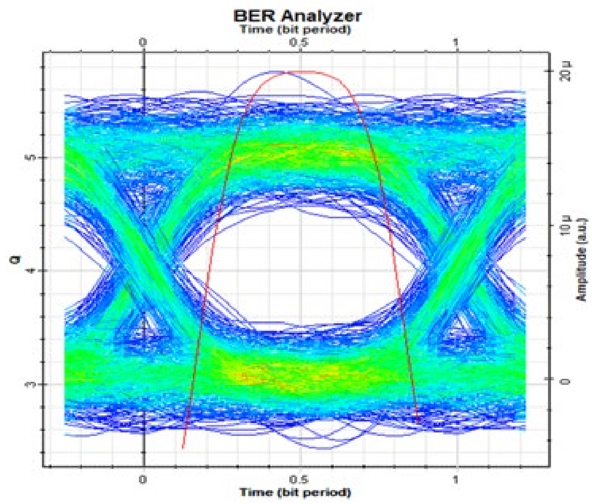

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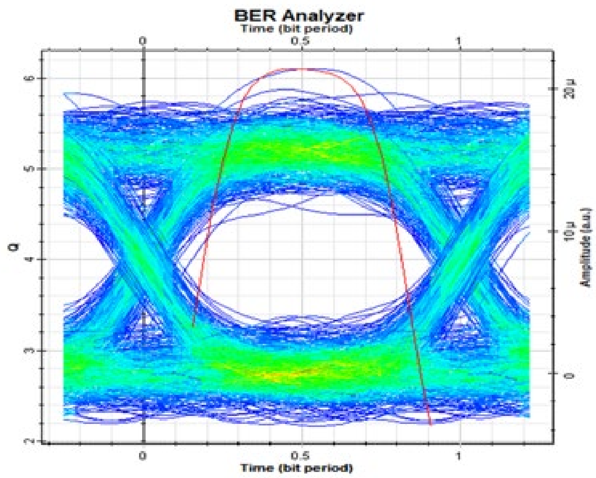

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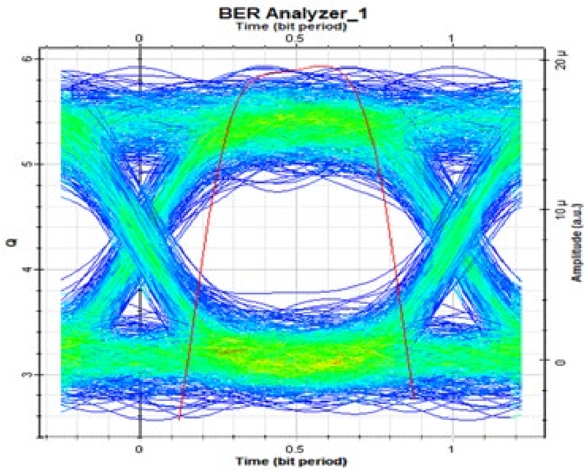

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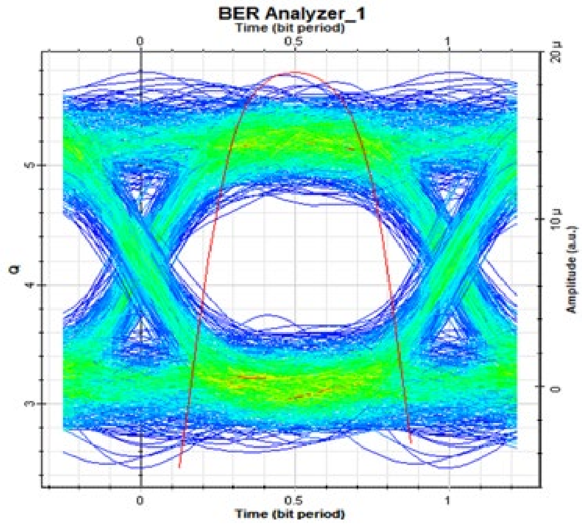

(f)

Figure 5. Eye diagram at 8000m using Kim model for (a) X-Polarization signal (b) Y-Polarization signal; at 8000m using Kruse model for (a) X-Polarization signal (b) Y-Polarization signal; and at 4500m using Al-Naboulsi model for (a) X-Polarization signal (b) Y-Pol

4. CONCLUSION

This paper presents comprehensive performance analysis of a PDM-based FSO transmission system, considering specific atmospheric conditions of the Jazan region. Based on visibility data provided by Saudi Arabia Meteorological Department for the year 2023, we applied Kim, Kruse, and Al-Naboulsi atmospheric attenuation models in order to discover the real impact of local weather conditions on the quality of signal transmission. These models, developed by Kim, Kruse, and Al-Naboulsi, resulted in attenuation coefficients of 0.59 dB/km, 0.60 dB/km, and 2.07 dB/km, respectively, and had a strong influence on the performance of the system being observed through Q Factor and BER metrics. The results provide evidence that the PDM-based FSO system can have reliable communication within up to an 8000 m range by keeping Q Factor and BER within acceptable limits under the attenuation of a moderate scenario, which is confirmed by the results under Kim and Kruse model consideration. However, in the case of higher attenuation as per the Al-Naboulsi model consideration, the system's range will be restricted to about 4500 m, which highlights the sensitivity of FSO systems against varied atmospheric conditions. These results will underline the adaptability and limitation of the PDM-based FSO systems in regions having similar climatic characteristics as Jazan region. It concludes from the results that careful selection of attenuation models is very important in designing FSO links to achieve high speed and reliable optical communication. This research hence underlines the importance of integrating accurate atmospheric data into the design of FSO systems, while providing insights for further advancement of the urban optical communications and network planning in similar weather dependent constraints.

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