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Performance evaluation of a 2.048-Tbps Hybrid WDM-FSO DP-16QAM system under different weather conditions

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Abstract

Improvements in free-space optics (FSO) networks have been driven by a growing need for higher data transmission speeds, broader channel capacities, and spectrally efficient communication lines with sophisticated modulation techniques. This paper details an FSO transmission approach that employs an eight-channel wavelength division multiplexing (WDM) scheme, combining dual-polarization amplitude modulation (DP-16-QAM) with spectrally efficient techniques to enable each channel to transmit at 256 Gbps. The integration adapts system performance using digital signal processing and signal degradation compensation techniques tailored for turbulence, atmospheric attenuation, and channel fading. To address this problem, an enhancement at the receiver side is proposed to be integrated in the form of a high-order Gaussian low-pass filter positioned before the signal enters the DSP to alleviate the effects of the atmosphere further. This approach helps to mitigate attenuation effects and enables more accurate and faster signal processing. We demonstrate, through numerical simulations, that 2.048 Tbps can be effectively transmitted over FSO connection ranges from 2.18 kilometers up to 111 kilometers, achieving acceptable bit error rates under varying meteorological conditions. We demonstrate the system's higher bit rate and range by comparing its performance to previous efforts. The proposed technology can be implemented to guarantee dependable high-speed data transfers for both front and backhaul networks, even under the most challenging meteorological conditions. Additionally, this system's capacity and resilience to harsh weather conditions make it suitable for emerging systems, such as the Internet of Things (IoT) and sixth-generation

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(6G) technology, ensuring seamless integration without significant modifications.

Keywords: Free space optics (FSO), Atmospheric attenuation, Wavelength multiplexing (WDM), Dual-polarization multiplexing (DPM), Quadrature amplitude modulation (QAM), Bit error rate (BER).

تقييم أداء نظام هجين WDM-FSO بسرعة 2.048 تيرابت في الثانية باستخدام تقنية DP−16QAM تحت ظروف جوية مختلفة

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الملخص

شهدت شبكات الاتصال البصري في الفضاء الحر (FSO) تطورات ملحوظة مدفوعةً بالحاجة المتزايدة إلى سرعات نقل بيانات أعلى، وسعات قنوات أوسع، وخطوط اتصال طيفية الكفاءة باستخدام تقنيات تعديل متقدمة. يعرض هذا البحث نهجًا لنقل البيانات عبر FSO يستخدم مخطط تقسيم الطول الموجي (WDM) يتكون من ثماني قنوات، حيث يتم دمج التعديل السعوي باستقطاب مزدوج (DP-16QAM) مع تقنيات طيفية فعالة لتمكين كل قناة من نقل بيانات بسرعة تصل إلى 256 جيجابت في الثانية. يتم ضبط أداء النظام باستخدام معالجة الإشارة الرقمية وتقنيات تعويض تدهور الإشارة المصممة خصيصًا للتعامل مع الاضطرابات والتوهين الجوي وتلاشي القناة.ولمواجهة هذه التحديات، يُقترح تعزيز أداء المستقبل من خلال دمج مرشح غاوسي منخفض التمرير عالي الرتبة يوضع قبل دخول الإشارة إلى وحدة المعالجة الرقمية، مما يساعد على تخفيف تأثيرات الغلاف الجوي بشكل أكبر. تُسهم هذه المنهجية في الحد من التوهين وتمكين معالجة أكثر دقة وسرعة للإشارة. ومن خلال المحاكاة العددية، نُظهر أن سرعة نقل بيانات تبلغ 2.048 تيرابت في الثانية يمكن تحقيقها عبر مسافات FSO تتراوح بين 2.18 كيلومترًا وحتى 111 كيلومترًا، مع معدلات خطأ في البت مقبولة في ظل ظروف جوية متنوعة .كما نُثبت تفوق النظام من حيث معدل البت والمدى مقارنةً بالمحاولات

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السابقة. ويمكن اعتماد هذه التقنية لضمان نقل بيانات موثوق وعالي السرعة في شبكات الربط الأمامي والخلفي، حتى في أصعب الظروف الجوية. وبفضل سعة النظام وقدرته على الصمود في وجه الظروف القاسية، فإنه يُعد مناسبًا للأنظمة الناشئة مثل إنترنت الأشياء (IoT) وتقنية الجيل السادس 6G، مع ضمان تكامل سلس دون الحاجة إلى تعديلات كبيرة.

الكلمات المفتاحية :الاتصال البصري في الفضاء الحر(FSO) ، التوهين الجوي، تقسيم الطول الموجي(WDM) ، التعدد بالاستقطاب المزدوج(DPM) ، التعديل السعوي التربيعي(QAM) ، معدل خطأ البت(BER)

1. Introduction

Free-space optics (FSO) technology has presented itself as a practical alternative to established wireless communication methodologies by capitalizing on the underutilized and unregulated electromagnetic spectrum in order to facilitate the secure exchange of information through rapid connections [1].

The magnitude of data traffic has increased dramatically in recent years due to the continual expansion of bandwidth-intensive applications, such as broadcasting services, the Internet of Things (IoT), smart-home innovations, online gaming, and video calls. Established broadband networks are proving themselves to be incapable of meeting the resultant needs for enhanced data rates, diminished lateness, and significant bandwidth [2,3]. One approach that would be extremely advantageous when it comes to meeting the demands for elevated data transmission rates is optical fiber technology [4]. The implementation of FSO technology presents a pragmatic but engaging resolution to the difficulties associated with spectrum overcrowding in wireless communication channels dependent on the ordinary radio frequency (RF) spectrum [5].

FSO communication systems offer several advantages over RF technologies, including wide bandwidth, lower strength and block limitations, limited beam divergence, higher directivity, and the lack of obligatory licensing requirements [6]. Moreover, they facilitate the secure conveyance of information, are immune to radio and electromagnetic intervention, have low mass and energy demands, are economically viable, and provide for last-mile connectivity. Notably, however, atmospheric attenuation brought about by adverse weather conditions and changes in both barometric pressure and the temperature along the signal spread trajectory significantly

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hinders the performance of FSO links by degrading the quality of the optical beam responsible for conveying information and restricting the link's operational range. This phenomenon leads to the formation of turbulence cells, which are distinguished by a range of refractive indices and sizes. These turbulence structures operate similarly to prisms, generating destructive and constructive interference within the optical beam that conveys information. As a result, spontaneous phase variations and alterations in the amplitude of the information signal at the receiving endpoint accrue—a phenomenon typically known as the scintillation effect. [7]
The repercussions of atmospheric degradation attributable to adverse meteorological phenomena greatly impair FSO communication systems' performance. This attenuation reduces the strength of the received signal, constraining the connection's transmission range. Atmospheric turbulence is a crucial factor here, as it negatively affects the effectiveness of FSO communication due to changes in the atmospheric pressure or temperature along the signal's route due to a phenomenon commonly referred to as the scintillation effect [8].

- **SAC-OSDMA using DDW**

The DDW optical CDMA code is still effective for FSO systems in terms of their power level and transmission distances—up to 5 km in foggy conditions with heavy haze. In such conditions, narrow-band frequency reduces the scattering of the signal, enabling strong performance even with high beam divergence [9].

- **WDM**

Today, the communications sector is undergoing a period of immense growth. This paper presents a WDM FSO system and explains how it works effectively in clear weather at distances up to 150 km and a 2.5 Gbps data-transmission rate. The simulations show that the system's throughput is inversely proportional to distance and increases with input power and clear weather (at the aforementioned distance and rate) [10].

- **WDM 32x3 Gbps**

This model is a 32-channel WDM-FSO communication link with a data-transmission rate of 3 Gb/s that uses NRZ modulation. This paper assesses the impact of its optimized parameters. The system can reach up to 431 km using SOA amplification. Although the range is restricted by atmospheric attenuation, the system reached 6.147 km and 40.2 km in heavy rain and heavy haze, respectively [11].

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- **Hybrid SAC-OCDMA-MDM-based FSO connection**

This project sends 10 channels, each carrying 10 Gbps of data, through an 8 km FSO link using MDM and OCDMA, the integration of which facilitates the establishment of many high-speed channels over a single FSO link, thereby conserving bandwidth. As expected, in the FSO link simulation, an acceptable BER of 8 km was observed to be achievable in clear weather; however, this range declined to 1500 m in light fog, 1,250 m in medium fog, and just 1,000 m in heavy fog [12].

- **Single-channel DP-16QAM DSP**

This study investigates the efficacy of coherent DP-16-QAM across a range of meteorological conditions, illustrating its capacity to achieve a peak data transmission rate of 120 Gbps while maintaining acceptable OSNR and BER levels. The system's maximum achievable transmission distance fluctuates between 0.4 km and 8 km depending on prevailing turbulence and meteorological variables. The proposed system offers a financially viable approach to addressing high-capacity last-mile issues and facilitating high-speed broadband connectivity through reliable data transmission capabilities [13]. This study introduces a coherent receiver for heightened transmission distance through a high-speed, spectral-efficient terrestrial FSO link that makes use of single-channel DP-QPSK. The system successfully transmitted QPSK signals at a rate of 160 Gbps, indicating a notable improvement in performance despite varying channel conditions due to the application of digital signal processing (DSP) techniques. Computational analyses indicate that the maximum possible distance declined from 98 km to 2.1 km when atmospheric absorption changed from clear to foggy conditions while escalating turbulence adversely affected the bit error rate (BER) [14].

- **8-channel DP-16QAM FSO 1 Tbps**

This research presents an innovative FSO transmission link that utilizes 1 Tbps super-channel transmission over distances of 1.05–10 km amid varying atmospheric and meteorological conditions. The link demonstrated a spectral efficiency (SE) of 7.46 bits/s/Hz, making it appropriate for future high-speed, high-SE optical networks. This is also pertinent to 5G technology. Future research could bolster the link's adaptability and resilience further by integrating mixed Nyquist-WDM super-channels and improving

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operational performance under challenging conditions through the application of adaptive optics and multi-input multi-output (MIMO) transmission techniques [15].

❖ **Hybrid WDM PDM CO-OFDM 16-level QAM 1.6 Tbps**

This study introduces a WDM-FSO system with polarization division multiplexing (PDM) and coherent orthogonal frequency division multiplexing (CO-OFDM) that facilitates a data-transmission rate of 1.6 Tbps across distances of 0.13–20 km depending on prevailing atmospheric and meteorological conditions. The system performs well in terms of BER and optical signal-to-noise ratio (OSNR) under rain, fog, haze, and dust. The proposed framework offers a practical approach to building long-distance optical wireless networks with a high capacity and advanced features for last-mile connection [16].

This paper presents an 8-channel WDM-FSO system with a 2.048-Tbps capacity using PDM-16-QAM modulation in a high schema format. The main goals of this study are as follows: (1) to create a long-range FSO connection with high capacity using WDM and PDM-16-QAM; (2) to improve the connection's effectiveness in terms of coherent detection and DSP; and (3) to investigate how atmospheric turbulence and environmental factors affect the FSO connection. The remainder of this paper is organized as follows. Section 2 discusses the overall design of the system. Section 3 details the channel modeling and link parameters used in this study. Section 4 presents the results of the assessment of the proposed FSO link, offering a comparison with similar prior efforts. Finally, Section 5 offers some concluding thoughts.

2. System Design

❖ **Transmitter**

The 16-channel WDM system's layout is visualized in Figure 1. The system features a coherence-detection receiver, designed using Optisystem software v21, that employs a dual-polarization 16-QAM approach.

The CW laser at the transmitter is split into X and Y polarizations to make it the optical carrier for the I/Q optical 16-QAM modulators with a 0.1 MHz line-width light beam. The polarization combiner pairs the modulated optical signals in the X and Y polarizations to produce the DP-16-QAM signal. A polarizing beam splitter (PBS) then splits the optical beam into two distinct beams that are

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orthogonally polarized at an angle of 45 degrees relative to the apparatus. Figure 2 illustrates the DP-16QAM transmission system. The optical signal in the lower arm exhibits a 90 relative phase shift, meaning that we have a 16-QAM modulated optical signal coming out of the cross-coupler. Each modulator operates at a bias voltage of 2 and -2 V when it reaches its null point. The specialized converter switches the midstream from serial to parallel when it comes from a pseudorandom binary sequence (PRBS). The QAM sequence generator converts the input bit stream into 16 QAM symbols, with each symbol containing 4 bits. The optical signals are subsequently modulated by M-ary pulses, and optical cross-couplers are used to connect optical signals to dual-drive Mach-Zehnder modulators (MZM). Finally, a coupler is used to merge the data signals from all sections of the DP-16QAM transmitter.

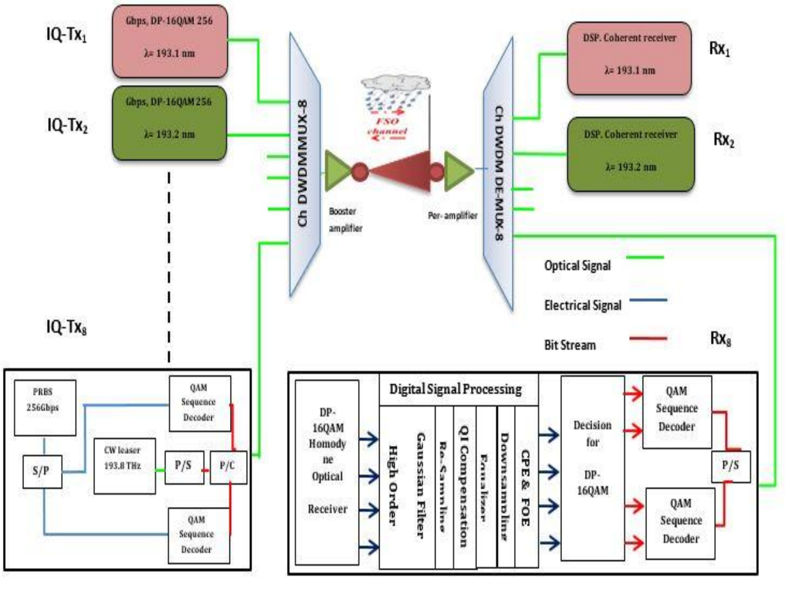

Fig. 1 Visualization of a WDM-FSO communication link using DP-16QAM signals.

The dual-polarization 16-QAM is an efficient modulation technique in optical communication. It works by splitting one laser beam into two orthogonal polarizations—either horizontal or vertical—upon which an independent 16-QAM (16 different points in the amplitude-phase plane) is used to encode data, enabling 4 bits per symbol. The addition of dual polarization to 16-QAM doubles the data capacity without increasing bandwidth. At the receiving end,

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the signal polarizations are separated using advanced DSP, any distortions are corrected, and all signals are decoded, facilitating high-speed data transmission over a long distance with greater spectral efficiency.

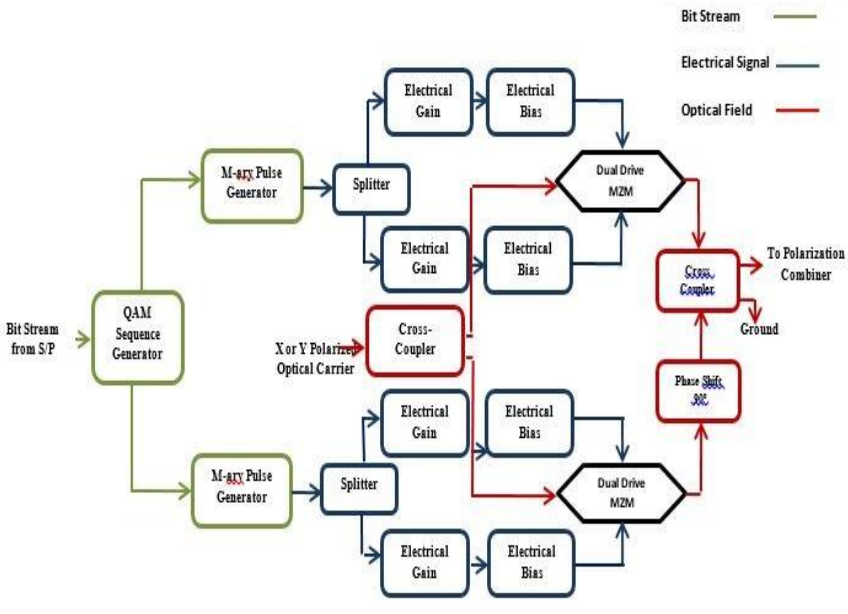

Fig. 2 Design of the optical 16-QAM modulator.

❖ Receiver

The structure that uses homodyne detection as a receiving approach is illustrated in Figure 3. The received signal is amplified at the receiver terminal using an optical amplifier (OA) and then split into several channels before being directed to a wavelength division multiplexing DE multiplexer (WDMDEMUX).

Each channel in the receiver comprises a decision unit, balanced photodetectors, electronic amplifiers (EA), and a (2×4) orthogonal optical hybrid. Several sophisticated algorithms are included in advanced digital signal-processing units to correct for varying signal impairments [17]. Each receiver unit contains a PBS and an LO, as shown in Figure 3. Before amplification by an amplifier (EA), the electrical signals corresponding to orthogonal polarization states are segregated into in-phase and quadrature-phase components, at which point improved signals are sent through a low-pass filter (LPF).

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The DSP unit entails multiple stages, including the use of adaptive equalization for re-multiplexing orthogonal polarized beams; applying quadrature-imbalance (QI) correction to lessen the amplitude and phase imbalances in the symbol, and using a fourth-order Bessel filter to mitigate noise power [18].
To improve signal quality before processing, we added a low high-order Gaussian pass filter at the receiver side, just before the digital signal processing (DSP) stage. This enhancement helps refine the received signal, reduces interference before digital separation, and speeds up system response. This minimizes processing time, resulting in a more responsive and effective system.

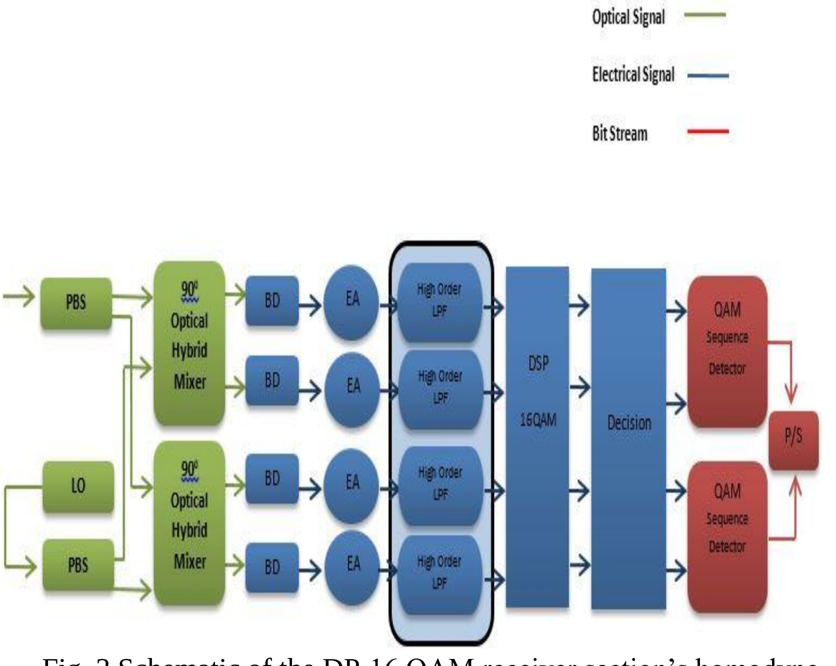

Fig. 3 Schematic of the DP-16 QAM receiver section's homodyne detection.

The DSP unit's internal design is fleshed out in Fig. 3 [13,26]. Its 6 main blocks are as follows:

1. Gaussian filter for the attenuation of undesired signals.
2. Resampling signal.
3. Compensation for QI to mitigate discrepancies in amplitude and phase between I and Q signals.
4. Chromatic dispersion (CD) to mitigate fiber nonlinearity and chromatic dispersion.

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5. DE multiplexing x-polar and y-polar signals using an adaptive equalizer.
6. Frequency offset estimation (FOE) and carrier phase estimation (CPE) to correct mismatches in frequency and phase [19].

The decision circuit processes the electrical signals received from the DSP step. The output of the decision block is sent to two 16-QAM decoders for processing. The decoded outputs are subsequently integrated with the S/P converter and the resultant output. A BER tester generates the sent bit sequence on the transmitter side and compares it with the received bit sequence.
The BER of a dual-polarization system is given by

$$\text{BER} = \frac{X_{Polar\ Errors} + Y_{polar\ Errors}}{Length\ of\ sequnces - (2 * Guard\ bits)} \text{ [20].}$$

The system's characteristics are listed in Table 1. The proposed design was analyzed under the influence of multiple atmospheric conditions, including varying degrees of haze, fog, rain, and dust.

Table 1: System Design Parameters

Parameter	Value
Data rate	8x256Gbps
Symbol rate (Gboud)	32Gbps
WDM MUX/DEMUX bandwidth	100GHz
Bit rate/channel	256Gbps
Channel spacing	100GHz
Operating frequency	193.1–193.8 THz
Transmission power/channel	20dBm
PIN photodetector dark current	10 nA
Transmitter/receiver aperture diameter	5/20cm
Beam divergence	0.25mrad
Laser line width	0.1 MHz
EDFA gain	20 dB
EDFA noise figure	4 dB
Number of samples	65536

Table 2: Weaver attenuation coefficients: World weather conditions

Parameter	Value
Clear	0.14 dB/km
Rain Attenuation	
Low rain	6.27 dB/km

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Medium rain	9.64 dB/km
Heavy rain	19.28 dB/km
Fog Attenuation	
Thin fog	9 dB/km
Thick fog	16 dB/km
Heavy fog	22 dB/km

3. Channel Modeling

The properties of the medium linking the transmitter and the receiver are subject to time-dependent variations brought about by environmental conditions that can negatively affect system performance. Evaluations of these meteorological phenomena can be based on the dimensions of the particles—more specifically their cross-sectional areas concerning the wavelength of use and the volume and density of particles. The reduction of signal strength in the atmosphere (expressed in decibels) may be described as follows:

$$Loss \;\; = -10log_{10}T_a \qquad (1)$$

In this context, T_a indicates the atmospheric transmittance, which is characterized as the fraction of the power received compared to the power supplied in the optical communication link.

A 2.048-Tbps transmission capacity is sent across the FSO in this study to assess the effects of different meteorological conditions. The FSO link may be expressed (in dBm) mathematically, as follows [19]:

$$P_{Received}(dBm) = P_{Transmitted}(dBm) + 10log_{10}\left(\frac{{d_R}^2}{(d_T+\theta Z)^2}\right) - \sigma Z \qquad (2)$$

Where Pr is the optical power received, Pt denotes the optical power transmitted, dR is the diameter of the receiver antenna aperture, dT is the diameter of the transmitter antenna aperture, and θ represents the angle of beam divergence. Additionally, α is the specific attenuation constant, the value of which is dependent on atmospheric conditions. Moreover, Z represents transmission distance. Many channel-scintillation models have been discussed in academic research as a means of assessing turbulence-induced fading in FSO links, such as the log-normal distribution model and the G-G distribution model, among others. Notably, however, the primary use of the G-G distribution model is to accurately characterize channel conditions, which can range from mild to

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extreme levels of turbulence. Different models for channel scintillation, such as the model that follows a log-normal distribution and the model that follows a negative exponential distribution, are available. The two models of double Weibull and gamma-gamma distribution have been widely researched in the literature as a means of analyzing turbulence-induced fading in FSO communication. This study employed the G–G model to examine the effects of atmospheric turbulence on the operational efficiency of FSO links. The G-G model's probability-density function is a channel expressed by the following mathematical equation [22]:

$$P(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\left[\alpha+\frac{\beta}{2}\right]-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}) \quad (3)$$

The attenuation coefficients observed at multiple visibility thresholds significantly influence the efficacy of FSO systems. Fog/haze reduction produces the greatest degree of attenuation because the particle dimensions are analogous to the operational wavelength of an FSO apparatus. This phenomenon may be anticipated using the widely recognized empirical framework of Mie scattering [23].

$$\beta_{fog,haze}(\lambda) = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-p} \quad (4)$$

V (km) represents visibility distance, λ (nm) denotes operational wavelength, and p is the scattering size-distribution coefficient, which can be determined using the Kim model [23].

$$P = \begin{cases} 1.6,\wedge V > 50 \\ 1.3,\wedge 6 < V < 50 \\ 0.16V + 0.341 < V < 6\,(5) \\ V - 0.50.5 < V < 1 \\ 0V < 50 \end{cases}$$

The value of the attenuation coefficient, which is shaped by rainfall conditions, has a degree of independence from operational wavelength and is reliant on rainfall intensity. In rainfall-characterized scenarios, the attenuation coefficient may be expressed as follows [24]:

$$\beta_{Rain} = 1.076R^{0.67} \quad (6)$$

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Where the rainfall rate is denoted by R (mm/hr). Weakening is thus brought about by rainy weather.

This study considers the effects of geometric loss and beam divergence when evaluating the proposed connection efficiency. While the optical beam moves through space, diffraction causes it to expand. Consequently, some of the transmitted beams do not reach the receiver antenna's aperture, leading to geometric loss (L_G), as described in [24].

$$L_G = -20log_{10}(d_R) + 40log_{10}(d_T + \theta Z) \qquad (7)$$

Where d_R stands for the diameter of the receiver antenna aperture, and d_T stands for the diameter of the transmitter antenna aperture (both in meters). The distance covered by the FSO link is represented by variable Z (in kilometers), and the beam-divergence angle is denoted by θ (in rad).

Figure 4 visualizes the relationship between geometric loss (also known as beam-divergence loss) and the distance over which FSO transmission can occur.

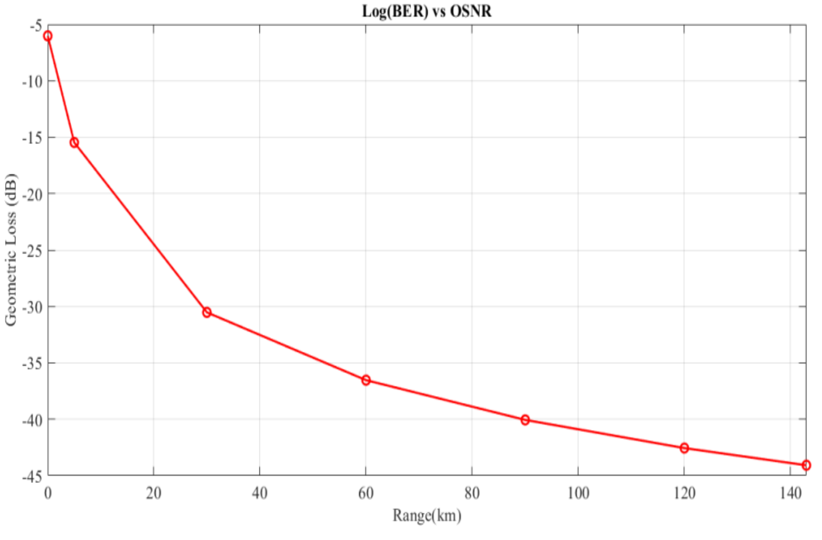

Fig. 4 Comparison of geometric loss/beam-divergence loss with FSO transmission range.

4. Results and Discussion

Figure 5 shows the relationship between the FSO transmission range and the BER in clear weather conditions; the system's BER worsens as the FSO transmission range increases. In addition, an increase in

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the transmission range leads to more distorted symbols in the constellation's information signals. This, in turn, makes it impossible for demodulator units to accurately identify the signals. In clear atmospheric conditions, the proposed system is capable of achieving a maximum transmission distance of 111 km at a BER log of −2.42, which corresponds to the forward error correction (FEC) threshold.

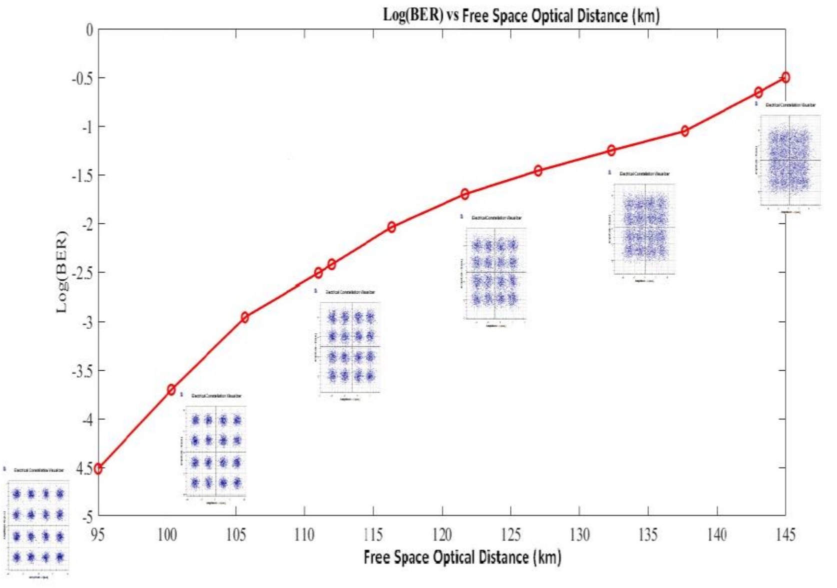

Fig. 5 Bit error rate compared to transmission distance (Km) under ideal weather conditions.

Figures 6 and 7 display the EVM, Q factor, and power plots obtained using the proposed link over different FSO transmission ranges when the weather is clear. Error vector magnitude (EVM), derived from the constellation diagram of the received signal, serves as a quantitative measure of the efficacy of demodulator outputs in the presence of channel-induced noise. For diagnostic purposes, the quality factor measures the level of noise in a pulse. Typically, the eye-pattern oscilloscope generates a report showing the Q factor value. The Q factor recommends the minimum SNR necessary for a signal to achieve a specific BER. The required OSNR (which was measured using decibels) increases alongside the bit rate.

A crucial factor in assessing a communication channel's performance is its Q Factor. The Q factor simplifies the system and serves as an SNR metric for binary/digital optical communication

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[25]. The higher the EVM% (see Figs. 6,7), the more stringent the transmission range becomes (increased values but reduced received power), thus making it difficult for demodulators to recover information from detected signals in their presence.

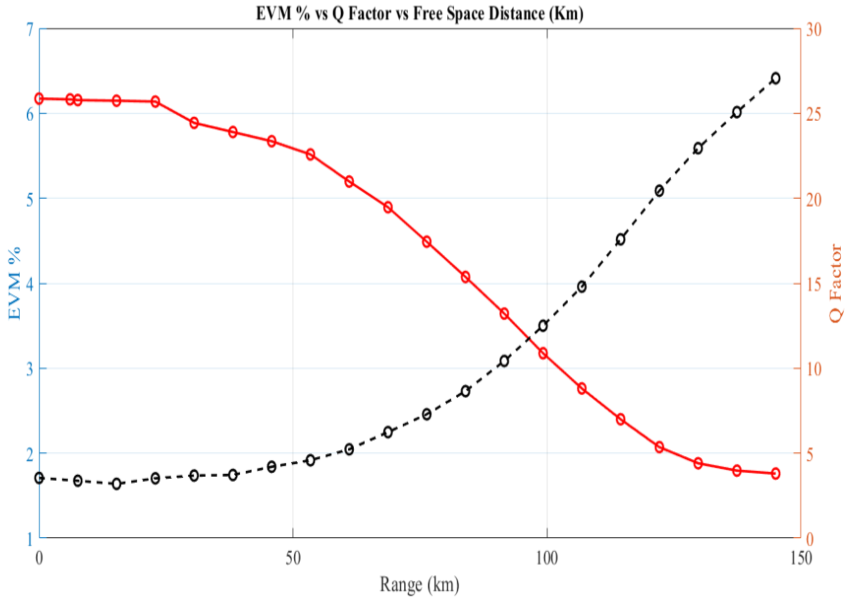

Fig. 6 Comparison between Q factor and transmission range (Km) in the absence of weather disturbances for EVM.

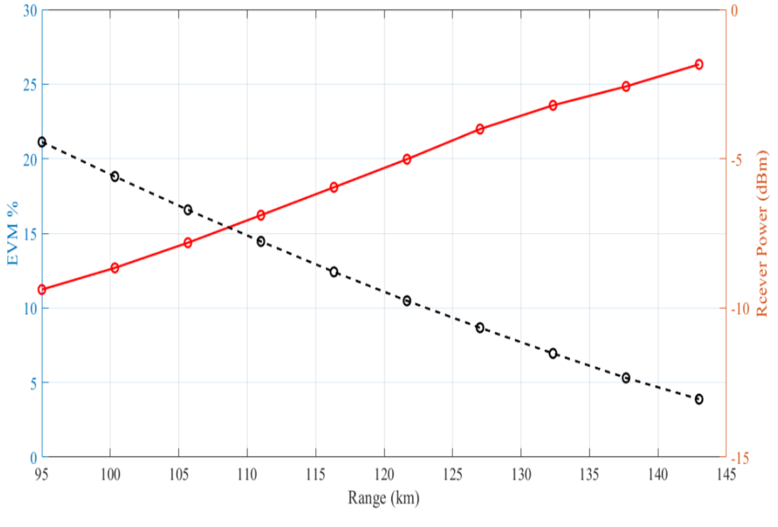

Fig. 7 EVM result showing power received compared to transmission distance (Km) under clear weather conditions.

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❖ OSNR penalty

The evaluation of the connection depends on the necessary OSNR. Meteorological conditions affect the received BER, the EVM constellation, and the maximum transmission distance. The graph in Figure 8 showcases the connection between log BER and OSNR (displaying both the B2B and 111 km transmission under clear weather conditions). The results show that an increase in OSNR leads to a decline in BER, indicating heightened link performance. For B2B transmission, an OSNR of 20.5 dB is required to achieve a BER of -2.42, as per the FEC limit [24]. This requirement rises to 23.5 dB for a 96 km transmission. We determined that the OSNR penalty increases by 3 dB (relative to the B2B communication) when the transmission distance was extended to 111 km.

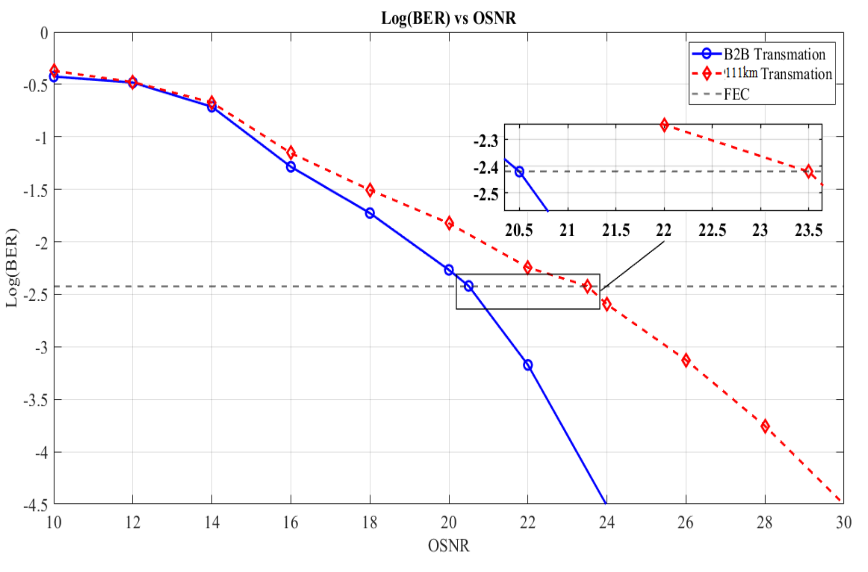

Fig. 8 Comparison of log (BER) for back-to-back (B2B) transmission and a transmission distance of 111 km versus OSNR.

❖ Evaluation of Link Performance Amid Rainfall

This study also assessed the relationship between log BER and optically presented OSNR at varying levels of rainfall (ranging from light to heavy) and various distances (see Fig. 10a). This dynamic is the result of an interaction between the optical communication link's performance and various degrees of rainfall when using the required OSNR for a reliably low BER value across several transmission distances. For instance, in the case of 6.28 km transmission, a 27.8

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dB OSNR is required amid light rain (Fig. 10b); this means that high signal strength and quality must be maintained, even under comparatively mild conditions, to overcome the impact of rain on the transmission link. Amid medium rainfall for transmission of 4.48 km, the required OSNR increases to 28.4 dB (see Fig. 10c). Logically, a slightly higher OSNR is needed to transmit on account of the more significant attenuation and scattering of the signal brought about by more substantial rainfall. Figure 10d presents the dynamic amid heavy rainfall: The required OSNR for reliable transmission rises to 28.8 dB at a distance of 2.45 km. Evidently, in more intense storms, there must be a stronger signal to maintain the integrity of the communication link, even at shorter distances. For every incremental increase in transmission distance, a corresponding increase in the OSNR is necessary to maintain a faithful BER. This adjustment is quantified in the form of OSNR penalties. When it comes to B2B transmission, refer to Fig. 8, which shows the baseline under optimal conditions without atmospheric interference. The OSNR values for light, medium, and heavy rain were 7.3 dB, 7.9 dB, and 8.3 dB, respectively. These penalties are increments of the OSNR burden that would be required to compensate for the effect of rain and, thus, to maintain the signal's level of quality. Amid moderate rainfall, higher penalties are needed to compensate for heightened signal degradation. Figure 6d plots the log BER performance as a function of transmission distance when the OSNR was maintained at 23.5 dB. This figure is essential to any effort to identify the variation in transmission distances amid different levels of rain intensity. In light rain, the maximum reach with reliable BER is about 5.97 km. In medium rain, that figure falls to 4.24 km, showing that the system still has some capacity to deal with some amount of rain at this fixed OSNR. However, amid heavy rainfall, the maximum achievable distance is 2.34 km, indicating the massive effect that heavy rainfall has on the transmission link. This study’s results demonstrate the influence of rainfall on the performance of optical communication systems. Light, moderate, and heavy rainfall exhibit varying degrees of signal absorption and reflection; therefore, specific OSNR adjustments are necessary to ensure reliable communication. These findings highlight the importance of accurately appraising environmental conditions during the design and optimization of optical communication networks. Moreover, they offer critical information on the OSNR

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values that will ensure reliable signal transmission at various distances and different levels of rainfall intensity.

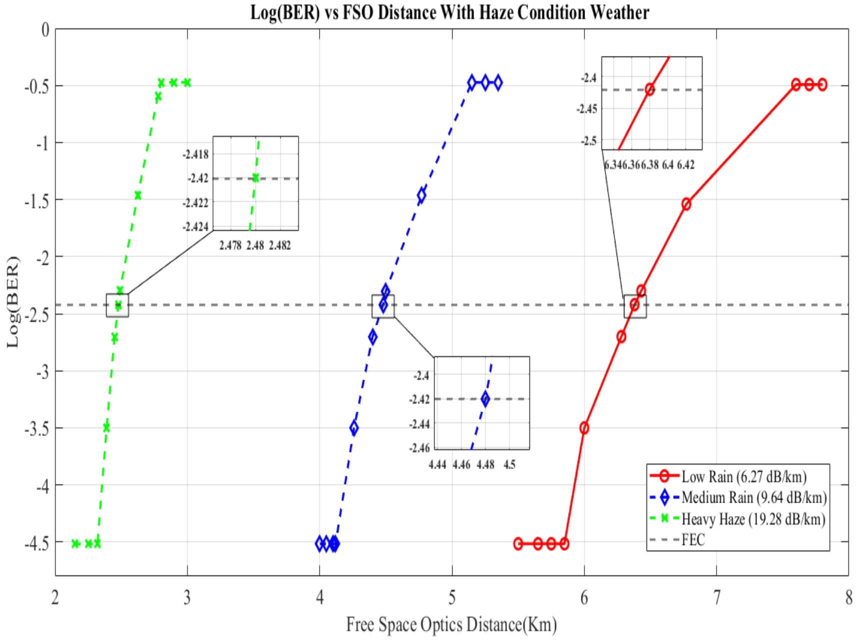

Fig. 10a Log of BER compared with distance under rainy conditions.

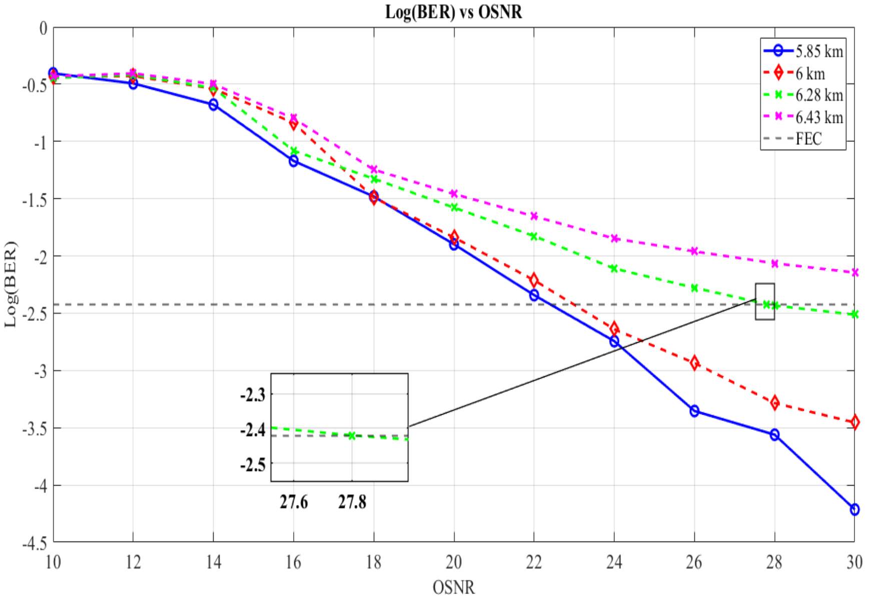

Fig. 10b Log of BER compared with OSNR under lightly rainy conditions.

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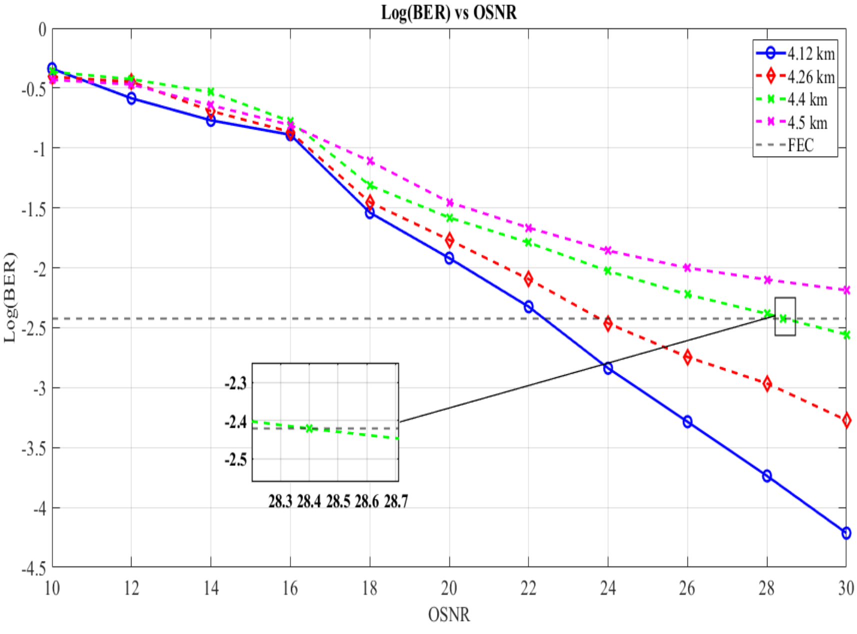

Fig. 10c Log of BER compared with OSNR under moderately rainy conditions.

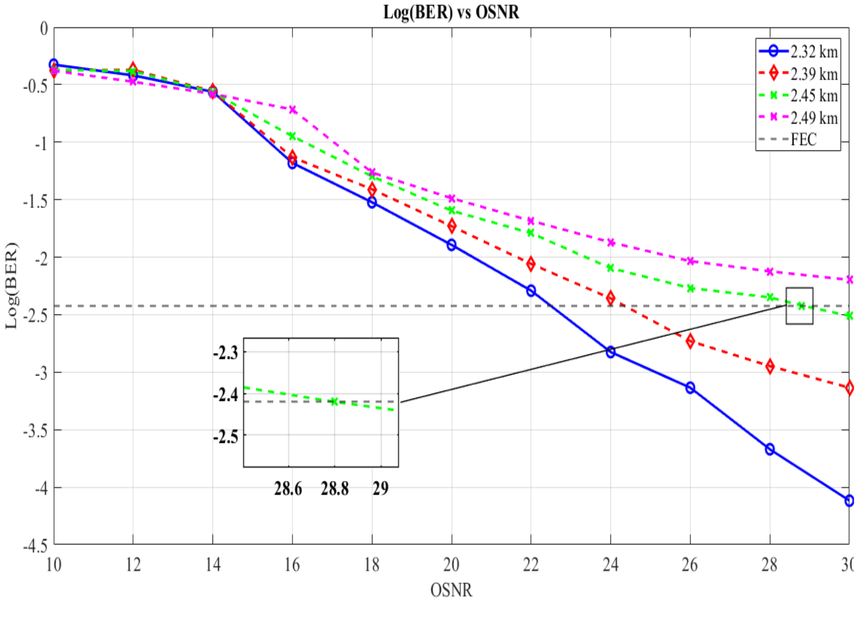

Fig. 10d Log of BER compared with OSNR under heavily rainy conditions.

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- **Evaluation of Link Performance under Foggy Conditions**

This study analyzed the relationship between log BER and OSNR at varying levels of fog (light, dense, and heavy) and various distances, the objective being to determine how fog density impacts optical communication links and identify the threshold values of OSNR that would ensure a reliable BER over different transmission distances. Specific OSNR thresholds were determined for different fog conditions to ensure a reliable BER (Fig. 11a). The threshold that ensures an error-free state for transmission over 4.66 km amid thin fog is 29 dB (Fig. 11b). At this OSNR, the signal is certain to be strong enough to combat attenuation and scattering in the fog. In dense fog, the necessary OSNR is 28.6 dB (Fig. 11c). Finally, in heavy fog, a transmission over 2.18 km requires an OSNR of 28.3 dB. This is the highest OSNR threshold among the three considered conditions (due to its lower-distance transmission), underlining what has already been said: Heavy fog introduces severe degradation into the signal; hence, a robust signal is necessary to ensure reliable communication. This study also delineated the OSNR disadvantages of the link about consecutive transmission. Fig. 8 presents a baseline under optimal conditions (with no meteorological or atmosphere interference); the OSNR values decrease to 8.5 dB in thin fog, 8.1 dB in thick fog, and 7.8 dB in heavy fog. These figures show the extra OSNR required to compensate for the foggy effects and maintain a reliable BER. The heavier penalties in the thicker fog scenarios indicate the serious influence of intense fog on signal transmission. Figure 7d plots BER performance as a function of the transmission distance across a range of fogginess levels at a fixed OSNR of 23.5 dB. The figure shows that 4.44 km is the maximum distance that can be reached in thin fog. The maximum distance declines to 2.74 km in thick fog and further still to 2.1 km in heavy fog, demonstrating how harmful fog can be to the performance of optical communication systems and data transmission more broadly. However, these findings emphasize the importance of carefully assessing environmental conditions when planning and optimizing optical communication networks. Moreover, they provide critical information on the OSNR needed to maintain reliable data transmission over various distances in foggy weather. By understanding these relationships, network designers can better prepare for and mitigate these weather

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conditions, making optical communication links more rugged and reliable.

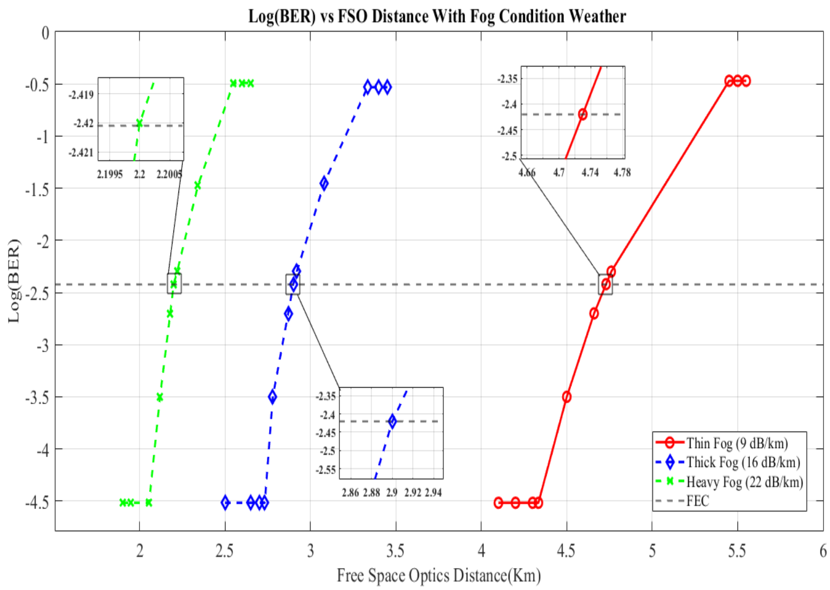

Fig. 11a Log of BER compared with distance under foggy conditions.

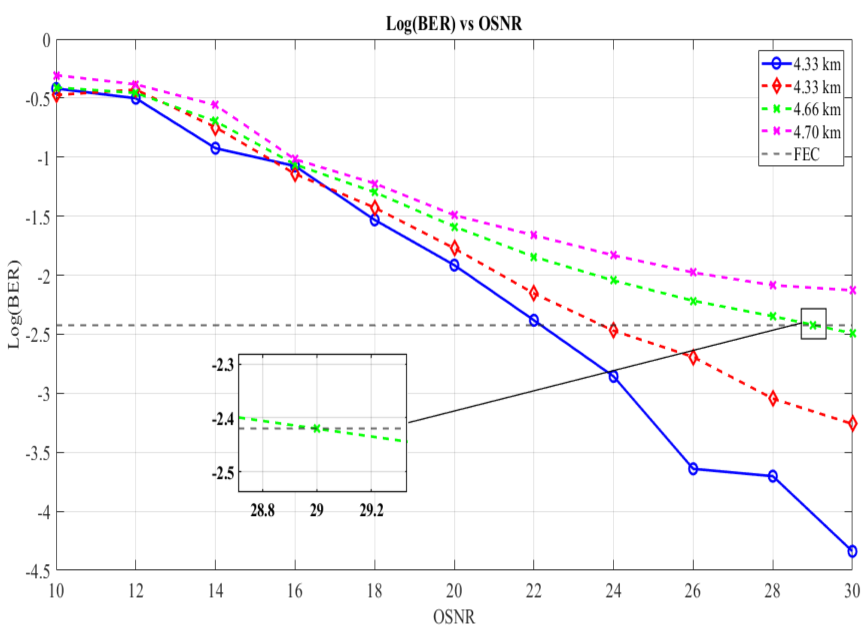

Fig. 11b Log of BER compared with OSNR under thin fog conditions.

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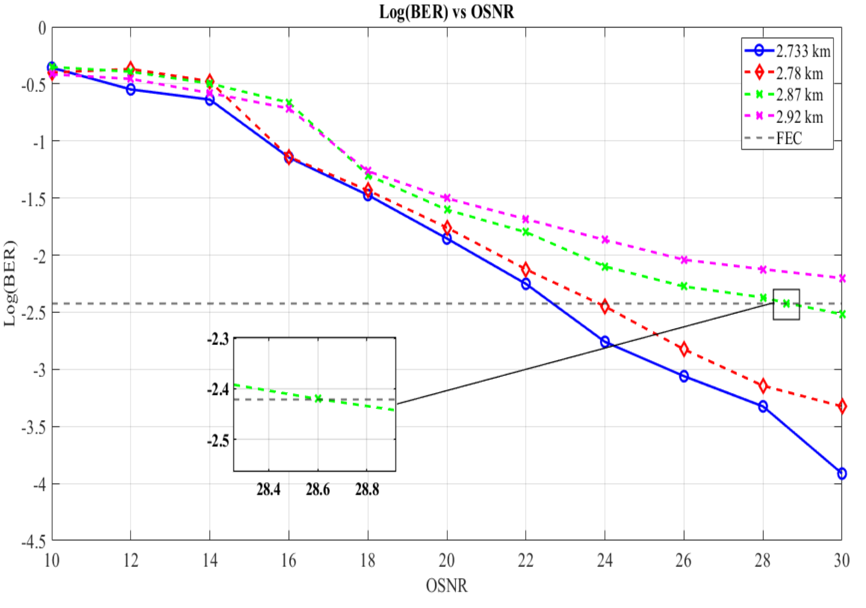

Fig. 11c Log of BER compared with OSNR under thick fog conditions.

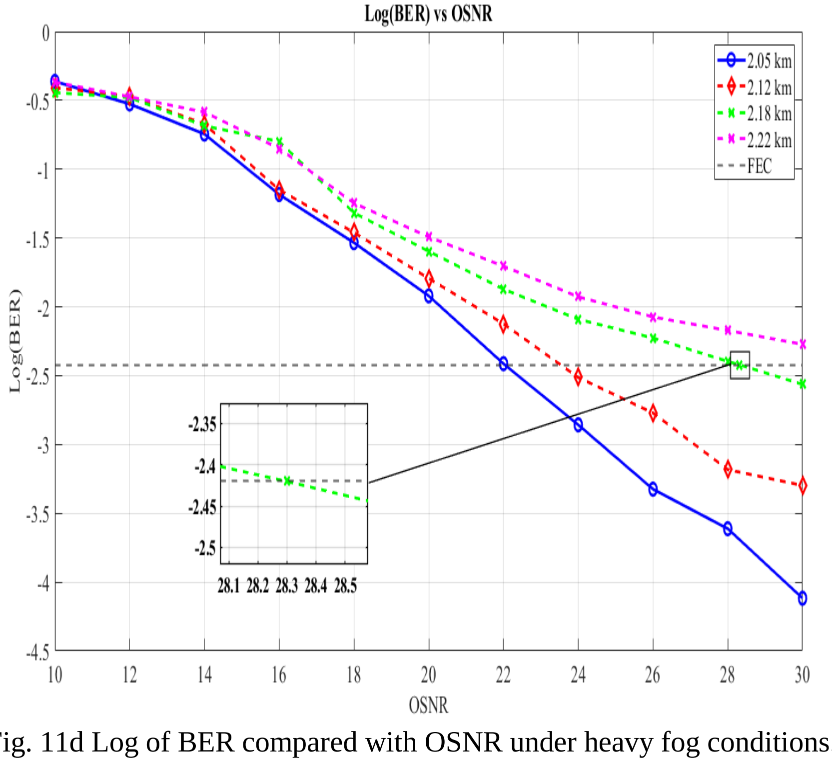

Fig. 11d Log of BER compared with OSNR under heavy fog conditions.

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Table 3: comparison of limitation distance with requirements: osnr varies by weather conditions

Parameter	Limitation Distance (km)	OSNR (dB)
Clear	111	23.5 dB
Rain Attenuation		
Low rain	6.28	27.8 dB
Medium rain	4.48	28.4 dB
Heavy rain	2.45	28.8 dB
Fog Attenuation		
Thin fog	4.66	29 dB
Thick fog	2.87	28.6 dB
Heavy fog	2.18	28.3 dB

5. Conclusion

This research presented an original transmission link for a WDM-FSO configuration. The setup, designed to operate at a remarkable data transmission rate of 8 × 256 Gbps, supports a PDM-16-QAM transmission system. It employs coherent detection, which requires accurate estimation of the carrier phase at the receiver, as well as advanced digital signal processing (DSP) to enable signal amplification. This paper specifically looked at the system's performance under different climatic and meteorological situations. The results show that the transmission range varies significantly with weather conditions. Under clear weather conditions, the system can achieve a data throughput of 2.048 Tbps over a long distance of 96 km using the FSO link. However, this range drops to just over 213 meters in highly dusty environments, showing the impact of adverse weather on signal transmission.

The graphical results further reinforce these findings. As illustrated in the presented graphs, the bit error rate (BER) increases with the transmission distance for a fixed optical signal-to-noise ratio (OSNR). For example, in haze condition scenarios, reliable transmission (with BER below the FEC threshold of approximately FEC = -2.42) is maintained at distances up to 19.43 km when the OSNR is about 28 dB, while in more challenging dust conditions, the maximum distance drops drastically. The graphs show that for shorter links (e.g., 1.95km to 0.213km), the system achieves very low BER values even at lower OSNR levels (12–20 dB). However, as the distance increases to several kilometers (e.g., 4.23 km, 8.58 km, and up to 19.43 km), maintaining a BER below the FEC limit

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requires a higher OSNR (often above 28 dB). Such results portray the offered system's efficacy and robustness as it stays consistently stable across a diverse range of distances and weather conditions. The results indicate that the system under consideration is capable of high-speed data transmission in severe atmospheric conditions. The main reason for this robustness is the combination of WDM technology and PDM-16-QAM modulation with coherent detection and powerful DSP. Essential conclusions are related to WDM-FSO technology perspectives that were made by the study. WDM-FSO technology, for example, stands out as a very effective means of ensuring high data transmission even during unfavorable weather conditions, thereby making it possible to construct modern telecommunications networks that can guarantee reliable and high-speed data transmission over varying terrains. In particular, the research was aimed at studying the potential of WDM-FSO systems for the creation of advanced communication networks, and it has yielded promising results. These results are of great importance in the development of communication technology because they demonstrate the potential for building resilient systems based on WDM-FSO. Furthermore, future enhancements may be realized through adaptive optical systems, machine learning-based weather prediction, MIMO technology, and adaptive modulation (by reducing the modulation order under extremely harsh conditions).

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