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# Hybrid MDM-MIMO radio-over-free space optical system for high-capacity 5G and beyond networks under strong and weak scintillation

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**Introduction:** The increasing demand for high-capacity, low-latency communication in 5G and Beyond networks necessitates innovative solutions to overcome the limitations of conventional wireless technologies. Optical Wireless Communication (OWC) technologies, particularly Radio-over-Free Space Optical (RoFSO) systems, offer a promising approach to addressing spectrum congestion and environmental attenuation challenges.

**Methods:** This study presents a hybrid Mode Division Multiplexing (MDM)-Multiple Input Multiple Output (MIMO) RoFSO system operating at an 80 GHz·mm-wave carrier to achieve high-capacity data transmission. The system employs a Gamma-Gamma turbulence model to analyze performance under weak and strong scintillation conditions. Performance metrics such as Bit Error Rate (BER) and spectral efficiency are evaluated for different MIMO configurations (2 × 2 and 4 × 4) to assess link reliability and robustness.

**Results:** The results demonstrate that MDM-MIMO configurations significantly enhance system performance, with the 4 × 4 MIMO setup exhibiting the lowest BER and superior signal quality over extended link distances. The system maintains reliable data transmission under weak and strong scintillation, showcasing its potential for high-speed wireless communication in challenging atmospheric conditions.

**Discussion:** The proposed hybrid MDM-MIMO RoFSO system provides a scalable and resilient solution for future wireless networks, including urban backhaul, emergency communication, and satellite-based optical links. While the technology offers substantial improvements in spectral efficiency and link reliability, practical deployment challenges such as hardware constraints, regulatory issues, and power consumption must be addressed to enable widespread adoption.

**Conclusion:** This study highlights the effectiveness of MDM-MIMO RoFSO systems in enhancing the performance of high-capacity wireless communication. The findings contribute to the development of next-generation networks capable of meeting the stringent demands of future communication infrastructures.

KEYWORDS

**millimeter waves, radio over free space optics, mode division multiplexing, multiple input multiple output, scintillations**

## 1 Introduction

The rollout of 5G networks marks a significant advancement in telecommunications, delivering ultra-fast data rates, low latency, and enhanced connectivity. However, as the demand for high-capacity, low-latency, and intelligent communication networks continues to grow, 5G alone may not be sufficient to support emerging applications such as holographic communication, ultra-massive IoT, and space-terrestrial integration [1, 2]. The primary challenges in 5G deployments include spectrum congestion, short-range coverage of mmWave frequencies, and susceptibility to environmental interference, which limit their effectiveness in urban, remote, and high-mobility environments [3]. While mmWave technology has expanded network capacity, its propagation loss and atmospheric attenuation necessitate the exploration of higher-frequency bands to ensure scalable, high-performance wireless communication. To address these limitations, wireless communication systems beyond 5G are expected to leverage higher mmWave and sub-terahertz (THz) frequencies. Among these, the 80 GHz (E-band) spectrum has emerged as a promising candidate due to its favorable balance between data rate, propagation range, and spectral availability [4]. The key advantage of mmWave frequencies lies in their ability to offer extensive bandwidths, which are crucial for achieving gigabit-level data transmission rates. However, the susceptibility of mmWave signals to atmospheric attenuation and environmental interferences poses significant challenges for practical deployment [5]. To overcome these challenges, RoFSO-based hybrid architectures provide a high-capacity, low-latency, and scalable solution by integrating free-space optical communication (FSO) with RF systems [6]. RoFSO technology takes advantage of the high bandwidth and interference-free nature of optical links, while ensuring reliable communication through RF fallback in adverse conditions. As 5G and Beyond networks move toward integrating AI-driven intelligent systems, quantum communication, and satellite-based backhaul, RoFSO emerges as a promising candidate to support next-generation high-speed, resilient communication infrastructures [7, 8]. This hybrid approach is particularly advantageous in addressing the range and reliability issues associated with mmWave communication, making it a viable option for extending the reach of 5G networks in complex urban settings where direct line-of-sight (LoS) paths are often obstructed. Although Visible Light Communication (VLC) has been explored as another optical wireless technology, particularly for indoor applications and short-range connectivity [9, 10], its reliance on ambient lighting conditions and limited transmission range restricts its effectiveness in outdoor and long-distance scenarios [11]. In contrast, RoFSO leverages both optical and RF technologies, providing a more reliable and scalable solution for high-speed wireless communication in diverse environments.

RoFSO is a novel technology that ingeniously combines the high data rate capabilities of FSO with the flexibility and mobility of RF systems [12–14]. At its core, RoFSO utilizes light propagation through the atmosphere to carry data, akin to fiber optics but without the need for physical cabling. This makes RoFSO particularly appealing for areas where infrastructure deployment is challenging, such as urban environments, remote regions, or over bodies of water [15, 16]. A pivotal aspect of RoFSO technology is its utilization of the 80 GHz frequency band, which provides high bandwidth capacity for transmitting vast amounts of data at ultra-fast speeds [4, 17, 18]. Furthermore, operating at 80 GHz significantly reduces interference from other wireless devices, which typically operate at lower frequencies [19–21]. To further enhance the performance of RoFSO integrated with 80 GHz mmWave technology, we introduce Multiple-Input Multiple-Output (MIMO) and Mode Division Multiplexing (MDM) schemes. MIMO enhances signal robustness and data rates by utilizing multiple antennas for simultaneous transmission and reception [22, 23], effectively turning multipath propagation from a limiting factor into a powerful advantage [24]. Meanwhile, MDM improves spectral efficiency by multiplexing distinct data streams within the same optical carrier, utilizing different spatial modes of light [25]. This integration of MIMO and MDM within RoFSO not only maximizes the system's capacity but also provides a scalable and robust solution to meet the ever-growing data demands of 5G and beyond networks. In 2021 [26], authors focused on the development and challenges of RoFSO technology in the context of evolving telecommunication needs. The key factors discussed include the integration of advanced multiplexing techniques and an analysis of the impact of atmospheric conditions on signal transmission. The study emphasizes the importance of RoFSO in bridging the digital divide and its potential in providing high-speed connectivity to rural and underserved areas. The last few years have witnessed a significant number of works in the development of RoFSO systems. Study in 2022 [27] delves into RoFSO's capabilities in high-data-rate transmission, highlighting the use of orthogonal polarization and MDM techniques. It presents a comprehensive analysis of the system's performance under various atmospheric conditions, examining factors such as signal degradation and bit error rates. The paper underscores the effectiveness of MDM in enhancing RoFSO's bandwidth and reliability. In the same year [28] focused on the implementation of RoFSO systems using Subcarrier Multiplexing (SCM) and MDM. The study demonstrates how these multiplexing techniques can significantly improve the data throughput and spectral efficiency of RoFSO systems. It also explores the application of RoFSO in urban environments and challenging geographical terrains, highlighting its flexibility and cost-effectiveness. In 2023 [29], a study introduced an Orthogonal Frequency-Division Multiplexing (OFDM)-based RoFSO system incorporating 2-level multiplexing with SCM and MDM. It achieved a 4 × 20 Gbps data rate and demonstrated the potential for further increases in channel capacity. The paper extensively analyzed the performance of transmitted data streams under various atmospheric conditions, contributing valuable insights into the reliability and efficiency of RoFSO systems. While another study [30] presented an advanced RoFSO system design using dual SCM-MDM configuration. It focused on achieving a high total transmission rate of 80 Gbps using 4-input data streams.

In this work, our primary focus has been the designing of a dual-channel Ro-FSO system capable of transmitting data at a rate of 20 Gbps, which is then upconverted to an 80 GHz mm radio signal for each channel by incorporating hybrid MDM-MIMO scheme. To address the limitations of 5G and Beyond networks, this study proposes a Hybrid MDM-MIMO RoFSO system operating at 80 GHz mmWave to enhance high-capacity, long-distance wireless communication. The key contributions of this work are as follows:

1. Development of a Hybrid MDM-MIMO RoFSO System: A dual-channel RoFSO architecture integrating MDM and MIMO to enhance spectral efficiency and data throughput.
2. Investigation of System Performance Under Strong and Weak Scintillation: A comprehensive analysis of atmospheric turbulence effects on system performance, evaluating Bit Error Rate (BER), signal reliability, and transmission range under varying turbulence conditions.
3. Utilization of the 80 GHz (E-band) Spectrum for RoFSO: The study explores the 80 GHz mmWave frequency band, leveraging its high bandwidth capacity and reduced interference, making it suitable for last-mile connectivity and backhaul applications.
4. Practical Implementation Challenges and Real-World Deployment Scenarios: A detailed discussion on hardware constraints, scalability, regulatory issues, and environmental factors affecting RoFSO deployment in urban, remote, and satellite-based communication systems.
5. Potential Applications in 5G and Beyond Networks: Demonstration of RoFSO's applicability in high-speed urban wireless backhaul, emergency communication networks, rural connectivity, and satellite-based optical links, highlighting its role in next-generation communication infrastructures.

The rest of this paper is organized as follows: Section 2 outlines the system modeling, providing a comprehensive overview of the design and theoretical foundation of our dual-channel RoFSO system, which incorporates a hybrid MDM-MIMO scheme. In Section 3, we present our results and engage in a thorough discussion on the performance of the proposed system, including its ability to transmit data at high speeds over significant distances and under various environmental conditions. Section 4 explores the practical implementation challenges of the proposed system and its potential applications in 5G and beyond networks. Finally, Section 5 concludes the paper, summarizing our main findings, the implications for 5G wireless communication systems, and suggesting avenues for future research in this exciting field.

## 2 System description

The schematic in Figure 1 delineates an advanced MDM-MIMO-RoFSO system to facilitate high-speed data transmission. This system is designed to transmit two separate data streams, each at a rate of 20 Gbps using Non-Return-to-Zero (NRZ) encoding. The data streams are upconverted utilizing a 80 GHz local oscillator via a mixer, leveraging distinct Hermite-Gaussian (HG) spatial modes—HG 00 for one user and HG 01 for the other as shown in Figure 2, to enhance the capacity and robustness of the communication channel.

In the architecture, each user's NRZ-encoded signal is first interfaced with an 80 GHz LO in a LiNbO3 modulator, which modulates the optical carrier with the RF signal. The modulated signals are then unified into a single optical stream and propagate through a $2 \times 2$ or $4 \times 4$ MIMO beam collimator module. This module's role is critical, as it precisely aligns the beams for transmission through the free-space optical medium. The FSO channel is represented by Equation 1 as follows [31]:

$$P_{Received} = P_{Transmitted} \times \frac{{d_R}^2}{(d_T + \theta R)^2} 10^{\frac{-TX}{10}} \times 10^{\frac{-RX}{10}} \times 10^{\frac{AD}{10}} \times 10^{-\alpha \frac{R}{10}} \tag{1}$$

Equation 1 encapsulates the relationship between various parameters in the FSO channel, including the receiver aperture diameter ($d_R$), transmitter aperture diameter ($d_T$), beam divergence ($\theta$), range ($R$), atmospheric attenuation ($\alpha$), transmission loss ($TX$), receiver loss ($RX$), and additional loss ($AD$). This equation is crucial for understanding and enhancing the performance of Ro-FSO systems. In the context of Ro-FSO systems, the impact of scintillation, which pertains to fluctuations in the intensity of the received light due to atmospheric turbulence, is of paramount importance and is typically classified into weak and strong turbulence categories. To model scintillation effects accurately, the Gamma-Gamma scintillation model is utilized. This model provides a probability density function (PDF) for the intensity ($I$) of the received signal, as specified by Equation 2 [32, 33]. This approach is instrumental in quantifying the variations in signal quality that can occur over an FSO link, facilitating the design and optimization of Ro-FSO systems to mitigate the adverse effects of atmospheric turbulence.

$$\mathrm{P(I)} = \frac{\left[\frac{2(\alpha\beta)(\alpha+\beta)}{2}\right]}{\Gamma(\alpha)\Gamma(\beta)} I^{\left(\frac{(\alpha+\beta)}{2}\right)-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right), I > 0 \tag{2}$$

In this context, $\mathit{\Gamma}(.)$ denotes the gamma function, and K (α,β) refers to the second-order Bessel function. The variable $I$ is designated as the irradiance intensity of the transmitted signal. The parameters α and β are critical as they represent the effect of small and large-scale turbulence cells within the channel, respectively. The interconnection between these parameters and their influence on the transmission quality is mathematically expressed through Equations 3, 4. These equations are fundamental in understanding the dynamics of light propagation through turbulent atmospheric conditions, allowing for a more precise characterization and mitigation of the impacts of atmospheric turbulence on the

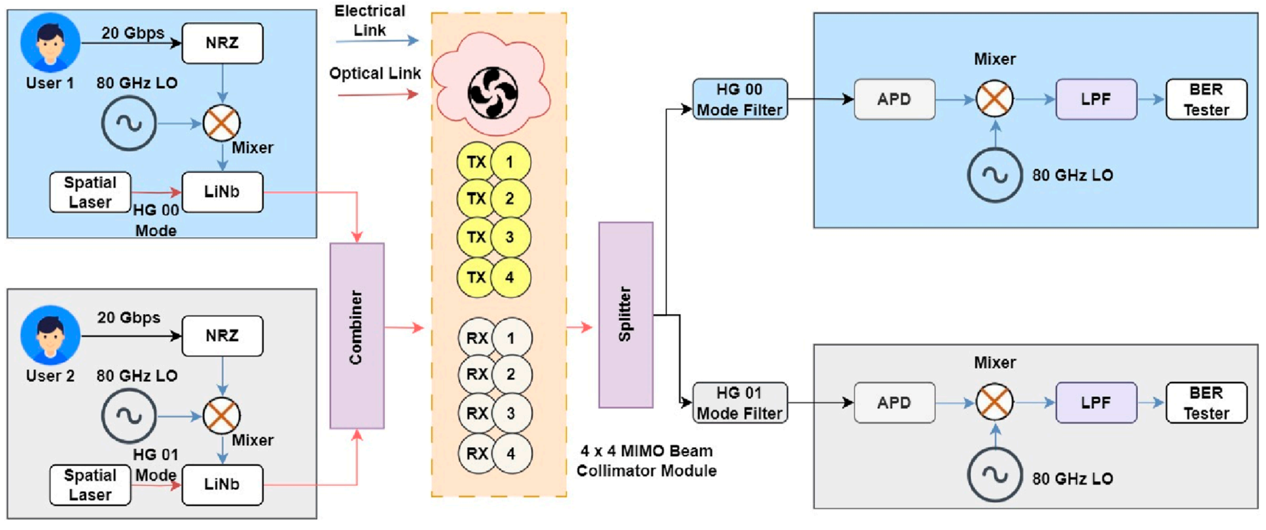

FIGURE 1
Proposed MDM-MIMO enabled RoFSO system.

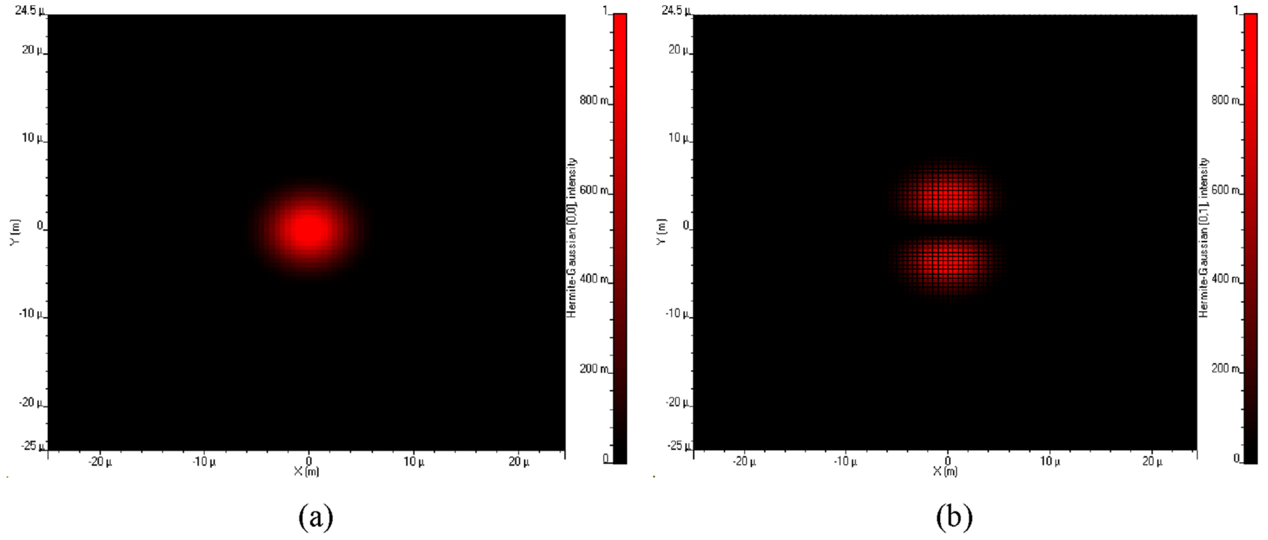

FIGURE 2
Mode profile **(A)** HG 00; **(B)** HG 01.

performance of FSO communication systems

$$\alpha = \exp\left[\frac{0.49\,\sigma_R^{\,2}}{\left(1+1.11\,\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}}\right]-1 \tag{3}$$

$$\beta = \exp\left[\frac{0.51\,\sigma_R^{\,2}}{\left(1+0.69\,\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}}\right]-1 \tag{4}$$

where $\sigma_R^{\,2}$ is the Rytov variance, determined by the Equation 5:

$$\sigma_R^{\,2} = 1.23 C_n^2 k^{7/6} z^{11/6} \tag{5}$$

The parameter $C_n^2$ is crucial in FSO communications, representing the index of refraction structure constant. It quantifies the strength of atmospheric turbulence, with values ranging from $10^{-13}\,m^{-2/3}$ in conditions of strong turbulence to $10^{-17}\,m^{-2/3}$ in scenarios of weak turbulence. Additionally, the symbol $k$ denotes the optical wavenumber, directly related to the frequency of the light wave, and $z$ signifies the propagation distance or range of the transmission. In our analysis, we incorporate channel time variations through the application of the theoretical quasi-static model, also known as the frozen channel model. According to this model, the fading effects within the channel are assumed to be constant for the duration of a symbol frame, referred to as the coherence time. After this period, the channel characteristics

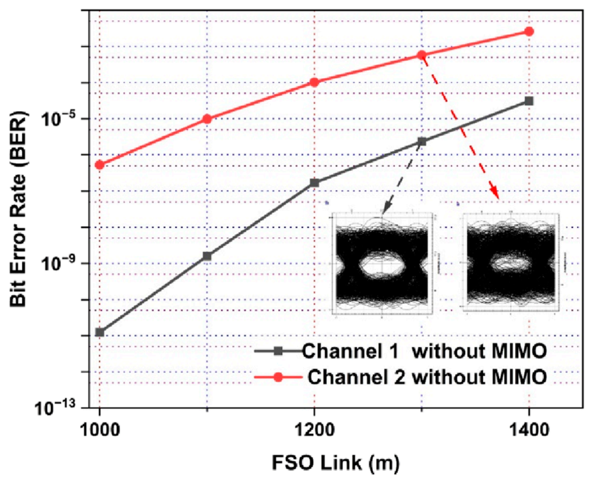

FIGURE 3
BER vs. Range without MIMO scheme.

transition to a new, independent state for the next frame. This approach is instrumental in assessing how atmospheric turbulence influences the performance of the Ro-FSO system, providing a foundation for understanding and mitigating the effects of turbulence on signal quality and system reliability. At the receiving terminus, the signals are first processed by a splitter, which segregates the multiplexed data according to their corresponding HG modes with mode filters. Subsequently, each mode-filtered signal is conveyed to an Avalanche Photodiode (APD) for optical to electrical conversion. The signal, now electrical, is mixed with an 80 GHz LO to down-convert the frequency for further processing. A Low Pass Filter (LPF) is then employed to eradicate high-frequency noise, and the signal's integrity is finally evaluated using a Bit Error Rate (BER) Tester. The designed RoFSO system stands as a robust solution tailored to overcome the challenges of atmospheric turbulence and scintillation, which are critical factors that can impede signal fidelity and integrity in free-space optical communications. By leveraging the MDM technique utilizing distinct Hermite-Gaussian spatial modes, HG 00 and HG 01, the system not only optimizes channel utilization but also significantly enhances the potential for high-capacity data transmission.

## 3 Results and discussion

In this section, we explore the performance outcomes of our MDM-MIMO-RoFSO system, focusing on the BER under various scintillation conditions. The results provide insight into the effectiveness of the MIMO configurations in enhancing link reliability when compared to conventional single-input single-output (SISO) systems. For the system without MIMO as shown in Figure 3, the BER performance for two channels shows that as the FSO link distance increases, the BER also increases, which is a common effect of signal degradation over distance.

Specifically, Channel 1 exhibits a BER that starts at around $10^{-11}$ at 1000 m and deteriorates to just under $10^{-07}$ at approximately 1400 m. Channel 2 follows a similar trend but with consistently higher BER values across the link range, indicating less favorable channel conditions or discrepancies in equipment performance.

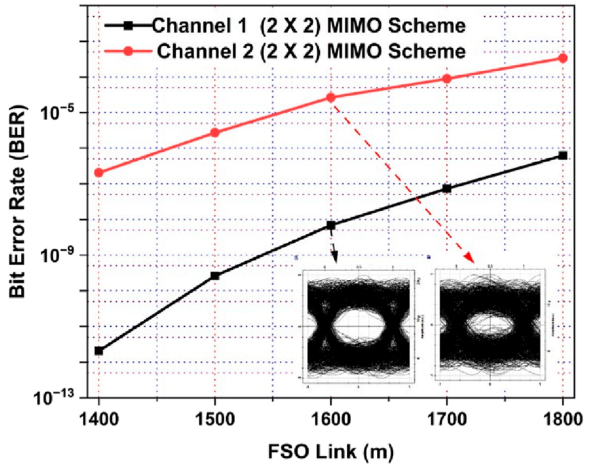

FIGURE 4
Computed BER with 2 × 2 MIMO scheme.

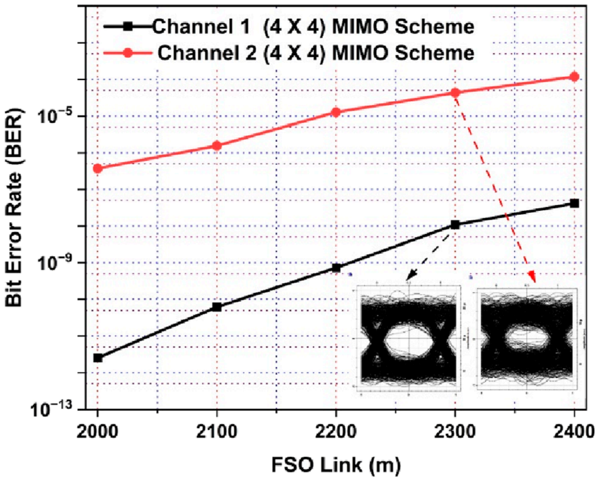

FIGURE 5
Computed BER with 4 × 4MIMO scheme.

Transitioning to the 2 × 2 MIMO scheme as shown in Figure 4, there is a significant improvement in BER. For Channel 1, starting at a BER near $10^{-12}$ at 1,400 m, the value rises to about $10–^{07}$ at 1,800 m. Channel 2 shows a BER starting slightly above $10^{-17}$ at 1,400 m, worsening to approximately $10^{-03}$ at the same 1800m distance. The disparity between channels suggests that while MIMO offers improved signal quality, the degree of enhancement may vary due to channel-specific conditions.

The results from the 4 × 4 MIMO configuration shown in Figure 5 indicate an even more pronounced improvement. Channel 1's BER begins at around $10^{-12}$ at 2000m and ascends to roughly $10^{-08}$ at 2,400 m. In contrast, Channel 2 starts with a BER just above $10^{-07}$ at 2,000 m and reaches close to $10^{-03}$ at 2,400 m. This demonstrates that a higher order MIMO system can provide better

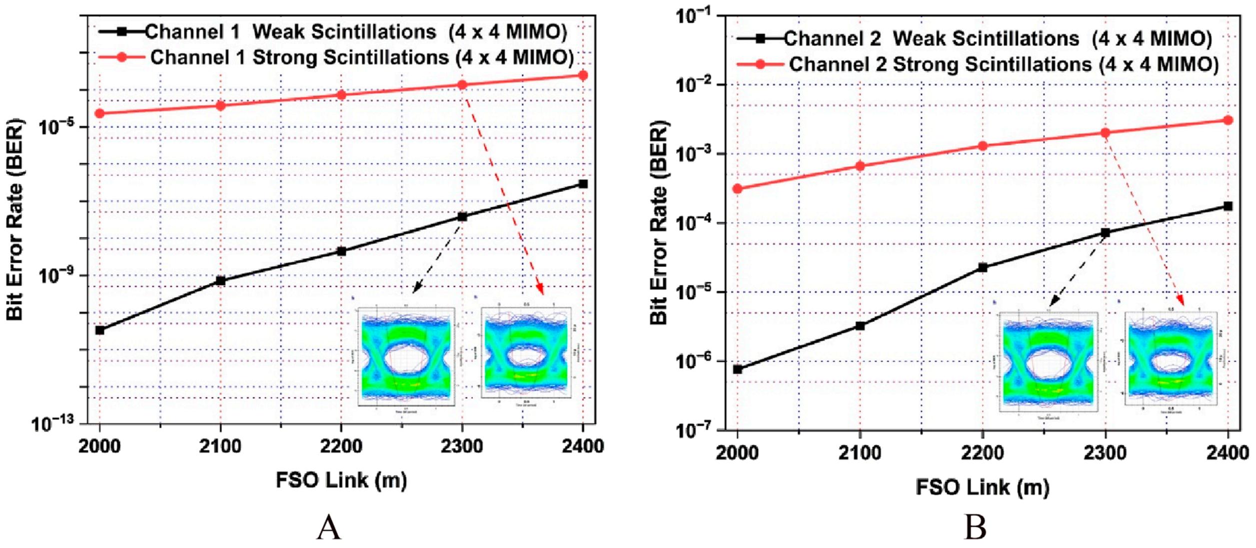

FIGURE 6
Computed BER under Weak and Strong scintillation with 4 × 4 MIMO scheme. **(A)** Channel 1 **(B)** Channel 2.

compensation for scintillation effects, benefiting from the increased spatial diversity that allows for enhanced signal reconstruction. The comparative analysis of the MIMO configurations reveals that the 4 × 4 MIMO system stands out with the best performance. This is evidenced by the lowest BER values and the clearest eye patterns observed in the insets of the figures. The eye diagrams progressively become more open as we move from non-MIMO to 4 × 4 MIMO systems, indicating improved signal quality and reduced noise interference. The distinct clarity in the 4 × 4 MIMO eye patterns aligns with its superior ability to maintain signal integrity over longer FSO links, making it the most suitable configuration for robust and reliable FSO communication. Thus, it can be concluded that, the 4 × 4 MIMO configurations emerges as the most suitable choice for maintaining optimal communication over FSO links. Its superior performance in mitigating the negative impacts of atmospheric disturbances is reflected in the lower BER values across longer distances. The utilization of multiple spatial paths provides resilience against atmospheric turbulence and scintillation, ensuring more reliable and stable signal transmission for high-bandwidth optical communication applications. Further the system is verified for the impact of weak and strong scintillation impact on the performance of 4 × 4 MIMO scheme.

Figure 6A depicts the BER performance for Channel 1 over an FSO link ranging from 2,000 m to 2400 m. Under weak scintillation conditions, the BER remains impressively low, starting at around $10^{-11}$ at 2000m and only slightly rising as the distance increases, reaching near $10^{-07}$ at 2,400 m. In contrast, under strong scintillation conditions, the BER starts at a $10^{-05}$ at 2,000 m but escalates more sharply, ending just below $10^{-03}$ at 2,400 m. Similarly in Figure 6B For Channel 2, the BER under weak scintillation starts off at approximately $10^{-07}$ at 2,000 m and experiences a gradual increase, reaching about $10^{-03}$ at 2,400 m. Under strong scintillation, however, the BER begins around above than $10^{-04}$ at 2,000 m and exhibits a steeper increase, approaching $10^{-03}$ at 2,400 m. The eye diagrams for both channels reveal a clear distinction between weak and strong scintillation effects. Under weak scintillation, the eye openings are relatively wide, indicating a lower level of signal distortion and noise, which correlates with the lower BER values. The diagrams show defined and open "eyes," suggesting that the system can effectively handle minor perturbations in the signal path. In the case of strong scintillation, the eye diagrams become less defined with the "eyes" appearing significantly more closed, which is a visual indicator of the higher BER values recorded. This suggests that the system is experiencing greater signal degradation, likely due to more severe atmospheric disruptions. Despite the challenges posed by strong scintillation, the 4 × 4 MIMO configuration still maintains a level of resilience, although with reduced performance, which is evident from the tighter eye openings.

## 4 Practical implementation challenges and 5G and beyond applications

While the proposed Hybrid MDM-MIMO-RoFSO system demonstrates significant theoretical advantages, its real-world deployment faces several practical challenges, including hardware limitations, scalability concerns, and regulatory constraints. Implementing MDM and MIMO in an RoFSO system requires high-precision optical components, such as mode multiplexers, adaptive beam collimators, and efficient photodetectors. Ensuring low insertion loss and minimizing mode crosstalk is critical for maintaining system performance. Additionally, the power consumption of MIMO-based architectures increases due to multiple antennas at both the transmitter and receiver, necessitating energy-efficient signal processing techniques for large-scale implementation. Another key challenge lies in the scalability of MDM technology. While higher-order mode multiplexing enhances spectral efficiency, mode filtering and separation introduce complexity, particularly when integrated with fiber-optic networks.

Furthermore, regulatory considerations play a crucial role in deploying 80 GHz RoFSO links, as spectrum allocation policies vary across regions. In some countries, the E-band (71–86 GHz) is partially unlicensed, while in others, strict licensing requirements may hinder widespread adoption. Additionally, environmental factors such as rain, fog, and atmospheric turbulence impact system performance, necessitating adaptive power control and hybrid RF-FSO switching strategies to maintain link reliability under varying conditions. Beyond theoretical enhancements, the proposed system has strong potential for real-world applications in 5G and beyond networks. It can serve as a high-capacity wireless backhaul in urban environments where fiber deployment is challenging, ensuring seamless connectivity for smart cities, AI-driven IoT applications, and industrial automation. In disaster-prone areas, the RoFSO system can rapidly establish emergency communication networks when conventional infrastructure is damaged. Additionally, its capability to deliver high-speed connectivity over long distances makes it a suitable solution for remote and rural regions, addressing digital divide concerns.

Moreover, the proposed RoFSO system is well-suited for satellite and high-altitude communication networks, where free-space optical links can enhance data transmission efficiency for Low Earth Orbit (LEO) satellites and high-altitude platforms. These practical applications reinforce the system's relevance to future wireless networks, where high data rates, long-range connectivity, and network resilience under dynamic environmental conditions are critical.

## 5 Conclusion

In this work, we have designed dual-channel a RoFSO system, designed to meet the rigorous demands of 5G telecommunications by leveraging an 80 GHz mm wave signal. The system's innovative incorporation of a hybrid MDM and MIMO scheme marked a significant advancement in addressing the challenges of millimeter wave transmission over free space optics. Through detailed system modeling and analysis, we demonstrated the system's capability to transmit data at rates of 20 Gbps per channel across distances extending to 2,400 m, achieving substantial improvements in link reliability and signal quality. Our results shed light on the critical role of MIMO configurations in enhancing the RoFSO system's performance under diverse scintillation conditions. The comparative analysis between non-MIMO, 2 × 2 MIMO, and 4 × 4 MIMO setups revealed that the 4 × 4 MIMO configuration offered the most pronounced improvements in BER performance across all tested distances. Specifically, it showed superior resilience against the detrimental effects of atmospheric turbulence and scintillation, maintaining lower BER values over longer distances. This was further evidenced by the progressively clearer eye patterns observed as we transitioned from non-MIMO to 4 × 4 MIMO systems, highlighting the enhanced signal integrity afforded by higher order MIMO configurations. Moreover, the system's robustness under varying scintillation conditions was rigorously evaluated. Under weak scintillation, the 4 × 4 MIMO scheme maintained impressively low BER values, while under strong scintillation, it exhibited a commendable level of resilience, albeit with somewhat reduced performance. This distinction underscores the system's capability to effectively mitigate the impacts of atmospheric disturbances, ensuring reliable and stable communication even in challenging environmental conditions. In conclusion, the developed MDM-MIMO-RoFSO system represents a significant leap forward in the quest for high-performance, reliable communication systems for 5G and beyond. Its superior performance in mitigating the negative impacts of atmospheric disturbances, combined with its ability to maintain high data transmission rates over extended distances, positions it as a highly promising solution for overcoming the limitations of current wireless communication technologies.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

SC: Conceptualization, Data curation, Formal Analysis, Writing–original draft, Writing–review and editing. SK: Conceptualization, Data curation, Formal Analysis, Writing–original draft, Writing–review and editing. MS: Formal Analysis, Validation, Writing–review and editing. AP: Formal Analysis, Validation, Writing–review and editing. AS: Formal Analysis, Validation, Writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

## Publisher's note

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