

ADVANCEMENTS & CHALLENGES IN MILLIMETER-WAVE OFDM-MDM ROFSO COMMUNICATION

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ABSTRACT

This review paper analyzes the combination of RoFSO technology and MMW hybrid OFDM-MDM communication system for 5G networks. The study reviews essential developments, challenges, and opportunities in the field. The performance of recent technologies, computation optimization approaches, and different weather conditions that affect transmission performance are evaluated. The review studies the importance of adaptive signal processing techniques, link reliability, and spectral efficiency. In addition, the study advocates concentrate on Multi-channel RoFSO architectures and improvements using artificial intelligence in the future.

Keywords: OFDM, MDM, RoFSO, 5G Networks, Millimeter-Wave

1. INTRODUCTION

As a result of the expansion of the wireless communication business, the need for technology that enables high-speed data transmission while having low latency is increasing. MMW communication has captured the attention of people with the advent of 5G Networks because of its capability to deliver high data rates, large bandwidth, and low latency. The increased use of MMW in wireless networks has also raised some concerns, such as issues of spectrum congestion, propagation losses, and environmental signal degradation [1]. Other novel approaches provide a solution to these issues, such as hybrid RoFSO which exploits the license-exempt spectral region of microwave frequencies which has a high electromagnetic interference tolerance [7].

RoFSO communication systems use wireless and optical technologies in a single system, thus allowing long-distance data transfer. Unfortunately, RoFSO links are susceptible to severe challenges posed by fog, rain, dust storms, and turbulence since these result in high signal attenuation and a decreased signal-to-noise ratio (SNR) [7]. Various research studies have been conducted aiming at understanding the impacts of these environmental factors and finding ways to improve the reliability of RoFSO systems [8]. These phenomena can be mitigated by using advanced multiplexing techniques like mode-division multiplexing (MDM) and orthogonal frequency division multiplexing (OFDM). The best ways to increase the performance of RoFSO is by using advanced multiplexing techniques, such as mode-division multiplexing (MDM) and orthogonal frequency division multiplexing (OFDM), which increase spectral efficiency and protective measures against signal degradation [3].

Multiple research works have studied hybrid RoFSO systems for incorporating advanced multiplexing and modulation techniques using multiple channels and some distortion for efficiency purposes.

The application of MDM and OFDM to reduce turbulence effects and improve spectral efficiency was investigated by Amphawan et al. (2018) [3]. In a similar vein, Alnajjar et al. (2017) suggested using erbium-doped fiber amplifiers (EDFA) to increase the FSO links' range during dust storms [9]. To increase the overall data transmission capacity of RoFSO networks, other research has concentrated on polarization-division multiplexing (PDM) and wavelength-division multiplexing (WDM) [15].

A combination of physical layer enhancements incorporating Artificial Intelligence and Machine Learning has

been implemented to improve the RoFSO system performance under different conditions [2]. Using AI, a predictive model can be developed to estimate atmospheric reduction and in turn, improve link reliability along with adjusting parameters in real-time to allow dialog with the network to improve overall network efficiency [4]. And, using aperture averaging techniques to reduce pointing errors while improving BER performance [8].

More recent research has looked into rain attenuation in hilly areas and its effects on RoFSO systems. Kaur et al. performed rain rate analysis in Meghalaya, India using Marshall and Palmer's model, which included system performance evaluation with real-time 8, 16, and 32-QAM modulation schemes [10]. The results of the study stress the importance of rain attenuation modeling in the improvement of the RoFSO link reliability for more complex terrains. This is an addition to growing studies aiming at the impact of adverse weather conditions on optical wireless communication and the use of signal processing in the system.

The goal of this review is to analyze new innovations in hybrid OFDM-MDM RoFSO systems, the impact of transmission performance in different atmospheric conditions, as well as computational models aimed at improving the efficiency of RoFSO links.

The rest of the paper is divided in the following manner: A literature review is given in Section 2, Computational Methods for Optimization of RoFSO Systems is in Section 3, some major difficulties are noted in Section 4, and some conclusions and further research recommendations are made in Section 5.

2. LITERATURE REVIEW

The potential for high-data-rate wireless transmission has led to significant interest in free-space optical (FSO) and radio-over-free-space optical (RoFSO) communications. However, the performance of these systems is influenced by various environmental factors such as fog, rain, and dust. This chapter aims to review key studies in this field, with a focus on attenuation, modulation, and mitigation techniques used to address these challenges.

2.1. Impact of Environmental Conditions on FSO and RoFSO Communication

A study conducted by [5] examined FSO communications in dust scenarios, investigating attenuation and bit error rate (BER) at various data rates. The results indicated changes in the amount of dust in the air can greatly affect the performance of FSO communication systems. When there is a lot of dust, the signal weakens significantly, around 297.38 dB/km. In contrast, when dust levels are very low, the signal can travel as far as 13.5 km. Using lower data rates, such as 0.3 Gbps, along with higher transmitter power, makes the system more stable. This combination helps keep the Q-factor high and reduces BER. Therefore, it is crucial to adjust the transmission settings based on environmental conditions to ensure reliable optical wireless communication. Similarly, research by [7] indicated that dust storms negatively impact signal propagation and suggested strategies to improve communication link reliability. The information is limited available on the performance of free-space optical (FSO) systems in arid and semi-arid regions that frequently experience dust storms. To address this gap, this study examines the behavior of FSO links under dust storm conditions, aiming to assess their limits and capabilities in such challenging environments. Various performance metrics, including signal-to-noise ratio (SNR), bit error rate (BER), and channel capacity, are utilized for evaluation. The results indicate that system performance experiences negligible improvement in the presence of dense dust. A comparison between fog and dust impairments suggests that dust causes significantly higher attenuation than fog. Consequently, dust is regarded as the most severe impairment for FSO links.

[9] Modification methods for free-space optical (FSO) communication links in complex environments have been proposed, with a focus on using multi-hopping and optical amplification to improve link performance. Additionally, [1] evaluated a millimeter-wave hybrid OFDM-MDM RoFSO system designed for deployment in desert areas with 5G coverage, testing its performance under various dust conditions. The study found that hybrids of QAM and OFDM outperformed other quadrature techniques, making them more suitable for harsh environments. The research also analyzed the system's numerical performance in both clear and dust-laden environments, using SNR and total received power as key performance metrics. It was found that mode 1 (HG00) consistently outperformed mode 2 (HG01) in terms of both SNR and total received power across all weather conditions. In clear weather, mode 1 attains SNR levels of 34.90 dB, 29.48 dB, and 23.62 dB at 30 km, 40 km, and 50 km, respectively, while mode 2 observes lower levels of 32.49 dB, 26.79 dB, and 20.69 dB. The

overall received power also shows a similar pattern, verifying mode 1's strong resistance to multipath fading. In extremely light dust conditions ($V \geq 10$ km), mode 1 retains greater SNR values of 35.19 dB, 29.94 dB, and 23.56 dB at 3500 m, 4000 m, and 4500 m, respectively, than mode 2, which drops to 32.80 dB, 27.27 dB, and 20.62 dB. This trend continues under light dust ($1 \text{ km} < V < 10 \text{ km}$), moderate dust ($0.2 \text{ km} < V < 1 \text{ km}$), and heavy dust ($V < 0.2 \text{ km}$) conditions, where both received SNR and total received power progressively degrade with an increase in the transmission distance but mode 1 maintains improved performance. For instance, in heavy dust, mode 1 gets 38.65 dB, 32.43 dB, and 23.53 dB at 125 m, 145 m, and 165 m, respectively, whereas mode 2 shows lower readings of 36.44 dB, 29.88 dB, and 20.59 dB.

[18] Free-space optics (FSO) communication is a wireless optical technology with high speed, but its performance is highly influenced by environmental conditions such as dust, turbulence, and atmospheric attenuation. In this study, the effect of dust conditions on an FSO link was examined, comparing important performance indicators such as bit error rate (BER), Q-factor, and received power through the non-return-to-zero (NRZ) modulation method. By comparing two data rates (0.3 Gbps and 0.7 Gbps), the research established that higher data rates result in higher BER, while lower data rates enhance the Q-factor, indicating a trade-off between speed and reliability. These results are consistent, which indicates that signal degradation caused by dust can be alleviated using methods like adaptive power control and hybrid RF/FSO systems. The BER is inversely proportional to transmitted power, and increased power levels enhance signal quality. Also, the Q-factor reduces as the transmitted data rate increases, which shows that there is a compromise between speed and signal quality in dust conditions. The received power versus transmitted power relationship revealed that at 0.7 Gbps, received power is greater because of greater system capacity. In general, denser dust conditions catastrophically impair system performance, calling for optimized power levels and data rates to ensure reliable communication.

[16] Recent research has extensively reviewed contemporary advancements and future challenges in free-space optics (FSO), particularly focusing on the impact of environmental factors such as fog, rain, and atmospheric turbulence on FSO link performance. Various attenuation models and mitigation strategies, including adaptive optics and power control methods, have been explored to enhance system reliability. The study highlights the advantages of FSO, such as high bandwidth and rapid deployment, making it a preferable alternative to traditional fiber-optic and RF-based communication systems. While FSO offers cost-effectiveness and ease of installation, attenuation within the transmission medium remains a challenge, potentially leading to power loss. However, careful pre-assessment of environmental conditions can aid in optimizing system parameters before deployment. Ongoing research aims to mitigate attenuation effects through innovative system designs like WDM-based FSO, with performance evaluations conducted using various models before installation. Techniques such as OFDM-FSO and WDM-FSO are emerging to improve transmission speed and range, and further advancements in these approaches are expected to enhance overall system design and efficiency.

A study conducted by [10] explored the impact of rain on RoFSO link connections in mountainous regions, employing real-time rain rate monitoring alongside various QAM modulation types. The study's primary contribution was the integration of rain attenuation modeling with adaptive power control methods to improve signal reliability under adverse weather conditions. Similarly, [12] developed a Kruze model to estimate the performance of a 26 GHz RoFSO link under fog, rain, and dust conditions for 5G applications, highlighting the significant potential for adaptation in FSO systems. The bit error rate (BER) performance of the RoFSO link has been assessed by varying the transmission distance while maintaining constant attenuation levels under different weather conditions. The analysis, based on the Kruze model, reveals that the link maintains a satisfactory BER of less than 10^{-9} for most conditions, except during heavy fog, dense fog, and heavy dust, where attenuation exceeds 90 dB/km. Under such extreme conditions, the link remains operational only up to 300 meters, whereas for other weather scenarios, reliable performance is observed beyond 1 km. Further evaluation of BER at a fixed link distance of 300 meters indicates that satisfactory performance can be maintained up to an attenuation level of 170 dB/km. Similarly, quality factor analysis highlights that the link performs well in most conditions, sustaining a Q factor above 7, except in heavy fog and dust scenarios where performance is limited to 300 meters. The findings suggest that the RoFSO system is well-suited for 5G networks under various weather conditions, with the exception of extreme attenuation scenarios. However, the integration of MIMO techniques could potentially enhance the operational range in such challenging conditions.

2.2. Multiplexing and Modulation Techniques for Enhanced Performance

2.2.1. Mode Division Multiplexing (MDM) with Laguerre-Gaussian (LG) and Hermite-Gaussian (HG) modes.

A study by [3] explored the use of Laguerre-Gaussian (LG) and Hermite-Gaussian (HG) modes division multiplexing (MDM) in RoFSO systems to enhance spectral efficiency. The research demonstrated that incorporating a spatial light modulator significantly reduces signal depletion caused by turbulence. The SNR and received power analysis also prove that Channel 3 (HG 11 mode) is the most robust, followed by Channel 1 (LG 02, vortex $m=2$), Channel 4 (HG 12 mode), and then Channel 2 (LG 03, vortex $m=5$), which is most vulnerable to multipath fading. SNR readings at 20 km, 40 km, and 50 km are still indicating that Channel 3 holds the highest SNR, whereas Channel 2 records the lowest, and the total received power continues to follow the same pattern. Measurements of the constellation at 50 km further indicate that LG02 is less prone to multi-fading than LG03, while HG11 resists better than HG12. Modal decomposition at the receiver highlights that intra-channel mode coupling predominantly occurs between modes with similar or adjacent azimuthal mode numbers, effectively reducing inter-channel crosstalk. Spectral analysis confirms that although power is distributed across multiple modes for HG launches, most energy remains within similar mode groups, leading to spectral widths comparable to LG launches. Under atmospheric turbulence, the FSO link is maintained up to 50 km in clear weather but reduces to 4 km in light fog and further reduces to 3 km and 2 km under thin and heavy fog conditions, respectively, with acceptable SNR and received power.

2.2.2. Hybrid WDM-MDM (Wavelength Division Multiplexing – Mode Division Multiplexing).

In addition, [15] proposed a hybrid WDM-MDM-multibeam RoFSO link, which boosts transmission capacity and improves performance under varying weather conditions. The study highlighted that MDM and wavelength division multiplexing (WDM) play a crucial role in increasing data flow. The transmission performance of the proposed WDM-MDM-based OFDM-RoFSO system has been analyzed using both single-beam and four-beam transmission approaches. The evaluation for channel 1 operating in HG01 mode indicates that the SNR values achieved with a single beam are 40.13 dB, 28.62 dB, and 14.05 dB at transmission distances of 1000 m, 1500 m, and 2000 m, respectively. In contrast, the four-beam transmission design provides improved SNR values of 52.13 dB, 41.57 dB, and 31.06 dB at the same distances. Similarly, the received optical power in the single-beam system is measured at -20.59 dBm, -42.43 dBm, and -62.69 dBm, whereas the four-beam configuration achieves higher power levels of 3.48 dBm, -18.35 dBm, and -38.72 dBm, respectively. This signifies an improvement of approximately 17 dB in SNR and 24 dB in received power when utilizing the four-beam transmission system. The results further illustrate that under heavy fog conditions, the proposed four-beam system can maintain a reliable SNR (~20 dB) up to a distance of 2000 m, outperforming the single-beam approach. A comparison of system performance across multiple channels (channels 2, 3, and 4) in terms of SNR and received optical power further supports the advantages of the multi-beam transmission strategy.

2.2.3. OFDM-PSK

A model of an OFDM-based RoFSO system for fifth-generation (5G) networks was developed by [2], focusing on channel turbulence and atmospheric distortions. The research integrated self-tuning, machine learning-based predictive algorithms to adapt transmission parameters according to the surrounding environment. The study demonstrated the effectiveness of computational intelligence and machine learning in enhancing the performance of RoFSO systems. The findings were validated through simulations conducted using MATLAB and OptiSystem.

Additionally, [2] developed an analytical model for transmitting phase shift keying (PSK) modulated OFDM signals over FSO links. The model accounted for optical noise, non-linear distortion, and atmospheric turbulence, all of which were represented using the gamma-gamma distribution. The study provided closed-form expressions for bit error rate (BER) and outage probability, while also addressing focusing error developments to enhance system performance. Furthermore, the research analyzed the impact of seasonal changes on BER, a higher Carrier-to-Noise-and-Distortion Ratio (CNR) results in higher Bit Error Rates (BER) across all seasons. The results indicate that summer experiences the highest wind speeds, leading to the poorest FSO performance due to increased attenuation. Summer exhibited the most degradation at 35 dB CNDR. The study also examined the impact of altitude on FSO performance, showing that increased building

heights improve BER, with a height of 30 meters demonstrating better system efficiency than lower altitudes at the same CNDR value.

2.2.4. *Beam Optimization Techniques, Adaptive Beam Control and Variable-Focus Lenses*

A study in [14] explored beam optimization techniques for space-based FSO systems and proposed an adaptive beam control method aimed at minimizing pointing and angle-of-arrival errors. Their findings demonstrated that incorporating non-mechanical variable-focus lenses contributed positively to link stability.

2.2.5. *MBMD Scheme (Multi-Beam Mode Division) combined with a Photodetector Array.*

Similarly, research in [13] focused on an advanced RoFSO system that was further enhanced using the MBMD scheme, integrating multiple beams and a photodetector array to improve performance under highly hazy conditions. The results indicated a noticeable improvement in the Q-factor and a corresponding reduction in BER, particularly over extended transmission distances.

2.2.6. *Gaussian Approximation and Monte-Carlo Simulations, Adaptive Beam Control with Variable-Focus Lenses.*

The study in [16] investigated various current and potential challenges associated with FSO communication systems, along with their applicability in both urban and rural environments. The performance evaluation and enhancement of FSOC systems have been conducted through Monte-Carlo computer simulations, validating the derived theoretical expressions, including the Gaussian approximation of AoA fluctuation-induced loss, probability density functions (PDF), cumulative distribution functions (CDF) of link loss, outage probability, and optimal beam sizes. The Gaussian approximation was found to be accurate for larger beam sizes, confirming the correctness of the derived expressions when compared with simulation results. The analysis further demonstrated that the proposed PDF and CDF expressions align closely with Monte-Carlo simulations, particularly for airborne FSOC systems where alignment errors are significant. Outage probability evaluations highlighted that optimal beam sizes identified through theoretical calculations were in strong agreement with those obtained via simulations, while the closed-form expressions significantly reduced computational time. Additionally, it was observed that fixed beam sizes could not ensure optimal performance across varying alignment errors; however, an adaptive beam control technique was shown to effectively minimize outage probability over a wide range of AoA fluctuations and pointing errors. The results indicated that larger receiver beam sizes and narrower transmitter beam sizes are preferable for higher AoA fluctuations, whereas the opposite is required for increased pointing errors. A variable-focus lens system was proposed to implement this adaptive control technique, demonstrating its feasibility for practical deployment, especially in long-distance FSOC links. The findings suggest that incorporating high-resolution voltage-controlled systems can enable precise adjustments, thereby improving FSOC system reliability under diverse conditions.

2.3. **Advancements in Error Correction and Reliability Enhancement**

[4] This study aimed to evaluate the performance of WDM-RoFSO communication systems under various weather conditions and study the advantages of employing a dual-channel FSO system. The results indicate that greater atmospheric attenuation is related to a decrease in communication distance, as also observed in earlier studies. The analysis reveals that for a single FSO channel, the communication range reaches a maximum of 1.3 km in clear weather but declines to 0.675 km in foggy conditions due to increased attenuation. However, with the incorporation of a dual FSO channel, a notable improvement in link distance is observed, extending to 1.9 km in clear conditions and 0.85 km in fog, indicating enhanced system resilience. A comparative assessment of single (S-FSO) and dual (D-FSO) channels at 1562 nm further supports this improvement, with performance gains of 46.1% in clear weather, 35% in haze, 29.4% in rain, and 25.9% in fog. Moreover, the evaluation of eye diagrams suggests that signal quality is enhanced when utilizing a dual-channel approach across various link distances. These findings underscore the advantages of employing a dual-channel configuration to improve communication range and system reliability under challenging weather conditions.

The research in [13] explored the RoFSO system from a theoretical perspective, emphasizing the advantages of deep learning compared to RF and fiber optic communication technologies. Their work analyzed various attenuation models and mitigation strategies as a means to optimize both terrestrial and airborne RoFSO links.

Similarly, the study in [8] assessed the performance of FSO communication links in the presence of dust, particularly examining the impact of non-return-to-zero modulation at varying data rates. The findings reinforce the significance of adaptive modulation and coding techniques in enhancing link resilience.

The study in [6] demonstrated the feasibility of high-capacity, short-reach optical interconnects. Error-free transmission has been successfully achieved in our experiment, with power penalties remaining below 2 dB. The experimental results confirm that the proposed scheme is a strong candidate for large-capacity short-reach optical interconnects. Mode crosstalk between the two converted vector modes remains below -20 dB, and further reduction can be achieved using a high-quality q-plate. The vector mode conversion is facilitated by the key q-plate, ensuring effective transformation between the TE₀₁ and TM₀₁ vector modes. A 120-Gbit/s mode-division-multiplexing (MDM) system employing these two vector modes, in combination with direct detection orthogonal frequency division multiplexing (DD-OFDM) and a 32-quadrature-amplitude-modulation (32-QAM) signal, has been demonstrated. These results highlight the feasibility of the approach in enhancing short-reach optical communication systems.

3. CLASSIFICATION OF EXISTING RESEARCH

The research conducted on RoFSO communication systems was divided into three major categories: the performance of an FSO system under various atmospheric conditions, modulation and multiplexing systems, and computation methods.

3.1. FSO Performance Under Atmospheric Conditions

[7] Various studies have investigated how weather changes impact FSO links, highlighting the detrimental effects of factors like fog, dust storms, and turbulence, which significantly degrade signal quality. These negative conditions increase attenuation and reduce the feasible range of the link. Research on dust storms, in particular, has demonstrated that dust particles scatter and absorb radiation due to their rough surfaces, making dust storms one of the most challenging weather phenomena for FSO systems. To mitigate these impairments, some studies have suggested that multi-hop transmission and short-segment link designs could be viable solutions for regions prone to severe weather.

3.2. Modulation and Multiplexing Techniques

MDM-WDM: Different efforts have been undertaken to improve the performance of RoFSO Communication regarding modulation and multiplexing. The combination of mode-division multiplexing MDM and wavelength-division multiplexing WDM was proposed to improve spectral efficiency and increase data rates [15]. Different modulation and hybrid modulation methods are techniques which that been developed to complement the different approaches aimed at improving the performance of the RoFSO.

Improving spectral efficiency and data throughput has been achieved by intercoupling MDM and WDM. [15]

Hybrid modulation schemes, OFDM coupled with QAM: In addition, hybrid modulation schemes with high order, such as orthogonal frequency division multiplexing OFDM, which have been coupled using QAM, have already shown great improvement in terms of signal strength. In addition, they have demonstrated the ability to perform well with channel impairments [1].

HG, LG: Furthermore, different spatial light modulators reputed ones such as Hermite-Gaussian HG and Laguerre-Gaussian LG have also done the rounds in an effort to improve data capacity and lessen the turbulence factors [3].

3.3. Computational Approaches

The application of computational methods has played a crucial role in advancing RoFSO technologies. Machine learning-based predictive models have been developed to assess atmospheric conditions and dynamically adjust transmission parameters [2]. Adaptive optics and error correction techniques have been introduced to mitigate turbulence-induced distortions, improving signal integrity and reducing bit error rates [4]. Simulation tools such as MATLAB and OptiSystem have been widely used to evaluate the performance of RoFSO networks under various conditions [2]. These approaches play a crucial role in improving the reliability and efficiency of next-generation RoFSO networks.

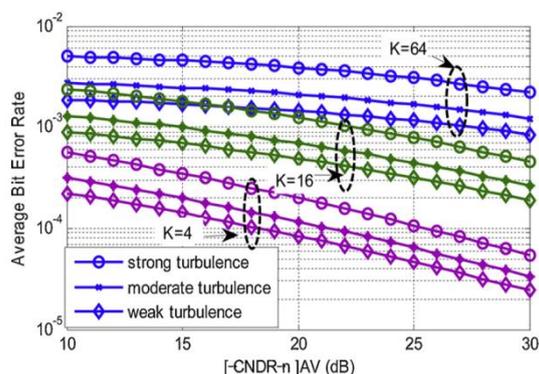


Figure 3.1 BER evaluation for a PSK OFDM FSO link using the gamma gamma distribution model, for various values of K and turbulent states as a function of the average CNDR(db) (Preeti Samhita Pati & Prabhu Krishnan, 2019).

In Figure 3.1 The system analysis of OFDM-FSO reveals that the mean Bit Error Rate (BER) rises with an increase in both turbulence strength and modulation order for the PSK scheme. When the modulation order increases from $K = 4$ to $K = 64$, the performance of the system decreases as a result of decreased symbol energy per bit, thus exposing the system to increased vulnerability towards noise and the effects of turbulence. For a given number of subcarriers ($N = 1000$), higher-order modulation formats suffer from poorer BER performance, illustrating the tradeoff between spectral efficiency and reliability. These results justify the necessity of an optimum modulation order choice balancing between data rate and system resilience for different levels of turbulence.

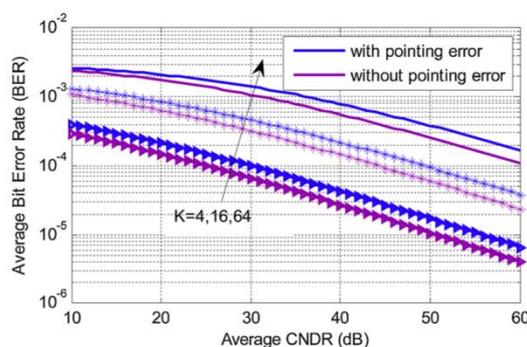


Figure 3.2 BER evaluation for PSK OFDM FSO link using the gamma gamma distribution model with pointing error with reference to the average CNDR (db) (Preeti Samhita Pati & Prabhu Krishnan, 2019).

In Figure 3.1 BER performance of the PSK-based OFDM-FSO system over a Gamma-Gamma (GG) channel with pointing errors is investigated in comparison with the average CNDR for different modulation orders. It is noticed that higher SNR values lead to lower BER, and a rise in the modulation order degrades system performance in terms of BER. As indicated in Figure 3.1, the system provides an improved BER of 10^{-5} at a CNDR of 50 dB when there are no pointing errors, demonstrating the important effect of pointing errors on system reliability.

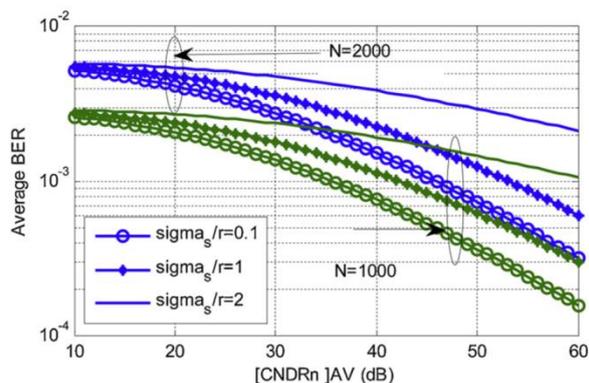


Figure 3.3 BER evaluation for a PSK OFDM FSO link with varying values of normalized standard deviation with reference to the average CNDR (db) (Preeti Samhita Pati & Prabhu Krishnan, 2019).

In Figure 3.3, shows the variation of BER with regarding CNDR for multiple values of α_s/r representing the normalized standard deviation of building sway, representing the influence of pointing errors. An increased jitter deviation produces greater pointing errors, further deteriorating system performance. The outcomes also indicate that a rise in the number of subcarriers from $N = 1000$ to $N = 2000$ results in a degradation of BER performance. This indicates the trade-off between spectral efficiency and system reliability, with a need for optimized subcarrier allocation to counteract performance degradation due to pointing errors.

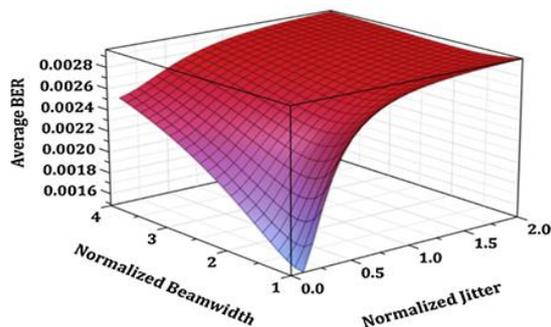


Figure 3.4 BER versus Normalized beamwidth and jitter (Preeti Samhita Pati & Prabhu Krishnan, 2019).

The effects of normalized beam radius and jitter standard deviation on pointing errors and the performance of OFDM-based RoFSO system are illustrated using 3D plots in Figures 3.4 and 3.5. The results show that increased values of normalized beam radius and jitter standard deviation cause BER degradation of the FSO link. In particular, in Fig. 5, under a normalized beam width of 1, the mean BER degrades from 0.0016 to 0.003 as the normalized jitter varies from 0 to 2. 6, with a CNDR of 10 dB, the BER deteriorates from 10^{-4} to 10^{-3} as the normalized jitter reduces from 2 to 0. These findings indicate that there is a need for an optimal beam width and smaller jitter values in order to obtain the desired BER performance in RoFSO systems.

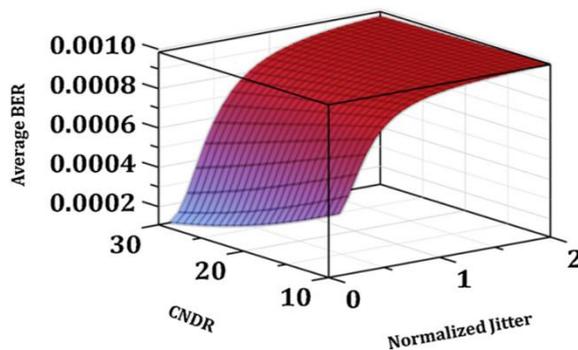


Figure 3.5 BER as a function of average CNDR (db) and normalized jitter (Preeti Samhita Pati & Prabhu Krishnan, 2019).

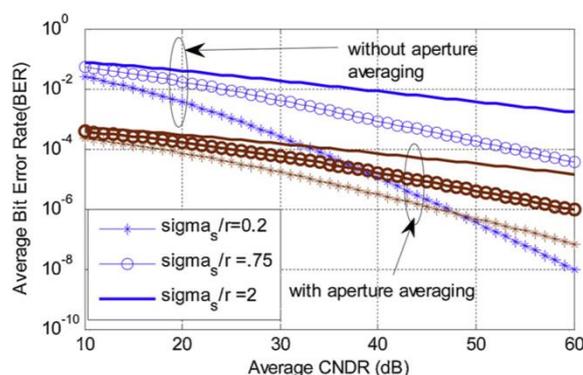


Figure 3.6 BER estimation with respect to average CNDR with an aperture with diameter of 4cm for a 64-PSK modulated OFDM FSO link (Preeti Samhita Pati & Prabhu Krishnan, 2019).

In Figure 3.6, it shows the impact of aperture averaging on the BER performance of a PSK-based OFDM-FSO system is presented, demonstrating considerable improvement with the increase in receiver aperture diameter. As can be seen from the figure, the inclusion of a receiver aperture diameter of 4 cm improves BER performance, with additional gains achieved as the aperture diameter is increased. However, for aperture diameters greater than 6 cm, performance gain saturates, reflecting a declining effect of aperture size on BER reduction. These findings emphasize the necessity of receiver aperture diameter optimization for performance and complexity balance.

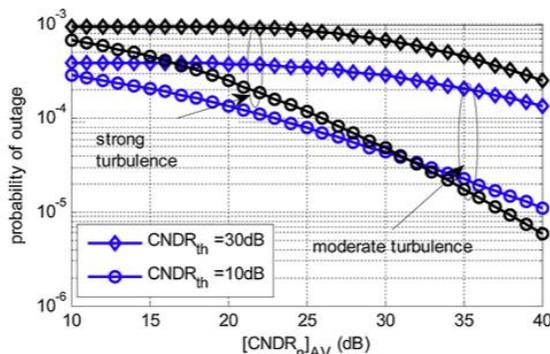


Figure 3.7 Outage probability for OFDM FSO link regarding to average CNDR for varying turbulence strength for N= 1000 and K= 64 (Preeti Samhita Pati & Prabhu Krishnan, 2019).

Figure 3.7 depicts The outage probability for the OFDM-FSO channel is examined with two different values of

threshold CNDR, which indicates that the outage probability goes up as the threshold value is increased from 10 dB to 30 dB. The system also performs more effectively in the moderate turbulence case than in strong turbulence when errors in pointing exist. This suggests that increased levels of turbulence, coupled with tight CNDR thresholds, greatly influence system dependability, highlighting the necessity for optimal threshold selection so as to reduce outage probability across different turbulence conditions.

4. CHALLENGES AND GAPS

Some problems remain unsolved with the DrFSO technology even with all the advancements made. One key area remains the degradation of the signals and links as well as the severe attenuation caused by adverse environmental conditions like dust storms, fog, and turbulence. These factors drastically affect a system's reliability and availability [7]. There are some multi-hop transmission and error correction techniques that help out, but these are very resourceful and extreme taking in some cases and are not as efficient or sufficient in most conditions [3].

Another problem that arises is the sparse validation of practical experiments when dealing with theoretical models. A vast majority of research conducted with RoFSO is based on estimations and simulations, thus making it hard to measure the effectiveness of these systems at different levels of atmospheric pressure and other conditions [2]. The simulated estimates need to be tested in the real world, so there is a necessity for deeper field tests, which could eliminate all discrepancies between models and simulations.

Also, the algorithms for hybrid multiplexer have proven hard to real MDM, WDM, and PDM X RoFSO systems. While these techniques produced better results for data transmission expansion, the practical implementation of these techniques in a working RoFSO is very complex due to the hardware constraints and increased overall expenditure on the whole system [15].

Finally, there is still much to learn about adaptive and real-time signal processing. Robust techniques to dynamically modify transmission parameters in response to current environmental conditions are absent from RoFSO systems. Performance could be further improved by combining real-time error correction with AI-driven adaptive optics [4].

5. FUTURE RESEARCH DIRECTION

Efficiency, security, and the modification or error-correcting methods of RoFSO systems require several additional studies focused on AI-based optimization frameworks, hybrid multiplexing systems, and the integration of novel structures. One of the approaches or areas needing attention is the atmosphere limitation prediction and compensation system, as advanced neural networks could learn and actuate compensation strategies in real-time. Besides, other enabling novel quantum-based optical communication systems can fundamentally change RoFSO networks. Aiming where the theoretical work meets practical execution, the defined computer models must be experimented with on a broad scale. Such novel findings will also further improve the integration of blockchains as new models for data-securing mechanisms and the combination of RoFSO with satellite optical communication systems.

6. CONCLUSION

The combined analysis demonstrates the impact of peripheral factors on FSO and RoFSO systems while also noting advances in beam optimization, multiplexing, and adaptive mitigation techniques. The infusion of artificial intelligence and machine learning in setting transmission parameters dynamically based on shifts in the environment optimizes system performance even beyond expectation. To sustain combat readiness for complex scenarios, future work on RoFSO optimization needs to focus on real-time adaptive signal processing and multi-layered AI-based optimization technologies. Additional FSO and RoFSO communication network modulation, multiplexing, and error correction coding should also be researched to further refine hybrid systems.

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