Tanzania Journal of Engineering and Technology 2024, **43**(**4**):77-92

Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v43i4.1006

Regular Research Manuscript

Performance Evaluation of Free Space Optical Communication in Dar es Salaam: Impact of Scintillation and Modulation Schemes

Mustafa H. Mohsini[1]†, Florence Rashidi[2] and Teck Kinte Chiyaba[2]

[1]Department of Computer Science and Engineering, The University of Dodoma, Dodoma, Tanzania
[2]Department of Electronics and Telecommunication Engineering, The University of Dodoma, Dodoma, Tanzania
†Corresponding author: mustafa.mohsin@udom.ac.tz; ORCID: 0000-0003-0219-7946

ABSTRACT

Free space optical communication (FSO) holds significant relevance in the modern communication system as it offers high and unlimited data rates, enhanced security, rapid deployment, and low cost for installation. However, the performance of FSO transmission is greatly affected by harsh atmospheric conditions such as wind, temperature, and humidity, which induce scintillation. With the rapid growth of internet users and Dar es Salaam being a business city in Tanzania, higher and unlimited bandwidth for communication is highly demanded. This study primarily aims to evaluate the performance of FSO transmission in Dar es Salaam, Tanzania, by investigating the impact of atmospheric conditions particularly scintillation on link availability and transmission quality. We evaluated link availability and the effect of scintillation in terms of eye diagrams, Bit Error Rate (BER), and two modulation schemes (i.e. Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ) schemes) in the Dar es Salaam region. Our work used weather data, including temperature, relative humidity, and wind speed average data, collected from January 2014 to December 2017 by the Tanzania Meteorological Authority (TMA) in the Dar es Salaam region for link availability and performance analysis. The simulation was performed to determine the FSO link availability, and the scintillation effect was analyzed using the Hufnagel Valley (HV) day prediction model. Results analysis indicates that link availability is significantly influenced by atmospheric conditions, with the simulation results showing that Dar es Salaam has higher FSO attenuation and that the transmission can sustain link availability up to a distance of two kilometers. A comparison of the two modulation schemes has shown that NRZ is the best modulation scheme that could be used, and January is the best month for transmission in Dar es Salaam. This technology is feasible and therefore is recommended for adoption.

ARTICLE INFO
First submitted: **June 3, 2024**

Revised: **Oct. 8, 2024**

Accepted: **Dec. 29, 2024**

Published: **Jan., 2025**

Keywords: *Free space optical communication, visibility, scintillation, bit error rate, Signal to noise ratio.*

INTRODUCTION

Free space optical communication (FSO) has emerged as a promising technology for high-speed data transmission using optical signals through the atmosphere, eliminating the need for physical fiber optic cables. FSO systems are increasingly gaining attention due to their potential to deliver high data rates, low latency, and enhanced security (Chaudhary and Amphawan, 2014). However, the performance of FSO systems is significantly influenced by various atmospheric conditions, particularly visibility and scintillation (Sharma *et. al*., 2021; SreeMadhuri and Mahaboob, 2017).

Visibility, characterized by meteorological parameters such as fog, haze, and rain, can severely affect the attenuation and scattering of optical signals in the atmosphere (Chaudhary *et. al*., 2014). On the other hand, scintillation arises from rapid fluctuations in the refractive index of air, leading to variations in the intensity and phase of the received optical signal (Andrews & Phillips, 2005; Amphawan and Chaudhary, 2015). Previous studies have highlighted the impact of these atmospheric factors on FSO communication in various settings (Chaudhary *et. al*., 2020), yet limited research has specifically addressed these phenomena in the context of Dar es Salaam, Tanzania.

Dar es Salaam presents a unique environment for FSO communication due to several geographical factors. Its coastal location subjects it to maritime weather influences, including high humidity and varying wind patterns, which can significantly impact signal propagation. Additionally, the city experiences a tropical climate characterized by distinct wet and dry seasons, contributing to fluctuations in visibility and atmospheric turbulence. These geographical features create a dynamic environment that necessitates a thorough investigation into the performance of FSO systems. Furthermore, the growing population and increasing demand for reliable internet connectivity in Dar es Salaam highlight the need for alternative communication technologies like FSO.

To address these challenges, our work utilized weather data specifically, average temperature, relative humidity, and wind speed collected from January 2014 to December 2017 by the Tanzania Meteorological Authority (TMA) in the Dar es Salaam region. This data was essential for analyzing link availability and assessing FSO performance in the context of local atmospheric conditions.

Given the diverse nature of FSO applications, selecting appropriate modulation schemes is vital for ensuring effective data transmission under varying atmospheric conditions. This study focuses on comparing two widely used modulation schemes i.e. RZ and NRZ. The selection of these schemes is based on their differing characteristics in terms of bandwidth efficiency, power consumption, and resilience to noise and distortions, particularly in environments affected by scintillation and visibility challenges.

Despite the growing interest in FSO technology, existing literature lacks in-depth studies focusing on the specific atmospheric and geographical conditions prevalent in Dar es Salaam. Accordingly, this paper aims to bridge this gap by providing a comprehensive analysis of FSO system performance in the region, considering both visibility and scintillation characteristics.

The contribution of our paper is fourfold:

- To assess the impact of varying visibility conditions on the performance of FSO communication in Dar es Salaam.
- To analyze the effects of scintillation on the quality and reliability of FSO links in the region.
- To analyze the NRZ and RZ modulation schemes and determine the one that best fits FSO realization in the Dar es Salaam region by comparing their BERs.
- To provide insights and recommendations for optimizing FSO communication systems in the presence of visibility and scintillation challenges.

The remainder of this paper is organized as follows: Section II presents the literature review. Section III describes the proposed FSO solution. Simulation results and discussion are provided in Section IV, and Section V contains the concluding remarks.

LITERATURE REVIEW

FSO is a technology that utilizes light to transmit data over distances without the need for physical cables. It offers high data rates, low latency, and secure communication, making it an attractive option for various applications, especially in environments where traditional fiber optics may be impractical. However, the performance of FSO systems is significantly influenced by atmospheric conditions, such as fog, haze, rain, snow, and scintillation, which can degrade signal quality and reliability. Understanding these atmospheric conditions is crucial for optimizing FSO system design and implementation.

Research on FSO has significantly focused on how these atmospheric conditions affect system performance and reliability. These studies are essential for developing effective models that enhance FSO technology in different environments.

Zhang *et. al*. (2017) conducted both theoretical and experimental research to explore the effects of scintillation in FSO systems. Their methodology included simulations that modeled atmospheric turbulence and empirical tests to measure signal degradation. The findings revealed that variations in the refractive index significantly degrade signal quality, emphasizing the need for robust modulation schemes. This study underscores the importance of accounting for scintillation in FSO system design, informing our current research focus on similar atmospheric challenges.

Sahota (2017) demonstrated that high scintillation levels correspond to elevated Bit Error Rates (BER), the ratio of erroneous bits received to the total number of bits transmitted. Sahota established a correlation between turbulence intensity and BER through detailed analysis, highlighting how atmospheric conditions can directly impact system performance. This connection is pivotal for our study, as it reinforces the necessity of understanding environmental factors when designing FSO systems.

Khandakar *et. al*. (2018) provided insights into the performance of FSO links in Qatar, identifying high temperatures and solar irradiance during summer as critical factors affecting FSO communication. Their approach involved both empirical measurement and simulation, highlighting how local climatic conditions can impact system reliability. This emphasizes the importance of tailoring FSO system designs to specific environmental factors, a principle that underpins our research objectives.

Singh and Malhota (2019a) focused on high-speed FSO systems with data rates of 2×20 Gbit/s and a carrier frequency of 40 GHz, providing performance metrics under various atmospheric conditions. However, while their study offers insights into data transmission capabilities, it does not specifically address scintillation, which is a significant factor in our research.

Subsequent research by Singh and Malhota (2019b) examined different modulation schemes in a high-speed MDM-based RoFSO transmission link, noting the influence of atmospheric turbulence on link performance while lacking an in-depth analysis of scintillation effects. (Singh *et. al*., 2021) proposed a hybrid approach combining OFDM and MDM techniques in desert environments, but again, the focus on scintillation was limited. These gaps highlight the need for our study to specifically address the impact of scintillation on FSO performance.

Moreover, Singh *et. al*. (2022) investigated RoFSO transmission links, emphasizing the benefits of combining RF and optical technologies for enhanced wireless communication. Nonetheless, this study also fell short in addressing the impact of scintillation on FSO performance.

Research by Twati (2014) in Libya examined the impact of rain on FSO performance using the CARBONNEAU empirical model. The study utilized a combination of theoretical modeling and field tests to assess how varying rainfall intensities affected signal quality. The results indicated that while rain can significantly degrade signal transmission, its impact varies based on local environmental conditions. This finding is relevant to our research, as it emphasizes the need to consider localized weather patterns when evaluating FSO performance.

In Namibia, Handura *et. al*. (2016) assessed FSO feasibility under various atmospheric conditions, employing theoretical models to predict atmospheric losses. Their comprehensive analysis included different weather scenarios, providing valuable insights into potential performance limitations of FSO systems. This study informs our research by illustrating the necessity of theoretical modeling to anticipate challenges in specific geographical contexts.

In Tanzania, Rashid and Semakuwa (2014a) analyzed the effects of rain on FSO in the Arusha region, concluding that optimal transmission power is essential for minimizing BER and power loss. Their research involved extensive field measurements to assess signal quality under various rainfall conditions. This study is particularly relevant to our work, as it provides a framework for evaluating transmission power requirements based on environmental variables.

Again, Rashid and Semakuwa (2014b) investigated the effect of rain on the performance of FSO communication in Dodoma and Dar es Salaam, Tanzania. Their findings revealed that to ensure minimal power loss and lower Bit Error Rates (BER), specific optical attenuation losses should be considered based on local conditions. This work underscores the need to account for environmental factors when designing FSO systems, informing our research focus on similar atmospheric challenges in Dar es Salaam.

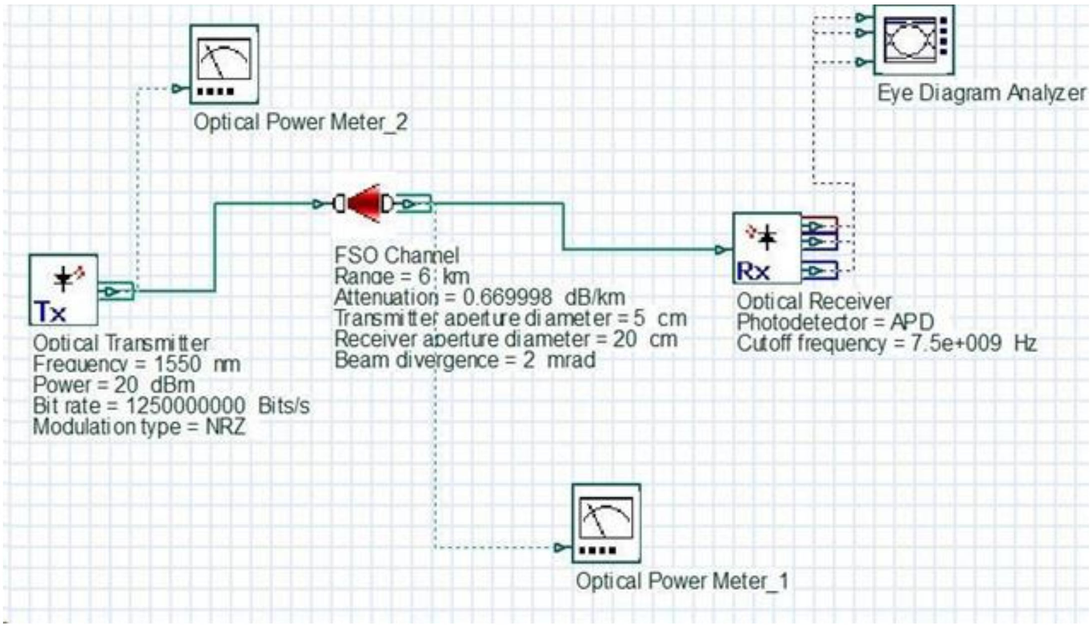
A recent study by Rashidi *et. al*., (2023) examined the performance of FSO communication links under the scintillation effect in Mwanza and Arusha regions, employing the Hufnagel Valley and Submarine Laser Communication models. This study provides a practical evaluation of link availability and the effects of scintillation on performance metrics like BER and Q-factor. Their findings demonstrate that atmospheric conditions, particularly scintillation, significantly impact FSO performance, reinforcing the need for localized studies. The methodologies used, including extensive data collection and simulation, align closely with our approach and strengthen the relevance of our research in understanding FSO systems in similar environments.

Despite the wealth of studies addressing FSO performance in various conditions, there remains a notable gap in research specifically examining FSO performance in tropical climates, such as that of Dar es Salaam. The unique atmospheric conditions prevalent in tropical regions, characterized by high humidity, frequent rainfall, and specific temperature ranges, require dedicated investigation to understand their impact on FSO systems. This paper therefore utilizes the analysis of attenuation to visibility in the Dar es Salaam region by employing RZ (Return-to-Zero) and NRZ (Non-Return-to-Zero) modulation schemes. FSO-RZ modulation is characterized by its ability to minimize inter-symbol interference by returning to zero between bits, making it advantageous in turbulent conditions. In contrast, FSO-NRZ modulation maintains a continuous signal level during the bit interval, which can enhance bandwidth efficiency but may be more susceptible to noise. The choice of these modulation schemes is influenced by factors such as the expected atmospheric turbulence, the required data rates, and the specific characteristics of the communication environment. Additionally, this study analyzes attenuation due to scintillation under the Hufnagel model using the same modulation schemes to comprehensively assess their performance in the region.

MATERIALS AND METHODS

Simulation Setup

The simulation setup for this study is illustrated in Figure 1. The simulations were conducted using OptiSystem version 7, a comprehensive software tool specifically designed for modeling and simulating optical communication systems. OptiSystem provides a robust platform for integrating various components of optical networks, allowing for detailed analysis of parameters such as modulation schemes, link distances, and environmental influences. The software facilitates the use of advanced algorithms to model the impact of atmospheric conditions on Free Space Optical (FSO) communication, ensuring accurate and reliable results.



Optical Transmitter
Frequency = 1550 nm
Power = 20 dBm
Bit rate = 1250000000 Bits/s
Modulation type = NRZ

FSO Channel
Range = 6 km
Attenuation = 0.669998 dB/km
Transmitter aperture diameter = 5 cm
Receiver aperture diameter = 20 cm
Beam divergence = 2 mrad

Optical Receiver
Photodetector = APD
Cutoff frequency = 7.5e+009 Hz

Figure 1. The detailed structure of the FSO system via the OptiSystem interface under the scintillation effect.

Table 1: Values and units of parameters for the experimental setup

Parameters	Value	Unit
Transmission bit rate	2.5	Gb/s
Transmitted power	10	dBm
Wavelength	1550	Nm
Transmitter aperture diameter	10	Cm
Receiver aperture diameter	10	Cm
Cut off frequency	0.75	Hz
Beam divergence	2	mrad
Receiver type	APD	
Modulation scheme	NRZ/RZ	

Key parameters (shown in Table 1) in the simulation included a transmission bit rate of 2.5Gb/s, a transmitted power level of 10dBm, and a wavelength of 1550nm. Both the transmitter and receiver had aperture diameters of 10cm, with a beam divergence of 2mrad, optimizing signal capture across distances ranging from 2km to 8km. This range was selected to reflect typical urban deployment scenarios such as that in Dar es

Salaam, where FSO systems may need to cover varying link lengths based on infrastructure and user demand. Distances closer to 2km represent more favorable conditions with lower atmospheric attenuation, while the upper limit of 8km allows for assessment under more challenging conditions, where factors such as scintillation and visibility become increasingly significant.

The study utilized two modulation schemes i.e., NRZ) and Return-to-Zero RZ to evaluate their performance under varying environmental conditions. The selection of these modulation types was guided by their differing characteristics in bandwidth efficiency and resilience to noise.

Environmental conditions were modeled using weather data collected (shown in Table 2) from the Tanzania Meteorological Authority (TMA) from January 2014 to December 2017, including average temperature, relative humidity, and wind speed. The values chosen for these parameters were based on historical data reflecting the climatic patterns typical for Dar es Salaam. For instance: the average temperatures range from 24.25°C in July to 28.7°C in January, representing the tropical climate of Dar es Salaam. These values reflect the warm temperatures that are prevalent in this coastal city, influencing the performance of optical signals due to thermal fluctuations; the average relative humidity varies from 76.75% in January to 88.5% in April, aligning with the city's wet season. High humidity levels can enhance scintillation effects, making it crucial to include these conditions in the simulation to accurately predict performance under realistic atmospheric scenarios; the average wind speed ranges from approximately 4.5 knots in April to 11 knots in January. These values reflect local weather patterns, where wind can cause turbulence and affect signal stability. Including a range of wind speeds allows for the evaluation of how different conditions impact the FSO link. This data was essential for simulating realistic atmospheric effects on signal propagation, particularly the impacts of humidity and temperature fluctuations on scintillation and link availability.

Table 2. Weather Data from TMA

Month	Temp (℃)	Relative Humidity (%)	Wind Speed (knots)
January	28.7	76.75	11
February	28.5	79	9.25
March	28.1	83.5	5.25
April	26.6	88.5	4.5
May	25.6	86.5	6
June	24.975	82.25	6.5
July	24.25	81	6.75
August	24.8	80	6
September	25.025	79.75	5.75
October	26.45	79	6
November	27.375	81.5	5.5
December	28.4	79.75	8.25

To calculate the atmospheric attenuation, we implemented the Kruse model for visibility attenuation and the Hufnagel Valley model for scintillation effects, ensuring a comprehensive evaluation of the FSO system's performance. A total of 358 simulation iterations were performed, encompassing various combinations of distances, months, and modulation schemes, which allowed for an in-depth analysis of how these factors influence Bit Error Rate (BER) and overall system reliability.

Visibility Attenuation and Total Scintillation

Total scintillation combines the effect of visibility and the attenuation due to scintillation. Visibility is defined as the range at which the image contrast drops to 0.02. The visibility information that is obtained can be used to determine the FSO channel availability. The atmospheric attenuation is a function of visibility and as a result, varying it will result in an increase or decrease in channel availability (Beshr & Aly, 2008). In tropical regions, haze, and rain are the factors that contribute to the signal degradation that affects FSO communication. These factors create low visibility and high attenuation occurs as a result. The high attenuation then reduces the link availability of the optical signal (Shumani *et. al.*, 2017). The visibility attenuation is given by the Kruse model and is expressed in (1)

$$\gamma = \frac{3.912*}{V}\left[\frac{\lambda}{550}\right]^{-q} \qquad (1)$$

where:

V is the visibility of the atmosphere in km, λ is the wavelength and q is the parameter relating to the particle size distribution of the atmosphere given by (2):

$$q = \begin{cases} 1.6\ for\ V > 50km \\ 1.3\ \ for\ (6km < V < 50km) \\ 0.585V^{\left(\frac{1}{3}\right)}\ for\ V < 6km \end{cases} \qquad (2)$$

Scintillation is caused by optical-power changes due to atmospheric turbulence (Perlot, 2007). Attenuation is defined as a physical process that creates changes in signal power throughout the transmission. There are many causes of signal attenuation such as rain, fog, snow, scintillation, etc. The attenuation due to scintillation is calculated by (3)

$$\alpha_{scint} = 2\sqrt{23.13k^{\left(\frac{7}{6}\right)} \times C_n^2 \times L^{\left(\frac{11}{6}\right)}} \qquad (3)$$

where k=2π/λ is the wave number (m^(-1)), L is the length of the link (m), and C_n^2 is the refractive index structure parameter (m−2/3). In this paper, we have considered only the visibility and scintillation for the losses due to the atmosphere to calculate the total scintillation. Accordingly, the total attenuation due to atmospheric losses as shown in (4)

$$\alpha_{total} = \alpha_{scint} + \gamma \qquad (4)$$

Data Collection Procedure and Data Analysis

Data Collection Procedure

The data collection for this study was conducted through a systematic approach to ensure the reliability and validity of the findings. The research focused on Dar es Salaam region in Tanzania. The location was selected due to its climatic conditions, which significantly influence FSO communication. By analyzing this region, the study aimed to capture a comprehensive dataset that reflects the variability in atmospheric conditions affecting FSO systems. Accordingly, data were collected from the Tanzanian Meteorological Agency (TMA), which provided historical weather data spanning from 2014 to 2017. The dataset included critical atmospheric parameters such as humidity, temperature, and wind speed. These parameters were essential for assessing visibility and scintillation, two key factors impacting FSO communication.

Data Analysis

The analysis of the collected data involved a combination of statistical methods and simulation techniques to evaluate the impact of visibility and scintillation in FSO communication. Initially, the study focused on calculating the visibility and scintillation attenuation using established equations i.e. equations 1 to 4. These calculations incorporated various atmospheric parameters, ensuring that the analysis accurately reflected the conditions in Dar es Salaam. Researchers of this work believe that using validated formulas from relevant literature enhanced the reliability of the results.

To further analyze the performance of FSO systems, simulations were conducted using OptiSystem version 7. This simulation tool allowed for the evaluation of different modulation schemes, specifically NRZ and RZ, under varying atmospheric conditions. By configuring parameters such as link distance and environmental factors, the simulations provided insights into performance metrics, including BER. This step was crucial for understanding how different conditions affect communication quality over the FSO link. The results from the simulations were subjected to comprehensive statistical analysis to derive meaningful conclusions. Descriptive statistics were employed to summarize the data, while comparative analysis facilitated the evaluation of different modulation schemes. Graphical representations, such as eye diagrams and attenuation plots, were generated to visually convey the findings.

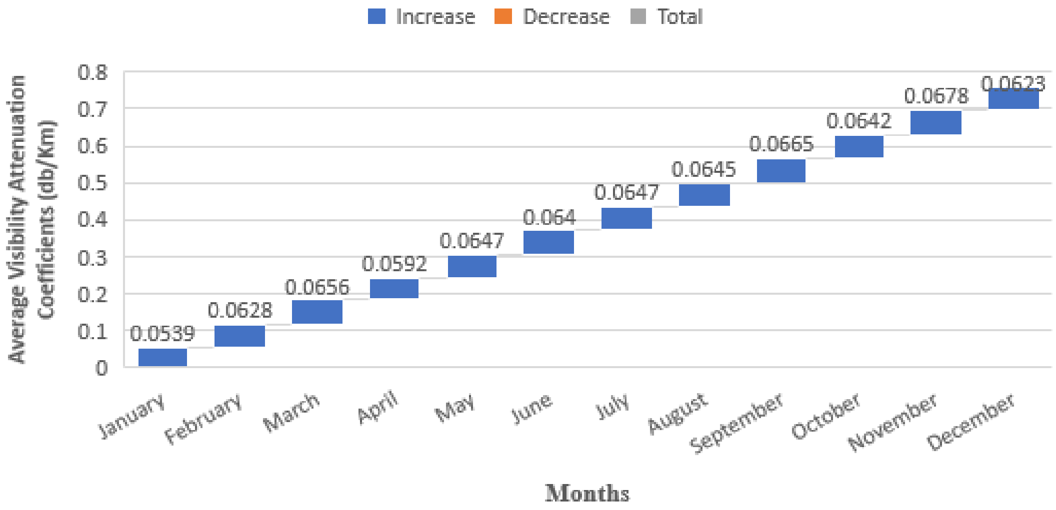


Figure 2: Monthly average visibility attenuation coefficients.

RESULTS ANALYSIS AND DISCUSSION

This study investigates the effect of visibility and scintillation on Free Space Optical (FSO) communication in Dar es Salaam, focusing on atmospheric-specific attenuation values. We collected and analyzed data spanning several years, specifically from January 2014 to December 2017, to assess the influence of weather conditions and seasonal changes on FSO link performance. The analysis explicitly tests for weather and seasonal variations by evaluating monthly average visibility and scintillation attenuation data, thereby providing a comprehensive view of how these factors impact FSO communication throughout the year. Accordingly, this section presents and interprets the results of the individual and total attenuation values due to visibility and scintillation for the Dar es Salaam region. These findings are crucial for understanding the performance of FSO systems in varying atmospheric conditions, particularly in urban settings.

Atmospheric Attenuation Analysis

The visibility attenuation was calculated using the Kruse model based on monthly average data. Figure 2 illustrates that January exhibits the lowest visibility attenuation coefficient of 0.0539 dB/km. This finding is significant as it highlights the temporal variations in atmospheric conditions that can affect FSO performance. This observation aligns with previous studies, such as that by (Chaudhary *et. al*., 2014), which emphasizes the critical role of seasonal weather patterns in optical communication.

Simultaneously, scintillation attenuation values, determined using equation (4), indicate that the lowest scintillation attenuation of 2.0791 dB occurs at a distance of 2 km in January as shown in Table 3. This suggests that shorter link distances during periods of low scintillation can enhance FSO transmission reliability. The implications of these results are profound as they suggest that optimizing link distances and timing for deployment can significantly improve communication efficacy in urban environments like Dar es Salaam. This finding supports the conclusions of (Sharma *et. al*., 2021), who noted that localized atmospheric conditions could drastically affect FSO performance.

Table 3: Monthly Average Scintillation Attenuation in Decibels

Month	Distances (Km)			
	2	4	6	8
January	2.0791	3.9234	5.6885	7.4040
February	2.0836	3.9324	5.7019	7.4219
March	2.0851	3.9353	5.7063	7.4277
April	2.0820	3.9291	5.6970	7.4153
May	2.0847	3.9345	5.7050	7.4261
June	2.0843	3.9337	5.7039	7.4246
July	2.0846	3.9343	5.7048	7.4258
August	2.0845	3.9341	5.7045	7.4254
September	2.0855	3.9361	5.7075	7.4294
October	2.0843	3.9338	5.7040	7.4247
November	2.0861	3.9374	5.7095	7.4320
December	2.0833	3.9319	5.7011	7.4209

However, unexpected results reveal that scintillation effects were more pronounced than anticipated, particularly during the months of higher humidity. While it was expected that visibility would primarily influence performance, the significant impact of scintillation suggests that atmospheric turbulence may play a larger role than previously documented. An alternative interpretation could be that humidity levels, rather than just visibility, significantly contribute to the refractive index fluctuations that cause scintillation. This highlights the complexity of atmospheric interactions and suggests a need for further investigation into the interplay between humidity and scintillation effects.

Table 4: BER for 2 km – 8 km under NRZ

Month	Distances (Km)			
	2	4	6	8
January	0	0	8.31E-290	6.13E-031
February	0	0	1.64E-284	4.04E-030
March	0	0	8.40E-283	7.20E-030
April	0	0	1.83E-286	1.99E-030
May	0	0	2.85E-283	6.11E-030
June	0	0	9.62E-284	5.29E-030
July	0	0	2.48E-283	5.98E-030
August	0	0	1.65E-283	5.75E-030
September	0	0	2.83E-282	8.66E-030
October	0	0	1.10E-283	5.29E-030
November	0	0	1.63E-281	1.13E-029
December	0	0	8.35E-283	3.57E-030

Total Attenuation Coefficients

The total monthly attenuation coefficients, derived from combining visibility and scintillation effects, reveal a clear trend i.e., total attenuation coefficients decrease with increasing link distance, as shown in Figure 3. This trend underscores the importance of selecting appropriate link distances based on the time of year and prevailing atmospheric conditions.

Lower total attenuation values correspond to higher transmission reliability, indicating that FSO systems can be particularly effective during January. These insights are critical for network engineers and telecommunications planners, as they emphasize the need to consider seasonal variations when designing FSO networks. This observation resonates with the findings of (Rashid and Semakuwa, 2014b), who pointed out that atmospheric conditions play a vital role in determining FSO feasibility in different regions.

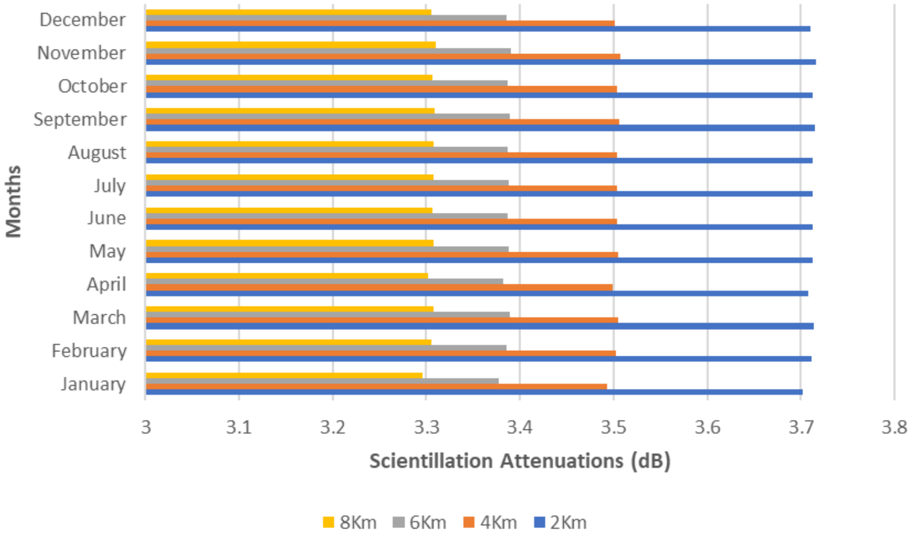


Figure 3: Monthly total scintillation attenuations.

Table 5: BER for 2 km – 8 km under RZ scheme

Month	Distances (Km)			
	2	**4**	**6**	**8**
January	0	0	3.65E-278	2.16E-030
February	0	0	2.59E-273	1.73E-029
March	0	0	9.57E-272	2.49E-029
April	0	0	4.19E-275	6.97E-030
May	0	0	3.53E-272	2.12E-029
June	0	0	1.30E-272	1.84E-029
July	0	0	3.12E-272	2.07E-029
August	0	0	2.15E-272	1.99E-029
September	0	0	2.90E-271	2.99E-029
October	0	0	1.48E-272	1.84E-029
November	0	0	1.45E-270	3.89E-029
December	0	0	1.39E-273	1.24E-029

Bit Error Rate (BER) Analysis

The calculated BER, using both NRZ and RZ modulation schemes shown in Tables 4 and 5 respectively, provides a direct measure of transmission reliability. Table 4 shows that January has the lowest BER rates across various link distances, confirming it as the optimal month for FSO transmission. In contrast, November exhibits the highest BER rates, suggesting that deployment during this month could lead to significant data loss and communication failures.

These results directly address the research objective of assessing the impact of atmospheric conditions on FSO performance. The findings highlight the necessity of selecting the NRZ modulation scheme over RZ, as NRZ consistently demonstrates lower BER values. This insight holds significant implications for future FSO deployments, indicating that engineers should prioritize NRZ modulation to enhance data integrity and transmission quality. This recommendation aligns with the work of (Singh *et. al*., 2019a), which advocated for NRZ modulation under specific atmospheric conditions due to its robustness.

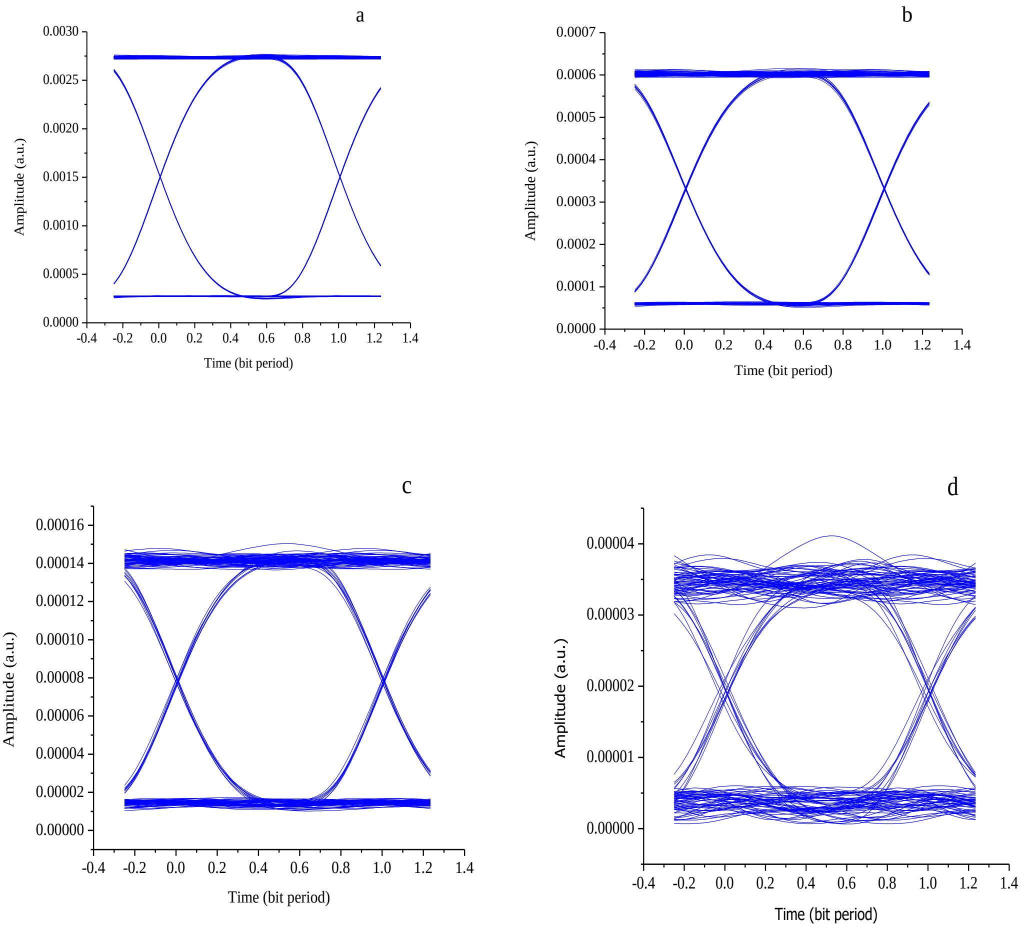


Figure 4: Eye diagram for Dar es Salaam under NRZ modulation at (a) 2 km (b) 4 km (c) 6 km and (d) 8 km.

An unexpected finding was the relatively high BER recorded during certain clear days in January. It was anticipated that clear weather would correlate with optimal transmission conditions, yet fluctuations in atmospheric refractive index due to thermal gradients may have contributed to this anomaly. An alternative interpretation could be that even minor variations in temperature gradients, perhaps caused by nearby urban development or vehicular traffic, may lead to localized turbulence, thus impacting signal quality. This complexity underscores the need for detailed environmental monitoring alongside data collection to fully understand the dynamics affecting FSO performance.

Eye Diagram Analysis

The eye diagram analysis for both NRZ and RZ modulation schemes at various link distances (2 km, 4 km, 6 km, and 8 km), as shown in Figures 4 and 5 respectively, reveals significant insights into signal integrity and performance. The eye diagram analysis reveals that both NRZ and RZ modulation schemes experience degradation in signal quality as the link distance increases. This degradation is primarily attributed to the effects of atmospheric conditions, such as scintillation and turbulence, which introduce noise and distortion to the transmitted signal. The narrowing of the eye openings at longer distances indicates a decline in the signal-to-noise ratio (SNR), leading to an increased likelihood of bit errors.

Despite this overall degradation, NRZ modulation consistently demonstrates superior performance, particularly at shorter distances, where it exhibits wider and clearer eye openings. This enhanced performance can be attributed to NRZ's efficient use of bandwidth, allowing for higher data rates and improved signal integrity under optimal conditions. However, it is important to note that RZ modulation shows a degree of resilience, particularly in the 2 km to 4 km range. Its unique pulse-shaping characteristics help maintain a more defined eye opening compared to NRZ at these distances, suggesting that RZ modulation could be beneficial in scenarios where shorter distances are involved, or where the effects of noise are more pronounced.

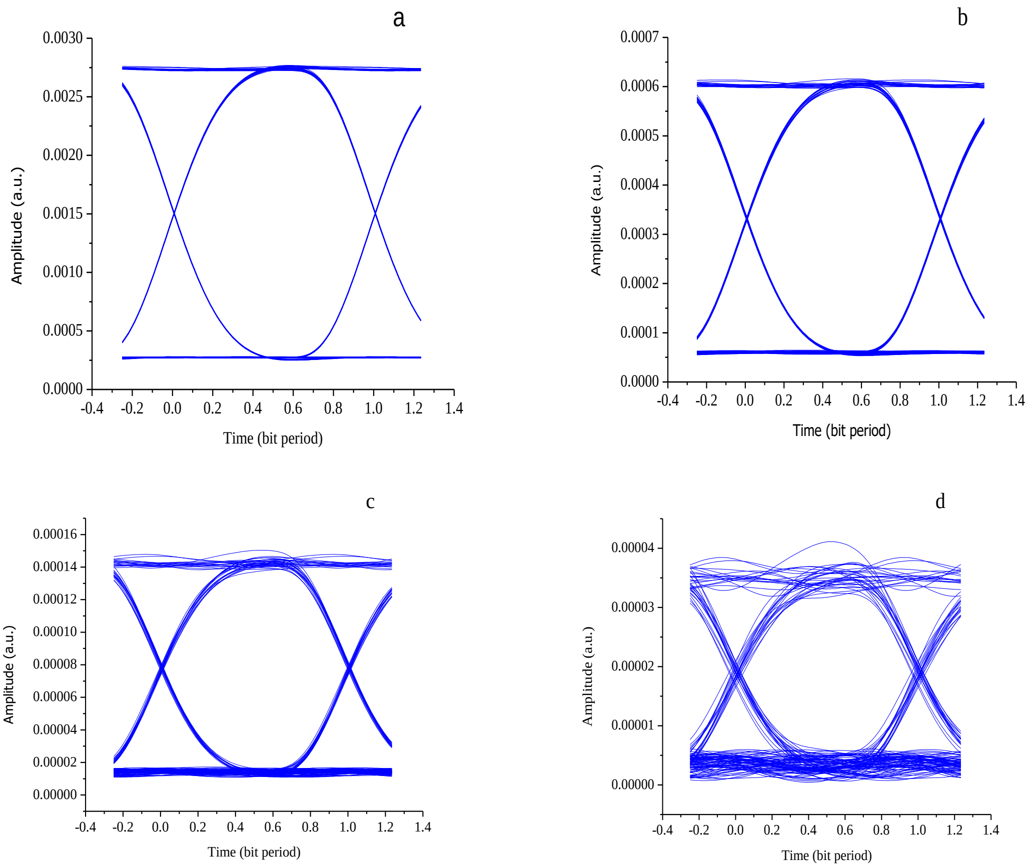


Figure 5: Eye diagram for Dar es Salaam under RZ modulation at (a) 2 km (b) 4 km (c) 6 km and (d) 8 km.

This resilience in RZ modulation highlights its potential applicability in specific environments or applications where signal integrity is paramount, and the transmission distance is limited. For instance, in urban settings with high levels of interference or where physical obstacles affect signal propagation, RZ might provide a more reliable option for maintaining data integrity. Thus, while NRZ may be favored for its overall efficiency and performance, RZ's ability to perform consistently well in certain conditions adds valuable flexibility to system designers when selecting modulation schemes for FSO systems.

Comparison of NRZ and RZ Schemes using BER and Link Distances

Figure 6 presents a comparative analysis of the BER for different modulation schemes across various link distances. The data illustrates how changes in distance and modulation type affect transmission reliability, with NRZ consistently outperforming RZ across all distances. This figure reinforces the findings that NRZ modulation is more resilient to atmospheric disturbances, particularly in urban environments where factors like turbulence and scintillation can introduce noise. The trend depicted in Figure 6 also highlights the increasing BER with distance, particularly for the RZ scheme, which suggests that this modulation type is more susceptible to the cumulative effects of atmospheric attenuation over longer distances.

The implications of these results are significant; they suggest that for optimal FSO system performance, especially in urban settings that experience varying atmospheric conditions, NRZ should be the preferred choice. This aligns with earlier findings and underscores the need for careful modulation selection in FSO system design. Additionally, Figure 6 serves to visually summarize the performance disparities between modulation schemes, making it easier for engineers and planners to make informed decisions in system design, particularly in environments characterized by high atmospheric turbulence based on empirical data. This finding is consistent with earlier research by (Khandakar et al., 2018), which highlighted NRZ as a more effective choice for high-speed FSO links in challenging environments.

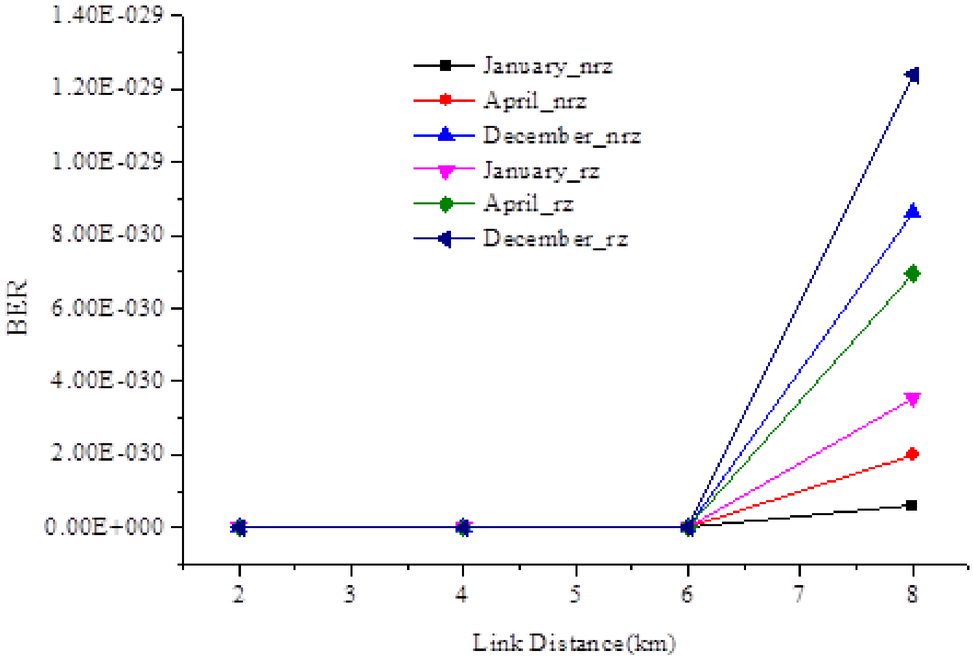


Figure 6: Comparison of BER between NRZ and RZ modulation for Dar es Salaam.

Broader Implications of the Findings for FSO Communication

Overall, this study's findings affirm the feasibility of implementing FSO technology in urban settings like Dar es Salaam, where high-speed data transmission is increasingly critical. The results emphasize that scintillation attenuation increases with distance, posing challenges for longer link distances. Strategic planning for FSO deployments must consider these factors to optimize performance. This is particularly relevant in light of the findings by (Alharbi *et. al.*, 2022), who pointed out that ignoring environmental factors can lead to underperforming systems.

Moreover, the identification of January as the best month for transmission, coupled with the recommendation to use NRZ modulation, provides actionable insights for stakeholders in the telecommunications field. By aligning FSO system design with local atmospheric conditions, operators can vastly improve the reliability and efficiency of communication networks.

The findings in this study contribute to the broader field of optical communication by demonstrating how environmental factors impact system performance. As urban areas continue to grow and demand for high-speed data increases, understanding these dynamics will be essential for the successful implementation of FSO technologies. This study builds on the existing literature by providing localized data and recommendations tailored to the specific atmospheric conditions of Dar es Salaam, thereby advancing the understanding of FSO performance in real-world applications.

CONCLUSION AND RECOMMENDATION

This study investigates the performance of Free Space Optics (FSO) communication systems in Dar es Salaam, focusing on the effects of atmospheric conditions on signal integrity and transmission reliability. Through the analysis of visibility and scintillation attenuation, as well as the evaluation of different modulation schemes, key findings reveal significant variations in performance based on seasonal and environmental factors.

The results indicate that January is the optimal month for FSO transmission, characterized by the lowest bit error rates (BER) and highest signal integrity. The eye diagram analysis demonstrates that both Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ) modulation schemes experience degradation with increasing link distance, though NRZ consistently shows superior performance. Notably, RZ modulation is slightly more resilient at shorter distances, suggesting its potential use in specific applications.

Overall, the findings underscore the importance of optimizing link distances and modulation schemes in FSO networks to enhance reliability and efficiency in urban settings. As demand for high-speed data communication continues to grow, these insights contribute to the broader field of optical communication by highlighting the critical role of environmental factors.

Based on the findings of this study, the following recommendations are proposed for stakeholders and practitioners involved in the deployment of FSO systems:

Firstly, network engineers should consider seasonal variations in atmospheric conditions when planning FSO deployments. January, with its favorable conditions, should be prioritized for installations and maintenance.

Secondly, while NRZ modulation is recommended for optimal performance, RZ modulation may be utilized in scenarios where shorter distances are involved and slight resilience to distortion is beneficial. Engineers should assess the specific requirements of their applications to determine the most suitable modulation scheme.

Thirdly, Optimization of Link Distances: To maintain high transmission reliability, careful consideration must be given to link distances. Implementing adaptive techniques that adjust parameters based on real-time atmospheric conditions could enhance the overall performance of FSO systems.

Lastly, future research should focus on the development of real-time monitoring systems that can track atmospheric conditions and automatically adjust FSO parameters. This would allow for dynamic optimization of link performance. Moreover, additional studies are warranted to explore the effects of varying humidity levels, temperature gradients, and urban development on FSO performance. Understanding these dynamics will be essential for refining existing models and improving system design.

REFERENCES

Alharbi, A. G., & Singh, M. (2022). Downstream Performance Evaluation Of A 4 × 112 Gbps Hybrid Wavelength-Polarization Division Multiplexed Next Generation-Passive Optical Network. *Optical and Quantum Electronics,* **54**, 384. doi:10.1007/s11082-022-03772-y

Amphawan, A., & Chaudhary, S. (2015). Free-space optical mode division multiplexing for switching between millimeter-wave picocells. *International Conference on Optical and Photonic Engineering* (icOPEN 2015). doi: 10.1117/12.2189694

Andrews, L. C., & Phillips, R. L. (2005). Laser Beam Propagation through Random Media. Chapter in a Book: *Free-Space Propagation of Gaussian-Beam Waves,* SPIE Press. doi:10.1117/3.626196

Beshr, M., & Aly, M. H. (2008). Outdoor Wireless Optical Communication System Attenuation at Different Weather Conditions. *18th International Conference on Computer: Theory & Applications (ICCTA) & Arab Academy for Science*, Alexandria, Egypt, pp. 194–199.

Chaudhary, S., & Amphawan, A. (2014). The Role and Challenges of Free-space Optical Systems. *Journal of Optical Communications*, **35**(4). doi:10.1515/joc-2014-0004

Chaudhary, S., Amphawan, A., & Nisar, K. (2014). Realization of free space optics with OFDM under atmospheric turbulence. *Optik - International Journal for Light and Electron Optics*, **125**(18), 5196–5198. doi:10.1016/j.ijleo.2014.05.036

Chaudhary, S., Choudhary, S., Tang, X., & Wei, X. (2020). Empirical Evaluation of High-speed Cost-effective Ro-FSO System by Incorporating OCDMA-PDM Scheme under the Presence of Fog. *Journal of Optical Communications*, **44**(s1). doi:10.1515/joc-2019-0277

Handura, M. R., Ndjavera, K. M., Nyirenda, C. N., & Olwal, T. O. (2016). Determining the feasibility of Free Space Optical Communication in Namibia. Optics Communications, **366**, 425–430. doi:10.1016/j.optcom.2015.12.057

Khandakar, A., Touati, A., Touati, F., Abdaoui, A., & Bouallegue, A. (2018). Experimental setup to validate the effects of major environmental parameters on the performance of FSO communication link in Qatar. *Applied Sciences* (Switzerland), **8**(12). doi:10.3390/app8122599

SreeMadhuri, A., & Mahaboob, S. T. (2017). Evaluating the performance of free space optical link in tropical climate. International *Journal of Advance Engineering and Research Development*, **4**(8), 273-278

Perlot, N. (2007). Evaluation of the scintillation loss for optical communication systems with direct detection. *Optical Engineering*, **46**(2), 025003. doi:10.1117/1.2436866

Rashid, F. U., & Semakuwa, S. K. (2014a). Performance Analysis of Free Space Optical Communication Under the Effect of Rain in Arusha Region, Tanzania. *International Journal of Engineering Research & Technology*, **3**(9), 1523–1526.

Rashid, F. U., & Semakuwa, S. K. (2014b). Analysis of Rain Effect in Free Space Optical Communication under NRZ Modulation in Two Regions of Tanzania. International. *Journal of. Advanced Engineering Nano Technology*, **1**(10), 13–16.

Rashid, F. U., Ulomi, G. S., Ndyalimo, E. E., & Mohsin, M. H. (2023). Performance Analysis of Free Space Optical Communication under Scintillation Effect: A Case of Mwanza and Arusha Regions. *Journal of ICT Systems*, **1**(1), 57–65. doi:10.56279/jicts.v1i1.33

Sahota, J. K. & Dhawan D., (2017). Analyzing the Effect of Scintillation on Free Space Optics. *International Journal on Recent and Innovation Trends in Computing and Communication,* **5**(6), 493–496. ISSN: 2321-816

Shaina, & Gupta, A. (2016). Comparative Analysis of Free Space Optical Communication System for Various Optical Transmission Windows under Adverse Weather Conditions. *Procedia Computer Science*, **89**, 99–106. doi:10.1016/j.procs.2016.06.014

Sharma, A., Kaur, S., & Chaudhary, S. (2021). Performance analysis of 320 Gbps DWDM—FSO System under the effect of different atmospheric conditions. *Optical and Quantum Electronics*, **3**(5). doi:10.1007/s11082-021-02904-0

Shumani, M. M., Abdullah, M. F. L., & Basahel, A. (2017). Outage analysis of terrestrial free space optical (FSO) link using measured visibility data in Malaysia. *AIP Conference Proceedings*, 1883. doi:10.1063/1.5002023

Singh, M., & Malhotra, J. (2019a). Performance Comparison of 2 × 20 Gbit/s-40 GHz OFDM Based RoFSO Transmission Link Incorporating MDM of Hermite Gaussian Modes Using Different Modulation Schemes. *Wireless Personal Communications*, **110**(2), 699–711. doi:10.1007/s11277-019-06750-y

Singh, M., & Malhotra, J. (2019b). Performance Comparison of Different Modulation Schemes in High-Speed MDM Based Radio Over FSO Transmission Link Under the Effect of Atmospheric Turbulence Using Aperture Averaging. *Wireless Personal Communications*, **111**, 825 – 842. doi:10.1007/s11277-019-06886-x

Singh, Pottoo, S. N., Malhotra, J., Grover, A., & Aly, M. H. (2021). Millimeter-wave hybrid OFDM-MDM radio over free space optical transceiver for 5G services in desert environment. *Alexandria Engineering Journal*, **60**(5), 4275–4285. doi:10.1016/j.aej.202

Singh, K., Singh, M., & Grover, A. (2022). Mode Division Multiplexed Terrestrial Radio-Over-Free Space Optics Transmission: Performance Analysis Under Weather Attenuation. *2022 IEEE Conference on Interdisciplinary Approaches in Technology and Management for Social Innovation* (IATMSI), Gwalior, India, 2022, pp. 1-6. doi: 10.1109/IATMSI56455.2022.10119328

Twati, M. (2014). Analysis of Rain Effects on Free Space Optics Based on Data Measured in the Libyan Climate. *International Journal of Information and Electronics Engineering*, **4**(6), 469–472. doi:10.7763/ijiee.2014.v4.485

Zhang, Y., Wang, P., Guo, L., Wang, W., & Tian, H. (2017). Performance analysis of an OAM multiplexing-based MIMO FSO system over atmospheric turbulence using space-time coding with channel estimation. *Optics Express*, **25**(17), 19995. doi:10.1364/oe.25.019995