Received: 14 May 2025 | Revised: 06 Mar 2026 | Accepted: 1 Jun 2026 | Published: 30 Jun 2026
Volume 4(1) Pages 26-42 DOI: https://doi.org/10.56279/jicts.v4i1.411

JICTS
Journal of ICT Systems

Performance evaluation of Free Space Optical Communication as Backhauling Network

Faraji Hassan, Eva Shayo

Department of Electronics and Telecommunications Engineering, University of Dar es Salaam, Dar es Salaam, Tanzania

[1]**Corresponding author**
Email: shayo.eva@udsm.ac.tz

Funding information

This work has, received partial funds from the University of Dar es Salaam, Tanzania.

Keywords

Bit Error Rate
Communication System
FSO
Transmission Distance
Q-factor

Abstract

Free Space Optical (FSO) systems use laser technology for telecommunication backhaul networks. They offer several advantages over conventional backhaul technologies including high data rates, license-free operation, and low deployment costs. However, their performance is highly susceptible to weather conditions, limiting their widespread deployment. This study evaluates the feasibility of deploying FSO systems as a backhaul solution in Dar es Salaam by proposing a double-channel FSO architecture to address the growing demand network capacity and extended transmission distances. The proposed system is compared with a conventional single-channel FSO system using Bit Error Rate (BER) and Quality (Q) factor as key performance metrics. In addition, the maximum transmission distance and data rate that satisfy reliable signal quality are determined. Simulation results under clear weather conditions demonstrate that the proposed double-channel FSO system meets the required BER of 10^{-9} and minimum Q factor of 6 while supporting transmission rates of up to 10 Gbps over a maximum distance of 14 km. This corresponds to a 46% increase in transmission distance compared with the single-channel configuration. The findings indicate that double-channel FSO systems significantly improve the capacity and coverage of backhaul networks, making them a promising solution for applications requiring a 14-km range.

Contribution to Sustainable Development Goals (SDGs)

SDG 9 – Industry, Innovation and Infrastructure

This work presents an innovative, high-capacity and cost-effective optical wireless backhaul solution by strengthening a digital infrastructure for sustainable urban services in Dar es Salaam.

1. Introduction

In recent years, there has been significant growth in demand for data bandwidth due to the development of several data-hungry applications, such as online video streaming, online games, and

video conferencing. Furthermore, the rapid growth in the use of Artificial Intelligence (AI) applications, including machine learning, generative AI, and data-intensive cloud services, has significantly contributed to the increase in bandwidth requirements. Several technologies, including twisted pair, coaxial cable, wireless radio frequency, and fiber optic cable, have been used to provide data services to support the aforementioned applications [1]. However, with the increased demand for data-intensive applications, such as video streaming, cloud computing, and the Internet of Things (IoT), traditional communication infrastructures cannot guarantee seamless connectivity. In addition, traditional backhaul networks, which are dominated by the use of fiber optics and microwave links, are limited in providing efficient data communications requirements [2]. On the one hand, the deployment of Fiber optics as backhauling network is limited by geographical obstacles (such as difficult terrain, rivers, mountains and urban structures that complicate cable laying), installation and operational costs, which are more serious in remote and rural areas [3]. On the other hand, microwave links are vulnerable to atmospheric disturbances like rain fade and electromagnetic interference, compromising their reliability significantly [4].

Free Space Optical (FSO) communication presents an alternative solution, leveraging optical wireless communication principles to transmit data through directed beams of light [5]. While fiber-optic cables can achieve extremely high capacities through wavelength-division multiplexing, FSO provides comparable Gbps-to-Tbps bandwidth in a wireless line-of-sight configuration, eliminating the need for physical cabling and making it particularly attractive where fiber deployment is impractical [3]. FSO system are advantageous for line-of-sight (LoS) communication, where fiber optics or radio frequency (RF) communications are not possible [6]. FSO technology, aligns naturally with objectives of the Tanzania's strategic framework to expand connectivity rapidly in cost-effective manner, especially in areas where physical cabling is challenging [7]. Despite its advantages, FSO technology are vulnerable to atmospheric conditions like fog, haze and physical obstructions, leading to signal loss and degradation which may limit its usability [8]. To address these challenges, advanced adaptive link management strategies have been proposed. The strategies include dynamic on-off switching, load balancing, and dual-mode transceivers that can switch between FSO and RF backhaul based on real-time link quality metrics and environmental sensing. These strategies enhance the backhaul network's resilience and reliability while allowing for context-aware resource allocation and quality of service (QoS) provisioning [9].

In this work, we have explored the potential of using FSO as a backhauling network solution to achieve higher data rates and long transmission distances. We proposed and evaluated the performance of a double FSO channels to address the demands of backhauling networks. The performance of the proposed system in comparison with single FSO channel system was evaluated using Bit Error Rate and Quality factors across various path lengths, data rates, and wavelengths under different atmospheric conditions collected from Dar es Salaam City.

The results indicated that, in clear weather conditions under the maximum required Bit Error Rate (BER) and the minimum Quality (Q) values, the proposed FSO system achieved a transmission capacity of up to 10Gbps over a maximum path length of 14 km. This result represents an increase in transmission distance for double FSO communication system by 46% compared with the single-channel communication system.

2. Related Work

Several studies have analyzed the suitability of FSO in providing short range communications in the far-end networks. A work by Singh et al. [10] evaluated the performance of FSO system focusing on a hybridizing FSO and Fiber optical cable system. The findings indicated FSO capabilities in providing transmission for networks of up to 1.72 km with BER of order 10^{-4}. While the results indicate great system performance at a distance of 1.72 km and a maximum of 1.25Gbps, its applicability is limited in applications that require transmission distance less than 1.72 km.

Jahid et al. [11] presented the challenges of managing the massive volume of mobile data and the high data rate in current networks and suggested that FSO could be a suitable option due to its numerous advantages, including ultra-high data rate transmission capacity, low latency, low cost, and lower power consumption. They emphasize the need for alternative high-capacity backhaul connections to meet the growing network demand. However, clear analysis of the FSO system's capacity in terms of maximum data rate and BER across various channel distances is not presented.

Eid et al. [12] evaluated the performance of FSO systems for short-range applications with low input signal power requirements. The results indicated the good performance of FSO for a short-range transmission up to a maximum distance of 800 m. The performance beyond 800 m is not presented.

Sood and Kaushik [13] investigated the BER of FSO communication system under varying atmospheric turbulence levels. While the results suggested the potential usability of the system up to a 2 km channel distance for a 1,550 nm wavelength, the study was restricted to clear weather conditions only. In addition, the authors did not analyse the achievable data rate and signal quality beyond the 2 km distance.

Owolawi et al. [14] evaluated the availability of FSO links in various cities of South Africa using meteorological data. The results indicated the lowest performance in regions with high occurrence of fog events as compared to other regions with FSO links availabilities of ~99.6% for link distances of 500 m and 600 m, respectively.

While existing studies have explored hybrid FSO-fiber links, short-range FSO, and single-channel performance under idealized conditions, there is limited research to address gigabit backhaul requirements under real tropical urban weather using double-channel architectures for extended reach. The present work identifies the gap in deploying FSO for reliable backhaul networks in Dar es Salaam and proposes a double-channel FSO system that provides spatial diversity to simultaneously improve bandwidth capacity and transmission distance while using local visibility data.

3. Proposed Double Channel FSO Communication System

The backhaul network requires high capacity to transport sufficient data between the access network and the core network (Figure 1). Since most users require bandwidths of 100 Mbps and 1Gbps for a single interface, a core backhaul network should be able to accommodate traffic with data rates greater than 1 Gbps, depending on the applications and network size. To enhance system performance, we have proposed an FSO backhaul network designed with two FSO channels to address the demand of high capacity in terms of data rate and longer transmission distances in the backhaul networks (Figure 2). The proposed double channel FSO link can be connected to the main network as describe in Figure 3. In this study, the double channels FSO communication system has been designed to achieve the requirements for the backhaul network (Table 1). The backhaul network requirements presented in Table 1 are based on

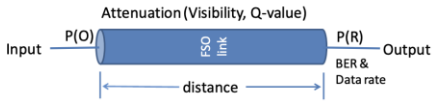


Figure 1. FSO link.

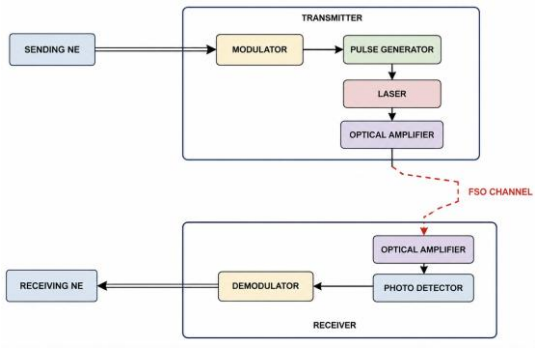


Figure 2. Proposed double channel FSO system.

IEEE 802.3z (1.25 Gbps Gigabit Ethernet) and IEEE 802.3ae (10 Gbps) standards together with typical 5G/6G backhaul quality targets (BER $\leq 10^{-9}$, Q-factor ≥ 6, link distance >10 km). The selected data rates correspond to the widely adopted Gigabit Ethernet (IEEE 802.3z) and 10-Gigabit Ethernet (IEEE 802.3ae) interfaces used in modern backhaul networks. The intermediate rates are supported by the same hardware, but were not simulated in the current study as the focus was on the two standard operating points.

The proposed double-channel FSO system in Figure 1 employs two parallel FSO links transmitting identical data streams. Each transmitter uses the same optical power as the single-channel baseline. At the receiver, the two detected signals are combined using maximal-ratio combining to exploit spatial diversity, in order to improve SNR and extending transmission distance without increasing the per-channel data rate. This architecture directly addresses bandwidth and reliability demands.

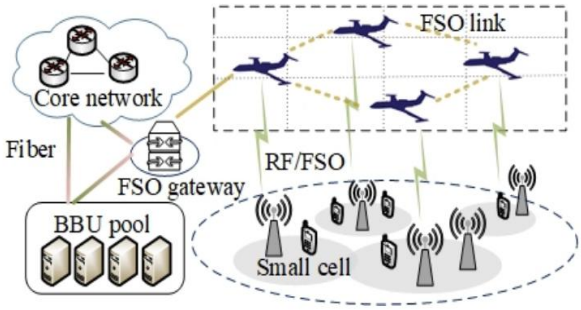


Figure 3. FSO backhaul connection with the core and main network.

Table1: Backhaul network requirements.

Parameter	Value
Data rates	1.25 Gbps and 10 Gbps
Q Factor	6
BER	10^{-9}
Transmission distance	>10 km under clear weather
Wavelength	1550 nm

In FSO system modelling, we integrated local weather conditions from Dar es Salaam City, such as clear, haze, and fog, to accurately simulate real-world scenarios, for assessing signal attenuation and propagation. To achieve the objective of this study, visibility data for Dar es Salaam spanning three consecutive months were collected from the Tanzania Meteorological Authority (TMA) as presented in Figure 4. TMA data were used to provide insights into local atmospheric conditions. Therefore, by analyzing historical visibility data for a specific location, designers can determine the expected availability and performance of the FSO link throughout the year. The data were also used in the system design and simulation to predict system performance.

JULIUS NYERERE INTERNATIONAL AIRPORT (JNIA) VISIBILITY (KM) DECEMBER 2023																													
HR/DATE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	18	30	10	30	30	30	5	30	18	30	30	5	30	30	30	30	30	30	30	8	30	30	30	30	30	30	30	30	30	30	30
3	22	28	26	30	17	30	30	30	15	8	30	11	15	30	30	30	28	30	30	16	30	30	30	30	30	30	30	30	30	30	30
6	17	30	18	10	15	30	30	8	30	18	20	9	30	30	30	20	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
9	10	30	15	30	30	10	30	30	30	30	10	2	30	30	30	30	30	30	28	30	30	30	30	30	30	30	30	30	30	30	30
12	23	30	30	30	22	30	30	30	30	30	30	6	30	30	30	20	25	30	30	22	30	30	30	30	30	30	30	30	30	30	30
15	23	30	17	30	30	30	30	30	30	30	30	0.7	30	30	30	30	30	30	30	28	30	30	30	30	30	30	30	30	30	30	30
18	30	30	18	30	28	30	17	30	30	18	20	1	36	20	30	30	30	30	30	30	23	30	30	33	30	30	30	30	30	30	30
21	30	30	22	30	30	30	30	30	30	30	30	3	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30

JULIUS NYERERE INTERNATIONAL AIRPORT (JNIA) VISIBILITY (KM) JANUARY 2024																													
HR/DATE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	30	30	30	30	30	33	30	30	30	12	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
3	30	28	30	30	30	30	30	30	30	30	30	30	30	30	8	30	30	30	30	30	15	30	30	30	30	30	30	30	30	30	30
6	30	30	30	10	15	30	30	30	30	30	20	30	7	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
9	10	17	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
12	30	30	30	30	30	35	30	30	30	18	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
15	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	12	30	30	30	30	30	30	30	30	30	30	30	30	30	30
18	30	25	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
21	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30

JULIUS NYERERE INTERNATIONAL AIRPORT (JNIA) VISIBILITY (KM) FEBRUARY 2024																															
HR/DATE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29		
0	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30		
3	30	18	30	30	30	30	30	30	30	16	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30		
6	30	30	30	10	15	30	30	30	30	30	20	30	22	30	30	30	30	30	30	30	30	30	12	30	30	30	30	30	30		
9	10	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	28	30	30	22	30	30	30	30	30	30	30	30	30		
12	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30		
15	30	30	30	30	30	30	30	30	30	30	30	30	28	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30		
18	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	14	30	30	30	30	36	30	30	30	30	30		
21	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30		

Figure 4. Proposed double channel FSO system.

The data in Figure 4 presents hourly visibility data (km) collected from TMA station located at Julius Nyerere International Airport (JNIA), Dar es Salaam. Visibility is the meteorological optical range that represents a horizontal distance at which a black object of suitable size can be seen against the horizon. As observed from TMA near the airport control tower, the measurements represent the lowest visibility in any direction during the observation period.

The low visibility readings recorded on 12 December 2023 reflect a documented period of dense haze/fog conditions at JNIA, which occasionally occurs in Dar es Salaam due to local meteorological phenomena and was retained as it is to capture the real-world variability.

FSO systems are sensitive to atmospheric factors resulting into Signal attenuation with propagation distance. In addition to weather-induced attenuation, FSO transmission requires an unobstructed line-of-sight path. Higher buildings and other physical obstacles can cause blockage; therefore, in practical backhaul deployments, the transceivers are mounted on elevated towers or rooftops to maintain clear LoS over the target distance. The present simulation assumes such elevated placement between the TMA headquarters and JNIA sites.

Therefore, a model was developed to analyze a relationship between signal attenuation and atmospheric visibility. According to Wan Ruslan et al. [15], scattering effect can be measured by using the Scattering coefficient (β), which can be related to visibility (V) by (1).

$$\beta = \frac{3.91}{V}\left(\frac{\lambda}{550nm}\right)^{-Q} \quad (1)$$

From (1), V is visibility measured in km, λ is wavelength measured in nm, and Q is the distribution of scattering particles and is much dependent on visibility value V as summarized by equation (2).

$$Q = \begin{cases} 1.3, & 6\ km < V < 50\ km \\ 0.16V + 0.34, & V < 6\ km \\ V - 0.5, & 0.5\ km < V < 1\ km \\ 0, & V < 0.5\ km \end{cases} \quad (2)$$

The attenuation of laser power in the atmosphere is described using the Beer's law as

$$Attenuation = \frac{Received\ power}{Transmitted\ power} \quad (3)$$

Equation (3) can be written symbolically as

$$\tau(R) = \frac{P(R)}{P(0)} = (e)^{-\sigma R} \quad (4)$$

where τ (R) is degradation at length R, P (0) is transmitted power at the light source, and σ is attenuation coefficient per unit length given in dB/km. According to Kaushal and Kaddoum [16], total atmospheric attenuation is represented by the atmospheric attenuation coefficient, which is expressed as a combination of both absorption and scattering of light expressed as the sum of four individual parameters given by equation (5).

$$\sigma = \alpha_a + \alpha_m + \beta_a + \beta_m \quad (5)$$

where α_a is aerosol absorption coefficient, α_m is molecular absorption coefficient, βm is molecular or Rayleigh scattering coefficient, and βa is aerosol or Mie scattering coefficient.

From (5), the Rayleigh scattering presented by β_m is inversely proportional to the fourth power of wavelength as λ^{-4}, making its value very small at near-infrared laser wavelengths, and hence it can be neglected. Also, the aerosol and molecular absorption coefficients are neglected as they are too small within the size of the wavelength window used during the simulation. Therefore, the only attenuation coefficient that was considered is Mie scattering. In this regard, (4) and (5) simplify to (6) and (7), respectively.

$$\tau(R) = (e)^{-\beta_a R} \quad (6)$$

Converting (6) in decibels leads to (7).

$$\tau(R) = -10log(e)^{-\beta_a R}$$

$$\tau(R) = 10\,\beta_a \mathrm{R} \log e$$

Substituting $\log e = 0.4342944819$ results into

$$\tau(R) = 4.343\beta_a \mathrm{R} \quad (7)$$

Replacing the value of β_a which is equivalent to β from equation (1), the attenuation equation in decibels (dB) becomes

$$\tau(R) = 4.343\mathrm{R}\frac{3.91}{V}\left(\frac{\lambda}{550nm}\right)^{-Q}$$

$$\tau(R) = \frac{16.981R}{V}\left(\frac{\lambda}{550nm}\right)^{-Q} dB \quad (8)$$

Equation (8) represents the mathematical model used to calculate attenuation coefficient values based on visibility, which, in turn, depends on local atmospheric conditions.

The BER estimation was computed using equation (9) as adopted from [17].

$$BER = Q\left(\sqrt{10^{\frac{SNR_{dB}}{10}}}\right) \quad (9)$$

where $SNR_{dB} = P_{rx}dBm - P_{noise}dBm$

$$P_{rx}dBm = P_{tx}dBm - Total_Attenuation_{dB}$$

where;

$P_{noise}dBm$ is Nose Power in dBm

$P_{tx}dBm$ is Transmitter Power in dBm

$Total_Attenuation_{dB}$ is Total attenuation computed using (8)

Although the analysis is based on three consecutive months of visibility data, characterized mainly by clear atmospheric conditions, it provides a valuable preliminary assessment of the visibility patterns in Dar es Salaam. Future studies should incorporate multi-year datasets to quantify seasonal variability and outage probability for network-grade availability targets.

The present model focuses on visibility-based Mie-scattering attenuation derived from local TMA data, which is the dominant impairment for the considered distances in Dar es Salaam. The model neglects atmospheric turbulence, beam wander, and other secondary effects.

4. Performance Evaluation of the Proposed Double Channel FSO System

To evaluate the performance of the proposed system, the network was modeled in the OptiSystem simulator, and performance of the proposed double channel FSO system in comparison with single channel was analyzed. Multiple iterations of Q factor and BER results were recorded at different path lengths, data rates, wavelengths, and atmospheric conditions based on visibility constant values for Dar es Salaam.

BER and Q-factor were selected as the primary performance metrics as they are standard end-to-end indicators of digital communication reliability and directly correlate with signal quality under atmospheric impairments. While parameters such as SNR, eye diagrams, and received optical power provide additional insight, BER and Q-factor encapsulate the overall system performance and are widely used in FSO literature for comparison with design targets of BER $\leq 10^{-9}$ and Q ≥ 6.

Additionally, the results were analyzed using MATLAB, and graphs were plotted to illustrate the variation and comparison performance between the single-channel FSO system and the double-channels FSO system.

In Dar es Salaam, TMA's weather data indicate that the majority of visibility values fall within the clear weather category, exceeding 30 km, with fewer instances categorized as haze or fog. Utilizing average visibilities of 30 km, 2 km, and 0.7 km for clear, haze, and fog weather conditions, respectively, the attenuation coefficients were calculated using (8) and the results are summarized in Table 2. In addition, the overall system parameters used in the simulation are detailed in Table 3.

The simulation process involved varying the channel path length and recording the respective values of Q and BER at each path length for different weather conditions, wavelengths, and data rates. Two common gigabit Ethernet data rates, as per IEEE standards 802.3z and IEEE 802.3ae, namely 1.25 Gbps and 10 Gbps respectively, were employed to evaluate system performance. The data streams at 1.25 Gbps and 10 Gbps were modulated using Non-Return-to-Zero On-Off Keying (NRZ-OOK) which is the most common format in OptiSystem-based FSO simulations because of its simplicity and compatibility with direct detection receivers. The link budget follows the parameters listed in Table 4, in which receiver sensitivity is implicitly accounted for through the BER and Q-factor evaluation at the OptiSystem photodetector output. Additionally, using the visibility data, distinct patterns corresponding to different weather conditions, including fog, haze, and clear weather ranges, were recorded.

Table 2. Attenuation coefficients used in simulations.

Weather Category	Visibility (km)	Q-value	Attenuation Coefficient (dB/km)	
			λ= 850nm	λ=1550nm
Clear	30	1.30	0.30	0.10
Haze	2	0.66	6	4
Fog	0.70	0.20	22	19

Table 3. Attenuation coefficients used in simulations.

Parameter	**Value**
Wavelength	850nm and 1550 nm
Path Length	Variable from 0.2 to 15 km
Diameter of Aperture of Transmitter	2.5 cm
Diameter of Aperture of Receiver	20 cm
Attenuation (dB/km)	Variable from 0.1 to 22 dB/km, based on visibility values.
Data Rates	1.25Gbps and 10Gbps
Beam Divergence	1mrad
Transmitter Power	20 dBm
Noise Power	-40 dBm

5. Results

The performance of the proposed double channel FSO system in comparison with single channel FSO system were evaluated by simulations considering Dar es Salaam atmospheric conditions. During simulations, wavelengths, weather conditions, data rates, and path lengths were varied to assess the performance across different scenarios using Q-factor and BER as performance parameters. Three atmospheric weather conditions considered in this study were clear, haze and foggy weather conditions.

5.1 Q-Factor Performance under Clear Weather

Figure 5 illustrates the Q-factor performance of double-channel FSO and single-channel under clear weather conditions. A decline in the Q-factor as the path length increases is noted in all scenarios. The poor performance is caused by signal attenuation due to absorption and scattering which reduce the signal power and increase noise, leading to a lower signal-to-noise ratio (SNR) and, consequently, a reduction in the Q-factor. However, the double FSO system consistently achieves higher Q-values than the single-channel FSO system. The minimum Q-value of 6 was attained at maximum transmission distances of 7.5 km for the single-channel system in all the scenarios. In double channel FSO system, the minimum Q value was achieved at the maximum transmission distance of 14.5 km with 1.25 Gbps and 1,550 nm, which is two times the distance achieved in single channel system with the same transmission parameters. In addition, 1.25 Gbps system outperforms the 10 Gbps system with higher Q-values for 1.25 Gbps compared with 10 Gbps as shown in Figure 5 (c) and Figure 5 (d), respectively.

5.1 Q-Factor Performance under Haze Weather

Q-factor for the double-channel system outperforms the single-channel systemin haze weather (Figure 6). However, in haze conditions, the maximum achievable transmission distance, based on the minimum required Q-factor of 6, decreases compared with clear weather, which is due to the impact of reduced visibility on signal transmission. The maximum transmission distances of 3.4 km for double-channel system for both 1.25 Gbps and 10 Gbps were achieved. This observation indicates that the double-channel FSO system can extend the transmission range when compared with the single channel FSO system. Similar to Q-factor in clear weather conditions, the system performance at lower data rates is better than that at higher data rates. The better performance in lower data rates is primarily due to bandwidth requirements in which lower data rates require less bandwidth compared with higher data rates. Therefore, at a fixed bandwidth, lower data rates reduce susceptibility to noise and interference, resulting in a higher signal-to-noise ratio (SNR), which implies better signal quality.

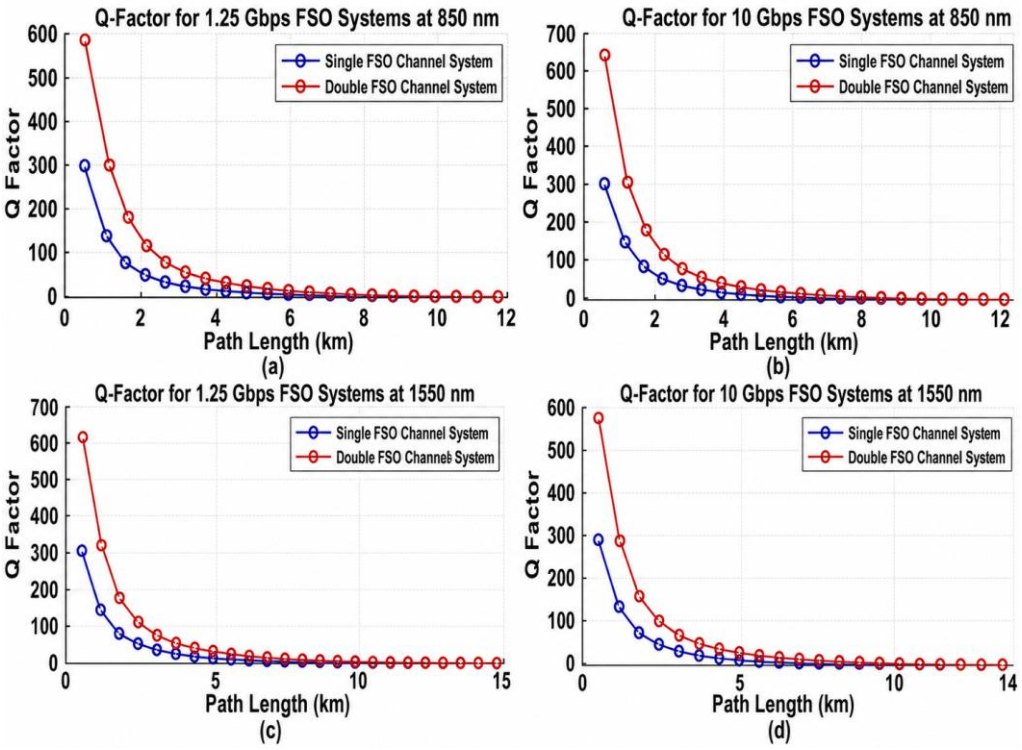


Figure 5. Q-factor performance under clear weather at: (a) 1.25 Gbps and 850 nm, (b) 10 Gbps and 850 nm, (c) 1.25 Gbps and 1550 nm, and (d) 10 Gbps and1550 nm.

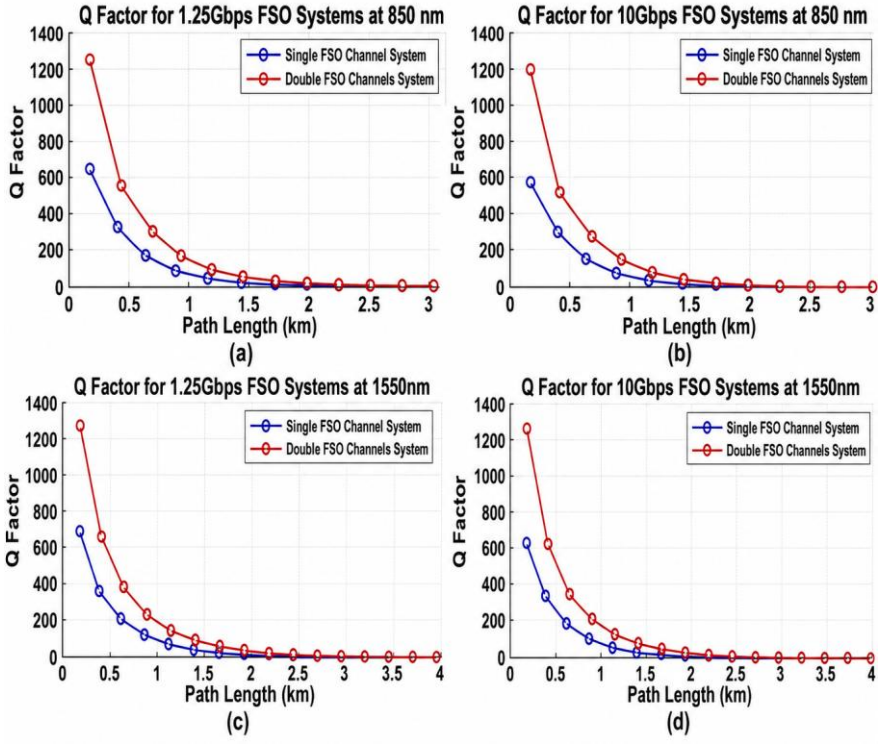


Figure 6. Q-factor performance under haze weather at: (a) 1.25 Gbps and 850 nm, (b) 10 Gbps and 850 nm, (c) 1.25 Gbps and 1550 nm, and (d) 10 Gbps and1550 nm.

5.2 Q-Factor Performance under Foggy Weather Conditions

Similar to the results under clear and hazy weather conditions, the Q-factor for the double-channel FSO system remain higher than those of the single-channel FSO system at every point along the transmission path in all scenarios (Figure 7). This indicates that the double-channel FSO system can improves transmission quality more than the single channel FSO system. It was also noted that the maximum achieved transmission distance decreases in all scenarios compared to clear and hazy weather conditions because of reduced visibility affecting signal transmission. Among the conditions, foggy weather has the lowest visibility compared with clear and hazy conditions, which results in the shortest transmission distance. From Figure 7, the minimum required Q-factor of 6 was achieved at maximum transmission distances of 1.2 km and 0.8 km for double-channel and single-channel systems, respectively, at 1.25 Gbps and 850 nm (Figure 7 (a)). The maximum distances attained by the double-channel and single-channel systems were 1 km and 0.8 km, respectively, for 10 Gbps at 850 nm (Figure 7 (b)). Similarly, at 1.25Gbps and 1550nm, the double-channel and single-channel systems achieved maximum transmission distances of 1.2 km and 0.8 km, respectively (Figure 7 (c)). Finally, at 10 Gbps and 1550 nm, as depicted in Figure 7 (d), the maximum transmission distances remain constant at 1 km and 0.8 km for both the double-channel and single-channel system, respectively.

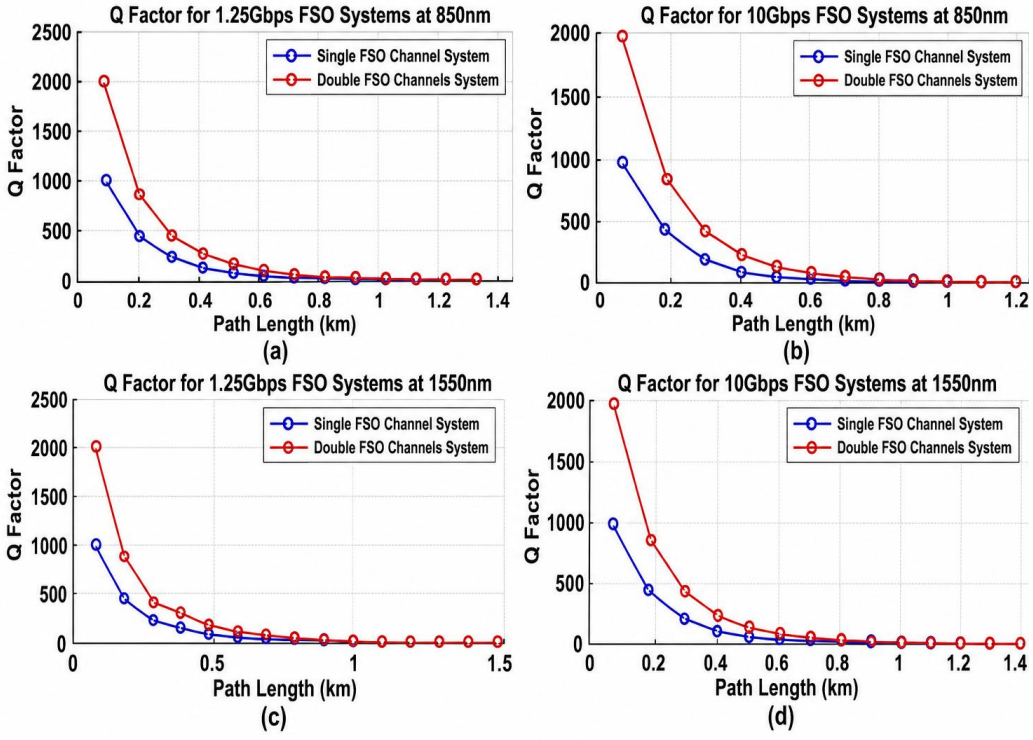


Figure 7. Q-factor performance under foggy weather at: (a) 1.25 Gbps and 850 nm, (b) 10 Gbps and 850 nm, (c) 1.25 Gbps and 1550 nm, and (d) 10 Gbps and1550 nm.

5.3 BER under Clear Weather Conditions

The system performance in terms of BER was evaluated across different weather conditions. Figure 8 represents BER performance comparisons between double FSO channels and single channel FSO system under clear weather conditions. In both scenarios, the BER for the double channel FSO

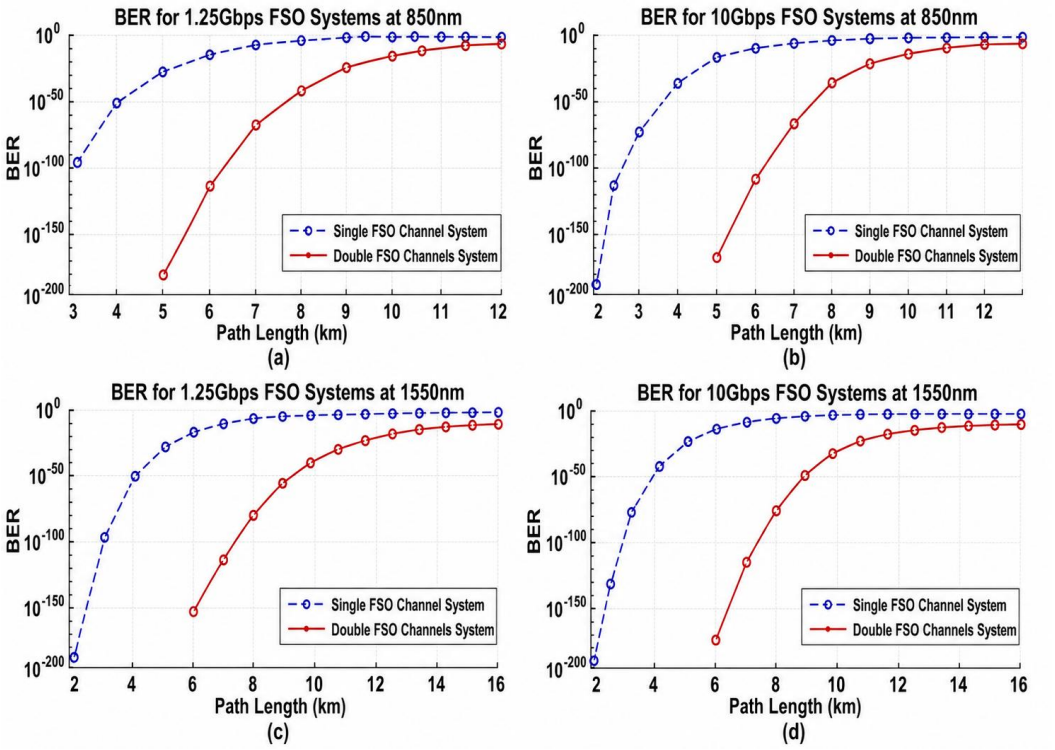


Figure 8. BER performance for single and double FSO systems under clear weather.

system is consistently below that of the single-channel system, indicating lower BER values across the transmission path length in a double channel FSO system. The low BER in double channel system is due to signal redundancy, which provides spatial diversity, meaning that if one path is degraded due to atmospheric conditions, the other path may still carry a clear signal which improves reliability and reduces the probability of errors, thus improving the overall BER. Since lower BER values indicate better performance, the double-channel system has demonstrated better performance compared with the single-channel system in all scenarios.

However, based on the required maximum BER of 10^{-9}, the maximum transmission distances were noted to vary depending on the data rate, wavelength, and system design. In figure 8 (a), the maximum transmission distances are 7 km for the single-channel system and 11.5 km for the double-channel system. In figure 8 (b), these distances are 6.5 km and 11.5 km, respectively. The distances increase to 8 km for the single-channel system and 15 km for the double-channel system as shown if Figure 8 (c), while in Figure 8 (d), the distances are 7.5 km and 14.5 km, respectively. This trend indicates that the double-channel FSO system has longer transmission range compared with single channel FSO system across all scenarios.

Also, the performance comparison of the two system at data rates of 1.25 Gbps and 10 Gbps under the same configuration and wavelength demonstrates that the proposed double channel FSO system performs better at 1.25 Gbps than at 10 Gbps. The improvement of BER at lower data rate is primarily due to bandwidth constraints. Lower data rates require less bandwidth compared with that at higher data rates. As a result, at a fixed bandwidth, lower data rate transmissions are less susceptible to noise and interference, leading to a lower probability of errors in signal transmission.

5.4 BER Under Haze Weather Conditions

The system performance in terms of BER was conducted under hazy weather conditions. Figure 9 illustrates the BER performance across different scenarios involving various data rate and wavelength combinations, represented by Figure 9 (a-d). Similar to the results under clear weather conditions, the BER for the double-channel system were lower than those of the single-channel system at every transmission distance. However, when comparing these transmission distances with those under clear weather conditions, considering the required maximum BER of 10^{-9}, the overall distances decrease in hazy weather conditions. The reduced transmission distance aligns with the reduced visibility affecting signal transmission. Haze consists of tiny suspended particles in the atmosphere that scatters light. This scattering weakens the optical signal as it travels, reducing the intensity that reaches the receiver and hence the transmission distance.

5.1 BER under Foggy Weather Conditions

Figure 10 represents BER performance for single- and double-channel FSO systems across various combinations of data rates and wavelengths (Figure 10 (a-d). Similar to clear and haze weather conditions, the BER plots for the double-channel system consistently remain below those of the single-channel system at every point along the transmission path in all scenarios. However, at the maximum required BER of 10^{-9}, both the double- and single-channel system designs showed the same maximum achieved transmission distance as with the Q Factor analysis, except in one case involving 10 Gbps at 1550 nm (Figure 10 (d)). In this case, the maximum achieved transmission distance was 1.2 km instead of the 1 km attained with the Q Factor analysis.

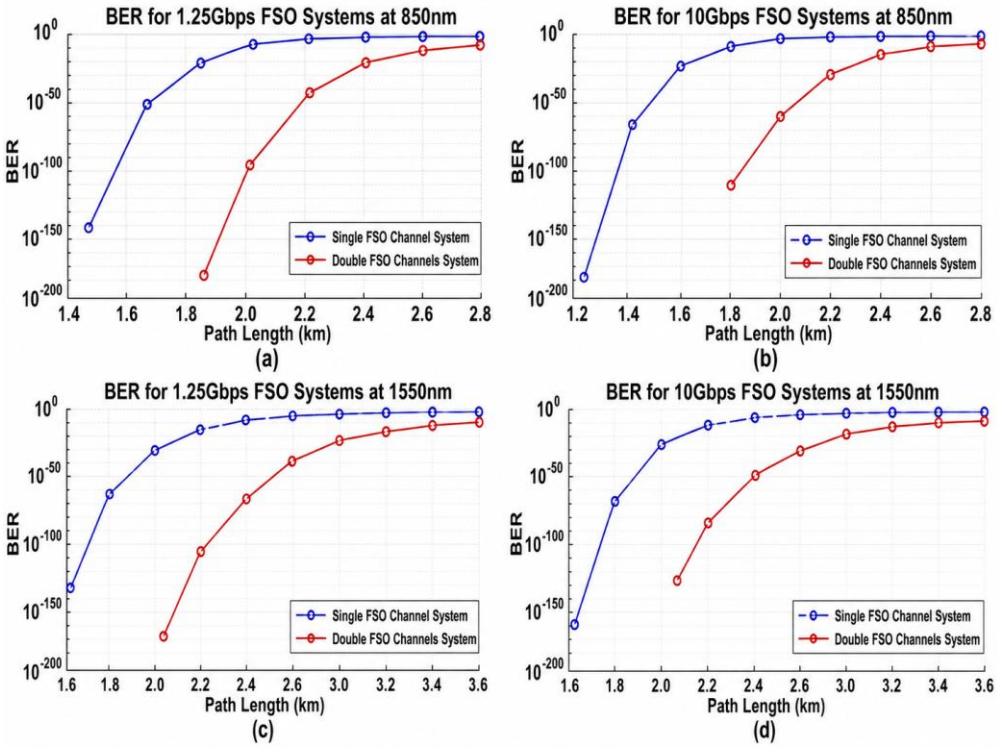


Figure 9. BER Performance for Single and Double FSO Systems Under Haze Weather.

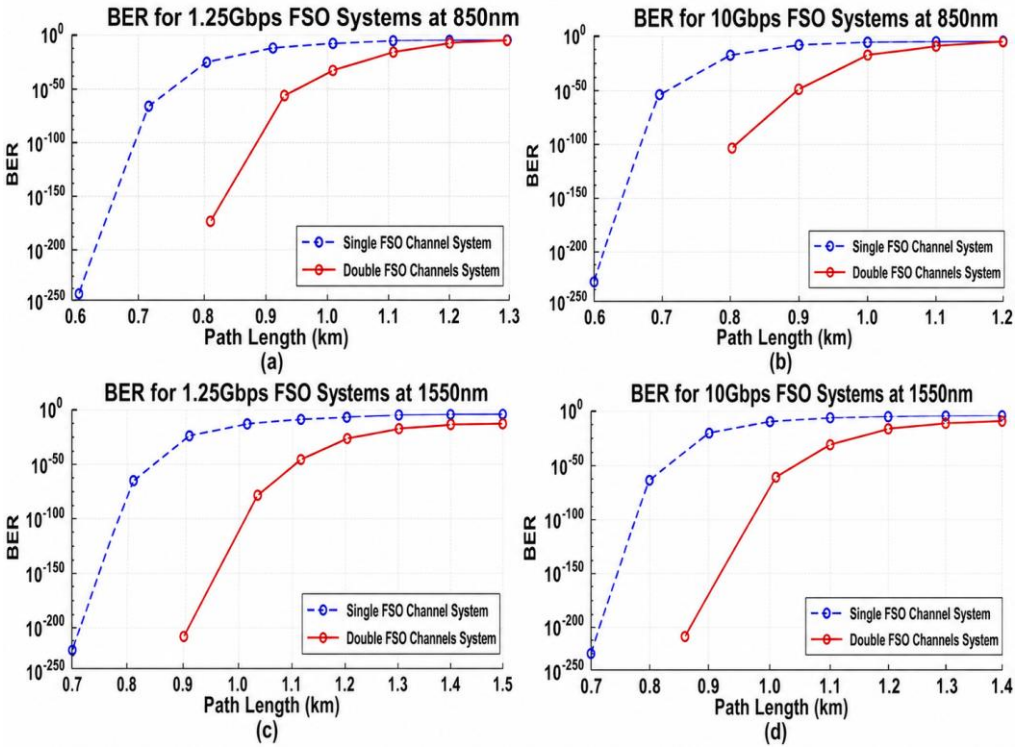


Figure 10. BER performance for single and double FSO systems under foggy weather.

In general, the maximum distance attained by the proposed double channel FSO communication system are longer compared with single channel in all cases (Table 3). The performance analysis of the FSO Network as a Backhaul Network in varying atmospheric conditions demonstrates its capabilities with optimal performance achieved in clear weather conditions operating at a wavelength of 1550 nm. The proposed enhanced FSO system achieved the required maximum BER and minimum Q Factors of 10^{-9} and 6, respectively, in clear weather conditions. Consequently, the enhanced FSO system delivered data at a data rate of up to 10 Gbps over distances of 14 km utilizing a wavelength of 1550 nm. Additionally, the system has shown the capability of delivering 1.25 Gbps for a maximum path length of up to 14.5km.

In haze conditions, the system's performance deteriorates due to increased attenuation, limiting the maximum achievable distance to 3.4 km at both data rates. However, there is notable signal quality at 1.25 Gbps compared with 10 Gbps, evidenced by relatively high Q Factors and low BER values at 1.25 Gbps compared with those at 10 Gbps.

5 Conclusions and Recommendations

The study focused on evaluating the performance of dual channels Free Space Optical (FSO) system as a backhaul network using Dar es Salaam atmospheric weather. The network was modelled by first reviewing literature and theories related to the scattering of optical light through the collision of air particles. Subsequently, the mathematical equations to account for atmospheric attenuation and BER due to weather conditions and wavelength, which are crucial metrics in optical signal propagation in the FSO systems were identified. The backhaul network model was designed to fulfil the high data rate demand and longer transmission distances by proposing FSO multiple channels communication system.

The findings of this study indicate that FSO communication system requires a clear line-of-

Table 4. Performance of double and single channels FSO systems under different weather conditions.

Weather Condition	No. of Channels	Data Rate (Gbps)	Wavelength (nm)	Max Distance Attained for Max Design BER (km)	Max Distance Attained for Min Design Q-factor (km)
Clear	Single Channel	10	1550	7.5	7.5
			850	6.5	6.5
		1.25	1550	8	7.5
			850	7	6.5
	Double Channel	10	1550	14.5	14
			850	11.5	11
		1.25	1550	15	14.5
			850	11.5	11.5
Haze	Single Channel	10	1550	2.6	2.4
			850	2.0	2.0
		1.25	1550	2.6	2.4
			850	2.0	2.0
	Double Channel	10	1550	3.4	3.4
			850	2.6	2.6
		1.25	1550	3.4	3.4
			850	2.6	2.6
Fog	Single Channel	10	1550	0.8	0.8
			850	0.8	0.8
		1.25	1550	0.8	0.8
			850	0.8	0.8
	Double Channel	10	1550	1.2	1.0
			850	1.0	1.0
		1.25	1550	1.2	1.2
			850	1.2	1.2

sight between transmitter and receiver nodes to mitigate signal attenuation and maintain desired data transmission rates. Compared with conventional microwave RF links, which are susceptible to rain fade and fiber-optic cables which have high deployment cost in obstructed areas, the double-channel FSO system offers a cost-effective, license-free alternative with Gbps capacity over up to 14 km in clear conditions. Hybrid FSO/RF or FSO/fiber deployments could further improve reliability for carrier-grade backhaul. Additionally, the network infrastructure should be equipped with redundancy mechanisms and failover provisions to mitigate the impact of potential link failures and ensure uninterrupted connectivity. Lastly, solutions like power control, diversity techniques, beam steering, and adaptive modulation can help address whether related outages in FSO systems.

The performance of the proposed double FSO communication system was evaluated under clear, haze and fog conditions with the minimum required Q Factor of 6 and the maximum required BER of 10-9 for reliable communications in backhaul

network conditions. However, further analysis of the system's performance under other adverse weather conditions, such as heavy rain, is required to assess its resilience and limitations in other challenging environments. Additionally, developing optimization algorithms for dynamically adjusting FSO system parameters, such as transmission power, modulation schemes, and beam steering, in response to changing atmospheric conditions, is another interesting area recommended for future studies. Furthermore, performance evaluation of hybrid backhaul network consisting of the proposed FSO communication system and existing communication technologies, such as microwave links or fibre optics networks for improved reliability in challenging environmental conditions, is proposed as an interesting future work.

Lastly, investigating methods to extend the maximum transmission distance of the proposed double FSO systems beyond current limitations is also crucial for the system to compete with other backhaul networks, such as fiber cable networks, which can provide higher transmission distances of more than 50 km. This could involve advancements in laser technology, adaptive optics, or novel atmospheric mitigation techniques. Additionally, the use of FSO links over shorter distances to complement existing WiFi or small-cell networks could be explored to create hybrid indoor or campus backhaul solutions with enhanced reliability.

ACKNOWLEDGEMENT

The authors are grateful to the Director of Public Services at University of Dar es Salaam, Prof. Neema Mori, for her support, which significantly contributed to the successful revision and completion of this manuscript.

CONTRIBUTIONS OF CO-AUTHORS

Faraji Hassan	ORCID: 0009-0003-3647-0020	Conceived the idea, conducted experiment, and analyzed results.
Eva Shayo	ORCID: 0000-0002-5730-4115	Analyzed results, wrote and proofread the paper.

REFERENCES

[1] Hassan, M Mubasher and G. M. Rather, "Free Space Optics (FSO): A Promising Solution to First and Last Mile Connectivity (FLMC) in the Communication Networks," International Journal of Wireless and Microwave Technologies, vol. **10**, no. **4**, pp. 1–15, 2020, doi: 10.5815/ijwmt.2020.04.01.

[2] O. Aboelala, I. E. Lee, and G. C. Chung, "A Survey of Hybrid Free Space Optics (FSO) Communication Networks to Achieve 5G Connectivity for Backhauling," Nov. 01, 2022, MDPI. doi: 10.3390/e24111573.

[3] T. Sharma, A. Chehri, and P. Fortier, "Review of optical and wireless backhaul networks and emerging trends of next generation 5G and 6G technologies," Transactions on Emerging Telecommunications Technologies, vol. **32**, no. **3**, Mar. 2021, doi: 10.1002/ett.4155.

[4] B. Lian, Z. Wei, X. Sun, Z. Li, and J. Zhao, "A Review on Rainfall Measurement Based on Commercial Microwave Links in Wireless Cellular Networks," Jun. 01, 2022, MDPI. doi: 10.3390/s22124395.

[5] Choyon, K, and Chowdhury, "Performance Comparison of Free-Space Optical (FSO) Communication Link under OOK, BPSK, DPSK, QPSK and 8-PSK Modulation Formats in the Presence of Strong Atmospheric Turbulence," Journal of Optical Communications, 2020, doi: 10.1515/joc-2019-0250.

[6] C. Joseph, A. Bazil Raj, R. Bopardikar, A. Bazil Raj, and G. Patel, "A Review Paper on Hybrid RF/FSO System for Communication," International Journal of Engineering Research and Reviews, vol. **12**, pp. 90–115, doi: 10.5281/zenodo.13848040.

[7] E. D. Arinze, "Enhancing Network Management Practices in East Africa: A Comprehensive Review," Idosr Journal of Computer and Applied Sciences, vol. **9**, no. **2**, pp. 36–42, Sep. 2024, doi: 10.59298/JCAS/2024/92.3642.

[8] Z. Xu, G. Xu, and Z. Zheng, "Ber and channel capacity performance of an fso communication system over atmospheric turbulence with different types of noise," Sensors, vol. **21**, no. 10, 2021, doi: 10.3390/s21103454.

[9] C. Madapatha, P. Lechowicz, C. Natalino, P. Monti, and T. Svensson, "Joint Fiber and Free Space Optical Infrastructure Planning for Hybrid Integrated Access and Backhaul Networks," Jul. 2025, [Online]. Available: http://arxiv.org/abs/2507.20367

[10] H. Singh, R. Miglani, N. Mittal, H. Singh, J. Kaur, and A. Gupta, "Development of a cost-effective optical network based on free space optical (FSO) and optical fiber links for enabling smart city infrastructure: A hybrid approach," Optical Fiber Technology, vol. **81**, no. October, p. 103544, 2023, doi: 10.1016/j.yofte.2023.103544.

[11] A. Jahid, M. H. Alsharif, and T. J. Hall, "Journal of Network and Computer Applications A contemporary survey on free space optical communication: Potentials, technical challenges, recent advances and research direction," Journal of Network and Computer Applications, vol. **200**, no. January, p. 103311, 2022, doi: 10.1016/j.jnca.2021.103311.

[12] M. M. A. Eid, V. Sorathiya, S. Lavadiya, E. Shehata, and A. N. Z. Rashed, "Free space and wired optics communication systems performance improvement for short-range applications with the signal power optimization," Journal of Optical Communications, 2021, doi: 10.1515/joc-2020-0304.

[13] A. Sood and R. Kaushik, “BER Analysis of 60GHz Millimeter Wave over Free Space Optical Communication System,” 2020 6th International Conference on Signal Processing and Communication, ICSC 2020, pp. 29–33, 2020, doi: 10.1109/ICSC48311.2020.9182756.

[14] S. O. Adebusola, P. A. Owolawi, J. S. Ojo, and P. S. Maswikaneng, “Optimized quality of service prediction in FSO links over South Africa using ensemble learning,” Opt. Commun., vol. **579**, Apr. 2025, doi: 10.1016/j.optcom.2025.131509.

[15] W. R. H. Wan Ruslan, S. M. Idrus, A. Ramli, and N. Ramli, “Terrestrial optical wireless communication propagation analysis considering Malaysia’s weather condition,” ICCAIE 2010 - 2010 International Conference on Computer Applications and Industrial Electronics, no. Iccaie, pp. 702–705, 2010, doi: 10.1109/ICCAIE.2010.5735025.

[16] H. Kaushal and G. Kaddoum, “Optical Communication in Space: Challenges and Mitigation Techniques,” IEEE Communications Surveys and Tutorials, vol. **19**, no. 1, pp. 57–96, 2017, doi: 10.1109/COMST.2016.2603518.

[17] A. Sharma, P. A. Xuereb, and L. Garg, “Evaluating the Impact of Snow on Free Space Optical Communication Using Artificial Neural Networks for BER Prediction,” in 2025 International Conference on Cognitive Computing in Engineering, Communications, Sciences and Biomedical Health Informatics, IC3ECSBHI 2025, IEEE Inc., 2025, pp. 1222–1226. doi: 10.1109/IC3ECSBHI63591.2025.10991099.