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Performance Analysis of Free-Space Optical Communication under Scintillation Effect: A Case of Mwanza and Arusha Regions

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Keywords

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Free Space Optical Communication
Signal to Noise Ratio
Scintillation

Abstract

Free-Space Optical communication (FSO) offers unregulated bandwidth of up to 200 THz, security, higher speed, unlimited data rate and shortest installation time. However, weather attenuation, especially scintillation, has a massive impact on the performance of the FSO transmission channel. This paper evaluates link availability and effect of scintillation on FSO performance in terms of eye diagrams, Bit Error Rate (BER), Q-factor, and signal-to-noise ratio. Our work used data collected from January 2018 to December 2021 by Tanzania Meteorological Authority (TMA) in Mwanza and Arusha regions for link availability and performance analysis. Simulation was performed to determine the FSO link availability, and we analyzed the scintillation effect on FSO performance using Submarine Laser Communication II and Hufnagel Valley (HV) day prediction models. It is observed that the HV day model performs better in predicting scintillation intensity compared to the former. In both regions, for the same transmission power of 20 dBm, the signal quality is better for a distance of 6 km where the BER value is found to be 10^{-8}. These results suggest that, to achieve high-speed data transmissions, the maximum separating distance between FSO transceivers should not exceed 6 km.

1. Introduction

Recently, the world has witnessed a massive increase in the usage of Information and Communications Technologies (ICT) related applications, such as Video Conferencing, Voice over IP, and Online Games. The applications require fast and reliable end-to-end connectivity, creating the need for a new transmission technology that overcomes the challenge associated with traditional radio frequency (RF) communication [1]. The limitations of communications systems, such as transmission speed and packet loss per kilometer, create the need to introduce optical fiber as a promising communication technology. Fiber optics transmit data through a glass or plastic core in the form of light at extremely high speed and with minimum attenuation [2]. However, the digging associated with delivering fiber optic implementation to end-users raises costs and sometimes disrupts the public infrastructure [3]. High installation costs associated with the implementation of RF transmission and aerial or underground Fiber optics links can be greatly reduced with the use of Free Space Optics (FSO) technology.

However, an atmospheric channel in FSO encounters enormous challenges, such as heavy rain, fog and snow. Consequently, the performance of the FSO communication system is mainly affected by rapid changes in the atmospheric conditions. Therefore, it is desirable to investigate the diverse atmospheric conditions, such as fog, smoke, and scintillation and analyze the system performance under different atmospheric conditions [4]. Scintillation occurs when temperature varies completely with different air pockets due to the heat uprising from the earth's surface. The phenomena generate regions of varying refractive index along the transmission path, thereby inducing transmission error due to a beam spread from the transceiver as a light propagates through heated air pockets.

2. Literature Review

Rashid and Semakuwa [5] investigated the effect of rain on the performance of FSO Communication in Dodoma and Dar es Salaam, Tanzania. Results from their study show that, to ensure minimal power loss and lower BER, the optical attenuation loss of 37 dBm/km and 80 dBm/km should be considered when designing FSO links in Dodoma and Dar es Salaam, respectively. Moreover, for a transmission power above 30 dBm, communication link was found to be reliable for up to 10 km and 15 km in Dodoma and Dar es Salaam, respectively, with received power of -100 dBm. However, the researchers did not discuss other atmospheric attenuation factors, such as scintillations.

Rao et al. [6] pointed out the variation of scintillation effect in a rain and non-rain periods. The authors found that the FSO link was greatly affected during midday, and peak-to-peak scintillation was higher in the midday compared to morning and evening. Furthermore, 6 dBm transmission power of peak-to-peak scintillation could be observed during the rain, and 34 dBm transmission power during the non-rain period. This observation indicates that the scintillation effect varies according to the environment, creating demands for investigating scintillation effect and how it affects FSO communication in surroundings.

Khalighi and Uysal [7] highlighted performance issues of FSO links based on communication theory. Their work presents different nature of losses encountered in terrestrial FSO link, as facts on FSO transceiver, channel coding, modulation, and gives ways to alleviate fading effects of atmospheric turbulence. It was noted that scintillation index, C_n^2, is elevation-dependent and is larger at lower altitudes and does not depend on distance, rather it varies mostly during daytime and at a given location. This observation necessitates a need to investigate the scintillation variations and effects on FSO link at different locations.

Sahota and Dhawan [7] discussed the impact of scintillation and proposed a mitigation technique on received BER. With an assumption of low turbulence condition for a link range of 2 km and 10 km, the authors observed BER values of 3.32×10^{-1} and 4.48×10^{-1}, respectively, using direct detection method. To improve BER, homodyne detection was proposed and the received BER was found to be 9.87×10^{-5} and 7.6×10^{-2} at 2 km and 10 km, respectively.

Rani et al. [8] presented performance comparison between homodyne and direct in terms of BER, Q-factor, and eye diagram for FSO channel under scintillation effect. To overcome limitations of direct detection technique, single beam wavelength division multiplexing (SB-WDM-FSO) and multibeam wavelength division multiplexing (MB-WDM-FSO) FSO system with homodyne detection were used. For SB-WDM-FSO, the BER and Q-factor for a link of 10 km was found to be 4.0 ×

10^{-10} and 6.13, respectively. For a link range of up to 25 km, MB-WDM-FSO system was used and the computed BER and Q-factor was 7.27×10^{-10} and 6.04, respectively.

Kolawole et al. [9] discussed impact of scintillation effect on outage probability and BER at various cities in South Africa. Their work presents mathematical expressions for outage probabilities and BER performances for FSOC links, employing various intensity modulation and direct detection (IM/DD) schemes. Using different models, the authors found that, the computed scintillation indices do not exceed 50%, 99%, 99.9%, and 99.99% of the time for the investigated locations.

Rahim et al. [10] provide comparison of cumulative distributions of tropospheric scintillation models (Karasawa, ITU-R, Van de Kamp, OTUNG and Ortgies (Ortgies-N and Ortgies-T)) with the measured scintillation aimed at determining a suitable model for prediction. The models are based on data collected from Germany, United Kingdom, Japan, Finland, and United States of America. It was observed that the Ortgies-N model performs well under scintillation fades and the Karasawa model on scintillation enhancement prediction. However, the models may not be suitable for tropical countries, such as Singapore, Malaysia and Tanzania as they have different climate patterns compared to the four season's countries. Thus, creating the need for research on investigating the variation of scintillation and associated effects on FSO links in different locations.

This paper presents a performance investigation of the FSO communication link under the scintillation effect for the two selected regions of Mwanza and Arusha in Tanzania. The two regions were selected based on trend of number of mobile subscribers registered to the available telecom service providers. It is reported that, Mwanza and Arusha regions account for 7.6 million mobile subscribers [11].

3. Method

A quantitative information on turbulence variability is required for accurate modelling of both RF and light propagation [12]. The index of refraction structure parameter C_n^2 is used when describing and computing the variation of optical turbulence intensity. Based on theoretical and empirical approaches, the parameter is further used to determine the attenuation due to scintillation [13]. This paper uses Hufnagel Valley and Submarine laser communication (SLC II) Day models with collected dataset parameters such as altitude and time of the day [14, 15]. Equation (1) and (2) represents the Submarine laser communication (SLC) Day and Hufngel Valley (HV) Day models, respectively.

$$C_n^2(h) = 6.35210^{-7}h^{-2.966} \tag{1}$$

$$C_n^2(h) = 0.094\left(\frac{v}{27}\right)^2(10^{-5}h)^{10}e^{h/1000} + 2.7\times10^{-6}e^{-h/1500} + Ae^{-h/1000} \tag{2}$$

Where h is a location altitude with reference to a sea level, v *is a* wind speed and $C_n^2(h)$ is a scintillation parameter.

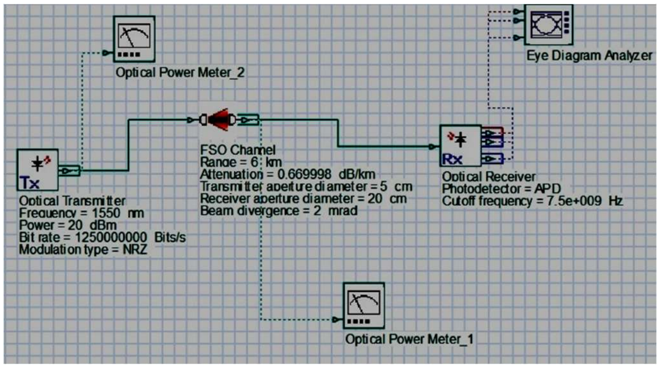
Properly selecting modulation schemes is necessary to ensure power and spectral efficiency. In this paper, we employ the On-Off Keying Non-Return to Zero (OOK-NRZ) modulation technique as it offers several advantages in implementing an optical system, such as system simplicity, reasonable bandwidth utilization and power efficiency [13]–[15]. In addition, the NRZ signal has a better compact spectrum than other known modulation schemes, hence its bandwidth efficiency [16]. It is further noted that, with the NRZ modulation scheme at 1550 nm wavelength using an APD photodetector, significant link performance is achieved while maintaining the received signal power and bit error rate threshold [17].

4. Experiments

The simulation setup, as illustrated in Figure 1, is performed in Opti-system version 16. We ran the simulation 384 times under different ranges, months, models, and regions to obtain BER and Q factors. Based on the modelling equations analysis, the set of simulation parameters is shown in Table 1.

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

Parameters	Value	Unit
Operating optical signal wavelength, λ	1550	Nm
Link range, L	2≤ L ≤ 8	Km
Receiver aperture diameter.	20	Cm
Transmitter aperture diameter.	5	Cm
Beam divergence	2	Mrad
Optical power, pt	20	dBm
Receiver Type	APD	
Cut off frequency	7.5	GHz
Modulation Scheme	NRZ	
Transmission Bit Rate	1.25	GBits/s



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 Opti-system interface under the scintillation effect

This study uses the averaged standard secondary data collected from 2018 to 2021 by Tanzania Meteorological Agency (TMA) for regions under investigation, as shown in Tables 2 and 3.

Table 2. Temperature, relative humidity, and wind speed average data from 2018 to 2021 for the Arusha region.

Month	**Temp (C)**	**Relative Humidity (%)**	**Wind Speed (knots)**	**Altitude (m)**
January	22.15	72.75	4.25	1372
February	22.45	69.25	5.50	1372
March	22.90	74.00	6.25	1372
April	21.53	86.75	7.25	1372
May	19.73	87.25	8.50	1372
June	18.73	82.00	8.50	1372
July	18.30	78.75	8.75	1372
August	19.10	73.25	9.25	1372
September	20.20	69.75	9.75	1372
October	21.86	70.75	9.75	1372
November	22.00	76.75	7.50	1372
December	21.90	76.00	5.00	1372

Table 3. Temperature, relative humidity and wind speed average data from 2018 to 2021 for the Mwanza region.

Month	**Temp (C)**	**Relative Humidity (%)**	**Wind Speed (knots)**	**Altitude (m)**
January	23.45	75.25	5.50	1140
February	24.15	72.50	6.25	1140
March	23.60	73.50	6.00	1140
April	23.68	78.75	5.00	1140
May	23.53	71.75	6.00	1140
June	23.30	65.50	6.25	1140
July	22.83	61.50	7.00	1140

August	22.45	62.50	6.75	1140
September	24.35	66.50	7.50	1140
October	24.10	72.00	6.75	1140
November	23.60	76.25	6.00	1140
December	23.45	76.50	6.00	1140

5. Results and Discussions

The availability of FSO links in two regions is estimated. The highest estimated attenuations for the Arusha region are 0.735 dB/km and 0.734 dB/km with the SLC II and HV day model, respectively. The lowest attenuation is estimated to be 0.588 dB/km with the SLC II-day model and 0.585 dB/km with the HV day model. For the Mwanza region, the highest estimated attenuation is 0.740 dB/km using the SLC II-day model and 0.738 dB/km on the HV day model. The lowest estimated attenuation is 0.638 dB/km using the SLC II-day model and 0.636 dB/km on the HV day model.

Furthermore, the Q-factor versus link visibility (range) is illustrated in Figure 2. The Q-factor for a link visibility of 8 km is 15 and 8 for HV and SLC II models, respectively. The high value of the Q-factor implies lower BER and better link performance. In Figure 3, a slightly higher Q factor is observed for the HV day model; however, as atmospheric attenuation increases, the difference in Q-factor between the two models is reduced.

Moreover, Log BER versus SNR for different models (SLC II, HV) under 2 km, 4 km, 6 km, and 8 km curve results are illustrated in Figure 4. It is observed that the HV day model requires the least transmission power compared to the SLC II-day model. Furthermore, for a desired BER performance, the required SNR of the SLC II-day model is about 0.92 dB more compared to the HV day model. Results analysis shows that the HV day model performs better in predicting scintillation effects than the SLC II-day model.

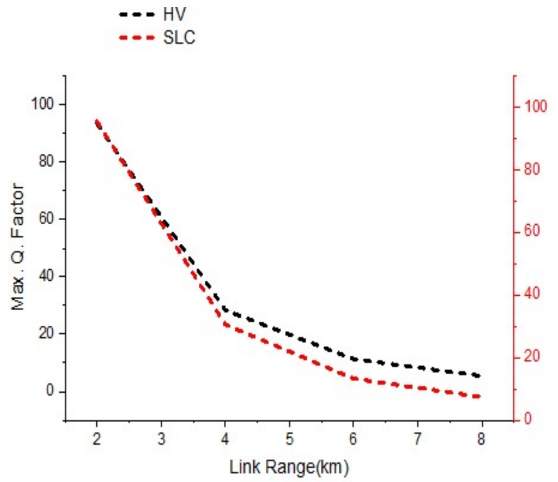


Figure 2. Simulated Q-factor for different link ranges.

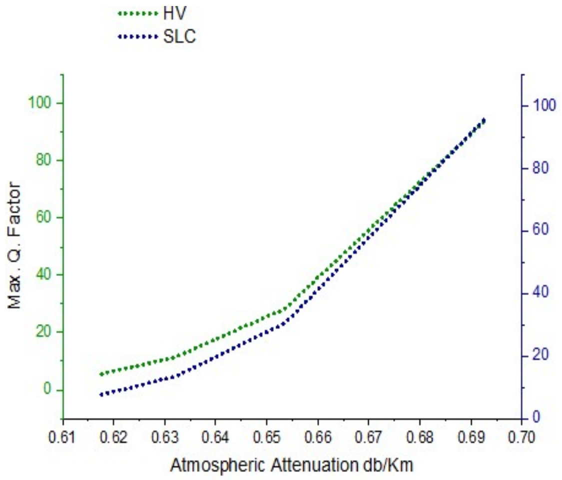


Figure 3. Variation of Q-factor with Atmospheric Attenuation.

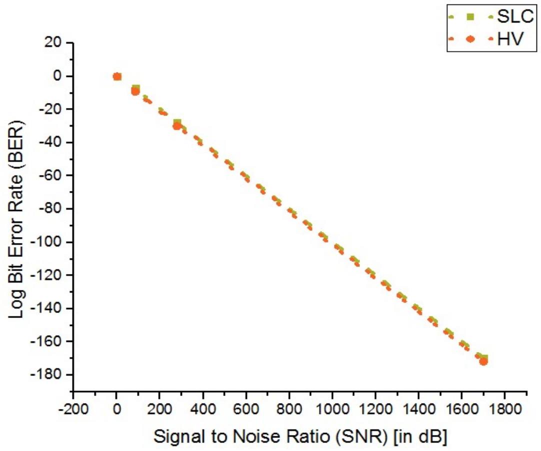


Figure 4. Log BER vs SNR for SC II and HV models.

The simulation results of BER and Q-factor for different months are presented in Figure 5 and Figure 6, respectively. It is observed that January is the worst transmission month for the Arusha region, with a lower Q-factor of 92.3961 for 2 km, 27.7242 for 4 km, 10.8611 for 6 km and 5.05207 for 8 km, while atmospheric attenuation of up to 0.78 dB per km is experienced.

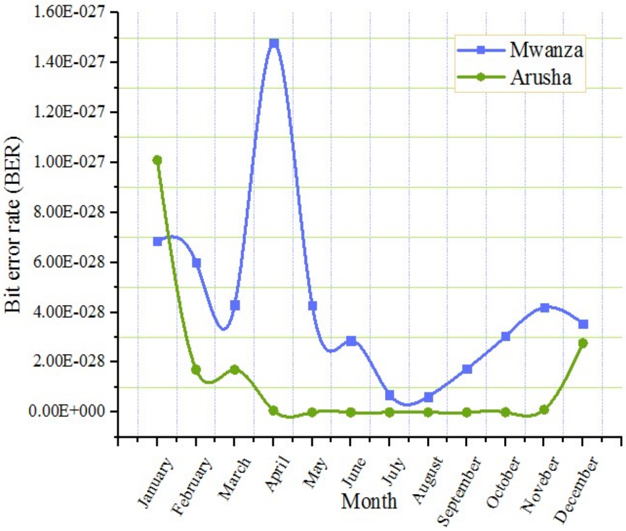


Figure 5. BER vs Months for Arusha and Mwanza regions.

Moreover, in the Mwanza region, April is observed as the worst transmission month with the simulated Q-factor of 92.2896 for 2 km, 27.6475 for 4 km, 10.8132 for 6 km and 5.02262 for 8 km and atmospheric attenuation of up to 0.79 dB per km.

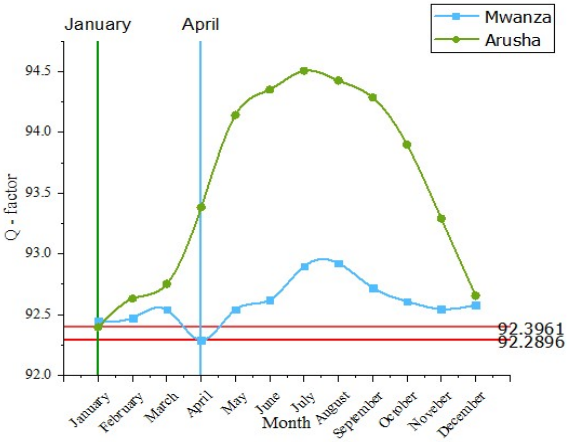


Figure 6. Q factor vs Months for Arusha and Mwanza regions.

The BER parameter is used to quantify the number of transmitted bits that are received incorrectly. To ensure link reliability, the lowest possible value of BER is desirable. In Figure 7, the BER for Arusha and Mwanza is less than 10^{-8} for 2 km, 4 km, and 6 km, and higher to about 10^{-7} for 8 km in the Mwanza region. This indicates that the reliability of the FSO transmission link is in the range of up to 6 km for both the Arusha and Mwanza regions.

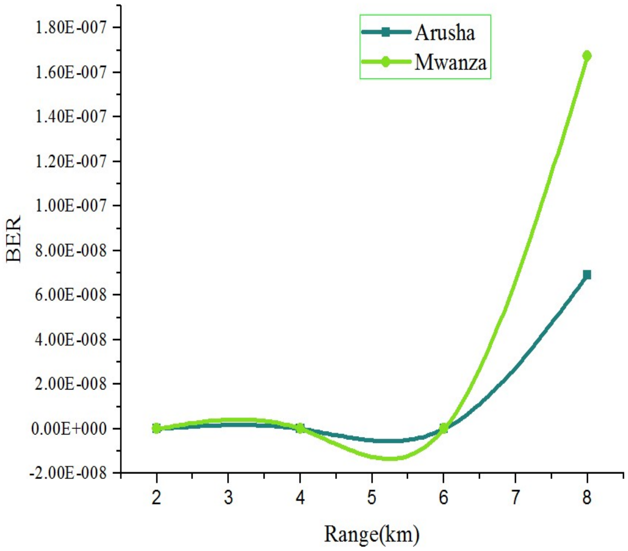


Figure 7. BER vs Range (km) for Arusha and Mwanza regions.

Gaussian noise and intersymbol interference are the two most known sources of signal distortion in digital transmission systems. Intersymbol interference mainly occurs when the energy of a transmitted symbol scatter to a subsequent symbol resulting in signal distortion. Figure 8 shows the eye diagram generated for 2 km, 4 km, 6 km and 8 km in both Mwanza and Arusha regions. A rectangular eye diagram pattern is preferred with maximum eye-opening for ideal communication. The eye pattern is clear and opens apparently up to 6 km. The eye pattern track begins to confound when the propagation distance increases to 8 km. Therefore, the maximum advisable range between two FSO transceivers is 6 km. Therefore, based on results presented in Figure 7 and Figure 8, respectively, it is technically advised to keep FSO

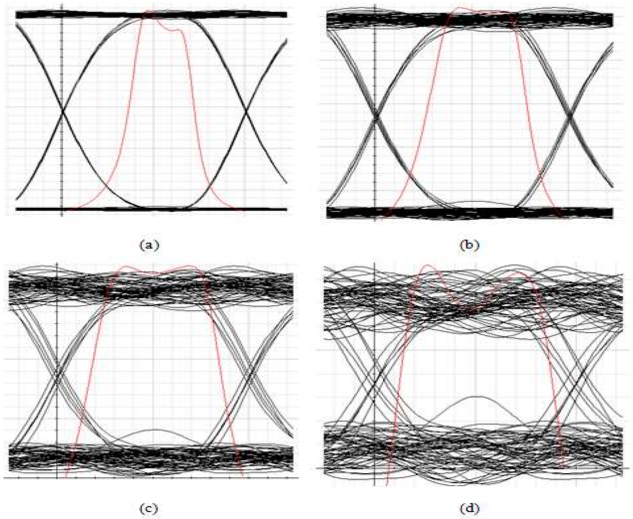


Figure 8. Eye diagram for Mwanza in different ranges (a) 2km (b) 4km (c) 6km (d) 8km.

transceiver at a maximum distance of 6 km to ensure good signal reception with preferable BER.

6. Conclusion

This paper presents the feasibility of FSO communication under the scintillation effect in the Arusha and Mwanza regions. Two models, namely Submarine Laser Communication (SLC II) Day and Hufnagel Valley (HV) Day models, are compared with the calculated scintillation data on the 1550 nm transmission window. From the analysis, the HV day model outperforms the SLC II-day model. From the simulation results, FSO communication is feasible for about a 6 km range in Arusha and Mwanza regions. The worst month for FSO transmission is January for Arusha and April for Mwanza, as a lower Q-factor is experienced compared to other months.

CONTRIBUTIONS OF CO-AUTHORS

Florence U. Rashidi	Conceived the idea, conducted an experiment, and wrote the paper
George S. Ulomi	Provided technical assistance on methods and materials. Performed result interpretation
Edson E. Ndyalimo	Conducted data collection and experiments
Mustafa H. Mohsini	Provided technical assistance on simulation tools usage and proofreading.

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