Free Space Optics Link Performance Estimation Under Diverse Conditions

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Abstract**—**Free Space Optics (FSO) uses air as a medium of transmission of signals and requires Line of Sight (LOS) for operation. Communication systems that employ FSO have gained prominence in recent times and have been used in mobile communications, broadcast, security, and other applications. They have proven a worthy substitute for fibre optics albeit with some notable disadvantages. FSO systems are usually installed above ground level and are therefore exposed to the prevailing atmospheric conditions which can negatively affect the optical signal. Tropical regions exhibit adverse weather conditions such as rain, fog, and haze that can affect FSO signals. There is a dearth of research on the use of FSO systems in tropical regions and on methods to mitigate the effect of FSO signal interference. In this research, we propose diversity techniques to improve the link performance of FSO systems in a tropical region. The simulation results indicate a better Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR) compared to other techniques.

Index Terms**—**Free space optics, optical communication, space diversity, atmospheric attenuation

I. INTRODUCTION

Free space optics (FSO) utilizes a medium that is freely available such as air, space, or vacuum to send information to an intended destination through an optical signal [1]. FSO has been used as a solution in many communication applications. Connections between wireless local area networks (WLANs) and local area networks (LANs) have been facilitated using FSO. It enables communications services to be sent to difficult terrains through the provision of remote mobile communications systems. FSO also facilitates the installation and operation of other communications solutions like fibre optics and radio frequency (RF) systems. This enables FSO to be considered as a redundancy option for the more established communication systems. FSO holds the prospect of providing the excessive bandwidth requirements of communications systems today and in the future [2], [3].

FSO offers many advantages over other optical communication methods such as fibre optics. It is also a strong alternative to RF communication methods. FSO systems are cheaper, as it does not require digging trenches to lay cables, a requirement in the installation of fibre optics. The installation process is simple and quick. Also, FSO is not subject to inference from other signals and no licensing regime is required for the installation. Security of signal transmission is also enhanced with FSO systems. An additional advantage of FSO systems is that frequency coordination is not required as is the case in other communication systems like radio or microwave. FSO systems also allow for the reuse of spatial resources [1], [4]-[6].

Although FSO systems have very promising data rates, they are installed above ground and are therefore affected by the prevailing atmospheric conditions owing to the line-of-sight (LOS) requirements for their operation [2], [7]. These conditions lead to signal absorption, signal scintillation, beam wandering, signal scattering, beam spreading, line-of-sight obstructions, propagation geometrics, and other effects [2]. Fog and water droplets are particularly disrupting for optical signals deployed in FSO. This is because of the ability of water droplets to absorb, refract or reflect the transmitted optical signal [5].

Several methods have been proposed to combat optical signal attenuation in FSO systems. Research in [7], considers improving FSO link performance during adverse weather conditions through the implementation of different optical windows for transmission. The optical windows correspond to different wavelengths. Their results show that at optical windows corresponding to higher wavelengths, the performance of the FSO link is poorer compared to the performance at lower wavelengths. In [8], the authors propose a technique to reduce anisotropic turbulence by developing an elliptical-aperture multimode diversity receiver. The technique is applied in detecting a dual-polarization 30-Gbaud QPSK signal, and the results indicate a significant reduction of outage probability from 14.63 % to 0.38 % compared to circular aperture reception. The authors in [2], propose a technique where the transceiver operates in the long-wavelength-infrared (LWIR) spectrum. An investigation into fog values from different geographical locations appears in [6]. The authors also create a channel attenuation model. An important consideration for communication systems is the security of transmitted signals. The authors in [9], consider mitigating eavesdropping on FSO signals over a large area due to

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scattering during foggy conditions. The authors propose a non-line of sight (NLOS) FSO channel.

Multiple-Input Multiple-Output (MIMO) systems have been successfully applied to mitigate the effects of fading of signals in RF or Infrared (IR) communication systems. These techniques could also be applied in FSO systems [3]. Multiple transmitter/receiver (Tx/Rx) configurations that provide spatial diversity have become an important alternative for communication over longer distances. In [10], the authors consider the performance of multiple Tx/Rx FSO links based on received power level (PR) and bit error rate (BER). The parameters simulated in the research include received power, eye diagram, and BER. The results show that doubling the number of transmitters can effectively increase the received power. Also, a lower BER enables the transmission to be carried out over a longer distance. The authors in [3], investigate methods aimed at improving the BER performance of FSO communication systems by employing multiple transmitters/receivers. They suggest ways to remedy amplitude and phase distortions by applying on-off keying (OOK) owing to its ease of use. The authors [11], propose a new all-optical FSO communication receiver that operates on a spatial demultiplexer and a photonic integrated coherent combiner. Experimental results indicated constant BER, high collection efficiency, and greater robustness to phase and intensity interferences when compared to other techniques. In [12], diversity is applied to deal with the outage capacity in the presence of turbulence in the transmission medium. The authors make assumptions of coherent synchronous and short-noise limited photodetection at the receiver. In [13], the authors consider modulation under different atmospheric conditions with and without space diversity. They investigate the BER performance of the identified modulation techniques. The authors in [14], investigate the performance of FSO communication between a satellite and a receiver on the ground in the presence of both atmospheric turbulence and internal satellite vibrations. They also investigate the performance of spatial diverse systems. In [15], the authors introduce a two-dimensional photodiode array (2D-PDA) configured FSO receiver with the characteristic of high optical alignment. They further employ the output of the 2D-PDA device with a maximum ratio space diversity technique and interrogate its BER performance.

Adverse atmospheric conditions in Ghana can lead to sudden changes to the operation of an FSO system. These varying weather conditions can affect the successful recovery of transmitted signals FSO signals. Physical structures such as tall buildings and even animals such as birds can interfere with optical signals during transmission. It has been demonstrated that spatial diversity and a carefully selected system power can combat signal attenuation. In this study, we apply a spatial diversity technique to improve the performance of an FSO system in rainy, foggy, or hazy weather conditions.

II. System Model

This section presents an overview and discusses the main components of the FSO system. It is followed by a mathematical analysis of the FSO model. Then, the proposed diversity technique which is presented as a solution to fading and loss of signal under critical weather conditions is discussed.

A. *Overview of an FSO System*

The block diagram of an FSO system is shown in Fig. 1. It comprises the following sections: transmitter, atmospheric channel, and the designated receiver. The transmitter is responsible for generating the optical signal that will be propagated through free space to the designated receiver. The transmitter transforms the electrical information into an optical signal. The function of the modulator is to generate a signal capable of being transmitted over free space [2].

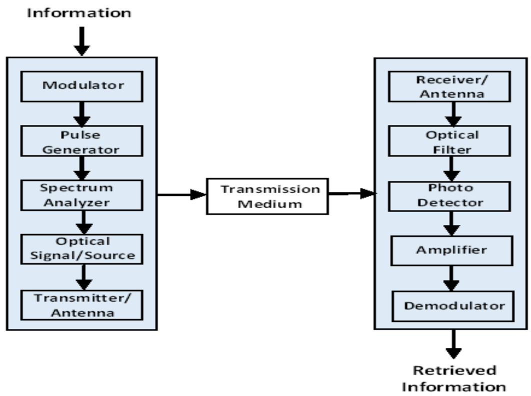

Fig. 1. Block diagram of an FSO system

The pulse generator produces the electrical signal by way of pulses. The input signal and the frequency wave of the equipment can be observed using the spectrum analyzer. At the receiver, an amplifier increases the signal strength to aid in the correct retrieval of the transmitted signal and its transformation to an electrical signal. To screen out noise, the electrical signal from the photodetector passes through a filter. The telescope performs the function of directing the optical signal onto the photodetector surface. The photodetector transforms the received optical signal energy into an electrical signal. The filter takes out background noise such as solar illumination from the optical signal. The output of the photodetector is amplified before demodulation recovers the signal [2]. The BER analyzer is used to assess the accuracy of the received signal.

In the analysis of FSO links, quality factor (*Q-factor*), minimum BER, and eye diagram are important parameters that are considered [7].

B. *Mathematical Modeling of an FSO System*

The power gains and losses in a communications system can be accounted for in a link budget [13]. The received power in an FSO system can be expressed as:

$$P_R = P_T + G - L \tag{1}$$

where P_R is received power, P_T transmitted power, G Gains and L losses. G can further be segregated into:

$$G = G_T + G_R \tag{2}$$

where G_T is the transmitter gain and G_R the receiver gain. G_T can be presented according to [16] as:

$$G_T = \left(\frac{\pi D_T}{\lambda}\right)^2 \tag{3}$$

and G_R also as:

$$G_R = \left(\frac{\pi D_R}{\lambda}\right)^2 \tag{4}$$

where D_T and D_R are the transmitter aperture diameter and receiver aperture diameter, respectively. Also, λ is the wavelength. Equations (3) and (4) confirm that the transmitter diameter and receiver aperture diameter share direct proportionality to the transmitter and receiver gains respectively. Losses can be segregated into:

$$L = L_T + L_R + L_{FS} + L_G \tag{5}$$

where L_T is the transmitter loss, L_R is the receiver loss, L_{FS} the free space path loss or channel loss, and L_G is the geometrical loss due to the transmitter and receiver aperture. According to the Beer-Lambert law [10], the atmospheric losses for any laser can assume an exponential equation:

$$L_{FS} = e^{-l\sigma} \tag{6}$$

where l (km) is the transmitting range of the laser and σ is the typical attenuation coefficient (0.1 for clear air). The geometrical loss, according to [17], is given by:

$$L_G = 10\log\left[\frac{D^2}{\left(D_T + (l\theta)\right)^2}\right] \tag{7}$$

where θ is the divergence angle of beam (in mrad) and l is the length of the communication link (in meters). From the analysis the above, the received power, P_R, can also be expressed as:

$$P_R = P_T + G_T + G_R - \left(L_T + L_R + L_{FS} + L_G\right) \tag{8}$$

The received power P_R can also be expressed in terms of the transmitted power in the Friis equation [18] as:

$$P_R = P_T\left(\frac{G_T G_R \lambda^2}{(4\pi R)^2}\right) \tag{9}$$

Equation (9) suggests that an increase in transmitted power could lead to an increase in the system's performance. The effect of transmitted power will be investigated in this research.

There is a relationship between the BER and the *Q-factor* of the FSO system. This relation can be captured according to [19] as:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{10}$$

where *erfc* is the complementary error function. However, generally for any $x(t)$ according to [20] we have:

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt \tag{11}$$

Equations (10) and (11) shows that a greater *Q-factor* guarantees a smaller BER.

An optical signal passing through free space is exposed to different levels of attenuation depending on the prevailing atmospheric condition. Equation (12) captures the total attenuation experienced due to fog, rain, haze and scattering of the signal. These weather conditions are typical to a region like Ghana. The total attenuation is presented according to [7] as:

$$\alpha = \alpha Fog_{\varphi} + \alpha Rain_{\varphi} + \alpha Haze_{\varphi} + \alpha Scattering_{\varphi} \tag{12}$$

where α is the attenuation and φ represents the operational wavelength in μm.

The performance of an FSO link is affected by the chosen wavelength, the light power source, the beam divergence angle, the sensitivity of the photodetector, and the aperture diameter of the device used [2].

C. Space Diversity Technique

Diversity-combining of independently fading signal paths is an effective method for mitigating the effects of signal fading in FSO systems [21]. Diversity-combining uses the fact that independent signal paths have a low probability of experiencing deep fades simultaneously. The idea behind diversity is to send the same signal over different independent fading paths, with the paths combined is a way to ensure that the fading of the resultant signal is reduced [18].

Our proposed space diversity technique is simulated for haze, rain and fog attenuation as applied to three independent FSO channels. The weather conditions simulated correspond to the climatic conditions for Ghana. The fork tool is used to replicate identical copies of the transmitting signal, which are then sent through the independent channels. A power combiner sums N number of input signals to the output. The technique is operated at a constant input power level. The system is composed of multiple Tx/Rx configurations, specifically, it has 3 Tx/3 Rx, 6 Tx/ 6 Rx, 9 Tx/ 9Rx, 12 Tx/ 12 Rx and 15 Tx/ 15 Rx. Simulations are carried out for the various configurations.

D. Results and Discussion

In this section, we present the simulation results of the proposed technique followed by an analysis and discussion of the results. The simulations are carried out using the Optiwave simulation platform. The parameters used for the simulations are shown in Table I.

TABLE I: SYSTEM PARAMETERS

Parameter	Value
Wavelength (λ)	1550 nm
Bit rate	2.5 Gps
Clear atmosphere attenuation	0.43 db/km
Haze attenuation	4.3 db/km
Rain attenuation	9.23 db/km
Fog attenuation	43 db/km
Link distance	6.4 km
Class 1 Laser Power (input)	10 dBm
Transmitter diameter aperture	8 cm
Receiver diameter aperture	20 cm

1) Single transmitter/Single receiver system (1 Tx/ 1 Rx)

In this section, we present the results of the FSO system over a channel with single transmitter/single receiver (1 Tx/ 1 Rx) arrangement under different attenuations. The FSO system performance at different atmospheric conditions (0.43 dB/km, 4.3 dB/km, 9.23 dB/km, 43 dB/km) are measured. These conditions correspond to clear, haze, rain, and fog respectively. The 1 Tx/ 1 Rx configuration is shown in Fig. 2. In this configuration, a bit sequence is generated by a pseudo-random bit sequence (PRBS) generator component and is then converted into a non-return to zero (NRZ) pulse by an NRZ pulse generator. The NRZ pulse is modulated with a Mach-Zehnder modulator (MZM). The modulator outputs an optical signal which is then amplified and transmitted through the FSO channel or medium. At the receiver, the amplified optical signal passes through the avalanche photodiode (APD) detector and is converted to an electrical signal. Unwanted frequency noise is removed using a low-pass Bessel filter. The filtered signal is passed through the 3R generator to connect the bit sequence and the electrical signals to a BER analyzer. The BER analyzer is used to determine parameters like minimum BER, *Q-factor*, and eye height.

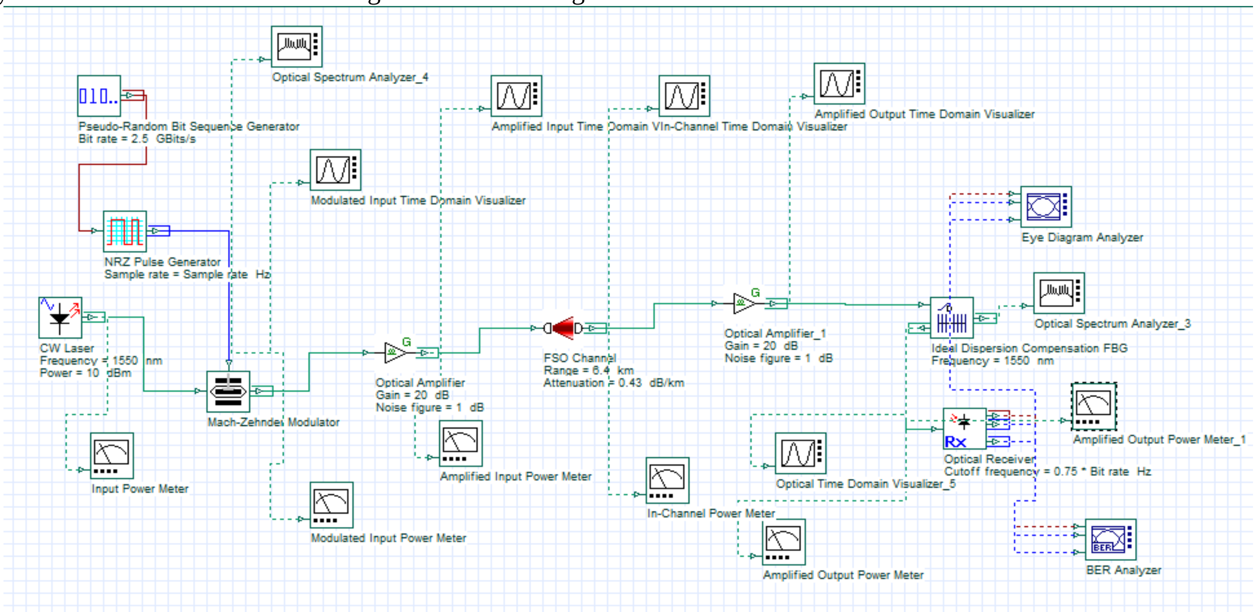

Fig. 2. (1 Tx/1 Rx) FSO link system under clear weather condition

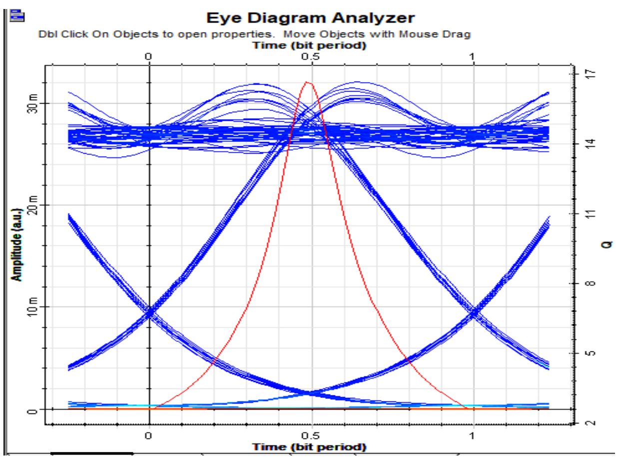

Fig. 3. (a) Eye diagram for 1 Tx/1 Rx FSO at 0.43 dB/km

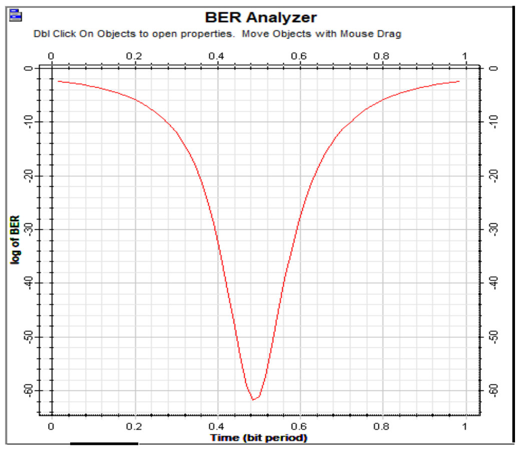

Fig. 3. (b) Q-factor for 1 Tx/1 Rx FSO at 0.43 dB/km

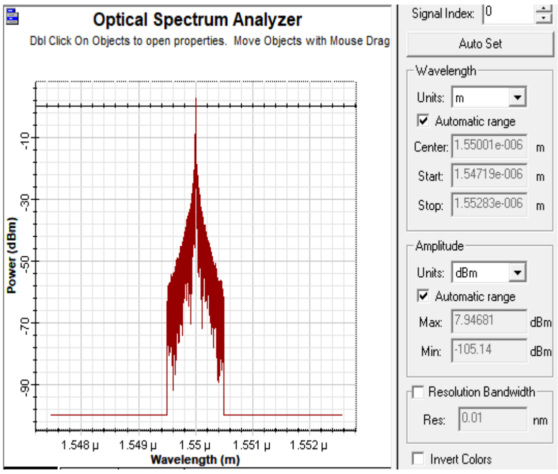

Fig. 3 (c) Output power for 1 Tx/1 Rx FSO at 0.43 dB/km

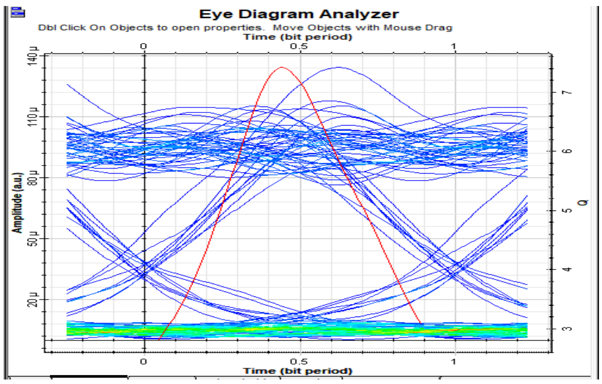

Fig. 4. (a) Eye diagram for 1 Tx/1 Rx FSO

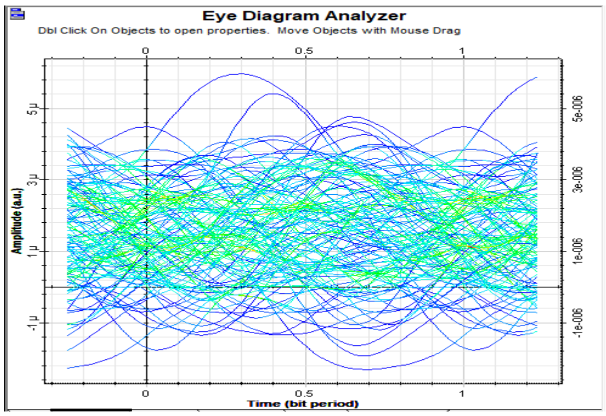

Fig. 4. (b) Eye diagram for 1 Tx/1 Rx FSO

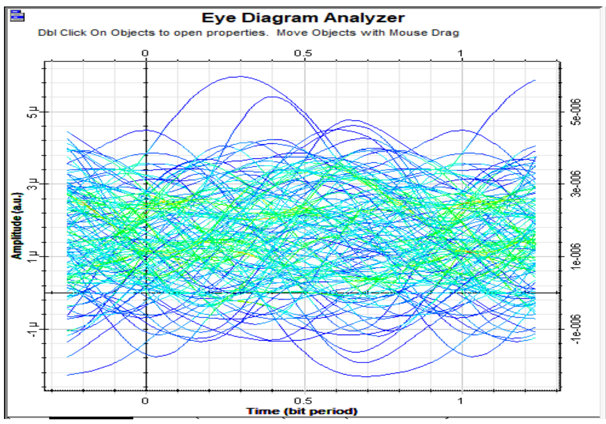

Fig. 4. (c) Eye diagram for 1 Tx/1 Rx FSO

Fig. 3 shows the performance of the 1 Tx/1 Rx configuration for different weather conditions. For clear weather, with attenuation of 0.43 dB, the *Q-factor* is 16.6331 and the BER is 1.82886e-062. The total received power is -7.162 dB indicating a loss of 2.838 dB when compared to the transmitted power. These values indicate a strong *Q-factor* and low BER but a reduced total received power. The 1 Rx/Tx configuration is simulated for different attenuation levels corresponding to hazy (4.3 dB/km), rainy (9.23 dB/km) and foggy (43 dB/km) conditions. Table II shows the output parameters of 1 Tx/ 1 Rx FSO under different atmospheric conditions at 10 dB input power. It can be seen from Fig. 4 that at hazy conditions, the quality of the signal is significantly reduced resulting in an increasing BER. There is also power loss at the receiver side. The received power also experienced a significant reduction to about -27.01 dBm.

TABLE II: OUTPUT PARAMETERS FOR 1 TX/1 RX

Parameter	Hazy condition (4.3 dB/km)	Rainy condition (9.3 dB/km)	Foggy condition (43 dB/km)
Max *Q-factor*	7.4158	0	0
Min. BER	4.79155e-014	1	1
Received power (dBm)	-17.136	-26.968	-27.010

2) *Multiple transmitter/multiple receiver system*

The simulation results of the multiple transmitter/receiver system are presented in this section for foggy conditions (43 dB/km). The setup is shown in Fig. 5. Fig. 6(a), Fig. 6(b) and Fig. 6(c) show the performance of the 3 Tx/3 Rx FSO system at 10 dBm input power obtained using eye diagram, BER, and spectrum analyzers respectively. From figure 6 (a), it can be observed that the *Q-factor* increases from zero (1 Tx/1 Rx) to about 4.365, the BER from 1 to about 5.21037e-06, and the received power from -27.010 dBm to -20 dBm. The multiple transmitter/multiple receiver system is also simulated for 6 Tx/ 6 Rx, 9 Tx/ 9 Rx, 12 Tx/12 Rx, and 15 Tx/ 15 Rx.

Fig. 7(a), Fig. 7(b), and Fig. 7(c) show the performance of 6 Tx/6 Rx FSO at 10 dBm input power. The value of the *Q-factor* increases from 4.365 in the 3 Tx/ 3 Rx configuration to about 6.316, the BER from 5.21037e-006 to about 1.05915e-01, and the output power from -20.932 dBm to -18.495 dBm. Fig. 8 (a), Fig. 8(b), and Fig. 8(c) show the performance of 9 Tx/9 Rx at 10 dBm input power. The value of the *Q-factor* increases from 6.316 in the 6Tx/6 Rx configuration to about 7.569, the BER from 1.05915e-01 to about 1.481e-014, and the received power from -18495 dBm to -16.942 dBm. Fig. 9(a), Fig. 9(b), and Fig. 9(c) show the performance of 12 Tx/ 12 Rx FSO at 10 dBm input power.

The value of the *Q-factor* increases from 7.569 in the 9 Tx/9 Rx configuration to about 8.482, the BER from 1.48131e-014 to about 8.79468e-018, and the received power from -16.942 dBm to -15.801 dBm. Fig. 10(a), Fig. 10(b), and Fig. 10(c) show the performance of 15 Tx/15 Rx FSO at 10 dBm input power. The value of the *Q-factor* increases from 8.482 in the 12 Tx/12 Rx configuration to about 9.179, the BER from 8.79468e-018 to about 1.72977e-020, and the received power form -15.801dBm to -14.898 dBm. The simulation results for the various multiple transmitter/receiver configurations are summarized in Table III.

From the results obtained for the different space diversity configurations discussed above it can be observed that at minimal input power (10 dBm), the system performs better in terms of BER and SNR as more transmitter/receiver pairs are added. However, increasing the transmitter/receiver pairs leads to a reduction in the received power.

TABLE III: OUTPUT PARAMETERS FOR MULTIPLE TX/RX CONFIGURATIONS

Parameter	3 Tx/ 3 Rx	6 Tx/ 6 Rx	9 Tx/ 9 Rx	12 Tx/ 12 Rx	15 Tx/ 15 Rx
Max Q-factor	4.36566	6.31684	7.56991	8.48203	9.17989
Min. BER	5.21037e-006	1.05915e-01	1.48131e-014	8.79468e-018	1.72977e-020
Received power (dBm)	-20.932	-18.495	-16.942	-15.801	-14.898

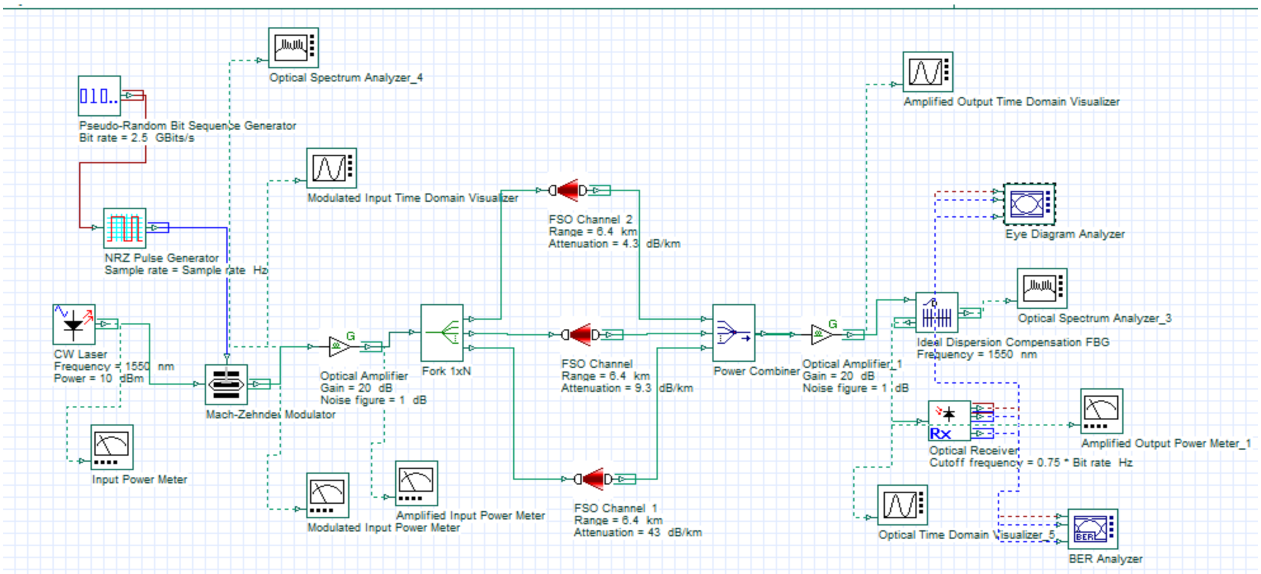

Fig. 5. (3 Tx/3 Rx) FSO link-system at 10dB input power.

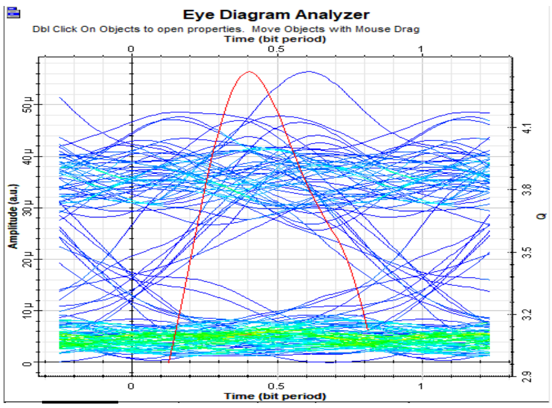

Fig. 6. (a) Eye diagram for 3 Tx/3 Rx FSO

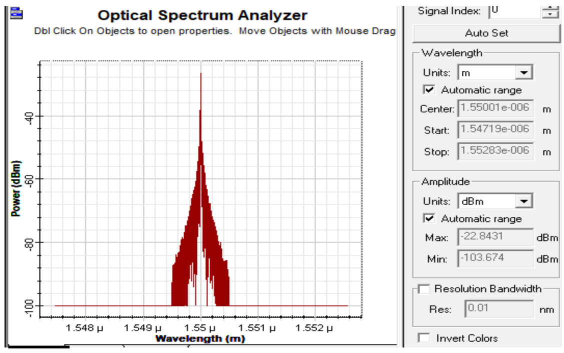

Fig. 6. (c) Output power for 3 Tx/3 Rx FSO

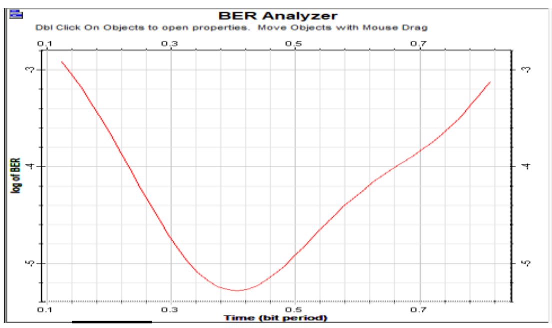

Fig. 6. (b) BER for 3 Tx/3 Rx FSO

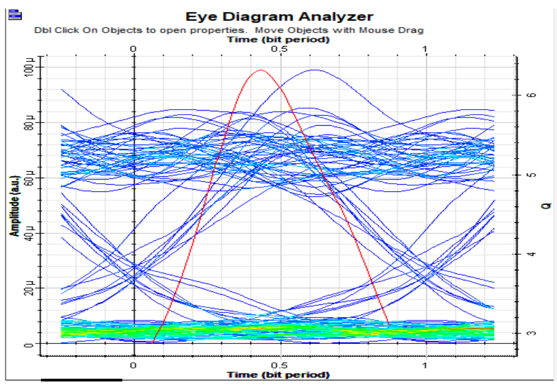

Fig. 7. (a) Eye diagram for 6 Tx/6 Rx FSO

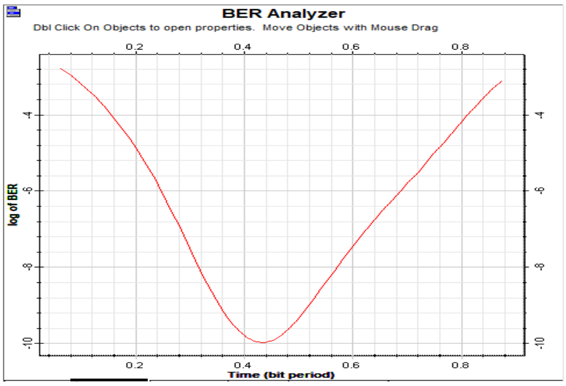

Fig. 7. (b) BER for 6 Tx/6 Rx FSO

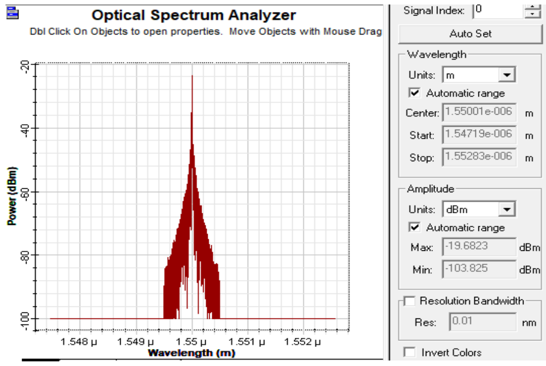

Fig. 7. (c) Output power for 6 Tx/6 Rx FSO

III. Conclusion

The aim of this research was to investigate methods to mitigate the effects of atmospheric turbulence on a FSO link in a tropical region like Ghana. Attenuation due to hazy, rainy or foggy conditions affect the transmission of the optical signal in an FSO system. We presented a space diversity technique with different multiple transmitter/receiver configurations. The simulation results showed that the more transmitter/receiver pairs are used, the better signal quality and the lower the BER over atmospheric turbulence. The drawback of the proposed scheme is the reduction in the received power with an increase of the transmitter/receiver count. A further improvement of the system could be achieved by implementing the optical amplify and forward (OAF) technique to the signal. This will be the focus of further research in the area.

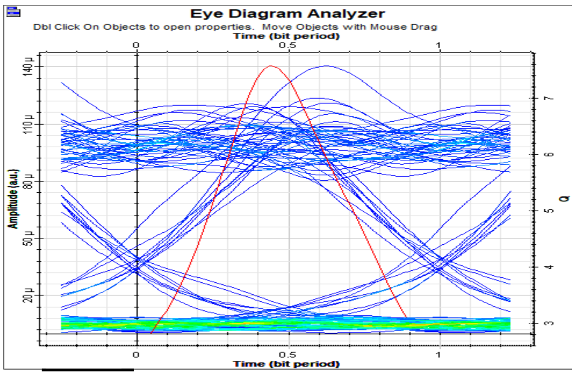

Fig. 8. (a) Eye diagram for 9 Tx/9 Rx FSO

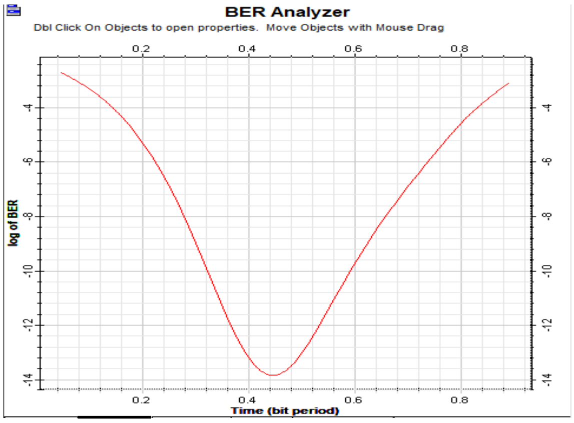

Fig. 8. (b) BER for 9 Tx/9 Rx FSO

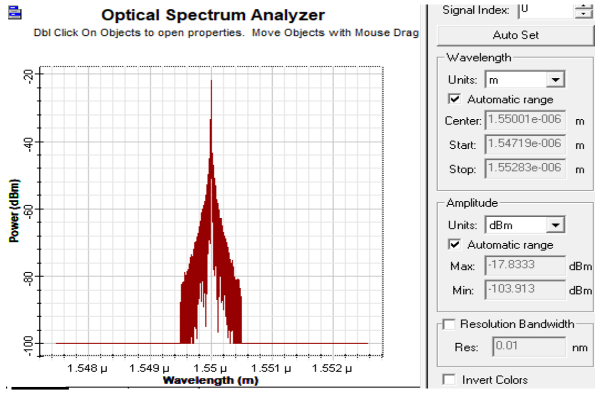

Fig. 8. (c) Output power for 9 Tx/9 Rx FSO

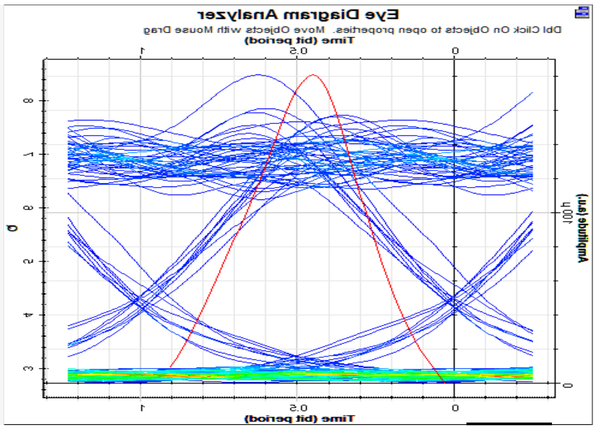

Fig. 9. (a) Eye diagram for 12 Tx/12 Rx FSO

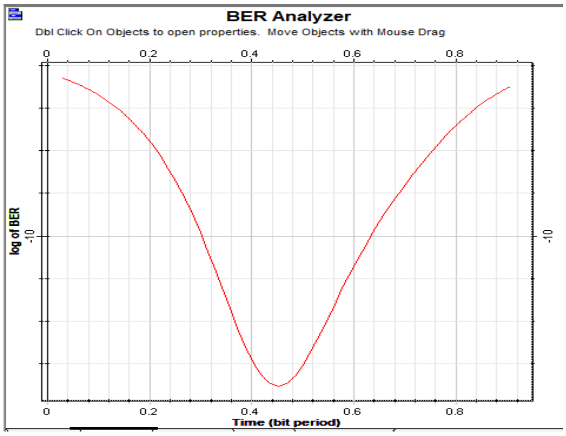

Fig. 9. (b) BER for 12 Tx/12 Rx FSO

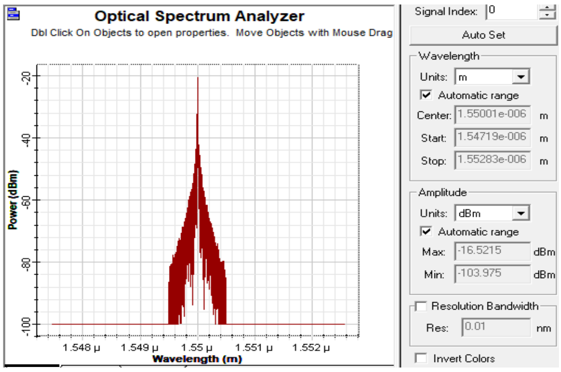

Fig. 9. (c) Output power for 12 Tx/12 Rx FSO

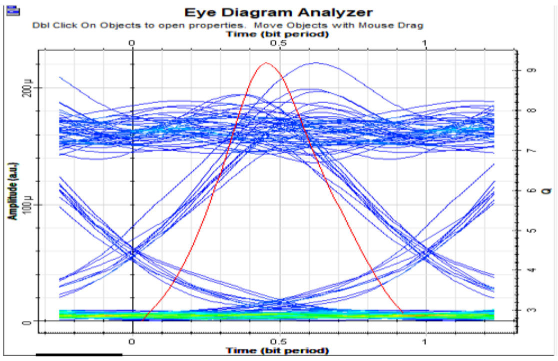

Fig. 10. (a) Eye diagram for 15 Tx/15 Rx FSO

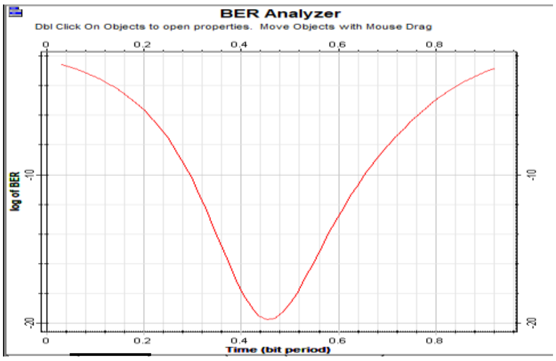

Fig. 10. (b) BER for 15 Tx/15 Rx FSO

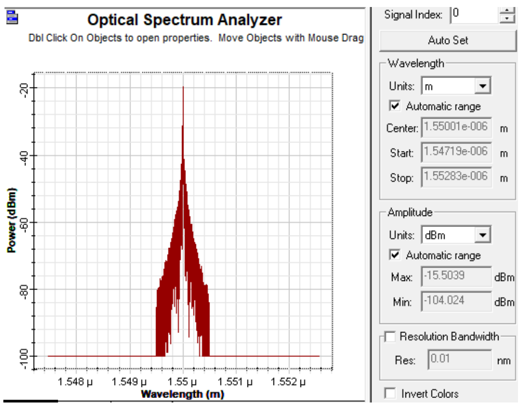

Fig. 10. (c) Output power for 15 Tx/15 Rx FSO

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Tagnon P. Okoumassoun conducted the experiments and obtained the results; Anita Antwiwaa analyzed the data and provided the corresponding interpretations; Nana K. Gerrar wrote the paper; all authors worked on the concept, and literature survey and approved the final version.

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