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Design and performance evaluation of a 350 m free space optical communications link for pico-macrocell backhauling

Abduljalal Yusha'u Kassim[1], Vitalice Kalecha Oduol[2], Aliyu Danjuma Usman[3]
[1]Department of Electrical Engineering, Pan African University Institute for Basic Sciences, Technology and Innovation, Nairobi, Kenya
[2]Department of Electrical and Information Engineering, Faculty of Engineering, University of Nairobi, Nairobi, Kenya
[3]Department of Electronics and Telecommunications Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria

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ABSTRACT

Fibreless optics or free space optical communications (FSOC) has been at the forefront of many academic research in telecommunications due to its numerous benefits of large spectrum, high-speed data transmission, security, low transmit power, unlicensed spectrum and non-interfering links. Among the technical challenges of dense deployment of small cells in heterogeneous networks (HetNet) is a flexible and cost-effective backhaul link. This paper proposes, designs, simulates and evaluates the performance of a 350 m FSOC link under different atmospheric impairments for picocell to macrocell backhauling applications. The performance of the FSOC link is assessed by evaluating bit error rate (BER), eye diagram and quality factor (Q-factor). Results obtained recommend the FSOC link deployment for pico-macrocell backhauling under the weather conditions of clear sky with/without turbulence, heavy rain, heavy haze, heavy fog and wet snow.

Corresponding Author:

Abduljalal Yusha'u Kassim
Department of Electrical Engineering, Pan African University Institute for Basic Sciences, Technology and Innovation
PAUSTI Complex Block B, JKUAT Main Campus, Juja, P.O. Box 62000-00200 Nairobi, Kenya
Email: yushau.abduljalal@students.jkuat.ac.ke

1. INTRODUCTION

In the last few decades, the interest of the academia and telecommunication industries has been channeled to the development of alternative technologies to radio frequency (RF) communication networks. The exponential growth of data-hungry devices and services has led to more restrictions on RF due to the limited spectrum resources. Additionally, spectrum license fees, radio resource management issues, power efficiency, cost management, inter- and intra-channel interferences, and the large bandwidth demand of new technologies are among the challenges faced by the industry. Free space optical communication (FSOC) is considered as a potential alternative to RF-based communication networks due to its unique features, such as low cost, high-speed data transmission, easy deployment, large bandwidth, high security, low power requirements, license-free spectrum and immunity to electromagnetic interference [1], [2]. The FSOC technology is based on the advancements in laser technology. It uses optical sources like continuous wave (CW) lasers, Fabry Perot lasers, light emitting diodes (LEDs), vertical cavity emitting (VCEL) lasers, at the transmitter end. At the receiver end, optoelectronic devices such as avalanche photodetectors (APDs) or positive intrinsic negative (PIN) photodiodes are used [3]. FSOC technology is a line of sight (LOS) communication where an optical carrier signal in the near-infrared (IR) or visible light (VL) spectrum modulates and propagates the data from the source via the atmospheric channel to the destination [4], [5]. Applications of the FSOC technology are found in backhaul for wireless cellular networks, unmanned aerial vehicles (UAV), military surveillance, campus connectivity, disaster recovery, inter-satellite communication, and high altitude platforms (HAPs), among others [6], [7]. Albeit of the positive merits of the FSOC technology, it is adversely affected along the atmospheric channel by the impact of atmospheric turbulences induced by scintillation, challenging weather conditions of fog, rainfall, snow and haze, and pointing errors/misalignment caused by building sways or mechanical vibrations between transceiver [8].

The fifth-generation-and-beyond (5 GB) wireless networks are characterized by dense deployment of small cells; particularly picocells, also known as network densification. This is an important feature of the 5 GB network architecture, as it being a capable scheme to improve the capacity and coverage of wireless networks in large buildings like malls and densely populated areas such as schools, markets and so on [9]. The anticipated dense deployment of small cells such as picocells in 5 GB networks and the traditional backhauling technologies that are either quite expensive to deploy and maintain or inefficient, necessitate the development of alternative solutions. Backhauling refers to the connection between the access and core network. In picocell deployment, a cost-effective backhaul system is a major challenge [10]. The existing traditional backhaul technologies are copper wire, microwave and fiber optic cables. Copper wire has the problems of low-capacity transmission, crosstalk, and noise. The main limitations of microwave are license fee, cost of installation and maintenance, interference, security and high-power requirements. With all the advantages of fiber optics, it has the disadvantages of cost, time and logistics of deployment, it also requires right of way permission. Looking at the capital expenditure (CAPEX) and operational expenditure (OPEX) of picocells deployment, FSOC addresses all the problems of the traditional backhaul technologies in terms of license, cost, way permits, interference, security, power requirements, time of installation and deployment. In heterogenous networks (HetNet) settings, the mobile operators deploy picocells to areas with poor quality of signal reception from the macrocell and there is a need to establish backhaul links between picocells and macrocell. Picocells can be defined as low-powered, short range (100-200 m or less) base stations that are fully functioning and typically deployed by operators in a particular network plan. In terms of access and backhaul, they share the same features with macrocells allowing for high data rate and low latency [11]. With these, the picocell needs to connect to the macrocell with the most cost-effective and high data rate backhaul technology. The flexibility and the effective cost of deployment and maintenance offered by FSOC technology serve as a motivation for the Researchers to explore the potential of its installation for mobile backhauling [12].

Research on the design and performance investigation of FSOC links considering various weather conditions and atmospheric turbulences was reported in literature. Malik and Singh [13] designed and evaluated the performance of two FSOC systems at 2.5 Gbps data rate under heavy and light haze, very clear and clear atmospheric conditions. Simulation results indicated that the Q-factor and bit error rate (BER) of each link deteriorates due to effects of atmospheric attenuation and link distances. Hussein and Askar [14] developed an FSOC link to improve the transmission of both data and power, even in challenging weather conditions. The link operates at a wavelength of 785 nm and at a speed of 1.25 Gbps. The link's performance was tested in heavy rain, clear skies, and haze conditions. It was found that atmospheric losses caused by these conditions can negatively affect the link's optimal performance in terms of BER, eye diagram, and received power. A multi-beam concept for enhancement of free space optic (FSO) link under heavy rain attenuation for tropical regions was proposed in [15]. Four beams operating at 850 nm and bit rate of 1 Gbps were analyzed. A relationship between received optical power, link distance and BER of the single and multiple beams was built and simulation results indicated better improvements for the four beams FSO link as related to three, two and single beams respectively, in relation to geometric losses, received optical power and link distance.

A study on the performance of hybrid dense wavelength division multiplexing in the multiple-input multiple-output (DWDM-MIMO) and dense wavelength division multiplexing-single input single output (DWDM-SISO) FSO systems under rain, fog and snow conditions was carried out in [16]. The atmospheric attenuation at various intensities of weather conditions were calculated using range of visibility of the atmosphere. Simulation results showed that atmospheric attenuation leads to degradation in received optical signal quality and increase in BER. There is enhancement in transmission distances and signal quality for the proposed hybrid scheme as compared to the traditional DWDM-SISO system. Performance analysis of a single beam 1 Gbps, operating at 850 nm FSOC link was conducted in [17]. Based on the rainfall data collected for four months in Malaysia, the rain attenuation model was derived, and simulations were done. At an acceptable BER and atmospheric attenuation of 19 dB/Km, the link can transmit data up to a maximum distance of 830 m. It has been observed that atmospheric attenuation increases in direct proportion to the link distance, while the link distance decreases inversely with the intensity of the rain. In study [3], an analysis was conducted to study the impact of rainfall attenuation on a 1 km FSOC link operating at 1,550 nm and 10 Gbps. BER and Q-factor of the system were evaluated for clear sky and different intensities of rainfall. The coefficient of attenuation was calculated using different precipitation rates and environmental parameters. Simulation results indicated degradation on the received signal quality and increase in BER due to rainfall. A hybrid 4×4 WDM/multibeam FSO link for application in multigigabit access network was proposed in [18]. The link was designed to mitigate the impact of atmospheric losses due to heavy rainfall in tropical regions. Downlink transmission from an FSOC base station to four FSO UEs each at 1.25 Gbps was studied and analyzed. Simulation results concludes that the hybridization of the WDM scheme and multiple beam FSOC reduced the impact of atmospheric attenuation due to rainfall and enhanced the operation of the link with respect to data rate, received optical power, scalability and link distance. In study [19], the impact of weather conditions and transceiver aperture diameters on an FSO link was studied based on 16-QAM and dual polarization quadrature phase shift keying (DP-QPSK) modulation schemes. The effects of different aperture diameters of 10 cm, 30 cm and 1 m, and clear weather, fog and haze conditions were analyzed in terms of BER and link distances. Simulation results indicated reduction in link distances and BER due to bad weather condition and improvement in BER and link distance due to increase in aperture diameters. The design and evaluation of the performance of a 4-channel WDM FSOC link based on differential phase shift keying (DPSK) modulation technique was reported in [20]. The study of the link was carried out in environments with heavy rain and haze attenuation. Optical power, Q-factor, bit rate, and multiplexer bandwidth relationships were established. Simulation results presented deterioration of the link data rate and range due to the impact of atmospheric attenuation. The implementation of the WDM technology enhanced the link throughput, BER and range to acceptable thresholds.

A unified channel attenuation model for FSOC systems under fog weather condition was proposed in [21]. Fog measurement data from different countries were examined, all existing attenuation models were also investigated and analyzed. Compared to the existing models in literature, the proposed model achieves 9 dB root mean square error enhancement. FSOC system under effects of light, moderate, thick and dense fog were studied, and results indicates poor performance of the system under long distance links. Increasing the transmit power or reducing the link distance can only enhance the operation of the link for light, moderate and thick fog, but not for the case of dense fog. The quality of data transmission via FSOC link subjected to different weather conditions was studied in [22]. At 2.5 Gbps, the system BER was analyzed under clear sky, heavy, medium and light rain, and heavy haze atmospheric conditions. Receiver aperture diameter, link distance, input power and data rate served as the performance optimization parameters. Simulation results indicated the significant influence of atmospheric attenuation on the link distance and BER performance of the FSOC link. A 100 m, 200 MHz bit rate, LED based optical wireless communication (OWC) link operating at 850 nm and in parallel with 60 GHz mm-wave link was demonstrated by the authors in [23]. The study involved outdoor field measurements of the performance of the links under rain and fog weather conditions. Based on the outdoor deployment, availability, latency and data rate of the two systems were analyzed. Measurement results for latency and data rate of the two links indicated that the OWC outperformed the mm-wave links and suggested to be suitable for wireless-to-the-home (WTTH) and small cells backhaul applications. Mazin [24] proposed a WDM-FSOC link for terrestrial applications based on NRZ-OOK modulation. BER, SNR, received power and Q-factor were investigated under different weather conditions, including heavy and light haze, very clear and clear sky, and light, medium, and heavy rain. Simulation results presented a significant decrease in link distance and other metrices due to atmospheric attenuation. Singh [5] reported the performance of a 32×10 Gbps (320 Gbps) WDM FSOC systems subjected to the influence of snow and rain attenuation. System I was designed using 32 lasers while System II was designed with a single laser. Both systems were examined under the impact of dry and wet snow, heavy and light rain weather conditions using received power, eye diagram, Q-factor, BER and SNR. Simulation and comparison of the two systems indicated that snow and rain weather conditions deteriorate the strength of received signal and that System II with single laser enhances longer link distances at acceptable performance levels.

Having stated the tremendous benefits of deploying FSOC technology in pico-macrocell backhauling and the current advancements in FSOC system link design and performance evaluations. To the best of our knowledge and considering application specific FSOC link design, we have not come across any study on design and performance evaluation of an FSOC link for pico-macrocell backhauling application. This research is motivated by conducting a feasibility study on the deployment of an FSOC link for pico-macrocell backhauling. The main contributions are listed: i) An in-depth literature review on FSOC link design and analysis is conducted; ii) An FSOC link is designed, simulated and the performance of the system is analyzed in varying atmospheric conditions; iii) The study covers the effects of the major causes of atmospheric attenuation in tropical and temperate regions of the world, which are rain and haze conditions, and fog and snow conditions respectively; iv) The effect of atmospheric turbulence, which is more prevalent under clear sky conditions, is also analyzed; and v) Finally, recommendation is given based on the achieved results for FSOC link deployment in pico-macrocell backhauling application.

The description of the system model, various atmospheric conditions equations, Gamma-Gamma atmospheric turbulence equation and simulation conditions is done in section 2. Section 3 present the results obtained from the simulation of different conditions and discussions are done. Section 4 contains the conclusion of the research.

2. SYSTEM MODEL AND SIMULATION CONDITIONS

The deployment scenario concept, channel modeling and system design for this study are presented in this section. The design concept depicts a scenario where the data in the form of voice, video, email, and music, generated by users at the picocell base station are backhauled to the macrocell via an FSOC link. The channel models of rain, haze, fog and snow for the atmospheric attenuation are described in the following subsections. For moderate to strong turbulence regimes, the Gamma-Gamma distribution is commonly used as the most popular fading distribution for atmospheric turbulences. Based on the interest that this paper is conducting more of a deployment feasibility study, the worst case of each condition such as: heavy rain, heavy haze, will be studied and its performance evaluated. Figure 1 illustrates the deployment case scenario for this study.

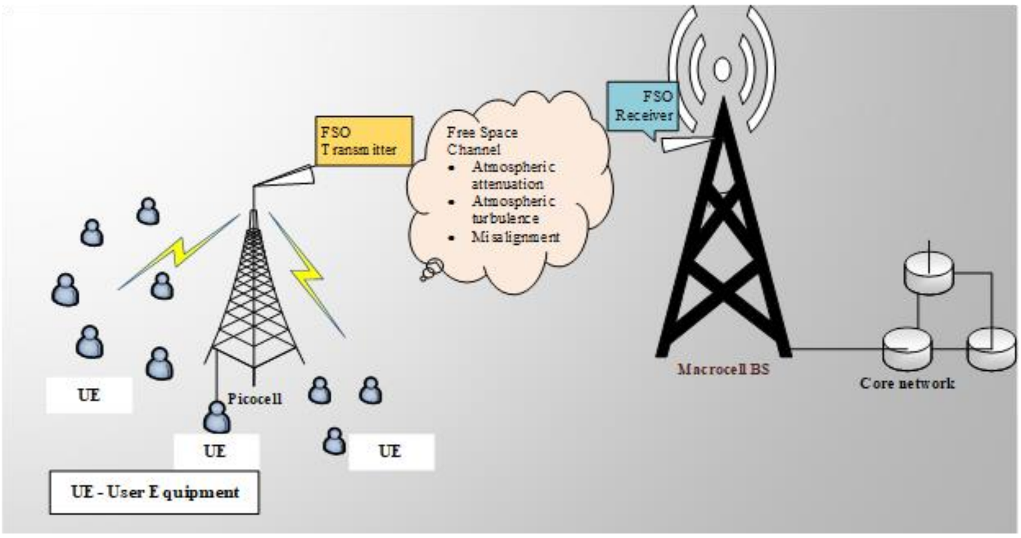


Figure 1. Deployment scenario conceptual diagram

Taking into consideration the atmospheric attenuation, transmitter and receiver parameters, link range, the FSOC link equation is given as [25]:

$$P_R = P_T * \frac{A_R^2}{[A_T + \theta * L]^2} * 10^{-\frac{\alpha L}{10}} \tag{1}$$

where the received power is denoted by P_R, transmitted power denoted by P_T, A_T and A_R represents transmit and receive aperture diameters (m), L is range of the link, $\theta(mrad)$ is the beam divergence, and the attenuation coefficient is denoted by α.

2.1. Atmospheric attenuation

The particles distribution present in the atmosphere constitutes the atmospheric attenuation and its coefficient depends on the level of visibility at a time. Two most popular methods of getting attenuation values are through temporary site installation [13] and observing system performance or using empirically based models of Kim and Kruse which are dependent on the visibility levels to do mathematical analysis. The Kim and Kruse models provides the specific attenuation (∝) as [22]:

$$\propto = \frac{3.91}{V}\left(\frac{\lambda}{550\text{nm}}\right)^{-p} \tag{2}$$

where the visibility is denoted by V, λ represent optical wavelength and p denotes scattering particle size distribution. Kim model provides more detailed definition of the scattering particle size distribution p for visibilities below 0.5 km and shows no wavelength dependency for such visibilities. Table 1 presents the particle size distribution based on the Kim model.

Table 1. Size distribution of scattering particles, p [26]

Visibility, V (km)	Type of visibility	p
V > 50 km	High visibility	1.6
6 km < V < 50 km	Average visibility	1.3
1 km < V > 6 km	Haze visibility	0.16 V + 0.34
0.5 km < V < 1 km	Mist visibility	V - 0.5
V < 0.5 km	Fog visibility	0

2.1.1. Rain attenuation

The rain attenuation γ_{rain} is presented in (3) and it is modeled based on the intensity of rainfall, R (mm/h) and the coefficients a and k of the characteristics of the rainfall obtained from measurements and experimentations [15].

$$\gamma_{rain} = a * R^k \tag{3}$$

The values for a=1.076 and k=0.67 based on the Carbonneau's model, which is the most accepted by ITU-R.

2.1.2. Haze attenuation

The haze particles stay longer in the sky compared to rainfall at a time, haze attenuation is also visibility level dependent. This weather condition is more prevalent in the tropical regions of the world. It is calculated using the Kim and Kruse model as in (2) [27] and the value for a heavy haze condition based on visibility level is given as 2.37 dB/km [2], [13], [20], [22].

2.1.3. Fog attenuation

The fog particles size is equivalent to the operating optical wavelength which leads to severe scattering of the photons. The reduced visibility translates to high attenuation and that made fog the major challenge in FSOC. Since fog attenuation is dependent on the visibility of the atmosphere, it is also calculated using the Kim and Kruse model and as given in (2) [27], [28].

2.1.4. Snow attenuation

Snow conditions are more prevalent in the temperate regions of the world, and it attenuates the optical beam as it propagates. The level of snow attenuation is determined by particle sizes and visibility. It is categorized as dry and wet snow based on the liquid equivalence ration (LER). Equation (4) gives the snow attenuation [5] where δ_{snow} denotes the snow attenuation, snow rate is denoted by S in mm/h, x and y represents the snow coefficients and their values vary for wet and dry snow.

$$\delta_{snow} = x * S^y \tag{4}$$

$$dry\ snow: x = 5.42 * 10 - 5 * \lambda + 5.4958776, \quad y = 1.38$$
$$wet\ snow: x = 1.023 * 10 - 4 * \lambda + 3.7855466, \quad y = 0.72$$

Using (2)-(4), at an operating wavelength of 1,550 nm, the values of the atmospheric attenuation are calculated based on the influence of clear sky, rain, haze, fog and snow weather conditions and presented in Table 2.

Table 2. Atmospheric attenuations under clear sky, rain, haze, fog and snow conditions

Weather condition	Attenuation (dB/km)	Reference
Clear sky	0.233	[13], [22]
Heavy rain	19.28	[5], [15], [20], [22]
Heavy haze	2.37	[13], [20], [22]
Heavy fog	26	[16], [19], [29], [30]
Wet snow	13.73	[5]
Dry snow	96.8	[5]

2.2. Atmospheric turbulences

The effects of atmospheric turbulence contribute to signal losses in the FSOC channel. The optical signal fluctuates due to sudden changes in atmospheric temperature and pressure, affecting both its phase and intensity upon reception. Channel models employed as the fading distribution include log-normal, negative-exponential, Malaga, Gamma-Gamma, among others. The Gamma-Gamma fading distribution fits best for medium to high turbulence regimes and is employed for the modeling of the fading of the channel. The probability density function for the Gamma-Gamma distribution can be presented as (5) [31]:

$$f_g(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \quad (5)$$

where $K_v(.)$ is the modified Bessel function of second kind. α and β represent small and large scales eddies scattering parameters respectively and are dependent on the refractive index structure (C_n^2). This determines the atmospheric turbulence strength. The turbulence regimes are classified into weak (C_n^2=8.4×10^{-15}m$^{-2/3}$), moderate (C_n^2=1.7×10^{-14}m$^{-2/3}$), and strong (C_n^2=5.0×10^{-14}m$^{-2/3}$) turbulences respectively [32], [33]. It is worthy to note that the turbulence effects only happen under clear sky weather conditions [29].

2.3. System design and simulation

The FSOC link uses intensity modulation/direct detection (IM/DD) with on-off keying (OOK) and is assumed to be a point-to-point link with transceivers in line-of-sight. For a pico-macrocell backhauling, a link capable of sup-porting up to 10 Gbps or more is required. For this study, a 10 Gbps FSOC link is proposed, designed, simulated and evaluated using OptiSystem 20 simulation software, which is popularly used by Engineers to design and optimize optical communication systems. The system consists of three main sections: the transmitter, free space medium, and receiver. The transmitter uses a Pseudo random bit sequence (PRBS) generator to produce binary information, such as voice, data, video, music. This information is then converted into an electrical pulse by a non-return-to-zero (NRZ) pulse generator. The Mach–Zehnder modulator (MZM) modulates the encoded electrical signal onto an optical carrier signal generated by a continuous wave (CW) laser at 1,550 nm central wavelength. The modulated optical signal is then transmitted through a transmit aperture and experiences different atmospheric attenuation and turbulences during its journey through the free space channel. At the receiving end, the received optical signal is converted back into an electrical signal using a positive intrinsic negative (PIN) photodetector. The signal then goes through a low-pass Bessel filter (LPF) to remove any unwanted noise present in the information signal. Next, the 3R regenerator regenerates and reshapes the electrical signal before passing it on to the bit error rate (BER) analyzer. The BER Analyzer calculates the bit error rate of the electrical signal, as well as the quality factor and eye diagram of the received signal. The system simulation setup is presented in Figure 2.

The remaining simulation parameters are presented in Table 3. Farzi *et al.* [34] in their work on zone-based load balancing in two-tier HetNet considered three different distances of 150, 250 and 350 m between picocell and macrocell base station. In this our study, we will consider the longest distance which is 350 m and that will serve as our link distance.

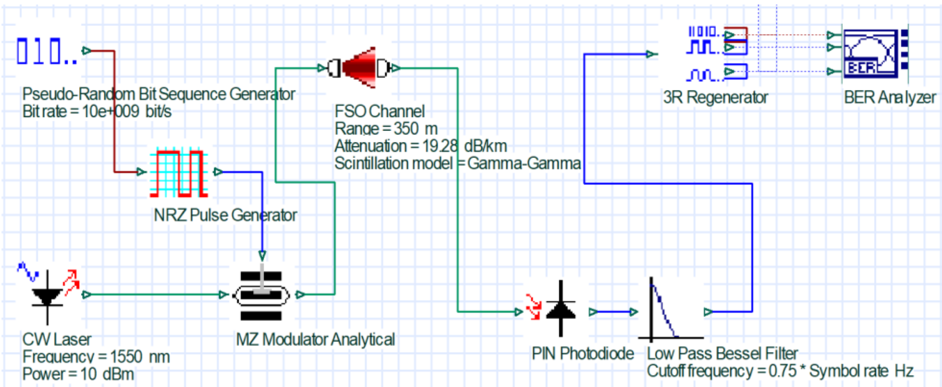


Figure 2. Simulation setup

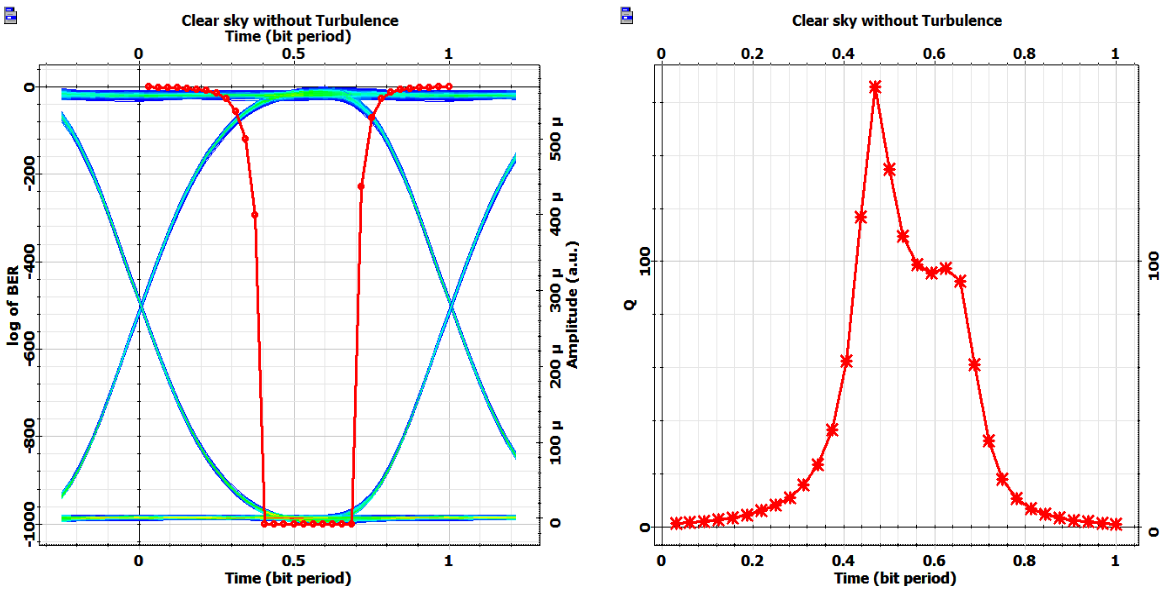
Table 3. Simulation parameters

Parameter	Value
Data rate	10 Gbps
Laser power	10 dBm
Wavelength	1,550 nm
Transmit aperture diameter	5 cm
Receive aperture diameter	20 cm
Beam divergence angle	2 mrad
Atmospheric attenuation	Values in Table 2
Link distance	350 m

3. RESULTS AND DISCUSSION

Based on the FSOC link equation given in (1), the various specific attenuations in (2) to (4), the atmospheric turbulence condition in (5), the design and simulation setup in Figure 2, and the parameters presented in Table 3, the FSOC link performance under the Clear sky without turbulence, Clear sky with strong turbulence, heavy rain, heavy haze, heavy fog, wet and dry snow weather conditions are studied and evaluated using BER, eye diagram and Q-factor as the key performance indicators. The results obtained from simulation of the various weather conditions are presented and discussed in this section. The minimum acceptable BER for FSOC links is 10^{-9} and a Q-factor of 6 [5], [20].

Figure 3 presents the simulation results for the performance of the FSOC link under clear sky and without turbulence conditions. The clear sky without turbulence is assumed to have no variation in temperature and pressure of the weather condition. At an attenuation of 0.233 dB/km, the link's performance was examined. The result in Figure 3(a) showed a widely open eye diagram, indicating good communication and a high signal collected at the receiver, and a BER of 0 indicating no bit was lost. The obtained Q-factor of 168.43 was far above the acceptable value as presented in Figure 3(b).



(a) (b)

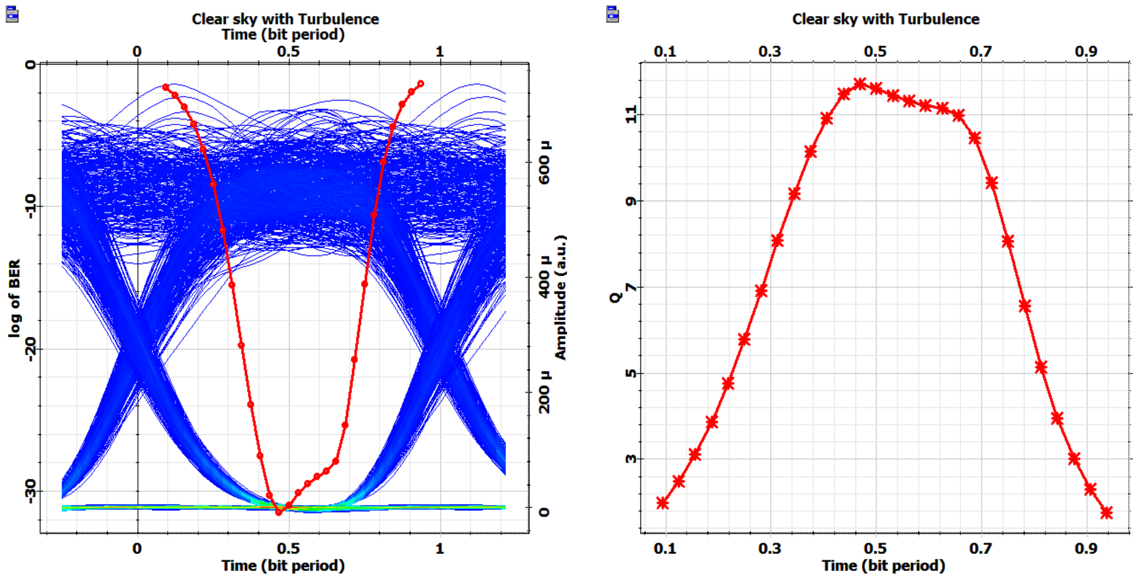
Figure 3. Under clear sky without turbulence weather condition (a) graph of BER and eye diagram and (b) graph of Q-factor

The performance of the FSOC link under clear sky with strong turbulence condition is shown in Figure 4. The atmospheric conditions were taken into account, assuming there would be variations in temperature and pressure that could cause scintillation effects. Strong turbulence and atmospheric attenuation of 0.233 dB/km were also considered when evaluating the link's performance. The simulation results showed a Q-factor of 11.56, which is above the acceptable threshold, and a widely open eye diagram, indicating good communication and confirming high signal collected at the receiver. However, the obtained BER of 1.76e-31 was also above the acceptable threshold. The results in Figures 3(a) and 4(a), and as well 3(b) and 4(b) clearly show how adverse atmospheric conditions affected the FSOC link performance.

In Figure 5, we can see the performance of the FSOC link during heavy rain conditions. When it rains, the optical beam scatters, which causes the optical signal to weaken. To analyze the link's performance, we considered a heavy rain attenuation of 19.28 dB/km. The results showed a widely open eye diagram, indicating good communication. We obtained a Q-factor of 54.84 and a BER of 0, both of which are above the acceptable threshold values as shown in Figures 5(a) and 5(b), respectively.

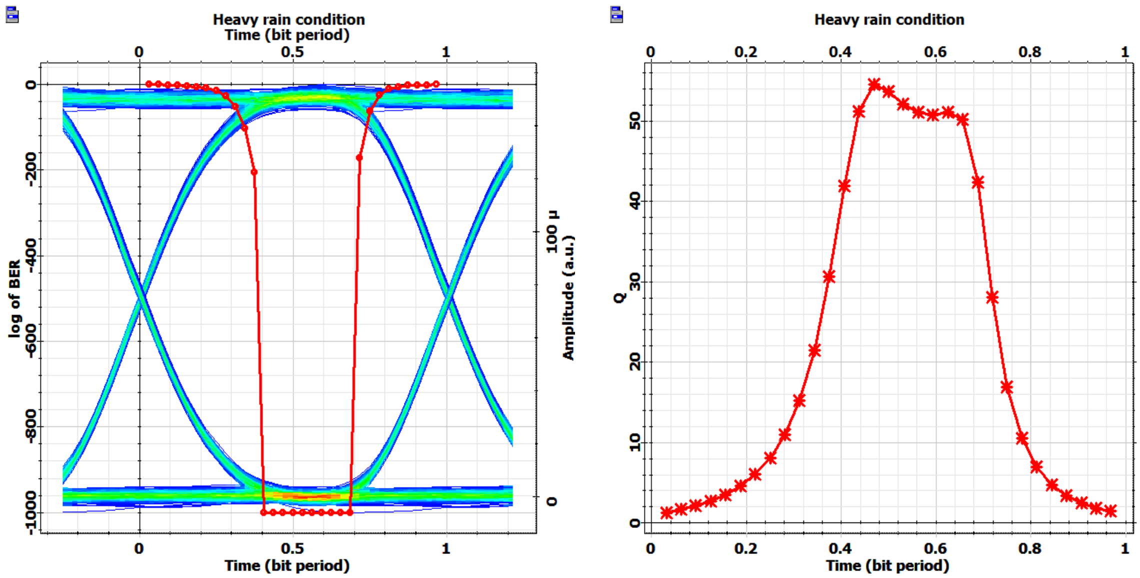
The findings of the FSOC link performance test under heavy haze conditions are shown in Figure 6. Due to the presence of haze particles, the optical signal is weakened and the visibility of the atmosphere decreases, which leads to a decline in the quality of the received signal. The simulation considered a heavy haze attenuation of 2.37 dB/km and analyzed the link's performance. The system level simulation results indicate that there was BER of 0 and the eye diagram was widely open as presented in Figure 6(a), which confirms that the communication was good and that the signal received at the receiver was of high quality. Figure 6(b) shows a Q-factor of 150.31 was obtained, which is significantly higher than the acceptable threshold.

In Figure 7, we can see the results obtained for the performance of the FSOC link under heavy fog conditions. The size of the fog particles is comparable to the transmission wavelength of the optical signal, which causes the signal to degrade. When the optical beam interacts with the fog particles, the signal becomes attenuated. For the evaluation of the link's performance, a heavy fog attenuation of 26 dB/km was considered. The simulation results achieved a BER of 5.41e-228 and a Q-factor of 32.21 as shown in Figures 7(a) and 7(b) respectively, both of which are above the acceptable thresholds. The open eye diagram indicates good communication and confirms that the receiver collected a high-quality signal.



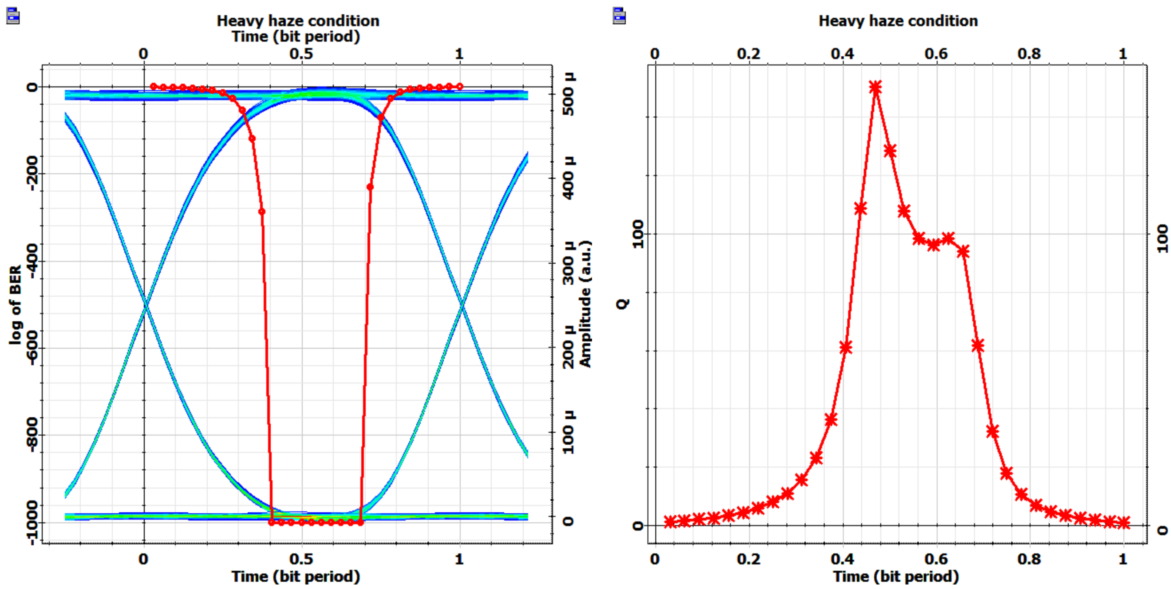
(a) (b)

Figure 4. Under clear sky with turbulence weather condition (a) graph of BER and eye diagram and (b) graph of Q-factor



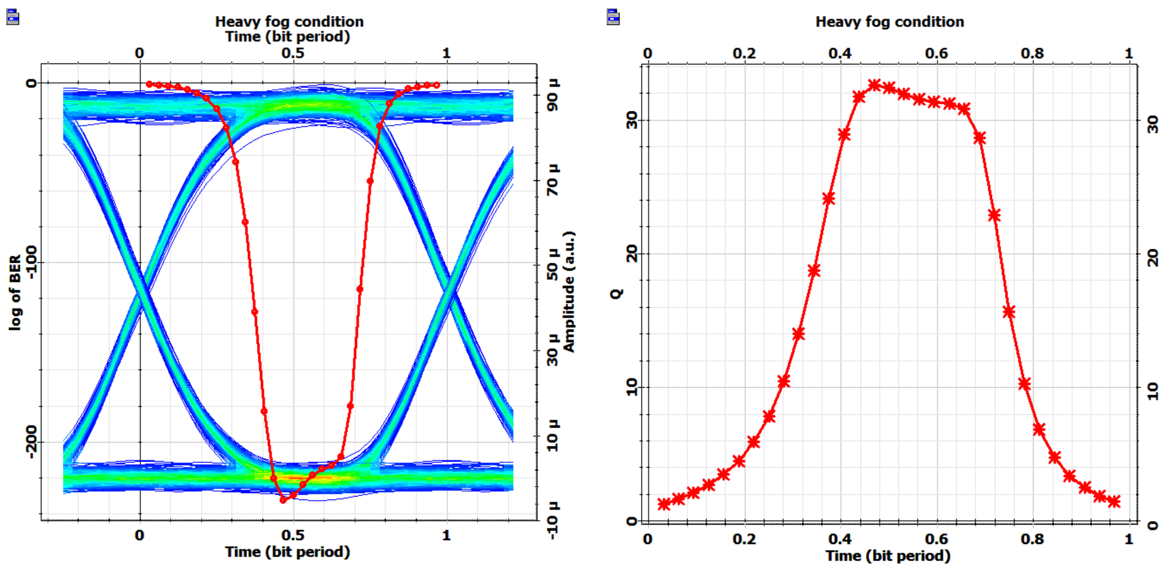
(a) (b)

Figure 5. Under heavy rain weather condition (a) graph of BER and eye diagram and (b) graph of Q-factor



(a) (b)

Figure 6. Under heavy haze weather condition (a) graph of BER and eye diagram and (b) graph of Q-factor

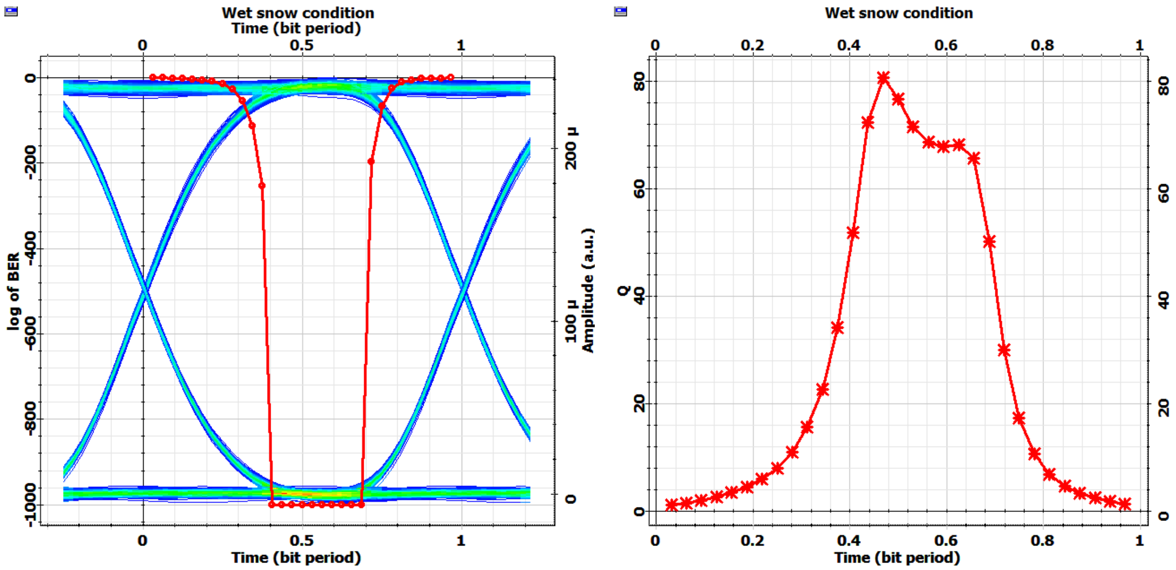


(a) (b)

Figure 7. Under heavy fog weather condition (a) graph of BER and eye diagram and (b) graph of Q-factor

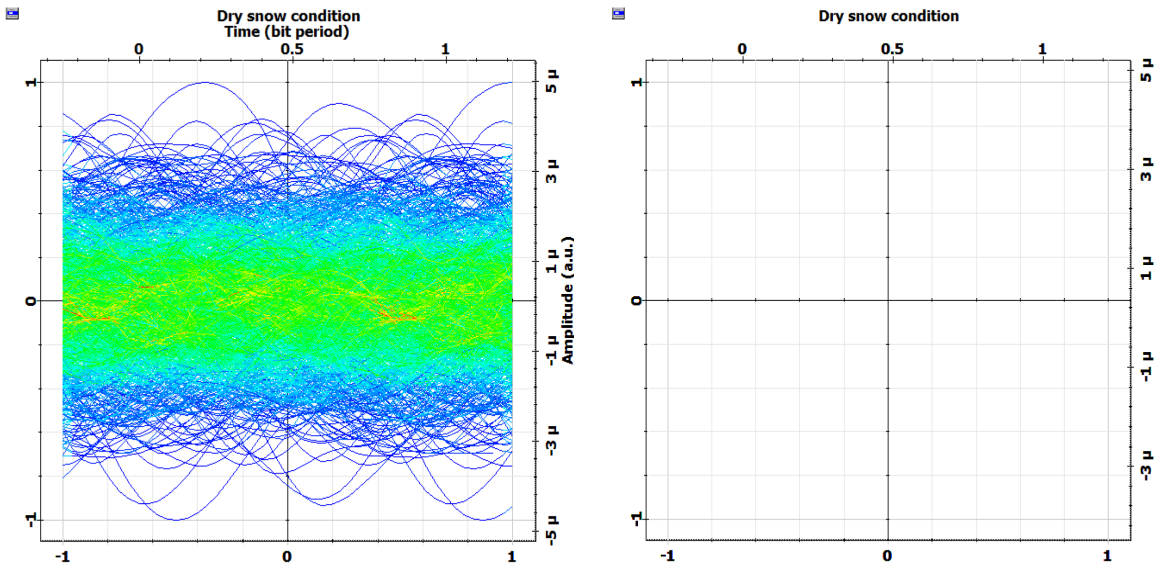
Figure 8 demonstrates the results for the performance of the FSOC link in wet snow conditions. The optical signal along the free space channel deteriorates due to the reduction in visibility and the smaller size of the snow particles. Wet snow has less impact compared to dry snow condition. A wet snow attenuation of 13.73 dB/km was considered, and the performance of the link was examined. Figure 8(a) result indicated a very widely open eye diagram, confirming high signal collected at the receiver and good communication was achieved, and a BER of 0. A Q-factor of 80.10 was obtained as shown in Figure 8(b), which is far above the acceptable threshold.

Figure 9 shows results obtained for the performance of the FSOC link under dry snow condition. Dry snow has a very high liquid equivalence ratio, with large particle sizes and severe reduction in visibility. This translates to significant degradation of the optical signal along the atmospheric channel. The dry snow attenuation of 96.8 dB/km was considered, and the performance of the link was analyzed. System level simulation results showed a closed eye diagram, indicating no signal collected at the receiver. A BER of 1 and a Q-factor of 0 were obtained as presented in Figures 9(a) and 9(b), respectively, which are the worst performance condition of the FSOC link. Table 4 presents the summary of the results obtained from the overall study. Inferring from the achieved results using the key performance indicators, recommendations are given for deployment of the FSOC link for pico-macrocell backhauling applications.



(a) (b)

Figure 8. Under wet snow weather condition (a) graph of BER and eye diagram and (b) graph of Q-factor



(a) (b)

Figure 9. Under dry snow weather condition (a) graph of BER and eye diagram and (b) graph of Q-factor

Table 4. Summary of simulation results obtained for various weather conditions

Weather condition	BER	Q-factor	Eye diagram	FSOC link deployment
Clear sky without turbulence	0	168.19	Very widely open	Yes
Clear sky with turbulence	1.76e-31	11.56	Widely open	Yes
Heavy rain	0	52.84	Very widely open	Yes
Heavy haze	0	150.31	Very widely open	Yes
Heavy fog	5.41e-228	32.21	widely open	Yes
Wet snow	0	80.10	Very widely open	Yes
Dry snow	1	0	Closed	No

4. CONCLUSION

The design and performance evaluation of a 350 m FSOC link for application in picocell to macrocell backhauling has been proposed, simulated and analyzed. The FSOC link is designed using IM/DD with OOK and PIN photodiode. Performance of the link under strong atmospheric turbulence and major causes of atmospheric attenuation in tropical (rain and haze) and temperate (fog and snow) regions of the world were investigated. Simulation results presented good performance and acceptable BER, Q-factor and Eye diagram under clear sky without turbulence, clear sky with turbulence, heavy rain, heavy haze, heavy fog and wet snow weather conditions. A worst case of BER=1, closed eye diagram and Q-factor of 0 was achieved under dry snow condition. This infers and recommends the deployment of FSOC link for the proposed application in all the studied scenarios except for dry snow weather condition.

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BIOGRAPHIES OF AUTHORS

Abduljalal Yusha'u Kassim received a B.Eng. in electrical engineering and an M.Sc. in telecommunications engineering from Ahmadu Bello University, Zaria, Nigeria in 2015 and 2019 respectively. Currently, he is a lecturer in the Department of Electronics and Telecommunications Engineering at Ahmadu Bello University, Nigeria since October 2018. In addition, he is a Ph.D. candidate at the Pan African University Institute of Basic Sciences, Technology, and Innovation (PAUSTI), Nairobi, Kenya. His research work mainly focuses on the design, simulation, and performance evaluation of free space optical communications links for high-capacity backhauling in 5 GB Networks. He is a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a member of the International Association of Engineers (IAENG). He has won several scholarships, including the MTN Foundation scholarship for Science and Technology in 2012-2015 and the African Union Ph.D. Scholarship in 2022. He can be contacted at email: yushau.abduljalal@students.jkuat.ac.ke.

Vitalice Kalecha Oduol was granted a CIDA scholarship to pursue electrical engineering at McGill University in Montréal, Canada, where he obtained his B.Eng. (Hons.), M.Eng., and Ph.D. degrees in 1985, 1987, and 1992, respectively, in electrical engineering. While studying at McGill University, he worked as a research associate and teaching assistant. After completing his studies, he worked at MPB Technologies (Canada), INTELSAT in Washington DC, USA, and COMSAT Laboratories, USA. He returned to Kenya in 2003 and has been with the Department of Electrical and Information Engineering at the University of Nairobi. His research interests include the analysis, modeling, simulation, and evaluation of communication systems' performance. This encompasses signal processing, spectrum sensing in cognitive radio, emerging areas (5G and beyond), and the mitigation of rain attenuation in RF signals at high frequencies. Besides, he is interested in vehicle-to-vehicle (V2V) communications and vehicle-to-infrastructure (V2I) communications. He is a member of IEEE and was a two-time recipient of the Douglas Tutorial Scholarship at McGill University. He can be contacted at email: Vitalice.oduol@gmail.com.

Aliyu Danjuma Usman a professor of electronics and telecommunications engineering from Ahmadu Bello University, Zaria-Nigeria. Had his M.Eng. and Ph.D. from Electrical Engineering Departments of Bayero University Kano and Universiti Putra Malaysia in 2006 and 2011 respectively. Self-motivated personality with excellent skills in communications engineering and IT. Had over 25 years cognate working experience in tertiary educational institution. An independent researcher with a unique combination of detail-oriented mindset, analytical skills, collaboration and proven ability of accomplishing several tasks. Published over 150 peer reviewed National and International Journals/Conferences and authored many books and book Chapters. A recipient of a Patent and many research grants locally and internationally. Graduated many MSc and PhD students and many under his supervision. A visiting scholar, consultant and external examiner for many institutions within Nigeria and internationally. His research interest include; tele-traffic engineering, satellite communications, antenna radiation, wireless communications, IoT, Terahertz frequencies, and 5G and beyond. He can be contacted at email: aliyuusman1@gmail.com.