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Modelling and Simulation of Free Space Optical Links for 5G Last-Mile Connectivity Under Nigerian Atmospheric Conditions

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Abstract: Free Space Optical (FSO) communication has emerged as a viable alternative for addressing the last-mile connectivity challenge in fifth-generation (5G) networks, particularly in regions where fibre deployment is economically or logistically impractical. This paper presents the modelling and simulation of an FSO communication link for 5G last-mile applications under atmospheric conditions representative of Nigeria. The system is modelled using the Beer–Lambert attenuation law, geometric loss formulation, and turbulence-induced fading models. Simulations are carried out in OptiSystem 21.0 with link distances ranging from 0.5 km to 5 km, optical transmit power between –3 dBm and +10 dBm, and an operating wavelength of 1550 nm. Performance metrics including received power, signal-to-noise ratio (SNR), and bit error rate (BER) are evaluated under clear air, haze, and fog conditions. Results indicate that reliable FSO transmission with BER below 10^{-9} is achievable up to 2 km under moderate visibility conditions, confirming the suitability of FSO for 5G last-mile connectivity in Nigeria. The study provides design guidelines for practical deployment of FSO systems in tropical environments.

Keywords: *Free Space Optics, 5G Last-Mile, Optical Wireless Communication, Atmospheric Attenuation, BER, SNR.*

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I. INTRODUCTION

The rapid growth of data-intensive applications and the deployment of fifth-generation (5G) mobile networks have significantly increased the demand for high-capacity and low-latency backhaul and last-mile connectivity. Although optical fibre provides ultra-high bandwidth and reliability, its deployment to the end-user remains challenging due to high installation cost, right-of-way issues, and frequent fibre cuts, particularly in developing countries such as Nigeria. As a result, alternative broadband technologies capable of delivering fibre-like performance are required.

Free Space Optical (FSO) communication, also known as optical wireless communication, uses laser beams to transmit data through the atmosphere without physical waveguides. FSO systems offer large unlicensed bandwidth, high data rates, low latency, and rapid deployment, making them attractive for 5G last-mile applications. However, the performance of FSO links is highly sensitive to atmospheric impairments such as fog, haze, rain, and turbulence, which introduce attenuation and signal fading.

Nigeria experiences diverse climatic conditions ranging from humid coastal regions to arid northern zones, resulting in varying atmospheric visibility and attenuation characteristics. Therefore, it is essential to model and evaluate FSO link performance under conditions representative of the local environment. This paper focuses on the performance modelling and simulation of an FSO communication link for 5G last-mile connectivity, analyzing key performance metrics under different atmospheric scenarios.

➢ *The Main Contributions of this Paper are:*

- Development of a mathematical model for FSO link performance considering geometric loss, atmospheric attenuation, and turbulence effects;
- Simulation of FSO link performance under varying distances, transmit power levels, and visibility conditions;

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- Evaluation of received power, SNR, and BER as key performance indicators for 5G last-mile deployment.

II. FSO SYSTEM MODEL

A typical FSO communication system consists of an optical transmitter, a free-space atmospheric channel, and an optical receiver. At the transmitter, digital data are modulated onto an optical carrier generated by a laser diode operating at 1550 nm. The modulated optical beam is collimated and transmitted through the atmosphere toward the receiver.

The free-space channel introduces attenuation due to absorption and scattering by atmospheric particles, as well as fading caused by turbulence-induced refractive index fluctuations. At the receiver, the collected optical signal is converted into an electrical signal using a photodetector and processed to recover the transmitted data.

➢ *Geometric Loss*

Geometric loss occurs due to beam divergence as the optical beam propagates through space. The geometric loss is expressed as

$$L_g = \left(\frac{D_r}{D_t + \theta d}\right)^2$$

where D_r is the receiver aperture diameter, D_t is the transmitter aperture diameter, θ is the beam divergence angle, and d is the link distance.

➢ *Atmospheric Attenuation*

Atmospheric attenuation is modelled using the Beer–Lambert law as

$$P_r = P_t e^{-\alpha d}$$

where P_t is the transmitted optical power, P_r is the received optical power, α is the attenuation coefficient dependent on weather conditions, and d is the link distance.

➢ *Turbulence-Induced Fading*

Atmospheric turbulence causes random fluctuations in the received optical intensity. For weak turbulence, log-normal fading is assumed, while moderate-to-strong turbulence is modelled using the Gamma–Gamma distribution. These models capture the statistical variations in received signal power.

III. NOISE AND PERFORMANCE METRICS

The received electrical signal is affected by shot noise and thermal noise, which degrade system performance. The signal-to-noise ratio (SNR) is defined as the ratio of the average signal power to the total noise power. The bit error rate (BER) for On–Off Keying (OOK) modulation under Gaussian noise is expressed using the Q-function.

IV. SIMULATION SETUP

Table 1 Simulation Parameters for the FSO Link

Parameter	Value
Operating wavelength	1550 nm
Transmit power	–3 dBm to +10 dBm
Link distance	0.5 – 5 km
Receiver aperture diameter	5 cm
Modulation scheme	On–Off Keying (OOK)
Simulation tool	OptiSystem 21.0
Atmospheric conditions	Clear air, haze, fog

The FSO system is simulated using OptiSystem 21.0. The main simulation parameters are summarized in Table 1 above.

➢ *The FSO System is Simulated Using OptiSystem 21.0. The Main Simulation Parameters are Summarized as Follows:*

- Operating wavelength: 1550 nm
- Transmit power: –3 dBm to +10 dBm
- Link distance: 0.5 km to 5 km
- Receiver aperture diameter: 5 cm
- Modulation scheme: On–Off Keying (OOK)

Atmospheric conditions considered include clear air, haze, and fog, represented by different attenuation coefficients derived from visibility values.

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V. RESULTS AND DISCUSSION

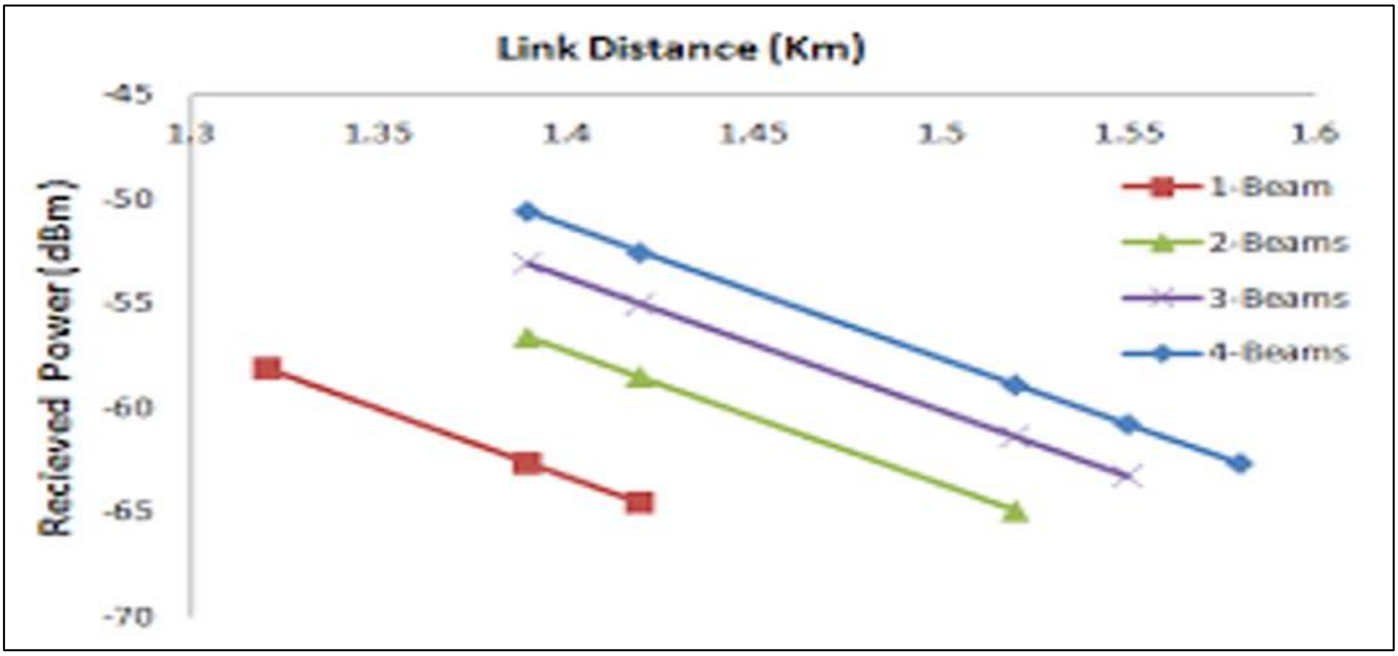

Fig 1 Received Optical Power Versus Link Distance

Figure 1 illustrates the variation of received optical power with link distance under different atmospheric visibility conditions. A sharp reduction in received power is observed as distance increases, particularly under fog conditions.

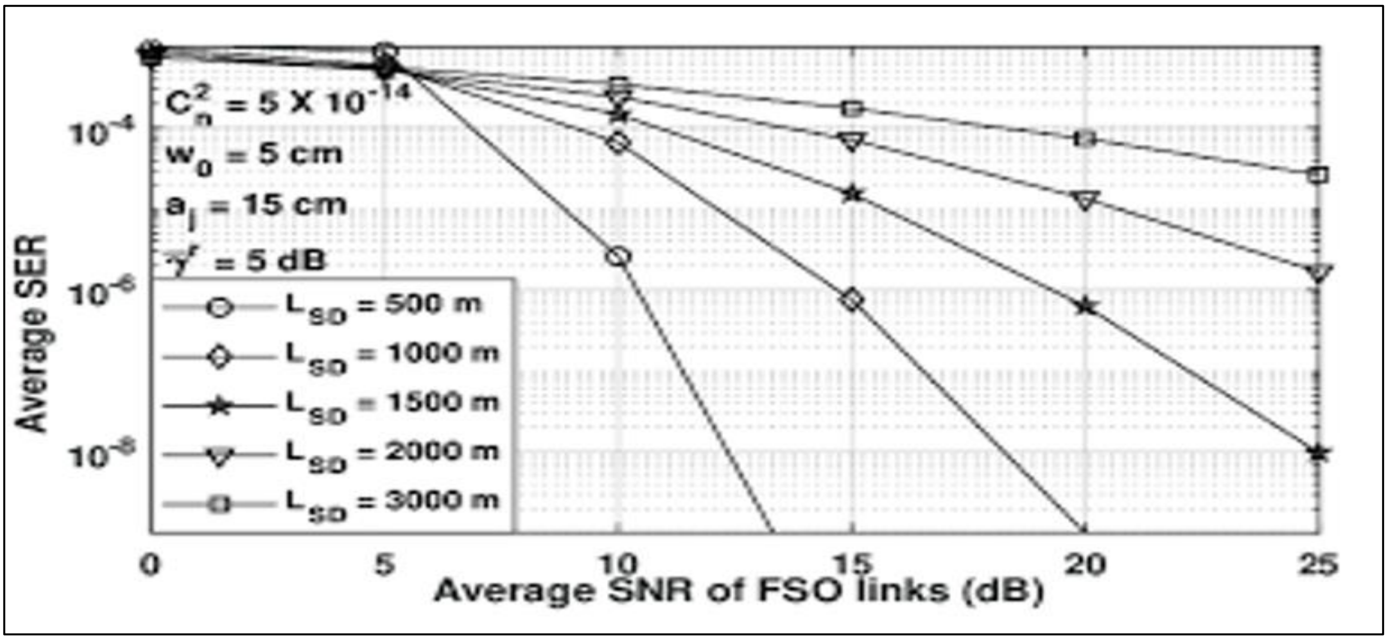

Fig 2 Signal-to-Noise Ratio (SNR) Versus Link Distance

Figure 2 shows the SNR performance of the FSO link for clear air, haze, and fog scenarios. High SNR values are maintained for short distances, while severe degradation occurs beyond 2 km under poor visibility.

Table 2 Received Optical Power Under Different Visibility Conditions

Visibility (km)	Kruse Model	Kim Model	Al Naboulsi
0.2	Very low	Extremely low	Low
1	Low	Moderate	Moderate
5	Moderate	High	High
10	High	Very high	Very high

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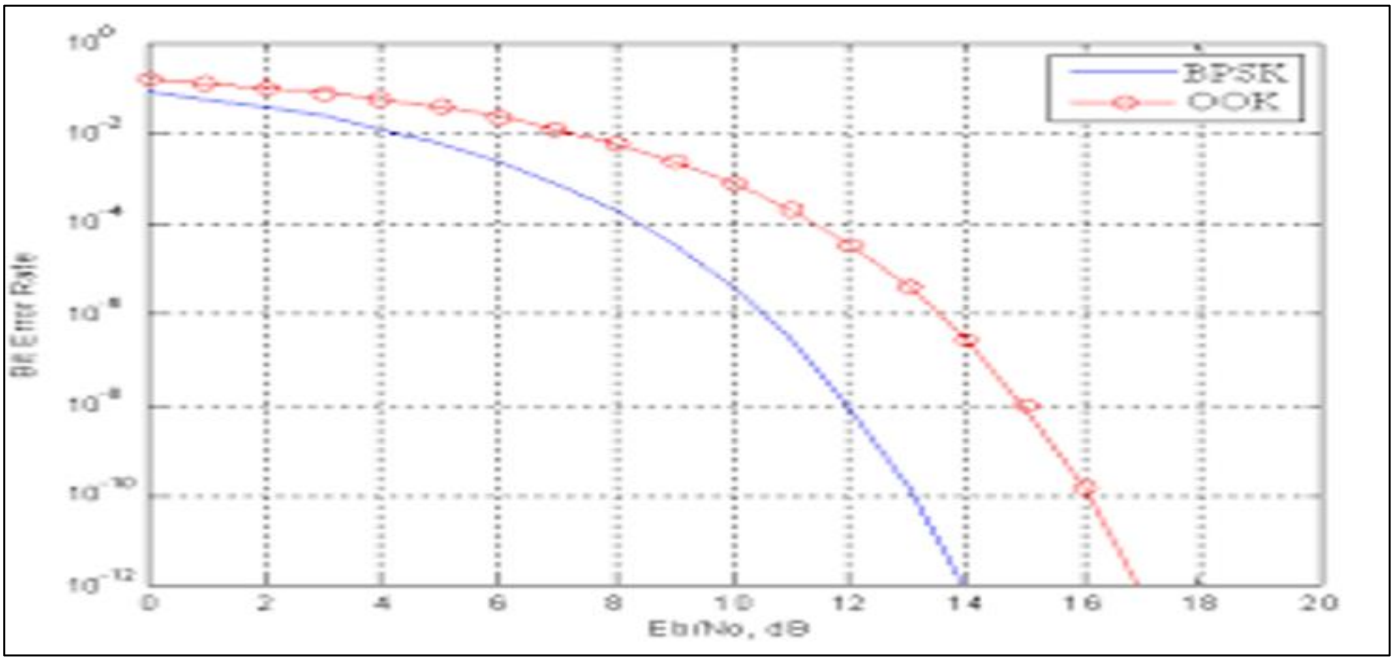

Fig 3 Bit Error Rate (BER) Versus SNR

Figure 3 presents the relationship between BER and SNR for OOK modulation. BER values below 10^{-9} are achieved at high SNR levels, confirming reliable transmission under favorable conditions.

Simulation results show that under clear atmospheric conditions, received power remains sufficiently high for reliable communication over distances up to 5 km. The SNR exceeds 30 dB for short-to-medium link distances, resulting in BER values below 10^{-9}.

Under haze and moderate fog conditions, attenuation increases significantly, leading to a reduction in received power and SNR. Reliable communication is maintained up to approximately 2 km under moderate visibility, beyond which BER degrades rapidly. Dense fog conditions cause severe attenuation, making long-distance FSO links impractical without mitigation techniques such as hybrid RF/FSO systems or adaptive power control.

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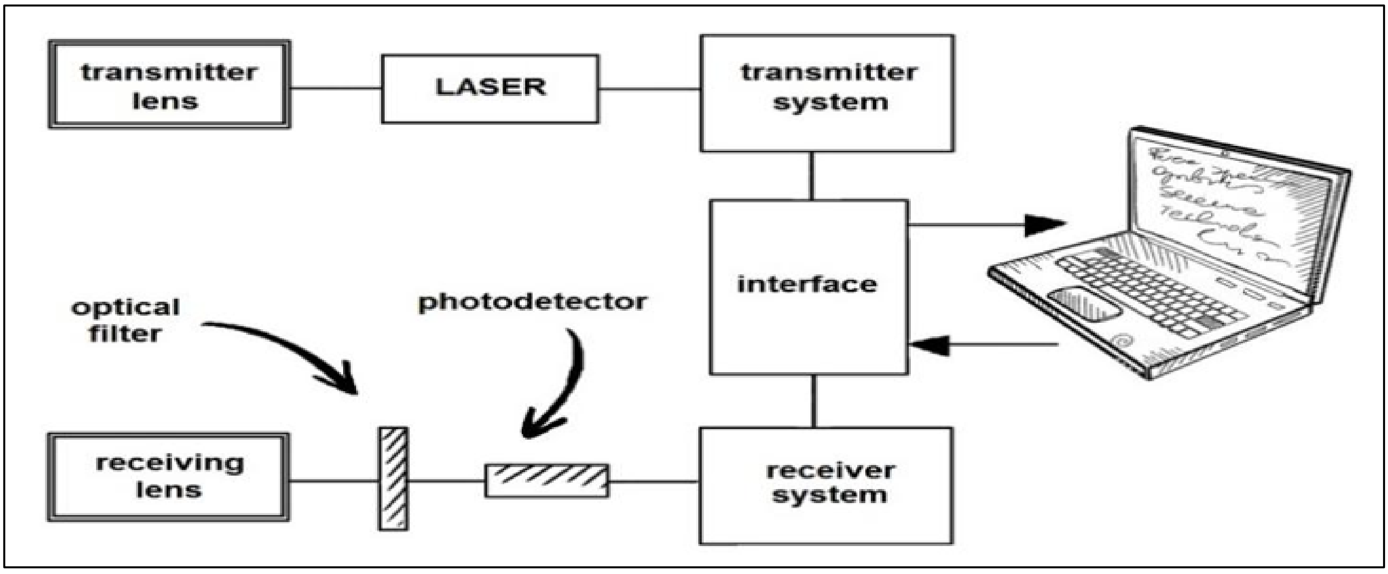

Fig 4 Block Diagram of an FSO Communication System

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VI. CONCLUSION

This paper has presented the performance modelling and simulation of an FSO communication link for 5G last-mile connectivity under Nigerian atmospheric conditions. Using established propagation and noise models, the impact of distance, transmit power, and atmospheric attenuation on received power, SNR, and BER was evaluated. Simulation results confirm that FSO is a viable solution for 5G last-mile deployment over distances up to 2 km under moderate visibility conditions. The findings provide useful design insights for telecom operators considering FSO as an alternative or complement to fibre infrastructure in tropical environments.

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