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IMPACTS OF AEROSOL SCATTERING ATTENUATION ON FREE-SPACE OPTICAL COMMUNICATION IN OWERRI, NIGERIA

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Abstract. In spite of the several benefits of using free-space optical (FSO) communication systems as complementary platforms for next-generation networks, the existence of atmospheric disturbances such fog and scintillations are key sources of signal impairment that affect system performance. Thus, it is crucial to learn about the specific weather patterns of the areas where FSO lines will be installed. The purpose of this work is to estimate the availability performance of FSO lines broadcasting at both 850 nm and 1550 nm by performing a statistical analysis of meteorological visibility data gathered for Owerri in Nigeria over a 21-year period (2000-2021). The results shows that the visibility during the most common fog events in Owerri is 100 meters. The probabilities of encountering and exceeding the scattering attenuations associated with Owerri's most common fog event are 0.0002 and 0.0229, respectively. This research could be expanded in the future by exploring the effects of varying localized climatic conditions on the many forms of optical signals, such as plane, spherical, and Gaussian beam waves.

Keywords: Free space optics, visibility, aerosol scattering attenuation, atmospheric turbulence, transmission wavelength.

1. Introduction

High-speed, point-to-point data transmission through laser beams across terrestrial networks is sometimes referred to as "Free-Space Optics" (FSO). Multimedia applications including social networks, OTT platforms, video conferencing, and multimedia streaming are driving up the demand for data rates and channel bandwidth, which has led to a telecommunications bottleneck [1]. As a low-priced option that guarantees error-free, high-velocity transmission for both front- and backhaul cellular networks, free space optics is an attractive possibility. It can fix problems at the very end of the chain. Whether used independently or in tandem with other technologies, FSO communication provides a strong foundation for the future generation of communication infrastructures. Many benefits accrue when 5G cellular backhaul networks use it, including adaptable network connectivity, secure transmission, high data throughput, simple set up, low deployment costs, resistance to electromagnetic interference, license-free spectrum, low latency communication, and low bit error rate (BER) [2].

Thus far, FSO's scope in the telecommunications industry has been limited to specialized use cases. Some examples include the wireless transmission of high-definition films; the installation of temporary links during emergencies; and the communication between buildings, universities, hospitals, or company sites [1]. When compared to more conventional forms of communication media, free space optics (FSO) provides many advantages, including increased data speeds, reliability, and transmission bandwidth. Like conventional wireless RF (Radiofrequency) communication, Free Space Communication is based on a simple but effective underlying idea. Data can be transmitted into empty space using a digital device as a light source. Data is encoded and modulated onto carrier light waves using techniques like Quadrature Amplitude Modulation (QAM), and then decoded using a different set of digital devices called decoders at the other end of the transmission channel [3].

This is analogous to the generation and transmission of radio frequency (RF) waves, in which antennas are employed to create electromagnetic waves of varying frequencies and polarizations that are subsequently detected by antennas at their destination. The data is retrieved in a format that is understandable to both the sender and the receiver after going through a series of filters, amplifiers, and decoders. Several decades prior to the discovery of Free Space Optics, traditional communication technologies had a number of drawbacks that made them unattractive to engineers and researchers in the field of communication. These drawbacks included a lack of bandwidth to accommodate exponentially increasing customer numbers, a lack of sufficient data rates, and a major licensing issue. Future networks, also known as Next Generation Networks, will rely heavily on optical communication technology, which [4] believe has great potential to become (NGN).

The physical range of the link, misalignment of the receiver and transmitter pair, and the optical qualities of the channel utilized for transmission all pose challenges for free space optics (FSO) despite the technology's many benefits. Since the atmosphere is the medium through which FSO communications travel, and since atmospheric conditions are generally accepted to be the same across the globe and across different geographical regions, the requirements for and performance of FSO communications are relatively unaffected by local weather [5]. In spite of this, the efficiency of an optical communication system deployed in such mediums is adversely impacted by changes in density and molecular composition as well as by weather phenomena such as rain, snow, fog, smog, etc. [2], [6]. Atmospheric scintillation is another name for the variables mentioned above that degrade FSO system performance.

Scintillation leads to fluctuations in the detected signal's strength and phase, which can introduce noise and create mistakes in decoding the original data [7]–[9]. FSO transmission wavelengths (often 785 or 1550 nm) have substantial interactions with a wide variety of atmospheric particles, including fog droplets (1-100 mm in radius), raindrops (0.1-10 mm), snowflakes (up to a few centimeters in radius), and many types of aerosols (e.g., dust, sand, and ash). These particles can greatly dampen an optical wave's energy if their concentration along the propagation route is high enough [10], [11]. Therefore, depending on climatology and local microclimate, the maximum allowed path length of an optical link can be significantly smaller than that of a mm-Wave link, given a specified link availability target. However, this can be managed to a significant extent by the link's optimization through reasonable adjustment in the link's internal parameters.

The main contributions of this paper are as follows:
1. Using the Ijaz and Kim models at transmission wavelengths of 850 and 1550 nm in Owerri, Nigeria, we report the cumulative distribution of visibility and aerosol scattering attenuations.
2. Influence of aerosol scattering attenuations at 850 and 1550 nm on FSO link performance is examined by calculating the probabilities of exceeding, deceeding, and encountering these values at the chosen location.

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2. Study Area

Nigeria is a nation on Africa's western coast. It has a variety of geographical features and weather, from dry to humid tropical regions. The country is bordered to the north by Niger, the south by the Gulf of Guinea of the Atlantic Ocean, the east by Chad and Cameroon, and the west by Benin. Nigeria's terrain is comprised of lowlands in the north and south combined with plateaus and hills in the region's centre. Nigeria has a tropical climate with alternating wet and dry seasons, depending on where it located. While it is dry in the southwest and more inland, the southern region is typically hot and wet throughout the year, especially in the southeast regions. While the far north has a steppe climate with little precipitation, the north and west have a savanna climate that is frequently characterized by wet and dry seasons. Away from the country's coast, rainfall gradually declines, while the far north only gets 500 mm of rain annually. The southern region experiences generally consistent temperatures and humidity throughout the year, while the northern region experiences significant seasonal variations. During the very dry season, the daily temperature range in the northern region increases. Due to low or no precipitation, the northern region is frequently dusty, especially during the dry seasons. Throughout the year, there are seasonal variations in both the northern and southern portions of the country's cloud cover. In this study, Owerri, Nigeria, (Figure 1) is chosen as a representative large city from the humid equatorial region where daily visibility data are collected, particularly for aviation purposes. The characteristics of the research location are shown in Table 1.

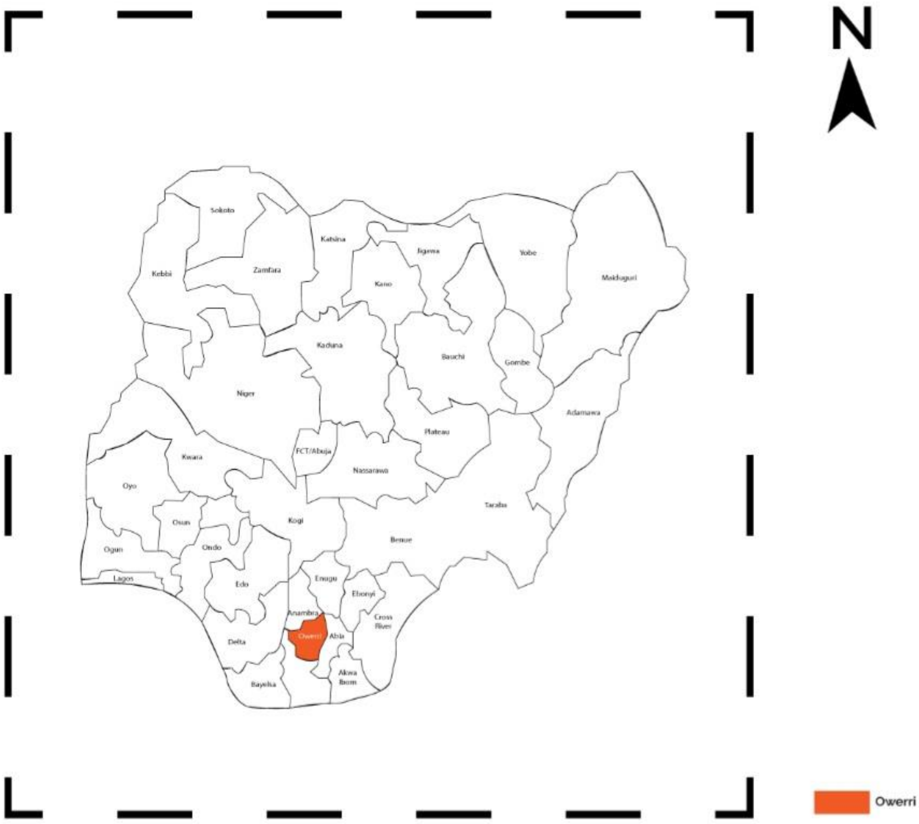

Figure 1: Map showing location of study.

Table 1: Characteristics of the study location.

Location	Latitude (°N)	Longitude (°S)	Elevation (m)	Average rainfall amount (mm/year)	Region
Owerri	5.4434	7.0659	75	2412	Humid

3. Visibility Distribution

Visibility has a major impact on optical signal scattering and absorption. Meteorological visibility is defined as the distance in the atmosphere at which 5% of the luminous flux transmitted by a collimated beam emitted by a 550 nm light source is attenuated. In other words, it is the optical range that determines how far away objects may be seen in various weather circumstances, such as snow, rain, or haze [12], [13]. The emergence of fog is caused by the presence of fine water droplets suspended in the atmospheric layer closest to the earth's surface. Fog is a meteorological phenomenon in which visibility goes below one thousand meters and atmospheric humidity exceeds 100 percent [14]. For Owerri, an urban city in the South-Eastern part of Nigeria, visibility measurements were collected from January 2001 to December 2021. The data were collected daily from dawn to dusk for a period of 21 years by Visual Crossing, a leading provider of meteorological data and enterprise analytic tools to data scientists, business analysts, professionals, and academics, whose objective has been to provide analysts and data consumers with the tools they need to use trustworthy, readily available data to make better decisions ever since it was founded in 2003. The duration of visibility events up to 35 kilometres across the analysed time period is depicted in Fig. 1, which best represents the visibility under hazy and clear weather conditions.

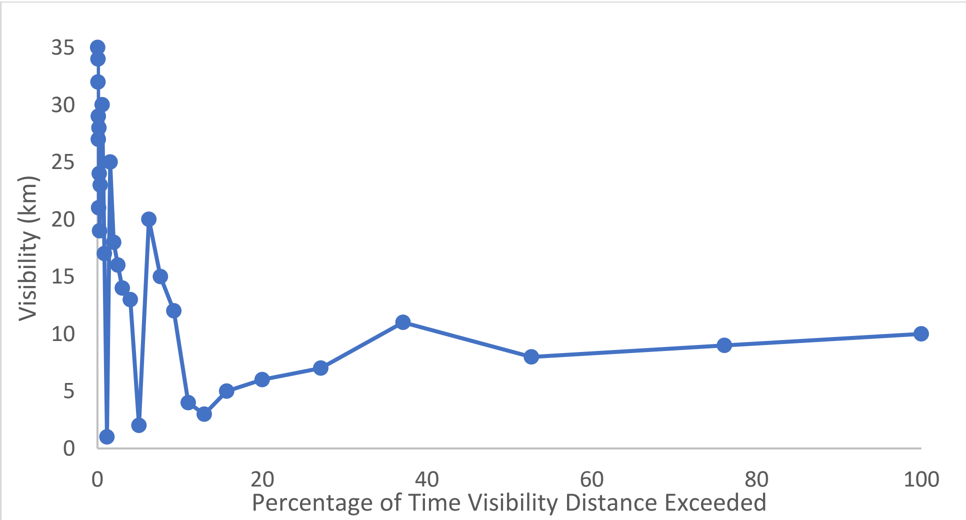

Figure 2: Visibility against percentage of time visibility distance exceeded for Owerri, Nigeria under haze and clear weather conditions (visibility up to 35km).

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4. Scattering Attenuation

In this study, Equation (1) through Equation (8) are required to calculate the impact of visibility on attenuation. Equation (1), which is derived from the Beer-Lambert law [15], can be used to represent the propagation of optical signals through the atmosphere as follows:

$$\tau(\lambda, L) = e^{-(\alpha L)} \tag{1}$$

where α denotes the atmospheric attenuation coefficient or total extinction coefficient, λ is the wavelength of the optical signal in nm, and L is the distance of propagation in kilometres. The transmittance of the atmosphere is denoted by $\tau(\lambda, L)$, and it is measured in (km^{-1}). In order to determine the coefficient of air attenuation from visible to near-infrared wavelengths, the Kruse model, which can be found in Equation (2), is utilized [15], [16]. It can be stated as follows:

$$\alpha = \frac{-\ln(T_{th})}{V}\left(\frac{\lambda}{\lambda_0}\right)^{-q_0} = \frac{3.912}{V}\left(\frac{\lambda}{\lambda_0}\right)^{-q_0} \tag{2}$$

where $T_{\mathrm{th}} = 2\%$ is the optical threshold, $\lambda_0 = 550$ nm is the maximum spectrum wavelength of the solar band, λ is the wavelength of the optical signal (850nm and 1550nm), V is the meteorological visual range in km and q_0 represents the particle size distribution characteristic. The total extinction coefficient, expressed as a decibel value per unit length, can be calculated using Equation (3) as follows:

$$\alpha_a(V) = \alpha 10\log_{10}(e) \approx 4.343\alpha \tag{3}$$

As optical signals move across the medium of free space, discontinuities in the atmosphere, such as aerosols and gas molecules, serve as sources of lower signal intensity. Scattering losses, which are often referred to as atmospheric attenuation, are the result of these channel blockages and can be approximated using Equation (4) [17]:

$$A_a(L, V) = \alpha_a(V) \times L \tag{4}$$

According to [17], atmospheric attenuation is approximately equal to the aerosol scattering coefficient. This is because the aerosol scattering coefficient is the most relevant atmospheric channel parameter for scattering losses in optical signals. That is;

$$\alpha_a(V) \cong \beta_{sa}(\lambda) \tag{5}$$

According to [15], [18], the aerosol scattering coefficient or the specific atmospheric attenuation in dB/km is:

$$\beta_{sa}(\lambda) = 10\log_{10}(e)\left(\frac{3.912}{V}\right)\left(\frac{\lambda}{\lambda_0}\right)^{-q_0} = \frac{17}{V}\left(\frac{\lambda}{\lambda_0}\right)^{-q_0} \tag{6}$$

A description of the Kim and Ijaz fog models can be found in Equation (6). The particle size distribution parameter, q_0, is described in Equation (7) in the Kim model [19] in terms of all types of visibility as:

$$q_0(V) = \begin{cases} 1.6 & \text{for} \quad V > 50 \text{ km} \\ 1.3 & \text{for} \quad 6 < V < 50 \text{ km} \\ 0.16V + 0.34 & \text{for} \quad 1 < V < 6 \text{ km} \\ V - 0.5 & \text{for} \quad 0.5 < V < 1 \text{ km} \\ 0 & \text{for} \quad V < 0.5 \text{ km} \end{cases} \tag{7}$$

On the other hand, according to the Ijaz fog model [20]), the value of q_0 is represented in Equation (8) in terms of wavelength as follows:

$$q_0(\lambda) = 0.1428\lambda - 0.0947 \tag{8}$$

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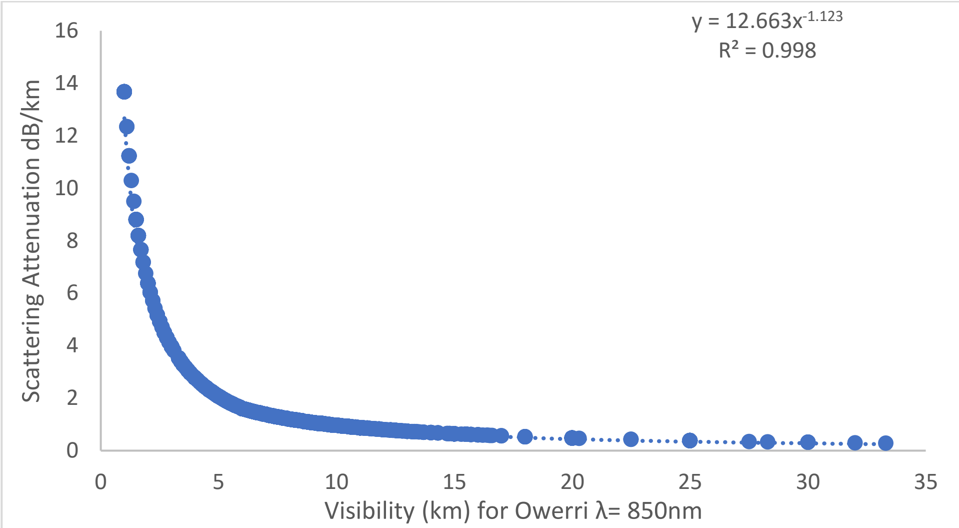
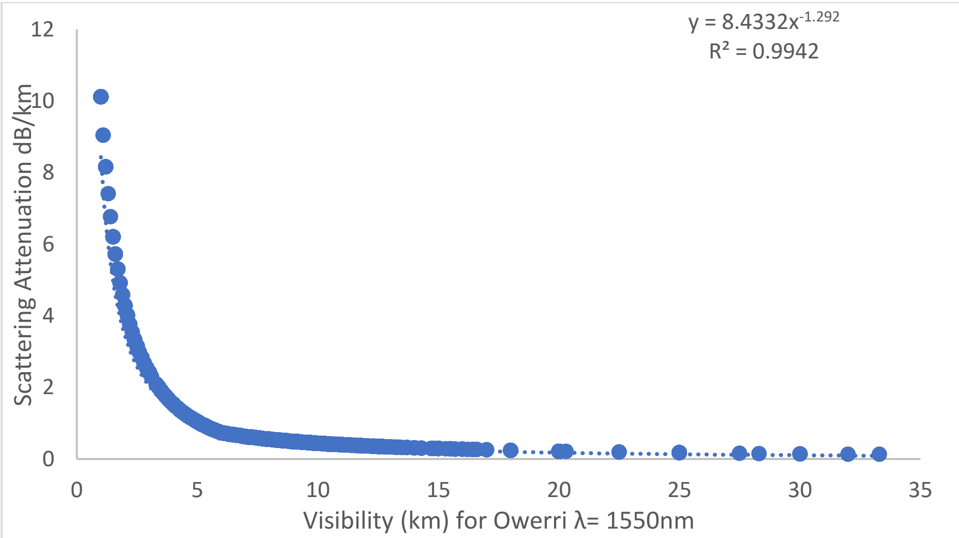


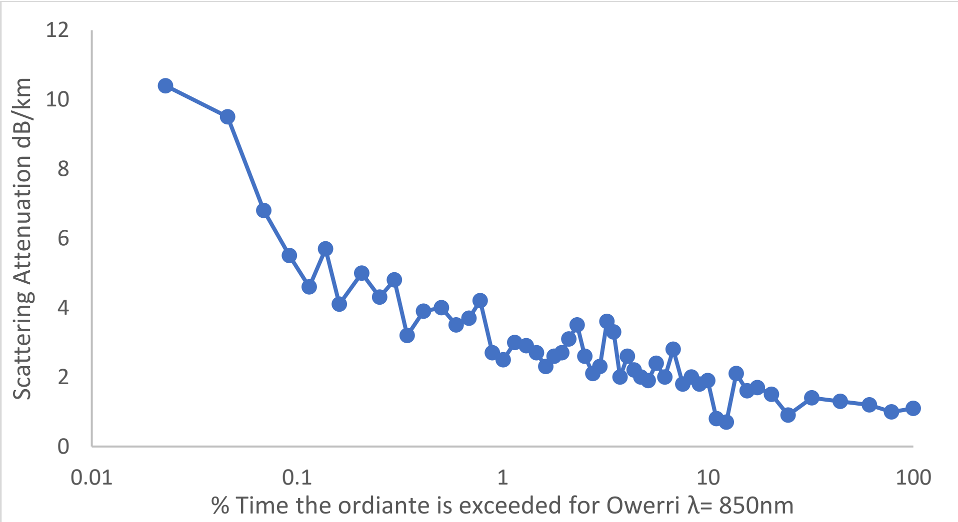
(a) 850nm



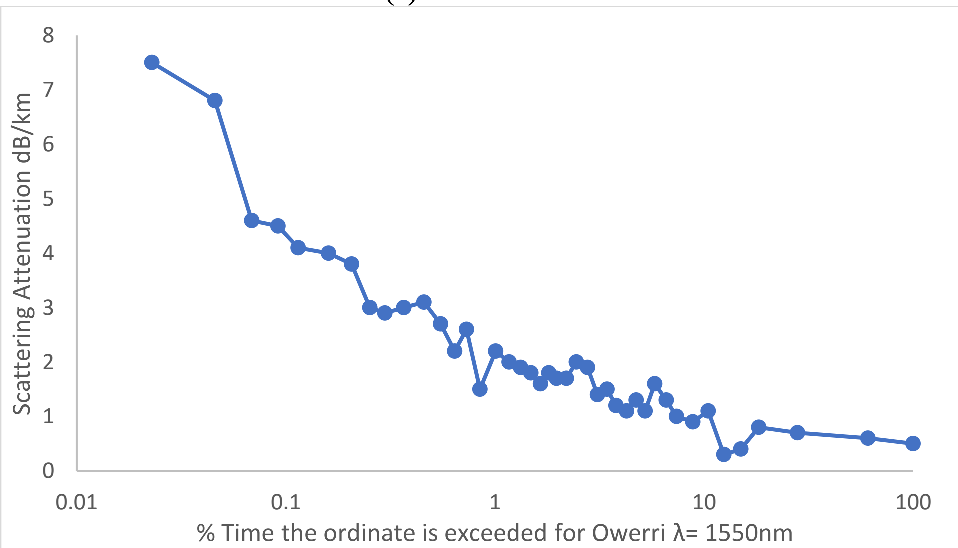
(b) 1550nm

Figure 3: Estimated specific attenuation against visibility at (a) 850 nm/352THz and (b) 1550 nm/193THz.

The estimated specific attenuations for Owerri are depicted in Fig. 2(a) and (b). For visibility data less than 1 km, the Ijaz model was used to determine scattering losses, whereas the Kim model was utilized for visibility measures greater than or equal to 1 km. Transmission wavelengths of 850 nm and 1550 nm were utilized to determine scattering losses with the two models, and it is shown that 1550 nm wavelength, among the two wavelengths considered has the minimum scattering attenuation [21], since attenuation decreases as visibility increases. Before establishing an FSO system, it is essential to comprehend the weather limitations that will be encountered in a certain location and at a given time. Once the maximum attenuation that the FSO system can withstand has been determined, the FSO system installer can anticipate the likelihood of system failure based on the probability of surpassing and encountering a particular atmospheric attenuation value. The influence of the wavelengths on the scattering attenuation based on the cumulative distribution are also presented in Fig. 3(a) and 4(b), which shows that the specific attenuations are comparatively higher for lower frequencies as compared to higher frequencies.



(a) 850nm



(b) 1550nm

Figure 4: Cumulative distribution of attenuation at (a) 850 nm/352 THz and (b) 1550 nm/193 THz.

Table 2: Most frequent fog measurement and its associated probability for Owerri, Nigeria.

LOCATION	Most Frequent Fog Event (Km)	Attenuation (dB/km)-850nm	Attenuation (dB/km)-1550nm	Probability of Encountering Scattering Attenuation (-)	Probability of Exceedance (-)
OWERRI	1	13.67	10.13	0.000229	0.022894

Table 3: Most frequent visibility measurement and its associated probability for Owerri, Nigeria.

LOCATION	Most Frequent Visibility (Km)	Attenuation (dB/km)-850nm	Attenuation (dB/km)-1550nm	Probability of Encountering Scattering Attenuation (-)	Probability of Exceedance (-)
OWERRI	33.3	0.2899	0.1328	0.0032	12.2711

Table 2 provides a summary of the scattering losses, probability of exceeding, and frequency of encountering the scattering losses associated with Owerri's most frequent fog event. The Ijaz model in (6) and (8) is used to compute the air attenuation values for 850 and 1550 nm wavelengths. The visibility during the most common fog events in Owerri is 100 meters. The probabilities of encountering and exceeding the scattering attenuations associated with Owerri's most common fog event are 0.0002 and 0.0229, respectively. In accordance with the most frequent visibility measurement in Owerri, Table 3 summarizes the precise attenuations, as well as the probabilities of exceeding and experiencing such losses. Probability of exceeding describes the likelihood of meeting values less than or equal to specific attenuation values in the atmosphere. Once the most frequent and highest atmospheric attenuations to be encountered by the link are identified, the FSO system installer can also anticipate the link's availability.

Conclusion

This study presents an examination of the availability of terrestrial FSO communication links in Owerri, Nigeria, based on the local climate. Using visibility measurements for the area of interest, cumulative distributions of aerosol scattering attenuation based on the Kim and Ijaz models were calculated. The probabilities of exceeding, falling short of, and encountering scattering attenuation are displayed. The results revealed a significant decreasing trend in scattering attenuation with increasing visibility and the 1550 nm wavelength with the equivalent frequency of 193 THz has the minimum attenuation, among the two wavelengths considered based on the range of visibilities across the study location. The results also align with the previous study; adopting a 1550 nm wavelength in transmission power will greatly improve optical transmission links when compared with 850 wavelengths. The general results are highly essential for the optimal design and budgeting of FSO networks in Owerri, Nigeria. This research could also be expanded in the future by exploring the effects of varying localized climatic conditions on the many forms of optical signals, such as plane, spherical, and Gaussian beam waves. This would aid in the modelling of different forms of attenuation for deployment sites of FSO or hybrid FSO systems.

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