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Analysis of visibility effects on free space earth-to-satellite optical link based on measurement data in Nigeria

S. E. Falodun, J. S. Ojo†, O. L. Ojo

Department of Physics, Federal University of Technology, Akure, Nigeria.

†Corresponding Author's Email: ojojs_74@futa.edu.ng

Abstract: The effect of atmospheric variables on signals propagating from earth to space are of concern in the design and performance of wireless communications systems. Since atmospheric effects which led to atmospheric losses (attenuations, fading and scintillation) are location-dependent, climatological phenomena such as fog, snow, rain, and haze has much effect on Free Space Optical (FSO) and can cause reduction in the link availability. This paper analysed the effect of fog on FSO communication links from earth to satellite links over five selected locations (Ikeja, Akure, Enugu, Jos and Port-Harcourt) in Nigeria. One year (2012) visibility data obtained at Nigeria Meteorological Agency (NIMET) have been used to estimate the specific attenuation caused by fog on FSO communication links in the selected locations. Link margin was deduced in all the five locations. The estimated specific attenuation caused by fog was based on operating frequencies associated with a typical commercial FSO. The result shows that at 352 THz frequency, Ikeja recorded the highest value of about 38.60 dB/km for the specific attenuation due to fog on FSO link followed by Akure with value of about 30.33 dB/km. Enugu recorded the least estimated attenuation of about 14.19 dB/km . The implication of the result is that Ikeja and Akure will suffer more signal loss, while Enugu will suffer less signal loss. Result on link margin performed on FSO link also showed that Ikeja has the highest link margin of -109.79 dB, Port-Harcourt with link margin value of -91.99 dB while Jos experienced lowest link margin of about -37.48 dB.

Keywords: Free space optical systems; Fog induced specific attenuation; Earth-space links; Link margin

1. INTRODUCTION

Wireless communication is the most significant avenue for technological advancement in modern telecommunication field. It involves transfer of signals via analog-digital-analog mode. It usually works through electromagnetic signals that are transmitted by an enabled device within the air, physical environment or atmosphere [1]. The transferring device can either be a sender or a middle device with the capacity to broadcast wireless signals. Communication takes place between two devices when the destination or receiving intermediate device captures these signals, generating a wireless communication link between the transmitter and receiver device. Wireless communication has many form of technology and delivery methods such as Satellite communication, Mobile communication, Infrared communication, Bluetooth communication to mention but a few. These communication technologies do not require physical or wired connection between their respective devices. The information can be transmitted through Radio Frequency (RF), Optical wireless Communication (OWC) also known as FSO communication, and sonic communication. One challenge that requires attention is the increase in high-bandwidth demanded by the Radio Frequency technology and other communication systems. These challenges draw the attention of researchers to FSO communication, since it is one of the promising technologies to overcome bandwidth shortage of a continuously crowded wireless available spectrum [1]. Norhanis *et al.,* [2] considered the atmospheric effects on free space earth-to-satellite optical link in tropical climate, the investigation analyzed the performance of FSO links from earth-to-LEO satellite in tropical regions considering rainy effect and haze on the link. It only considered the rainy effect and haze without other atmospheric ensembles. Xiaoming and Joseph, [3] worked on Free-Space Optical Communication through atmospheric turbulence channels, using Intensity modulation direct detection (IM/DD) under lognormal turbulent channel model. IM/DD is analyzed only under weak turbulence and requires that the distance between the two receivers must be greater than the correlation length of fading which is very hard to achieve.

In this work, visibility effect on FSO communication link based on measured data from five selected stations in Nigeria are considered. For the purpose of effectiveness of transmitting link, we also considered the amount of link margin to be accounted for over the study stations.

Table 1: Characteristics of the sites

Location	Coordinate °N	°E	Altitude above sea level (m)	Average annual Accumulation (mm /year)
Akure	7.18	5.12	303.00	1485.57
Enugu	6.24	7.24	139.00	1876.30
Ikeja	6.46	3.38	41.00	1425.20
Jos	9.50	8.50	1217.00	1186.89
Port-Harcourt	4.42	7.02	18.00	2803.10

2. SITE AND DATA ACQUISITION

Nigeria lies between latitudes 4° and 14°N, and longitudes 2° and 15°E within West Africa. Two seasons (wet and dry) are experienced in Nigeria. The dry season, influenced by the Northwest trade wind runs through November to March; and the rainy season, spans from April to October and is also influenced by the Southeast trade winds. The rainy season is always associated with heavy rainfall, which is sometimes accompanied by thunderstorms. Nigeria, a tropical region, experiences abundant sunshine throughout the year [4]. One year (2012) visibility data obtained at Nigeria Meteorological Agency (NIMET) have been used to estimate the specific attenuation caused by fog on FSO communication links over five selected locations in Nigeria namely: Akure, Enugu, Ikeja, Jos and Port Harcourt at 0900 hour of the day. Table 1 presents the characteristics of the locations, while Figure 1 shows the Map of Nigeria depicting the areas under study.

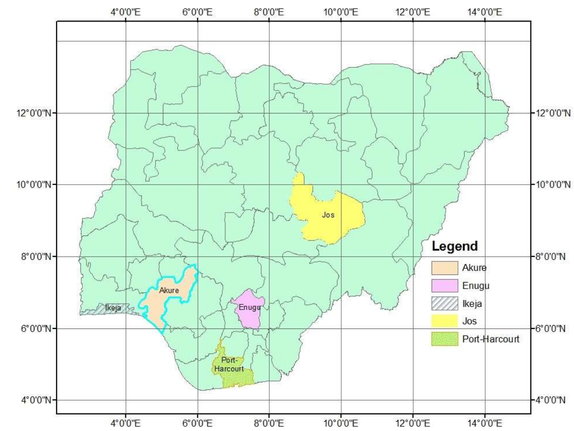

Fig. 1. Map of Nigeria depicting the areas under research

2.1 Visibility and fog

The distance to which human visual perception is limited by atmospheric conditions is called visibility. The physical mechanisms that influence visual perception during the night in distinguishing lights differ from those in the day time in distinguishing objects illuminated by daylight [5]. Basically, visibility describes the transparency of the air in the horizontal direction and represents the maximum distance that one can see in the atmosphere at any given time. Meteorological visibility concerns the transparency of the atmosphere as related to human vision. The transparency of the atmosphere is affected by the presence of hydrometeors (rain, snow, mist, fog) or litho-meteors (dust, smoke etc.). A transmissometer is normally used for measuring the atmospheric transmittance at visibility deterioration (fog, rain etc.). This instrument is mainly installed at the runways of airports in order to determine the visual range for the flight control safety service at different synopsis hours of the day. Transmissometer has been used to obtain one year (2012) visibility data at Nigeria Meteorological Agency (NIMET) for the selected stations. For the sake of this study, only 9-hour of the day is considered because of the availability of the data. The equipment is available for 96% of the year, the remaining 4% unavailability is due to equipment maintenance. Fog is the visible cloud of small water droplets suspended in the air near the earth's surface, thereby scattering the incident light and hence reducing the visibility. Different types of fog result in different levels of optical losses and this is mainly due to the distribution of the fog particles, size and the location. Table 2 shows the International Visibility Code for different types of weather conditions.

Table 2: International Visibility Code for different types of weather conditions [3].

Weather condition	Visibility (m)
Dense fog	50
Thick fog	200
Moderate fog	500
Light fog	770-1000
Very light fog	1000-2000
Light mist	2000-2800
Very light mist	4000-10000
Clear air	18000-20000
Very clear air	23000-50000

3 METHODOLOGY

The Mie-induced attenuation (mainly fog) in the FSO systems uses both theoretical and empirical approach. The value of the atmospheric attenuation, $\Upsilon_{(\lambda)}$ coefficient is dependent on the optical wavelength, which is composed of both atmospheric absorption and scattering terms and can be expressed as [2, 6]:

$$\Upsilon_{(\lambda)} = \alpha_{m\,(\lambda)} + \alpha_a(\lambda) + \beta_m(\lambda) + \beta_a(\lambda) \quad (1)$$

where $\Upsilon_{(\lambda)}$ is the atmospheric attenuation, $\alpha_{m\,(\lambda)}$ is the molecular absorption coefficient, $\alpha_a(\lambda)$ is the aerosol absorption coefficient, $\beta_m(\lambda)$ denotes the molecular scattering coefficient and $\beta_a(\lambda)$ is the aerosol scattering coefficient. The wavelengths used in FSO are basically chosen to coincide with the atmospheric transmission windows, as presented in Table 3 resulting in the

Table 3: Optical transmission windows [7]

Electromagnetic spectrum	Wavelength range (μm)
Visible and very-near Infrared	0.4 – 1.4
Near Infrared	1.4 -1.9 and 1.9 – 2.7
Mean Infrared	2.7 – 4.3 and 4.5 -5.2
Far Infrared	8 – 14
Extreme Infrared	16 – 28

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attenuation coefficient being dominated by scattering. The atmospheric attenuation is reduced to attenuation due to scattering as [2]:

$$\Upsilon_{(\lambda)} \sim \beta_a(\lambda) \quad (2)$$

Table 4: Technical Specifications of the MRV TereScope 5000 [8]

Parameter	Value
Light Source	Laser
Eye Safety	Class 1M
Transmit Power	100 mW (20 dBm)
Transmit Beam Divergence Angle	2 mrad
Wavelength	850 nm
Detector	Silicon Photodiode
Receiver Sensitivity	-46 dBm
Receiver Field of View	5 mrad
Data Rate	155 Mbps

3.1 Anomalous propagation and its component

Attenuation caused by fog depends on factors such as the location, particle size distribution, liquid water content and average particle diameter. The particle concentration and size distribution vary from one location to another; the fog-induced attenuation of the optical signal is only predicted using empirical models derived from the experimental observations. The empirical model uses the visibility V data in order to characterize the density of fog and subsequently the link visibility (i.e the meteorological visual range, MVR) is used to measure the attenuation due to the fog. Attenuation coefficient based on empirical measurement data can be estimated based on Kruse model. The Kruse model relates the atmospheric attenuation coefficient to the meteorological visibility of the atmosphere and the optical wavelength, λ [9]:

$$\mathrm{Ba}(\lambda) = \frac{10\log_{10} T_{th}}{V(km)}\left(\frac{\lambda}{\lambda_0}\right)^{-q} \quad (3)$$

where T_{th}, is the optical transmittance threshold (2% or 5%). 2% optical transmittance threshold is used in optical communication systems and 5% transmittance threshold is used in airports to measure the runway visual range. V is the visibility of the atmosphere in km, λ_0 is the wavelength corresponding to the maximum spectrum of the solar band (550 nm) and q is the parameter relating to the particle size distribution of the atmosphere.

For the Kruse model, the value of the index, q, in (3) depends on visibility as:

$$q = \begin{cases} 1.6 & if \quad V > 50\ km \\ 1.3 & if \quad 6\ km < V < 50\ km \\ 0.585V^{1/3} & if \quad 0\ km < V < 6\ km \end{cases} \quad (4)$$

Kruse model is chosen for this research among other models, because the model indicates that the fog attenuation is wavelength dependent for all visibility V (km) ranges.

3.2 Link margin and link availability

The links margin is the process of accounting for all the gains and losses from the transmitter, through the medium (free space, cable, waveguide, fiber, etc.) to the receiver in a telecommunication system. FSO system performance can be quantified in terms of the link margin. Link margin predicts how much margin, or extra power will be available in a link under any particular set of operating conditions [10]. The calculation of link margin is essential to design an acceptable system. The FSO system designer begins with the transmitted power and identifies all power losses along the propagation path. The power level received is compared with the receiver sensitivity to obtain the link margin. The receiver sensitivity represents the minimum amount of optical power needed for the system to achieve a given level of performance, related as [11]:

$$M_{link}\,(dB) = P_t - S_r - A_{Geo} - A_s - A_{fog} \quad (5)$$

where P_t is the transmit power, S_r is the receiver sensitivity, A_{Geo} is the geometrical attenuation, A_s is the absorption, and A_{fog} is the fog attenuation.

Since experimental scenario of FSO links were not performed, in this study, the parameters of a typical commercial FSO system were adopted to estimate the system availability in all the selected five stations; its specifications are listed in Table 4 [8].

Table 5: Summary of estimated Specific Attenuation for the five selected locations.

Location	Attenuation at 1550 nm, 193 THz ($dBkm^{-1}$)			Attenuation at 1300 nm, 230 THz ($dBkm^{-1}$)			Attenuation at 850 nm, 352 THz ($dBkm^{-1}$)		
	Min	Max	Average	Min	Max	Average	Min	Max	Average
Akure	0.6782	21.3388	11.0085	0.8524	23.6514	12.2519	1.4809	30.3252	15.9031
Enugu	0.8477	9.1142	4.98095	1.0655	10.3758	5.72065	1.8512	14.1915	8.0214
Ikeja	1.0173	27.8579	14.4376	1.2786	30.6501	15.9644	2.2214	38.6048	20.4131
Jos	0.4069	17.1196	8.76325	0.5115	19.0977	9.8046	0.8886	24.8709	12.8798
Port-Harcourt	1.0173	17.1196	9.06845	1.2786	19.0977	10.1882	2.2214	24.8709	13.5462

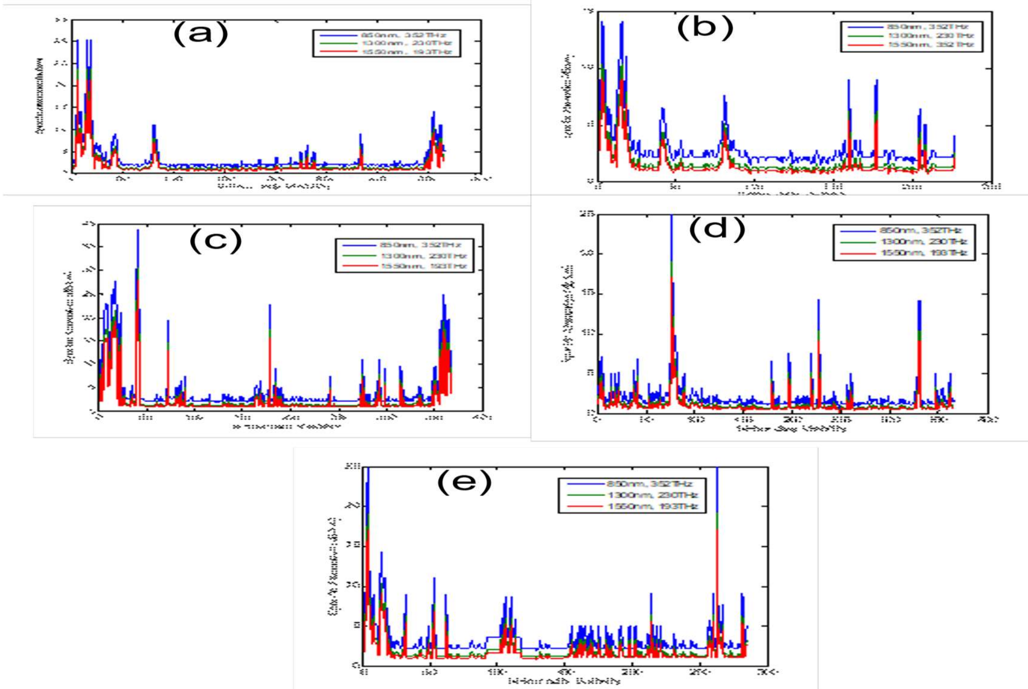

Fig. 2. Estimated specific attenuation (dB/km) for (a) Akure (b) Enugu (c) Ikeja (d) Jos (e) Port-Harcourt at 850, 1300 and 1500 nm

4. RESULT AND DISCUSSION

The estimated attenuation due to fog based on the visibility measurements taken at 0900 hour of the day has been obtained using the Kruse model. The specific attenuation for each location is estimated on three optical wavelengths using frequencies typically used in commercial FSO systems (i.e. (850 nm, 352 THz), (1300 nm, 230 THz) and (1550 nm, 193 THz)). Figures 2 (a-e) present the estimated daily optical attenuation for the study locations Akure, Enugu, Ikeja, Jos and Port-Harcourt respectively. As earlier stated, 0900 hour of the day has been used for the comparison based on the available data in each of the stations. Generally, the result shows that for Akure, the maximum estimated attenuation was 21.34 dB/km at 1550 nm wavelength, 23.65 dB/km at 1300 nm wavelength and 30.32 dB/km at 850 nm wavelength. Maximum optical attenuation value was observed on the 5th and 19th days of the year for the three optical wavelengths. The 5th and 19th days of the year belongs to the month of January when visibility conditions are relatively poor. The implication of the result is that Akure will suffer more signal loss during these days than other days of the year. Summary of the daily estimated specific attenuation for all the selected stations at the chosen frequencies are presented in Table 5. For a typical commercial FSO system whose parameters are specified in the Table 4, the achievable link range as a function of the link margin for different values of visibility in the study locations are presented in Figures 3 (a-e). In Akure, for example (Figure 3a), by operating the link under consideration in atmosphere with visibility of 10 km, the link margin between 15.24 and -72.79 dB was obtained for link range of 1 to 10 km. For atmosphere with visibility of 12 km, the link margin of about 16.97 to -55.56 dB was also obtained for link range of 1 to 10 km. Consequently, for atmosphere with visibility of 15 km, the link margin of about 18.38 to 40.44 dB was obtained for link range of 1 to 10 km. The same trend could be observed in other locations although with different values of link margin at different link range. The link margin can be improved by increasing the transmitted optical power and thereby increasing the achievable link range. However safety standards must be considered when increasing the transmitted optical power. Similar precaution has earlier been recommended in the work of [2].

4. CONCLUSION

Atmospheric effects are the main challenges to design of FSO link as the transmission channel is space. In this paper the feasibility of reliable FSO Communication links in Nigeria was investigated. Atmospheric specific attenuation caused by fog was estimated in five selected stations in Nigeria (Akure, Enugu, Ikeja, Jos and Port-Harcourt). The Kruse model has been used on 850 nm wavelengths with equivalent frequency of 193 THz, 1300 nm wavelength with equivalent frequency of 230 THz and 1550 nm wavelength with equivalent frequency of 352 THz. The results obtained show that 1550 nm wavelength with equivalent frequency of 193 THz has the minimum fog

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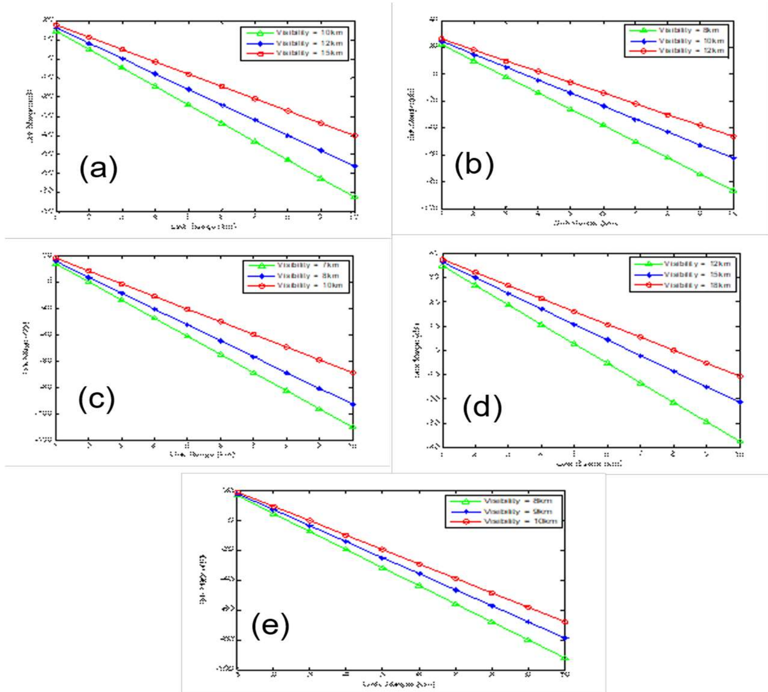

Fig. 3. Link Margin against Link Range for different values of Visibility for (a) Akure (b) Enugu (c) Ikeja (d) Jos (e) Port-Harcourt

induced attenuation in all the five locations. The implication is that for FSO systems operating in the tropical region like Nigeria, 1550 nm wavelength with equivalent frequency of 193 THz is recommended for optimal performance during bad weather condition. Also link margin has been investigated on FSO communication link in Nigeria. The specifications of commercial FSO system parameter was used in the link margin analysis. The importance of the link margin analysis is to ascertain the achievable link range for different link margin and receiver sensitivity. The result also revealed that the achievable link range increases with increase in atmospheric visibility conditions. The link range can be increased by increasing the transmitted power.

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