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Effects of Atmospheric Conditions on the Quality of Free Space Optical Communication Link In Borno Nigeria

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Abstract: *Free space optical communication (FSOC) in recent years has become an emerging solution for last-mile broadband connectivity in areas where fibre deployment is expensive. FSOC is an optical means communication technique that wirelessly transmits data for telecommunication and computer networking by propagating the light in free outer space. Currently, FSO is capable of up to 2.5 Gbps of data, voice and video communications through the air, through optical connectivity without requiring any medium such as fibre optic cable. FSOC basically operates between a wavelength band of 750 – 1600 nm and using alternate O/E and E/O converters. FSO requires light, which can be projected by using sources such as light emitting diodes (LEDs) or lasers. The use of lasers is based on a similar concept as optical transmissions using fibre optic cables; the only difference is the medium of transmission. FSO communication has proved to be considered as an alternative to radio relay link line-of sight (LOS) communication systems. This paper determines the effect of atmospheric conditions on the quality of free space optical communication link in Borno (Nigeria). Meteorological data (Wind speed, Visibility and Altitude) were used to determine the atmospheric losses for Borno State. Optimal link distance is computed under worst and average atmospheric condition by evaluating the atmospheric condition against the power link margin. This preliminary study shows that FSOC can be deployed in Borno for last mile access networks, where the link distances are mostly less than 150km.*

Keywords: *Free Space Optical Communication, Atmospheric Losses, Optimal Link Distance, Power Link Margin,*

Introduction

Free space optics is a line-of-sight transmission that uses unlicensed frequency band to transmit data over relatively short distance. The free space optical beam travels through the atmosphere in order to provide optical communication link. Due to its ease of installation, free space optical system has proved to be a viable alternative for last-mile access as compared to optical fibre cables [2]. Despite providing lower bandwidth than optical fibre cable networks, the cost of its installation is less. Free space optical system, unlike radio frequency carrier, does not require spectrum licensing, hence providing high modulation bandwidth. They are characterized by low power usage, less complex receiver design, increased directivity and are secured as its laser beam is highly directional with a narrow beam divergence making it difficult to intercept [6]. All these benefits are achievable under clear atmospheric conditions. Meteorological

factors like fog, rain, wind speed and scintillation etc. may result in the fluctuation of light intensity causing transmission to be interrupted [5, 11].
This study is aimed at determining the effects of atmospheric condition on the quality of free space optical communication in Nigeria. Borno state is selected for the casepilot study and the meteorological data (Visibility, Wind speed, Altitude) were obtained from the meteorological agency (NIMET) for each state over 10 years period. Atmospheric losses, optical link margin and optimal link distance of each location were calculated under clear and worst atmospheric condition. A detailed analysis of the result is carried out to determine the effect of atmospheric condition on the quality free space optical communication link.

1. Fundamental of free space optical communication

The atmosphere has effect on the laser beam passing through it, the quality of data received has to be affected, to reduce this effect, the fundamental system components must be designed to adopt with the weather conditions. This design is mostly related to transmitter and receiver components. The techniques used to convey data carried by a laser beam through the atmosphere while FOS offers broadband service, it requires Lone of Sight communication between the receiver is shown in Fig (1)[1].

2.1 FSO Communication Subsystem.

The FSO communication is a line of sight technology that uses laser beam for sending the very high bandwidth digital data from one point to another through atmosphere. This can be achieved by using a modulated narrow laser beam launched from transmission station to transmit it through atmosphere and subsequently received at receiver station. The generalised FSO system is shown in Fig (2) it has transmitter, FSO Channel and a receiver.

TRANSMITTER

Transmitter transforms the electrical signal to an optical signal and it modulates the laser beam to transfer carrying data to the receiver through the atmosphere channel. The transmitter consists of four parts, laser modulator, driver, optical source and transmitter telescope.

❖ Laser Modulator

Laser modulator means the data were carried by laser beam. The modulation technique can be implemented in following two common methods: internal modulation and external modulation [2].

Internal Modulator

Is a process which occurs inside the laser resonator and it depends on the change caused by the additive components and change the intensity of the laser beam according to the information signal.

External Driver

Is a process which occurs outside the laser resonator and it depend on both the polarization phenomena and refractive dualism phenomenon.

Driver

Driver circuit of a transmitter transforms an electrical signal to an optical signal by varying the current flow through the light sources.

Optical Sources

Optical sources may be a laser diode (I.D) or light emitting diode (LED), which used to convert the electrical signal to optical signal.

A laser diode is a device that produces optical radiation by the process of stimulated emission photons from atoms or molecules of a lasing medium, which have been excited from a ground state to a higher energy level. A laser diode emits light that is highly monochromatic and very directional. This means that the I.D's output has narrow spectral width and small output beam angle divergence. I.Ds produce light waves. There are two common types of laser diode, solid state laser and fabry-perot and distributed-feedback laser (FP and DFB) [3].

Laser Sources Selection Criteria for FSO

The selection of a laser sources for FSO applications depends on the various factors. The factors can used to select an appropriate source for a particular application. To understand the description of the sources of performance for a specific application, one should understand these detector factors. Typically the factors that impact the use of a specific light sources include the following [4]:

i. Price and availability of commercial components

ii. Transmission power and lifetime

iii. Modulation capabilities

iv. Physical dimensions and compatibility with other transmission media

v. Eye safety

Transmitter Telescope

The transmitter telescopes collectors, collimates and directs the optical radiation towards telescope at the other end of the channel.

FSO Channel

For FSO links, the propagation medium is the atmosphere. The atmosphere may be regarded as series of concentric gas layers around the earth. Three principle atmospheric layers are defined in the hemisphere [5], the troposphere and mesosphere. These layers differentiated by their temperature gradient with respect to the attitude. In FSO communication, we are especially interested in the troposphere because this is where must weather phenomena occurs and the FSO links operate at the lower part of this layer [5].

Propagation characteristics of FSO through atmosphere drastically change due to communication environment, especially, the effect of weather condition is strong, the received signal power fluctuates and attenuates by the atmospheric obstacles such as rain, Fog, haze and turbulence in the propagation channel. The atmospheric attenuation results from the interaction of the laser beam with air molecules and aerosols along the propagation. The main effects on optical wireless communication are absorption, scattering and scintillation [7]

1. ***Losses due to atmospheric Conditions and Optical Link margin considerations***

2.1 Atmospheric attenuation

This is the process where part or all of the electromagnetic wave energy is lost as it passes through the atmosphere. Absorption and scattering vary with time and depends on the current weather condition of a locality. Mathematically, total attenuation coefficient is given as:

$\beta = \beta_{abs} + \beta_{scat}$
(1)

$\beta = \rho_m + \rho_a + \beta m + \beta a$ (2)

Where:

ρ_m is the molecular absorption coefficient, ρ_a is the aerosol absorption coefficient, βm is the Rayleigh coefficient and βa is the Mie scattering coefficient.

At a wavelength of interest (1550nm) aerosol absorption, molecular absorption and Rayleigh coefficient are negligible [10].

Therefore, Mie scattering dominates the total attenuation coefficient and Eq. (2) is rewritten as:

$\beta = \beta_a$

Atmospheric Attenuation due to scattering can be obtained using [3]:

$A_{atm} = \beta_a \times L$ [dB] (3)

Where:

β_a : is the atmospheric attenuation coefficient, L : is the distance between the transmitter and the receiver in kilometres

Attenuation due to Mie scattering varies with Wavelength and Visibility and can be expressed according to these variables (wavelength and visibility) as [7]:

$$\beta a = \frac{3.91}{V}\left(\frac{\lambda}{550nm}\right)^{-q}$$ [dB/km] (4)

Where:

V: is the visibility in kilometres, λ: is the laser wavelength in nanometres, q: is the particle size distribution coefficient.

The value for q is determined according to [12] as:

q $=\{1.6\ for\ v > 50km \quad 1.3\ for\ 6\ km < v < 50\ km\ 0.16v + 0.34\ for\ 1\ km < v < 6km\ v - 0.5\ for\ 0.5\ km < v < 1\ km\ 0\ \ for\ v < 0.5\ km$

2.2 Turbulence

This is a phenomenon that affects the propagation of optical beam as a result of variation in temperature, pressure and wind along the optical propagation path [8]. Wind and altitude are the important variables in its change. Atmospheric turbulence causes a phase shift of the propagated optical signal causing distortion in the wave font. Turbulence has three main effects namely; scintillation, beam wander and beam spreading [13]. Scintillation is the most noticeable source of turbulence [1]. Turbulence loss according to [9] is determined by using:

$$\rho(L) = 2\ X\ \sqrt{23.17 * k^{7/6} * C_n^2 * L^{11/6}}$$ [dB] (5)

Where:

k: is equal to $\frac{2\pi}{\lambda}$, C_n^2: is the refractive index structure parameter in $m^{-\frac{2}{3}}$

The refractive index parameter can be determined using Huffnagel-Valley equation model as follows [14]:

$C_n^2(h) = 0.00594 * (\frac{v}{27})^2 * (10^{-5}h)^{10} \, exp \, exp \left(\frac{-h}{100}\right) + 2.7 * 10^{-16} \, exp \, exp \left(\frac{-h}{1500}\right) + A_0 exp(\frac{-h}{100})$ (6)

Where:

V: is the wind speed in [m/s], h: is the altitude in [m] and A_0: is the turbulence strength at the ground level, given by 1.7 x 10^{-14} $m^{-2/3}$

The Hufnagel-Valley model is one of the most popular models that allows an easy day/night time variation by varying certain field parameters such as altitude, wind speed, and isoplanatic angle.

2.3 Optical link margin and link availability

Certain parameters such as; laser power, beam divergence, receiver sensitivity, coupling losses and receiver lens area define how the free space optics can reduce or eliminate atmospheric effects [3]. The power link margin according to [3] can be expressed as:

$$M(L) = P_0 - A_{TX} - 20log\frac{\sqrt{2L\theta}}{D} - A_{RX} - P_{RX_{min}} \quad (7)$$

Where:

P_0: is the mean optical power of a laser diode, A_{TX}: includes the coupling loss between the laser and the transmitter lens and the attenuation loss in the lens, A_{RX}: is the coupling loss between the receiver lens and photodiode, attenuation and the reflection at the lens, $P_{RX_{min}}$: is the receiver sensitivity, θ: is the divergence half angle, D: is the lens aperture diameter, L: is the length which is expressed in meters [5]

In order to determine the effect of turbulence and scattering on the propagation of laser beam, the free space optical communication system can be characterised only by the receiver lens area and the power link margin.

A simplified version of Eq. 10 can be used to compute the power link margin [3]

$$M(L) = M_0 - 20logL \quad \text{[dB]} \quad (8)$$

Where M_0= 80 represents all constant values in Eq. 10, defining a real FSOC systems that is designed for a data range of 1 Gbps [3]

The optical link margin according to [4] shows the extent at which a system can attune for scattering and turbulence losses at a given range. Free space optical communication link will operate efficiently if the condition below is achieved [3]

$$M(L) \geq A_{atm}(L) \quad (9)$$

Where

$A_{atm}(L)$: refers to the atmospheric losses at a distance L

Another condition for free space optical communication availability is that for all optimal link distance, the average visibility of any given locality must be higher than minimum visibilities. The minimum required visibility for an efficient operation of the free space optical communication is stated as [3]

$$V_{min} = \frac{13L}{M(L)} * \left(\frac{\lambda * 10^9}{550}\right)^{(-q(v))} \quad \text{[km]} \quad (10)$$

2. *Atmospheric Loss Calculations for Nigeria*

Total atmospheric losses were calculated by summing up the scattering and turbulence losses. Based on the turbulence loss equation it is clear that turbulence loss depends on the altitude and to a lesser degree wind speed while scattering loss largely depends on visibility.

Table.1 Altitude, Wind speed and Average Visibility Borno state Nigeria

Location	Latitude	Longitude	Altitude (m)	Average Wind Speed (m/s)	Average visibility (km)
Borno	13.1520	11.88469	621	2	20

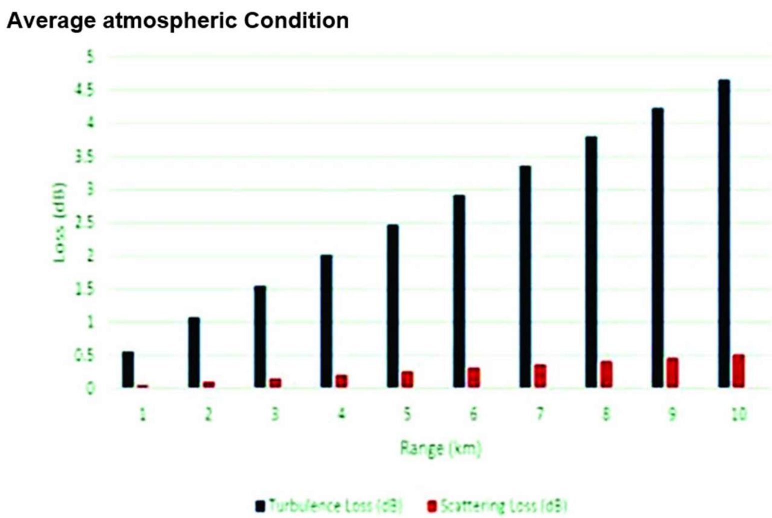

Fig. 1 Loss in Borno under average atmospheric condition scattering against Turbulence

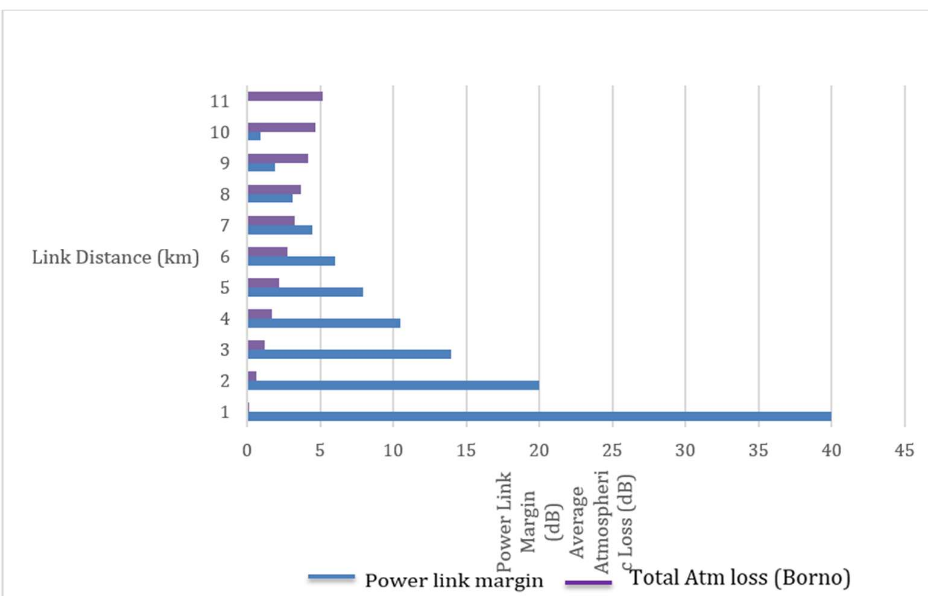

Fig. 2 Power link margin vs average atmospheric losses.

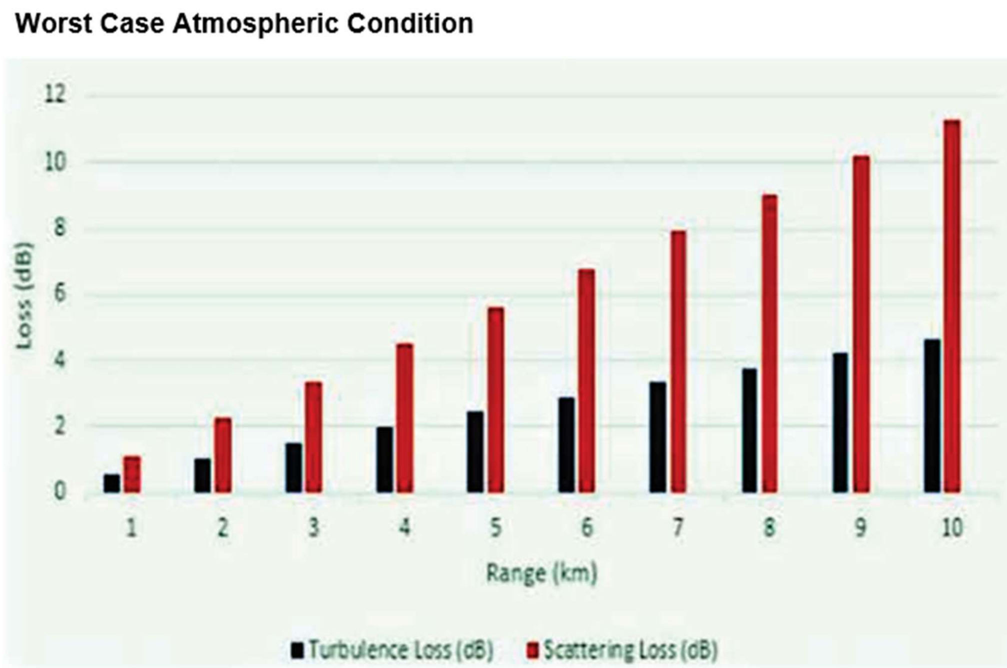

Fig. 3 Turbulence against Scattering Loss in Borno under worst atmospheric condition

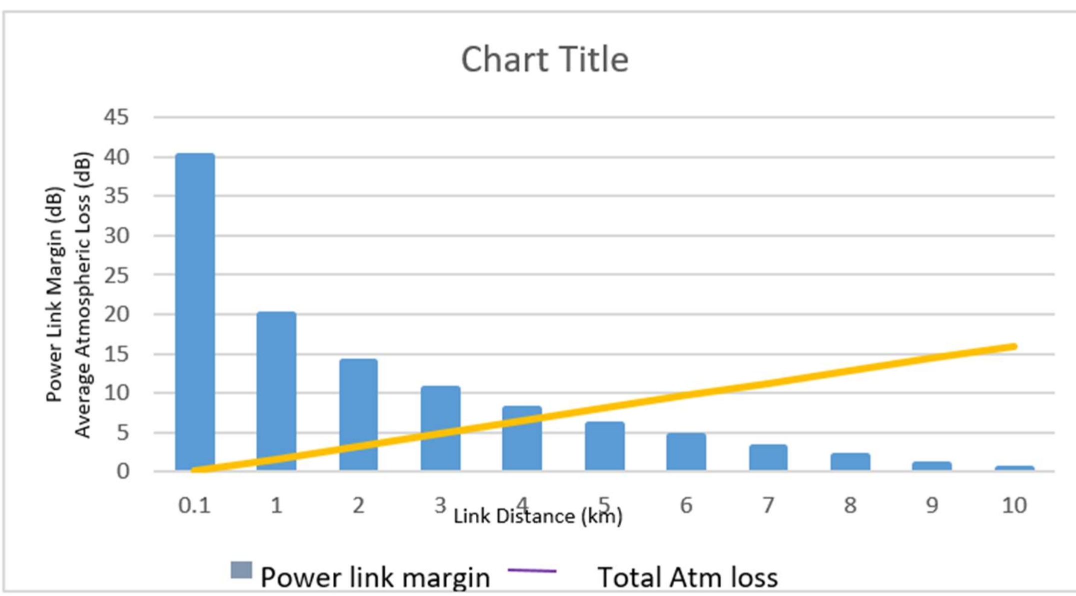

Fig. 4 Power link margin against average atmospheric losses.

1. Conclusion

The average wind speed (m/s) and the altitude (m) of Borno state is shown in table 1. These values were used to calculate the refractive index structure parameter C^2_n for all the locations. Borno has refractive index structure parameter of $1.2431 * 10^{-16} m^{-\frac{2}{3}}$ at an altitude of 621m. These results clearly indicate that altitude has a significant impact on the refractive index structure parameter. As the altitude increases the refractive index structure parameter decreases.
An optimal link distance is achieved when the power link margin is equal of greater than the total atmospheric loss. The values of the maximum link distance and their corresponding power link margin are obtained at the point the power link margin line intersects the total atmospheric loss line. Borno has link distances ranging from 6300 to 6600m with similar atmospheric losses. It can be concluded that at an average atmospheric conditions FSOC can be deployed.
At worst atmospheric conditions, scattering loss increases due to lower visibilities. Borno has a low total atmospheric loss, resulting in the longest FSOC link at 4535m which satisfies the minimum visibility requirement of FSOC. Under worst atmospheric conditions therefore, FSOC can be deployed in these locations.

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