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Effects of Atmospheric Conditions on the Quality of Free Space Optical Communication Link in 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 transmit 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 bands 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 Nigeria. Meteorological data (Wind speed, Visibility and Altitude) were used to determine the atmospheric losses for Bauchi 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 Bauchi for last mile access networks, where the link distances are mostly less than 10km.*

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

1. 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. It is estimated that installing optical fibre link in metropolitan areas approximately cost about US $200,000 per kilometre, where 85% of the amount is spent on excavation and installation while installing free space optical system cost 20% of fibre based system [10]. 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. Bauchi state is selected for the pilot 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. 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:

$$\beta = \beta_{abs} + \beta_{scat} \tag{1}$$

$$\beta = \rho_m + \rho_a + \beta m + \beta a \tag{2}$$

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]:

$$A_{atm} = \beta_a \times L \quad [dB] \tag{3}$$

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]:

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

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:

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

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:

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

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]

$$M(L) = M_0 - 20logL \qquad [dB] \qquad (8)$$

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]

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

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]

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

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.

Location	Latitude	Longitude	Altitude (m)	Average Wind Speed (m/s)	Average Visibility (km)
Bauchi	10.3134	9.8433	621	2	20

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

Average atmospheric Condition

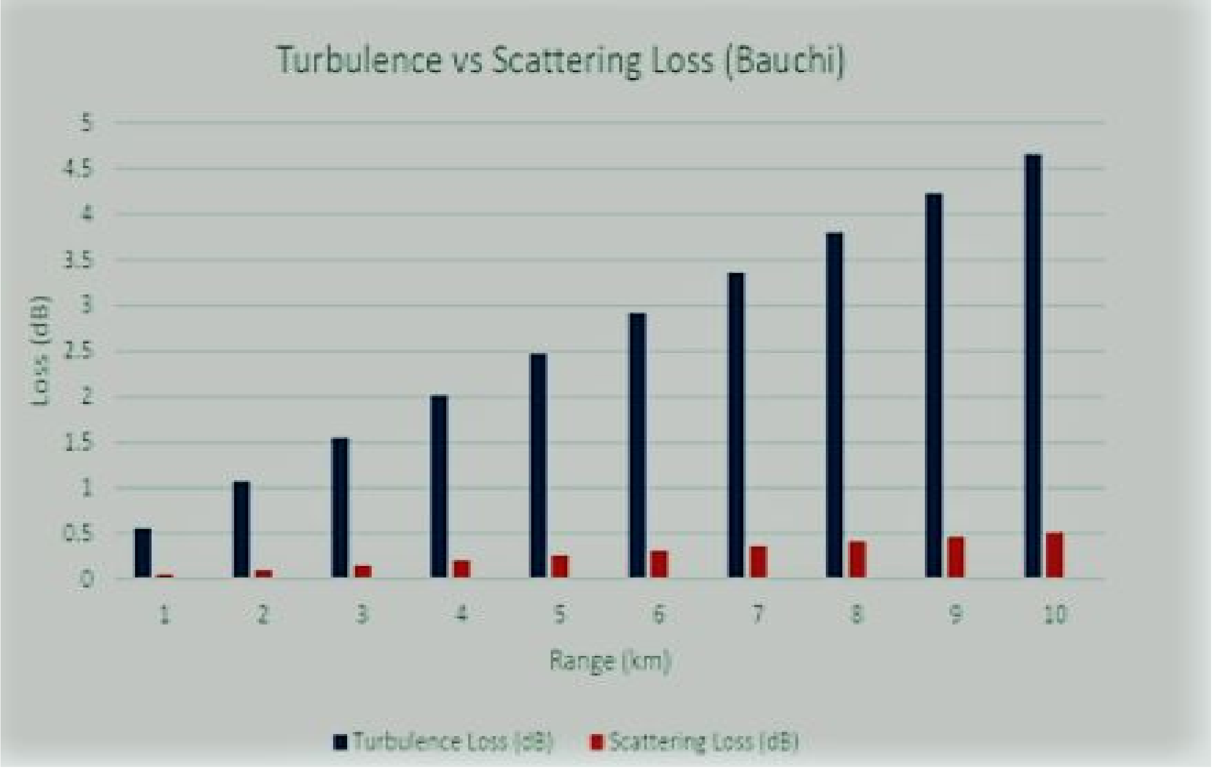

Fig. 1 Turbulence vs Scattering Loss in Bauchi under average atmospheric condition

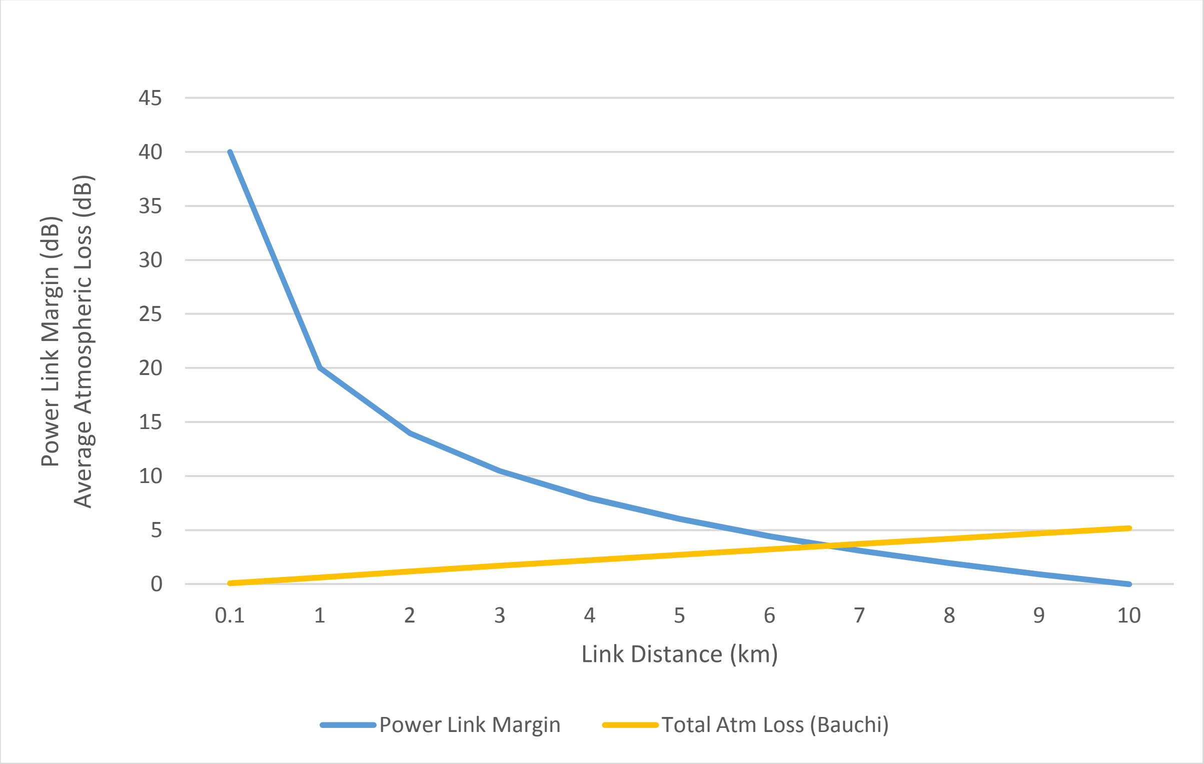

Fig. 2 Power link margin vs average atmospheric losses.

Worst Case Atmospheric Condition

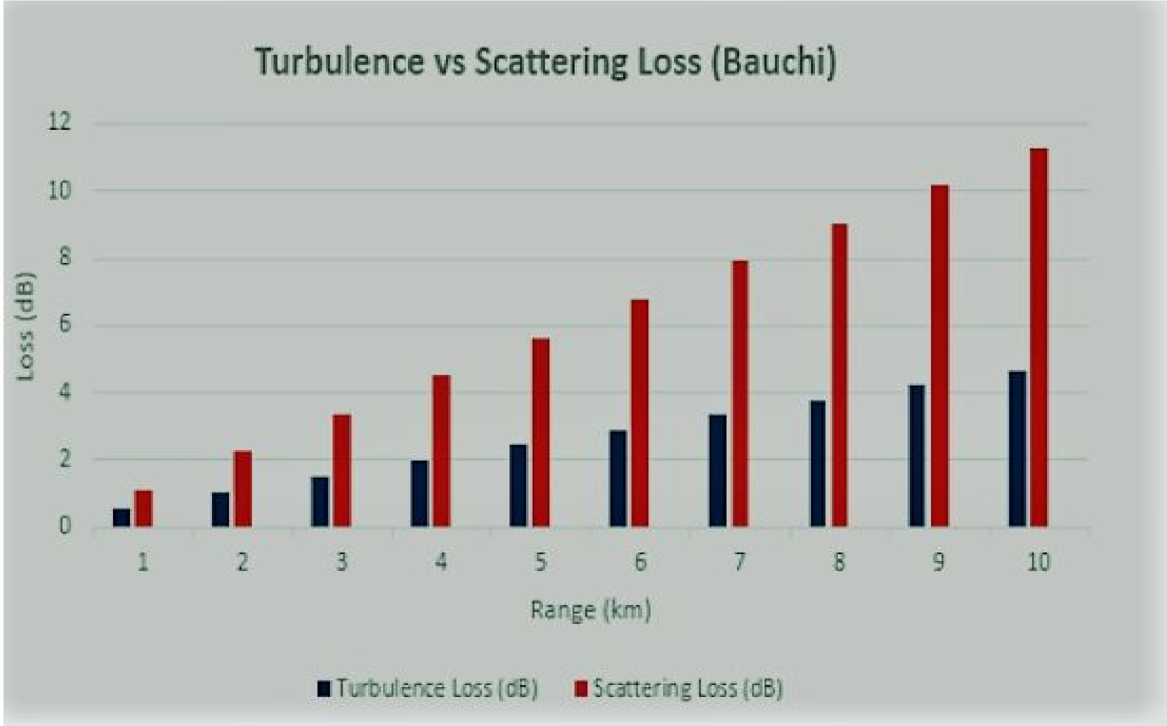

Fig. 3 Turbulence vs Scattering Loss in Bauchi under worst atmospheric condition

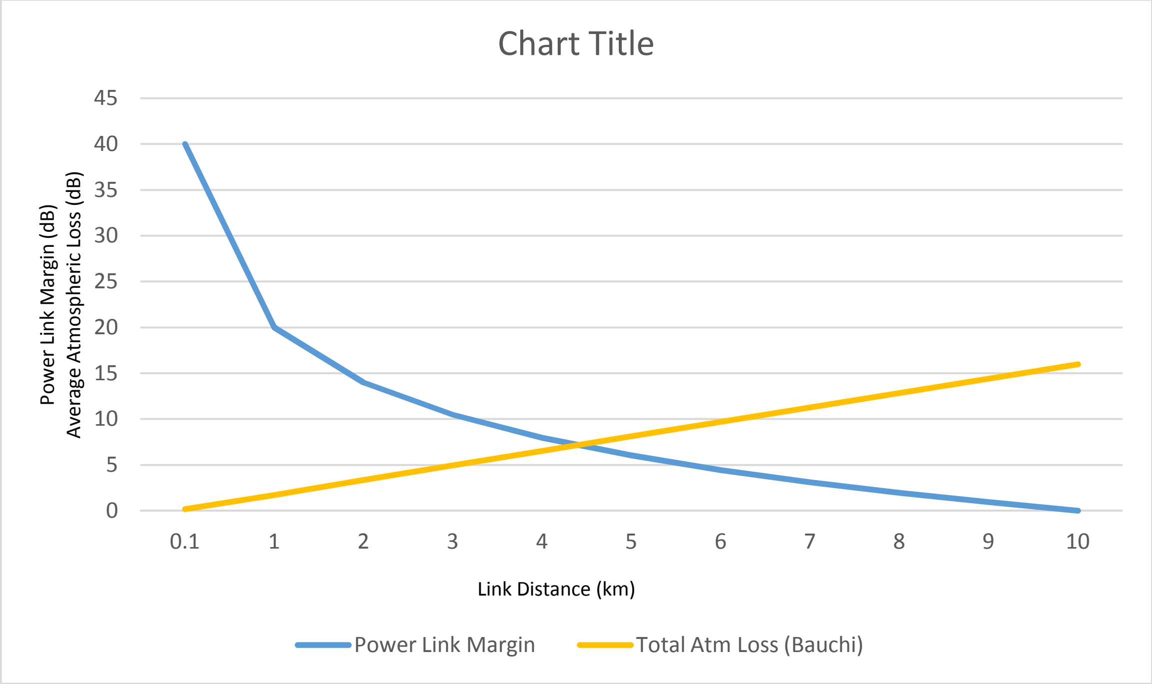

Fig. 4 Power link margin vs average atmospheric losses.

1. Conclusion

The average wind speed (m/s) and the altitude (m) of Bauchi state is shown in table 1. These values were used to calculate the refractive index structure parameter C^2_n for all the locations. Bauchi 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. Bauchi 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. Bauchi 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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