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Improved Transmission Equation for Terrestrial FSO Link

Oluwole J. Famoriji[1], Kazeem B. Adedeji[2], Oludare Y. Ogundepo[3]

[1]Department of Electrical and Electronics Engineering College of Engineering, Afe Babalola University P. M. B. 5454, Ado-Ekiti, Ekiti State, Nigeria
[2]Department of Electrical and Electronics Engineering, School of Engineering and Engineering Technology, Federal University of Technology, PMB 704, Akure, Nigeria
[3]Department of Electrical and Electronics Engineering, Federal University of Petroleum and Resources, PMB 1221, Effurun, Delta State, Nigeria

Abstract: **Free space optical (FSO) communication system has proven to be a solution to the overcrowded radio frequency due to its cost-effectiveness, license free and wide-bandwidth access technique for high data rates, which has attracted significant attention recently for a variety of applications. However, FSO communication channel severely suffers from turbulence-induced tropospheric scintillation fading caused by the dynamic nature of the atmospheric conditions thereby impairing its performance and reliability: this induced channel fading effect must be accounted for in the link transmission equation. In this paper, we have proposed an improved transmission link equation by taking into account the scale of turbulence eddies, the effect of aperture averaging, and magnitude of the refractive-index structure parameter that play very important role in FSO links calculations. This transmission model provides the basis for optical and photonics system communication engineers a platform to work with, in the link budgetary for planning and design of low margin systems of FSO communication link.**

Keywords: **Transmission Equation, Atmospheric Turbulence, Scintillation fading effects, FSO Communication.**

1. INTRODUCTION

Free space optical communication system’s channels have wider bandwidth and therefore are able to support more users compared to the local or traditional radio frequency (RF) counterparts. By relaying techniques, outdoor FSO optical transceivers can also cover large transmission distances (Tsiftsis *et al.*, 2006; Safari and Uysal, 2007). With its high-data-rate capacity and wide bandwidth on unregulated spectrum, FSO communication system is a promising solution for the “last mile" problem, however its performance is highly vulnerable to adverse dynamic atmospheric conditions, which is unstable at the tropospheric layer of the atmosphere where it’s been accessed. Kolawole (2003) reported that the troposphere contains 99% of the water vapour whose concentrations vary with latitudinal position in the atmosphere. Atmospheric turbulence occurs as a result of the variations in the refractive index due to inhomogeneities in temperature and pressure changes (Tsiftsis *et al.*, 2009). This results in rapid fluctuations of the amplitude and phase of the optical wave front at the received signal, i.e. known as fading or scintillation, impairing the system performance and reliability particularly for link ranges of 1 km and above.

Over the years, some turbulence-induced tropospheric scintillation models—e.g. Karasawa model, Otung model, Van De Kamp model, Ortgies-N and Ortgies-T models, ITU-R model etc.—have been developed that account for this fading effect (Nadirah *et al.*, 2012): they are only applicable at the gigahertz frequency range. Of recent, Famoriji *et al* (2014) developed a turbulence-induced tropospheric scintillation model that is applicable in the petahertz frequency range.

P_t/P_r relationship is a fundamental expression in antenna propagation technique (Kolawole, 2014). Friis antenna and propagation equation is an essential tool in the design and analysis of wireless communication system, which relates the power fed P_t to the transmitting antenna and the power received P_r by the receiving antenna when the two antennas are separated by a sufficiently large distance *R; i.e.*,

$$R >> \frac{2D_{\max}^2}{\lambda} \qquad (1)$$

where, at far zones, D_{max} is the maximum antenna aperture diameter (m), and λ is wavelength (m). However, antenna and propagation model that factors in environmental influences (turbulence-induced tropospheric scintillation effect) in the petahertz (PHz) frequency range requires consideration.

2. TROPOSPHERIC SCINTILLATION MODEL FOR FSO COMMUNICATION SYSTEM

Terrestrial laser beam communication is affected above all by scintillations (Prokeš, 2009). In this paper, the modified tropospheric scintillation index σ developed for foggy conditions is used (Famoriji *et al*., 2014). Specifically,

$$\sigma = \sigma_{ref} f^{\frac{7}{12}} \left[\frac{g(x)}{2(sin\theta)^{1.2}}\right] \ (dB) \qquad (2)$$

where

(i) the normalized or reference standard deviation σ_{ef} is given by

$$\sigma_{ref} = 3.6x10^{-3} + N_f \qquad (3)$$

(ii) refractivity, N_f:

$$N_f = N_{wet} = \frac{3.732x10^3 U}{T^2}\left(6.1121\exp\left[\frac{17.502}{t+240.97}\right]\right) \qquad (4)$$

applicable in the temperature range of -20°C ≤ t ≤ 50°C where T is the measured temperature (in K) and U is the relative humidity (in %). However, or completeness, in desert or semi-desert areas –constituting part of Nigeria, fog (or rain) is seldom. For these cases FSO systems can be deployed over long distances and the turbulence effect has to be taken into consideration, so refractivity in Eqn. (4) is replaced with N_{dry}, thus (Olasoji and Kolawole, 2010):

$$N_f = N_{dry} = 77.6848\frac{P}{T} \qquad (5)$$

This is valid for frequency up to 30 GHz and for normally encountered ranges of pressure, *P*, temperature, *T* and humidity, *U*.

(iii) antenna averaging factor *g(x)*:

$$g(x) = \sqrt{3.86(x^2+1)^{\frac{11}{12}} \sin\left(\frac{11}{6} arctan \frac{1}{x}\right) - 7.80x^{\frac{5}{6}}} \qquad (6)$$

where

$$x = \frac{1.22\eta f D^2}{L} \qquad (7)$$

$$L = \frac{2h_L}{\sqrt{(sin\theta)^2 + 2.35\times10^{-4}} + sin\theta} \quad (m) \qquad (8)$$

D is antenna aperture diameter; η is antenna efficiency (0 ≤ η ≤1);

θ = elevation angle (°);

f = frequency (Hz); for optical beam communication, 1 ≤ *f* ≤ 5.5 PHz.

h_L = height of the turbulent layer. The effects of atmospheric turbulence in optical communication are still relatively unknown. Technological progress can be useful only if accurate quantitative measurements prove to be feasible through atmospheric turbulence. Several boundary layers—namely planetary, the surface and the internal or constant flux—are pertinent to the study of atmospheric turbulence. The surface layer is the lowest layer of the atmosphere (and troposphere—the region of interest). It is the layer, where air is in contact with the surface and where strong vertical gradients in temperature, humidity, wind and scalars exist. The layer is between 1 and 2 km of the atmosphere.

2.1 Proposed Modification to Friis Transmission Equation:

The main disadvantage of Friis' method is the need to incorporate the two simultaneously changing parameters causing fluctuation in the received optical power, namely scintillation index σ and polarization loss factor, L_{pf}. In this paper, unlike other works, the changing parameters are incorporated in the FSO links transmission equation thereby broadening its practical applications.

Friis transmission equation gives amount of power an antenna received under ideal conditions from another antenna. Using Fig. 1 as a guide, the Friis transmission equation works under certain conditions:

(a) antennas must be in radiating far-field, i.e. R [given by Eqn. (1)], or R > 10 λ for small antenna (Kolawole, 2013) where D and λ are as previously defined;

(b) antennas are in unobstructed free space i.e. line of sight transmission mode which is the same as that of FSO;

(c) Bandwidth is narrow enough that a single wavelength can be assumed and antennas are correctly aligned and polarized (Nikolova, 2012).

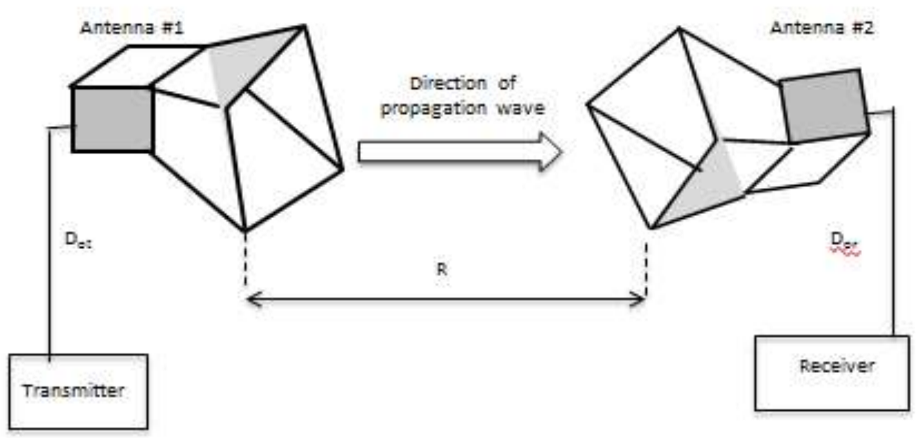

Figure 1: Two antennas separated by distance R. (Source: Kolawole, 2014)

Suppose the transmitting and receiving antennas are not matched to their respective lines or loads (reflection efficiencies are not unity) and the polarization of the receiving antenna is polarization-matched to the impinging wave (polarization loss factor and polarization efficiency are not unity), then the power ratio P_t/P_r expression can be written as (Kolawole, 2014):

$$\frac{P_r}{P_t} = \eta_{or}\eta_{ot}\left(1-|\Gamma_t|^2\right)\left(1-|\Gamma_r|^2\right)\left(\frac{\lambda}{4\pi R}\right)^2 d_{or}d_{ot}\left|L_{PF}^2\right| \quad (9)$$

where η_{or} and η_{ot} are receiving and transmitting antenna efficiency, respectively; and Γ_r and Γ_t are voltage reflection coefficient at the input terminals of the receiving and transmitting antenna, respectively, which are related to their respective impedances; and d_{or} and d_{ot} are receiving and transmitting antenna *directivity*, respectively. In reality, directivity and polarization loss factor are direction dependent, i.e. azimuth ϕ and incident ϕ. However, if reflection and polarization-matched antennas aligned for maximum directional radiation and reception, then Eqn. (9) reduces to:

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 G_{or}G_{ot} \quad (10)$$

the well-known *Friis Transmission Equation*, where G_{or} and G_{ot} are receiving and transmitting antenna gain, respectively, defined as $G_{or} = \eta_{or} d_{or}$, and $G_{ot} = \eta_{ot} d_{ot}$. The term $(.)^2$ in Eqn. (10) is called the called the *free-space loss factor*, and it takes into account the losses due to the spherical spreading of the energy by the antenna. Incorporating Eqn. (2) in Eqn. (9), the Friis Transmission Equation is modified to account for factors in environmental influences and polarization losses suitable for FSO communication link. Specifically:

$$\frac{P_r}{P_t} = 10^{0.1\sigma} \eta_{or} \eta_{ot} \left(1 - |\Gamma_t|^2\right)\left(1 - |\Gamma_r|^2\right)\left(\frac{\lambda}{4\pi R}\right)^2 d_{or} d_{ot} \left|L_{PF}^2\right| \quad (11)$$

bearing in mind that the unit of the losses or fading due to scintillation (σ—as in Eqn. (2)—is in decibel (dB) whose absolute value is $10^{\sigma/10}$.

3. SIMULATION

In order to validate our modifications to transmission equation for FSO communication link, we first simulate ideal situation without environmental effects, and second with the scintillation index. The results presented here give an idea of the reliability of free space communication ensured by a particular FSO deployed at various distances.

The antenna efficiency was assumed to be unity though this may not exist in practice. Turbulent height (h_L) was taken to be 1000m as proposed by ITU-R. Elevation angle θ considered is 30^0, which falls within the range of ITU-R. The temperature t and relative humidity U were set at 37.1^0C and 24%, respectively, while the antenna aperture diameter was taken to be 15m. Also, the transmitted power was set at 3000W, frequency at 5PHz, transmission distance between 0.2km to 8km while the transmitting and receiving antenna gains were set at 34 and 32, respectively while the pressure was set at 431.52mmHg. It was assumed that reflection and polarization-matched antennas are aligned for maximum directional radiation and reception.

Figures 2, 3, 4 and 5 show the results of simulation for the transmission equation without and with scintillation fading effect with wet refractivity, dry refractivity and dry-wet refractivity respectively, for typical representatives of FSO links in dependence on the link distance. The variation in amplitudes is an indication of the effect of atmospheric turbulence causing fluctuation in the received optical power.

As seen from Figs. 3, 4 and 5, the scale of turbulence eddies, the effect of aperture averaging, and magnitude of the refractive-index structure parameter play very important role in FSO links calculations. It could also be deduced that the FSO link is greatly impaired by foggy environment which will consequently limit the coverage area. Also, as shown in Fig. 6, its performance is seasonal based which means it's more reliable during dry season than wet season; the most pertinent seasons in Nigeria.

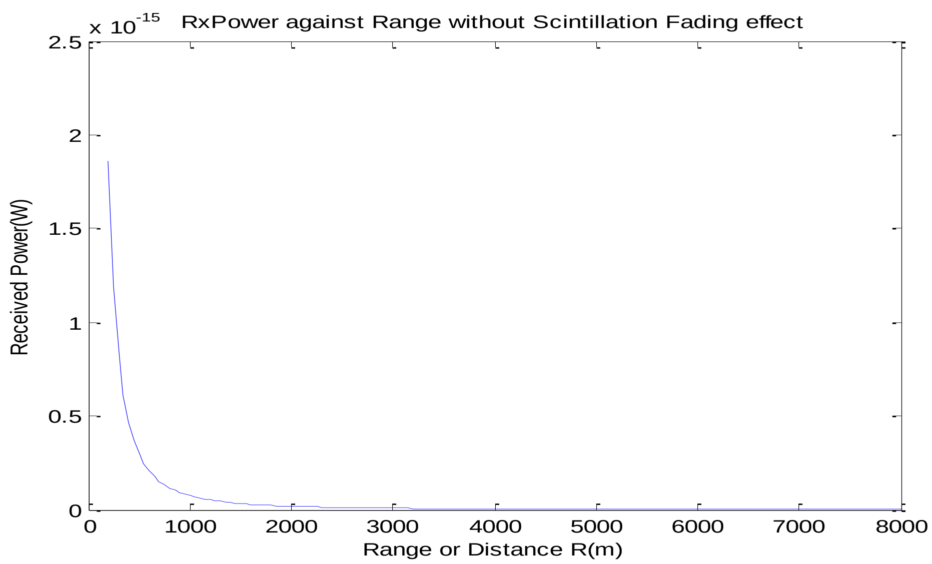

Figure 2: Plot of Received Power against Transmission Distance without Scintillation-index Effect

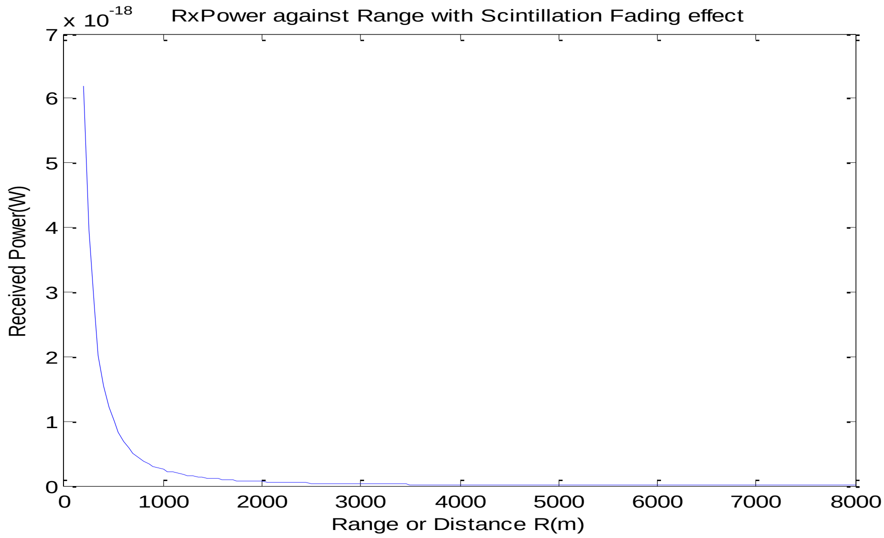

Figure 3: Plot of Received Power against Transmission Distance with Scintillation-Index for Wet Refractivity

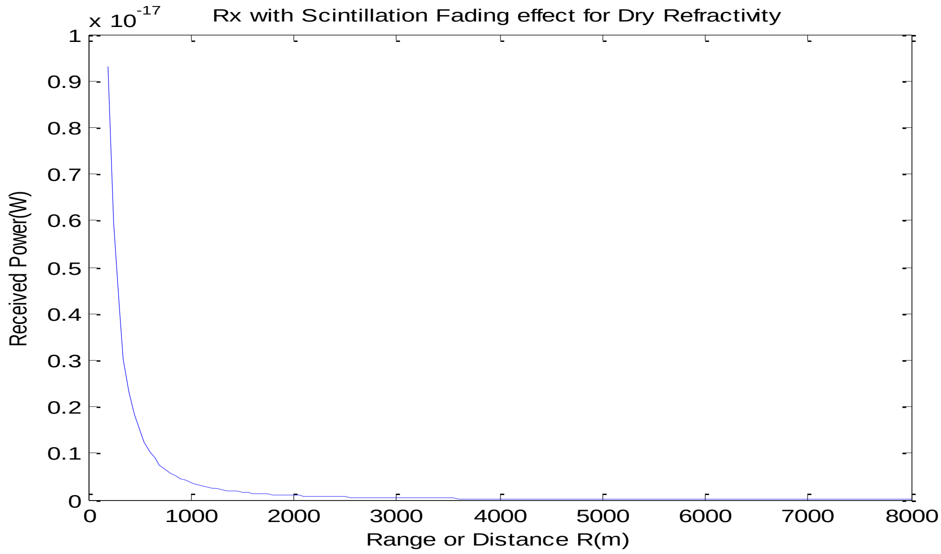

Figure 4: Plot of Received Power against Transmission Distance with Scintillation-Index for Dry Refractivity

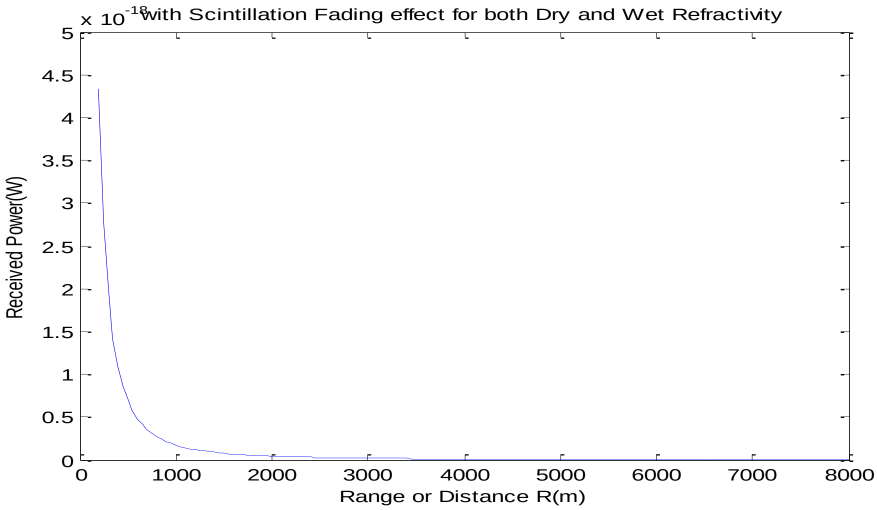

Figure 5: Plot of Received Power against Transmission Distance with Scintillation-Index for both Wet and Dry Refractivity (N_f=N_{dry}+N_{wet})

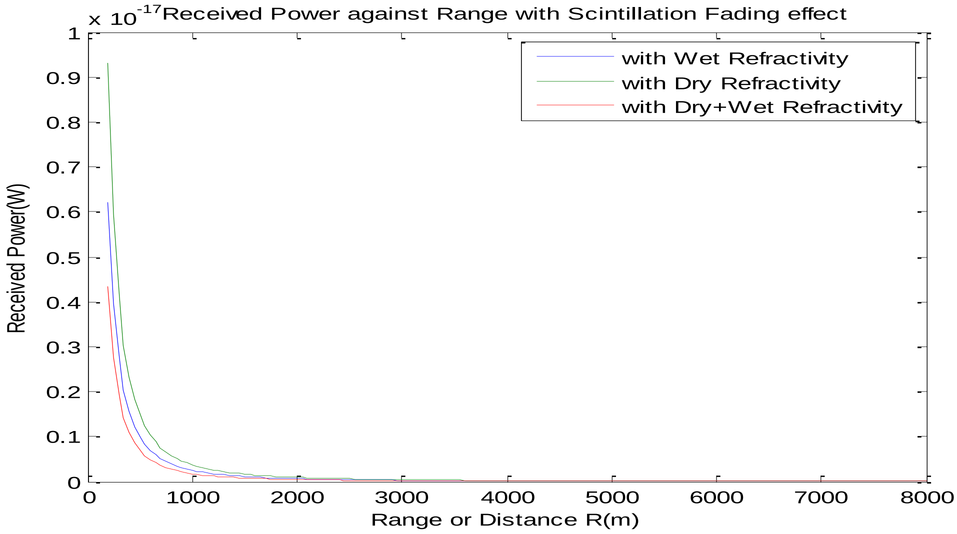

Figure 6: Plot of Power Received against Range with Scintillation Fading Effect for Wet, Dry and Wet-Dry Refractivity

4. CONCLUSION

In this paper, we have improved the transmission link equation by taking into account two simultaneously changing parameters affecting the reliable free space communication. Free space optical communication's channel suffers severely from fading caused by turbulence-induced tropospheric scintillation index, thereby limits its deplorability in many cases. This transmission model provides the basis for optical and photonics system communication engineers a platform to work with, in the link budgetary for planning and design of low margin systems of free space optical communication link.

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