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TURBULENCE EFFECTS ON FREE SPACE OPTICAL COMMUNICATION SYSTEMS: A REVIEW

ELIZABETH T. ESO

Department of Electrical and Electronics Engineering
Faculty of Engineering and Technology, University of Ilorin, Nigeria

ABSTRACT

The continuous demand for higher bandwidth availability is the motivation behind research studies in free space optics (FSO) technology. This is because FSO technology assures rich supply of bandwidth providing very high transmission speed in the in the gigabits per second (Gbps) and and recently in the terabits per second (Tbps) range. However this is limited to the prevalent atmospheric conditions and effects such as fog, snow, rain and atmospheric turbulence along the transmission path. Nevertheless, in clear atmospheric conditions (where fog, snow or rain are absent), atmospheric turbulence considerably impairs the achievable quality factor (Q-factor) of the received signals. This paper presents an overview of FSO technology, its applications, characteristics (merits and challenges), atmospheric effects with focus on atmospheric turbulence effects and the challenges it poses to FSO technology with prospects for improvement.

Keywords: *free space optics (FSO), turbulence, signals*

1. INTRODUCTION

The high rise in data and voice traffic has steered the demand for more bandwidth [1] which in turn has led to the congestion of the Radio Frequency (RF) spectrum. But with the discovery of free space optics (FSO) technology also known as optical wireless communication (OWC) technology it is believed that it can serve as an adjunct or substitute to RF communication where necessary, due to its unique advantages.

FSO transmission can be described as a type of optical transmission technology that uses modulated infra-red or visible beams to transmit information (voice, video and data) from source to destination through air, water, free space or vacuum [2]. It is fundamentally, the same theory for FSO and fibre optics except that the modulated beam is transmitted to the destination through air from the source without the beam being guided through an optical fibre.

Importantly, FSO is a promising type of communication technology that provides very high transmission speeds in the gigabits per second (Gbps) and even in the terabits per second (Tbps) range recently. It is employable especially by large bandwidth applications since it has the advantage of providing larger bandwidth than RF systems and offers very high bit rate transmission of data up to 1.6Tbits/s [3]. FSO also has other advantages over RF as described in the next section.

However there are limiting factors that can reduce the performance of FSO links as it needs a direct line of sight for communication. These limiting factors are physical obstructions like buildings and atmospheric effects such as fog, snow, rain and variations in temperature along the propagation path. These all have negative effects on FSO links as they disrupt the line of sight, thereby weakening the performance of the link. Also, attenuation of signals by absorption and scatter are the prevailing atmospheric effects, affecting the performance of FSO links [4]. Eardley and Wisely cited in [4] reports that power attenuation up to 40dB per kilometre can be caused by rain and even up to about 100dB per kilometre power attenuation can result from snow. Nevertheless, fog causes the highest power attenuation which can be up to 300dB per kilometre when the fog is heavy (Eardley and Wisely, cited in [4]). Besides, importantly impairing the performance of FSO link in clear weather conditions is atmospheric turbulence.

2. MERITS OF FREE SPACE OPTICAL (FSO) COMMUNICATION SYSTEMS

High speed: FSO has the capability of providing large bandwidth which transforms into high data transmission speeds than RF technology [5-9].
License free: As oppose to RF communication technique, which requires purchase and allocation of frequency spectrum, FSO is frequency purchase free and no license fee is involved [10].
High security: There is very high security in FSO communication systems due to the reason that, to hack into the information been transmitted, the hacker needs to expose his/her equipment to be able to receive any information transmitted. Also the fact that the beam propagating is usually travelling in a straight line and collimated makes it more difficult to hack into [10,11].
No electromagnetic interference: There are no electromagnetic interferences as there are in RF communication, therefore FSO technology can be employed in situations where electromagnetic interference is highly avoided [12].

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Quick to install: Installation of FSO systems is relatively fast and can be deployed easily [10, 13].
***Cost effective*:** This communication technique is cost effective as equipment involved are relatively cost effective [14].

2.1 CHALLENGES OF FREE SPACE OPTICAL (FSO) TECHNOLOGY FOR COMMUNICATION

***Requires line of sight for operation*:** Proper alignment of the transmitter and receiver is required for communication in FSO. Physical obstructions like buildings can obstruct the line of sight since the beam does not penetrate through objects [15].
***Adversely disturbed by weather*:** Atmospheric effects like fog, rain, snow and atmospheric turbulence, affects FSO links by disrupting its line of sight [7,8,16].
Eye and skin safety: Increasing the optical power of an optical source will improve the signal to noise ratio (SNR), however this is limited to eye and skin safety standards because some laser sources (depending on the wavelength and class) can inflict eye and skin injuries.

2.2 APPLICATIONS OF FREE SPACE OPTICS (FSO)

FSO is applicable in the following areas:
Multi-campus/organisation network: FSO can be used for communication from one building to another, within a campus or organisation. This can be achieved by setting up the FSO link on top of the desired buildings. It can also be employed in hospitals and airports for data transfer [4].
Optical fibre and RF wireless back up: The provision of back up in the occurrence of loss in signal or sudden impairment of an optical fibre or RF wireless communication system can be achieved using FSO technology [15].
Problematic topographies: FSO is a good alternative that can be employed in problematic topographies or terrains difficult to access easily, e.g. mountainous/rocky regions and over water bodies [17].
Short term/disaster recovery link: It is used to provide short term/temporary link in the incidence of a breakdown in the main communication system link [17].

2.3 ATMOSPHERIC TURBULENCE IN FREE SPACE OPTICAL (FSO) COMMUNICATION

2.3.1 TURBULENCE DEFINITION

Turbulence in FSO communication is caused by irregularities in the pressure and temperature of the atmosphere bringing about disparities in the index of refraction on the path of transmission [18], whereby 'zones of differing density acts as lenses, scattering light away from its intended path' [4]. These therefore results in fluctuations (a rise and fall) in the phase and intensity of the signals received, thereby weakening the performance of the link [19] (see Fig 2).

Figure 1: Outdoor FSO link set up on two buildings

2.3.2 MEASUREMENT OF TURBULENCE

In order therefore to measure and quantify the effects of atmospheric turbulence there are basically two broad ways employed which is either to measure turbulence under real atmospheric conditions or measuring turbulence under controlled laboratory conditions.

Method 1: Measurement of turbulence under real atmospheric conditions

A FSO link can be set up on the top of two or more buildings, or otherwise as desired where there will be no line of sight obstruction as shown in Fig. 1. A laser beam generator is placed facing the receiver with a desired distance between them both, whereby the received optical power is then measured by a signal analyser [20]. There could also be a FSO antenna set up to measure the optical attenuation and intensity fluctuation simultaneously [20] and temperature measurements carried out using thermometers. However, in this method there will be the challenge of waiting for suitable weather conditions (disappearance of rain, snow or fog) to take measurements for turbulence independently. Therefore this method has a great disadvantage as there could be a mixture of weather conditions (snow, rain and fog).

Method 2: Measurement of turbulence under controlled laboratory conditions

The effects of turbulence on FSO transmission can also be measured indoors under controlled laboratory conditions so as to estimate the effect of turbulence by modelling a turbulence channel to mimic outdoor FSO channel. This method however is preferred and has been used by researchers in this field [21-32] to estimate the effects of turbulence, as this method provides the means of controlling the air temperature within the laboratory channel and excludes other atmospheric effects like rain, fog etc that can also affect the measurements. Turbulence under laboratory conditions is achieved by using heat and cold generating machines to cause temperature variations along the path of propagation.

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2.4 ATMOSPHERIC TURBULENCE OVERVIEW AND THEORY

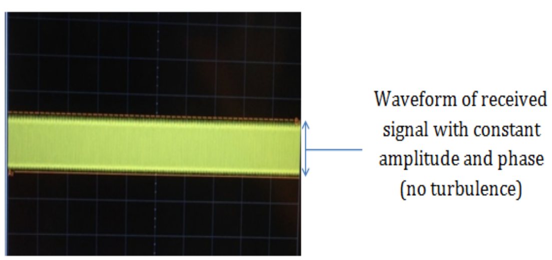
2.4.1 TURBULENCE OVERVIEW

Atmospheric turbulence is one of the prevalent atmospheric conditions affecting FSO transmission, resulting from in-homogeneities in the temperature and pressure along the path of transmission causing fluctuations in the amplitude and phase of the received signal as shown in Fig. 2. The variations in temperature and pressure consequently leads to disparities in the refractive indices of the atmosphere along the transmission path thereby scattering light away from its intended path and giving rise to 'scintillation' [4]. Turbulence strength is normally grouped into four regimes with the help of the Rytov variance σ_R^2 as follows: (i) weak turbulence regime (σ_R^2< 1), (ii) moderate turbulence regime (σ_R^2 =1), (iii) strong turbulence regime (σ_R^2> 1), and (iv) the saturation regime ($\sigma_R^2 \rightarrow \infty$) [33]. σ_R^2 is given by [33]:

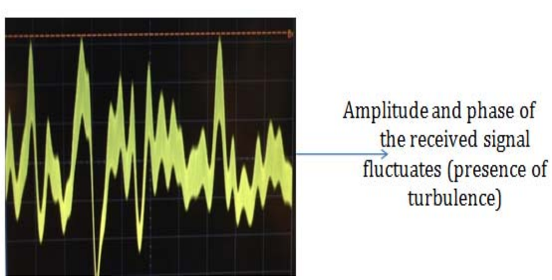
$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \tag{1}$$

where C_n^2 (in $\mathrm{m}^{-2/3}$) and L (in m) are the refractive index structure parameter and the optical link span, respectively.

As can be seen from the figure below for Fig 2(a), the waveform of the signal received at the receiver for the case of no turbulence has a constant amplitude and phase whereas this signal under the presence of turbulence as can been if Fig 2(b) has a fluctuating amplitude and phase.



(a)



(b)

Figure 2: Captured waveform of the received signals viewed from an oscilloscope at the receiver end of a FSO link for (a) no turbulence case and (b) presence of turbulence case

2.4.2 TURBULENCE THEORY

It is known that the atmosphere has two different states of motion in terms of a viscous fluid, namely turbulent and laminar states. Several years ago when turbulent flow was originally studied at the beginning, a non-dimensional quantity $R_e = Vl/v$ was defined by Reynolds, presently called the Reynolds number , where l is the dimension of flow in m, V and v are the characteristic velocity and kinematic viscosity in m/s and m/s^2 respectively [33]. The change of state of motion from laminar to a more chaotic situation called turbulence occurs when a critical Reynolds number is exceeded whereby eddies of different scale sizes represents turbulent air motion, ranging from large scale size L_o to small scale size l_o [33]. The former and latter are known as the outer and inner scales of turbulence which makes the range of inertial [33].

2.4.3 VELOCITY FLUCTUATION

A visualization tool known as the energy cascade theory of turbulence is suitable to be adopted in order to understand atmospheric turbulence structure [33]. At large scales, energy source is usually wind shear or convection and from the cascade theory, the velocity of wind rises up to a point that the critical Reynolds number is exceeded [33]. The latter results in local unstable air masses commonly called eddies to form and under the presence of inertial forces, there will be a break up of larger eddies into smaller eddies resulting in a scale range of eddies between L_o to l_o [33].

It is assumed that the outer scale L_o rises linearly with the order of the height above the ground from the point of observation to about 100 meters and also assumed to be statistically isotropic and homogenous are eddies of smaller scale sizes smaller than L_o, while those that are larger or equal to L_o are said to be non-isotropic [33].

In the inertial range, Kolmogorov demonstrated that the structure function of wind velocity satisfies the universal 2/3 power law, as given below [33]:

$$D_{RR}(R) = <(V_1 - V_2)^2> = C_V^2 R^{\frac{2}{3}},\ l_0 \ll R \ll L_0 \tag{2}$$

where C_V^2 is the velocity structure constant in $m^{4/3}/s^2$, which is a measure of the total quantity of energy in the turbulence, V_1, V_2 denotes the velocity components at two points with a distance of R in between them.

At small scale sizes (R<<l_o) the structure function's behaviour changes with the square of the distance of separation R. This can be obtained from a Taylor series expansion of the structure function given in [33] as

$$D_{RR}(R) = \begin{cases} C_V^2 l_0^{-\frac{4}{3}} R^2, & 0 \le R \ll l_0 \\ C_V^2 R^{2/3}, & l_0 \ll R \ll L_0 \end{cases} \tag{3}$$

2.4.4 TEMPERATURE FLUCTUATIONS

Originally velocity fluctuations were the major ideas used in the characterisation of turbulence, but now the essential ideas of Kolmogorov about velocity fluctuations have also been utilised in relation to scalars like temperature [33]. When Kolmogorov's theory of structure fluctuations as shown under the velocity fluctuations theory above, is extended to temperature fluctuations we have [29]:

$$D_T(R) = \langle (T_1 - T_2)^2 \rangle = \begin{cases} C_T^2 l_0^{-\frac{4}{3}} R^2, & 0 \le R \ll l_0 \\ C_T^2 R^{\frac{2}{3}}, & l_0 \ll R \ll L_0 \end{cases} \quad (4)$$

whereby C_T^2 represents the temperature structure constant in $\deg^2/\mathrm{m}^{2/3}$ and T_1, T_2 are the temperatures at two points with distance *R* in between them.

2.4.5 REFRACTIVE INDEX FLUCTUATIONS

One of the key parameters for optical wave propagation through the atmosphere is the refractive index *n*, because of its high sensitivity to small scale fluctuations in temperature.

Mathematically, the refractive index *n*, at a time denoted as *t* and a point *R* in space is given as [33]:

$$n(R,t) = n_0 + n_1(R,t). \quad (5)$$

But $n_0 = \langle n(R,t) \rangle \cong 1$, which is the mean value of the refractive index, the random deviation of $n(R,t)$ from its mean value is denoted by $n_1(R,t)$, therefore $\langle n_1(R,t) \rangle = 0$. Equation 5 above is generally written as shown below, where *n(R)* is normalized by n_0 (its mean value) [33]:

$$n(R) = 1 + n_1(R). \quad (6)$$

The variations in the refractive index *n* of the atmosphere are associated with pressure and temperature disparities. Consequently *n* is written mathematically for infra-red (IR) and optical wavelengths below as [33]:

$$n(R) = 1 + 77.6 \times 10^{-6}(1 + 7.52 \times 10^{-3}\lambda^{-2})\frac{P(R)}{T(R)} \quad (7)$$

$$\cong 1 + 79 \times 10^{-6}\frac{P(R)}{T(R)}, \quad (8)$$

where *P* is the pressure in millibars, λ is the optical wavelength in μm and *T* is the temperature in Kelvin.

But since $\langle n_1(R) \rangle = 0$, the covariance function of *n(R)* can be shown as below [33]:

$$B_n(R_1, R_2) \equiv B_n(R_1, R_1 + R) = \langle n_1(R_1) n_1(R_1 + R) \rangle \quad (9)$$

Consequently for statistically isotropic and homogenous turbulence, the behaviour of the structure function is given as [33]:

$$D_n(R) = 2[B_n(0) - B_n(R)] = \begin{cases} C_n^2 l_0^{-\frac{4}{3}} R^2, & 0 \le R \ll l_0 \\ C_n^2 R^{\frac{2}{3}}, & l_0 \ll R \ll L_0 \end{cases} \quad (10)$$

where the refractive index structure is denoted by C_n^2 in units of $m^{-2/3}$. The value of C_n^2 shows the strength of variations in the index of refraction and can be calculated easily when the temperature structure constant C_T^2 is known. C_T^2 can be found by taking temperature measurements at specific points and finding the mean of the squared temperature differences measured. C_T^2 is obtained from Eqn. (4) above and C_n^2 from Eqn. (8) which then gives [33]:

$$C_n^2 = \left(79 \times 10^{-6}\frac{P}{T^2}\right) C_T^2. \quad (11)$$

Typical values of C_n^2 ranges from 10^{-17} when the turbulence is weak to 10^{-13} for strong turbulence situations for outdoor FSO links [33].

2.4.6 THE EFFECTS OF TURBULENCE ON FSO SYSTEMS

Turbulence as the potential of greatly impairing the performance level of FSO systems causing link outage, low quality factor (Q-factor) [23,25,34,35] leading to increased likelihood of detection error. Refs [23,24] have shown that the higher the strength of turbulence the lower the quality factor and the performance of the FSO link generally. From various works carried out, it can be seen that turbulence can seriously diminish the performance of a FSO link as in seen in Refs [23-27] especially when the turbulence is in the moderate to strong regime as shown in [24,25]. Most of the works carried out on turbulence are based on theoretical simulations with few experimental works to back up the idea being developed. Moreover experimental works have also unfortunately being mainly constrained to weak to moderate turbulence regimes and very little on moderate to strong turbulence regime due to limited equipment, limited link span for experiments and generally the complexity of achieving such a condition. Over the years the aim of studying the effects of turbulence in FSO is to derive and identify a compliant probability density function (PDF) of the irradiance under irradiance fluctuation conditions [33].

The research work carried out in [24,25] has contributed more and valuable information to the existing research works on FSO system under turbulence channel by successfully demonstrating the possibility of generating moderate to strong turbulence regimes in an indoor environment. Therefore further researches can still be carried out on this idea to further investigate the effects of turbulence in the strong regime.

It has been demonstrated in [24,25] that the higher the modulating amplitude used for FSO systems employing on-off keying signalling scheme the better the signals received under the same turbulence conditions. Therefore, it is highly recommended that the modulating amplitude used for FSO-OOK systems should be as high as possible, but still within the linear operating range of the laser source employed. This will help to compensate for the turbulence induced fading, reduce signal distortions which will result in lower bit-error rates (BER) due to lesser likelihood of detection error.

Consequently, all the results obtained in [24,25,27] revealed that the performance of FSO systems employing OOK-NRZ or OOK-RZ signalling scheme suffered highly under turbulence, it is therefore recommended that mitigating techniques should be employed to combat these turbulence-induced effects, by adopting other modulation schemes like BPSK as proposed in [22,26], where the data to be transmitted is not impressed directly on the intensity of the laser beam. Space diversity reception technique (SDRT), aperture averaging and coding are also other alternatives used to mitigate turbulence [36].

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3. CONCLUSION AND RECOMMENDATIONS

This paper presented an overview of FSO, highlighting its merits and challenges. The theory of atmospheric turbulence and a general overview were also highlighted. Furthermore, this paper has also reviewed the effects of turbulence on FSO as reported in various literatures and makes the following recommendations:

- More experimental research studies should be conducted on the effects of turbulence as more research studies on turbulence based on theoretical simulations have been reported in literatures.

- There is the need to carry out more experimental research studies on the effects of turbulence in the moderate to strong turbulence regimes as majority of the experimental studies reported in literatures have been restricted to the weak to moderate turbulence regimes.

- OOK signalling scheme is the widest signalling scheme adopted by FSO systems. Based on the work reported in [22, 26] it was proved that BPSK signalling scheme was less susceptible to the effects of turbulence than OOK, therefore more experimental investigations should be carried out on other signalling schemes under turbulence.

- A novel experimental method for achieving moderate to strong turbulence with limited link span presented in [24, 25] can be further developed upon to achieve higher turbulence strengths in the strong turbulence regime.

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AUTHOR PROFILE

Elizabeth T. Eso has a B.Eng in Electrical and Electronics Engineering from the Federal University of Technology, Bauchi (ATBU), Nigeria and a Masters degree in Microelectronics and Communication Engineering from the Northumbria University Newcastle, England. Her field of specialization and current research interest includes free space optical communication and Radio Frequency communication systems.