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A Survey of Atmospheric Turbulence on Laser Propagation

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Abstract: Free space optical communication is relatively new. It is expected to be a viable alternative to the fiber optics technology in several applications. However, these systems are vulnerable to atmospheric turbulence, such as attenuation and scintillation. This study describes the facilities and examines the intensity fluctuation of the laser beam through laboratory atmospheric turbulence. A 2 m laboratory simulated turbulence box established to investigate laser beam propagation through atmospheric turbulence. We characterize the effects of atmospheric turbulence and observe numbers of changes when visible light passes through laboratory turbulence box. The statistical method was used in data analysis in this study. This system can be used in comparison of intensity fluctuation whether a greater or less for determining whether the turbulence is weak or strong. And also can be used to calculate the mean of intensity from different number of activities relative to changing variable parameters. Probability density function is also researched based on the analysis of experiment data collected in each event of experimental set up.

Key words: Free space optical communication, atmospheric turbulence, scintillation

INTRODUCTION

The exponential increase in deployment and use of information appliances such as digital still and video camera, PADs music players, watches mobile phones and laptops leads to demand for connectivity between them in a wireless manner. A migration of computing power from the desk top to mobile formats devices such as digital still and video cameras, portable digital assistants and laptop computers offers user the ability to process and capture vast quantities of data. The desire for costless high speed links satisfying these requirements have motivated the interest in infrared wireless communication. Experimental observations have been conducted to evaluate turbulence introduced intensity scintillation and its effects. The kolmogorov theory has been certified by many of them, but there are still some experiments that show disagreements with it, especially on high frequency power spectrum (Tunick, 2007). It is clear that there is logic lying behind the difference. Although, there is limitation on its uses, but the radiated power must not exceed the limits established by the International Electro-Technical Commission (standard IEC6082-1). However, eyes safe limits vary with wave length, wave length greater than 1400 nm are absorbed by cornea and lens and do not focus on the retina. Because of this, approximately 50 times greater intensities are allowed for wavelengths above 1400 nm than for wavelength around 850 nm. This additional power allows the system to propagate over long distances and support higher data rate. Light propagation through scattering media has been a problem in optics since decade. Recently, both meteorology and the possibility of optical communication have stimulated considerable interest in the propagation of light through the atmospheric turbulence.

FREE SPACE OPTICAL COMMUNICATION SYSTEM

There are 3 main components of a free space optical communication systems, Fig. 1 illustrates the components of FSO. The light propagates through the atmospheric to the receiver which converts the light back into an electronic signal. The main functions of the transmitter are to convert the electronic signal into light and to produce a suitable beam divergence matching a desired beam diameter at the receiver. The transmitter includes a modulator, a laser driver, a LED or laser and a telescope. The modulator converts bits of information into signals in accordance with the chosen modulation method. The driver provides the power for the laser and stabilizes its performance. It also neutralizes such effects as temperature and aging of laser or LED. The light source converts the electrical signal into optic radiation and the

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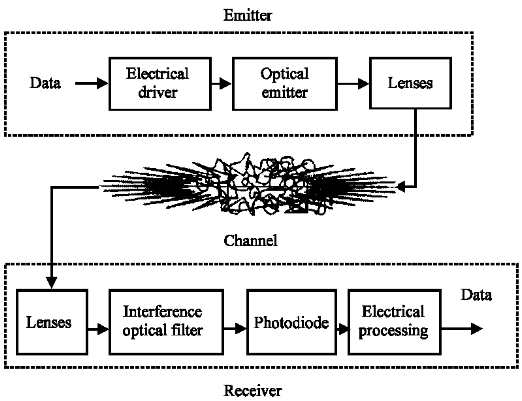

Fig. 1: Free space optical communication system

telescope aligns the laser-LED radiation to a collimated beam and direct it to the receiver. The infrared part of the spectrum ranges from 10^{12}-10^{14} Hz. Infra red is widely used for short range communication, for example in remote controls for TVs and VCRs. Infrared is also used for indoor wireless LANs. Infrared waves do not pass through solid objects. It's clear that infrared can not be used for long distance communications, infrared performs much like a visible light. However visible light is scattered by atmospheric haze but infrared radiation is not. Because of this, infrared radiation can be used to obtain pictures of distance objects obscured by haze. Light wave (visible) part of spectrum is just after infrared using visible light for unguided optical signaling (using lasers and photo detectors) offers very high bandwidth at very low cost. Free space optical communication is unaffected by electromagnetic interference, this is a great advantage when compared to both licensed and unlicensed RF systems, which definitely suffer from electromagnetic interference. Free space optical communication is also unaffected by radio magnetic interference (RFI) which increasingly plagues RF systems. Free space optical communications require no spectrum Licensing and interference to and from other systems is not a concern. In addition, the point-to-point signal is extremely difficult to intercept, making it ideal for covert communications. Free space optical communications offer data rates comparable to fiber optical communication. FSO does have its share limitations. As a line of sight technology, FSO is vulnerable to the severance of connection because of bad weather and physical constructions. Since FSO requires a free line of sight, a pre-installation site evaluation must be done to ensure that paths between the FSO units are clear and will remain so far along time. The atmospheric free space channel is a natural medium for optical wireless. The Free Space Optical (FSO) atmospheric channel has a wide bandwidth, many more users than an RF channel, for infrared links the most viable modulation is Intensity Modulation-(IM) in which the desired modulated on to the instantaneous power of the carrier. The most practical down conversion technique is direct detection in which a photo detector produces current proportional to the square of the received electrical field. FSO-Links have advantages in various situations, as a last mile telecommunication link, as a LAN link between buildings, as a LAN link within a room using diffusive optic. For communications between spacecraft, including elements of a satellite constellation and can be found in an interstellar communication. Tactical links in defense systems also can be deployed, portability, high bit-rate and low risk of exposure make FSO a very interesting alternative for military applications. For example communication between tanks, battle ships and unmanned.

THE TURBULENCE THEORY OVERVIEW

The atmosphere is not ideal communication channel. Atmospheric turbulence can cause fluctuation in the received signal level, which increases the bit errors in a digital communication link. In order to quantify the performance limitation, a better understanding of the effect of the intensity fluctuations on the received signal, all turbulence level is needed. When a laser beam propagates through the atmosphere turbulence causes number of effects including scintillation. Scintillation can be described as the destructive and constructive interference of optical waves caused by the fluctuations in the index of refraction along the optical path.

Refractive index structure function is the parameter which describes the magnitude of turbulence effects in the atmosphere for optical range. This turbulence as an effect of turbulent air motion and fluctuations where the source of energy for this motion are gradients or changes in heating and cooling of the atmosphere and earth surface caused mostly by sun light. The physical meaning of the refractive index structure function (c^2_n) is a measurement of strength of the fluctuations in the refractive index in the atmosphere. This parameter can be classified in 2 different regimes: weak turbulence and strong turbulence. Typically the values for weak turbulence regime are 10^{-17} $m^{-2/3}$ or less and for strong turbulence 10^{-13} $m^{-2/3}$ or more. The $m^{-2/3}$ units are derived from dimensional analysis. The Rytov method provides a solution for the variance of the log intensity fluctuations seen by point detector. The scintillation index is defined by:

$$\sigma_i^2 = \frac{<I^2>}{<I>^2} - 1 \quad (1)$$

where,

I = The intensity

<......> = Denotes an ensemble average.

The scintillation index is easy variable to measure in function of space and time and that allow a direct relationship with the c^2_n parameter. Applying the optical wave model of an infinite plane wave, it can be characterized by the Rytov variance which represent scintillation index or normalized irradiance variance. By the Rytov approximation (Andrews *et al*., 2001), then:

$$\sigma_{Rytov} = \sigma^2_i = 1.23\, c^2_n\, K^{7/6}\, L^{11/6} \quad (2)$$

where,

$K = 2\pi/\lambda$ = Optical wave number.

λ (m) = Wave length, L (m) is propagation path length.

Now let us talk about Atmospheric attenuation. When laser beam propagates through the air, it is exposed to attenuation depending on the weather condition. The equation of the laser transmission in air is described by Beer's law as (Isaac *et al*., 1998):

$$\tau(z) = \frac{P_{Receiver}}{P_{Total}} = e^{-\alpha} = F_l = 10\log(e^{-\alpha}) \quad (3)$$

where,

τ = Transmission.

F_l = Attenuation (dB).

$P_{receiver}$ = Received power.

P_{total} = Transmitted power.

σ = Atmosphere attenuation or total extinction coefficient.

Z = Distance between transmitter and receiver in km. the atmosphere attenuation can be obtained by the sum of 4 coefficients.

$$\sigma = \alpha_m + \alpha_\alpha + \beta_m + \beta_\alpha \quad (4)$$

where,

α_m = Molecular absorption coefficient.

α_α = Aerosol absorption coefficient.

β_m = Molecular or Rayleigh scattering coefficient.

β_α = Aerosol or mie scattering coefficient. The attenuation is related to wavelength by the Empirical formula.

$$\sigma \approx \beta_a = \frac{3.91}{V}\left(\frac{\lambda}{550\text{nm}}\right)^{-q} \quad (5)$$

where,

V = Visibility in km.

λ = Wave length in nanometers.

q = The size distribution of scattering particles.

q = 1.6 for high visibility V > 50 km.

q = 1.3 for average visibility 6 km <V< 50 km.

q = 0.585 $V^{1/3}$ for low visibility V < 6 km.

Scintillation index is used to indicate the strength of intensity function. It is defined as the normalized variance of the intensity fluctuations which can be expressed as Eq. (1)

$$\sigma^2_i = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1$$

for weak fluctuations, scintillation index is equal to the Rytox variance which can be calculated as Eq. (2). Probability density function (PDF) of normalized intensity should be lognormal (Andrews and Phillips, 1998) and it can be described as:

$$P_W(I) = \frac{1}{\sqrt{2\pi\sigma^2_I}}\frac{1}{I}\exp\left[-\frac{(\ln I + \sigma^2_I/2)^2}{2\sigma^2_I}\right] \quad (6)$$

According to kolmogorov theory (Andrews and Phillips, 1998) if the atmosphere turbulence is homogenous and isotropic, for weak fluctuation, the probability distribution of received intensity should be lognormal. For strong fluctuation far into the saturation PDF is assumed to be governed by the negative exponential distribution (Al-habash *et al*., 2001):

$$P_S(I) = \frac{1}{\langle I \rangle}\exp\left[-\frac{I}{\langle I \rangle}\right] \quad (7)$$

EXPERIMENTAL SET UP

To characterize and analyze atmospheric turbulence on the Laser beam, Helium-Neon is used and simulated turbulence box, detector along connected with power meter. Figure 2 show the experimental set up which is used to simulate turbulence on a laser beam, we create laboratory simulated turbulence box (0.5 m wide, 2 m long and 0.5 m height) and Laser source with 632.8 nm, 7 mw power. Optical detector connected with optical power meter. The heating elements are used to produce warm air inside the turbulence box and 4 small fans are used to produce wind inside the turbulence box and to increase the homogeneity of turbulence inside the box. Our experiment is divided into the study with respect to activities performed in the study, we observed the light beam through the turbulence box without switching on the fans and in the study, we observed the light beam

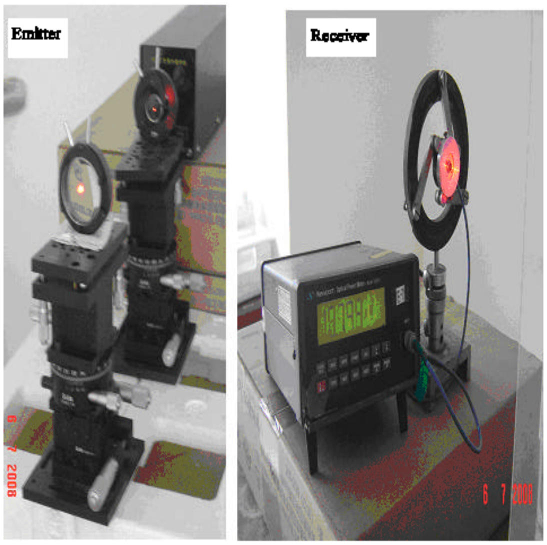

Fig. 2: Experimental set up

through the turbulence when we put on the fans. The turbulence induces intensity random fluctuation in the beam known as scintillation; in the study we were able to create scintillation. This is an effect of many random changes in the index of refraction along the path of the beam propagation due to turbulence and we saw beam deformation occur, because of small scale dynamic changes in the index refraction of the atmosphere. When the Fans are switched on the artificial wind blowing inside the turbulence box creates different scintillation indices in regimes.

ANALYSIS AND EXPERIMENT RESULTS

Low visibilities will decrease the effectiveness and availability of FSO systems; we analyzed the attenuation by using Beer's law the attenuation is related to wavelength and visibility. And we saw that the atmospheric attenuation coefficient a function wave length. The Fig. 3 shows that the attenuation against visibility of our experimental wave length is 632.8 nm. Figure 4-6 show our simulation results. Figure 4 shows a theoretical comparison of the attenuation between the laser wavelengths 632.8 and 1550 nm using Eq. 3 and 5 and Fig. 6 shows a simulation results when laser beam passes through simulated turbulence box when fans switched on.

In the FSO link, the scintillations of the received beam cause signal degradation. And receiver will collect all transmitted data or intensity; in our case we observed the reading of optical detector by using optical power meter. The statistical method was used in the data

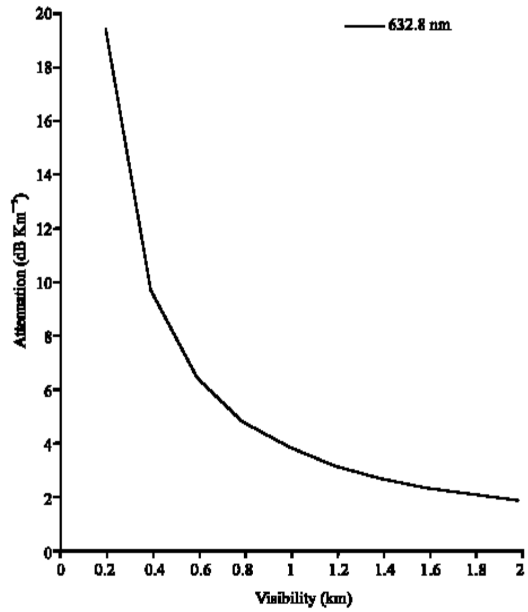

Fig. 3: Theoretical of attenuation of 632.8 nm against visibility by using Eq. 3 and 5

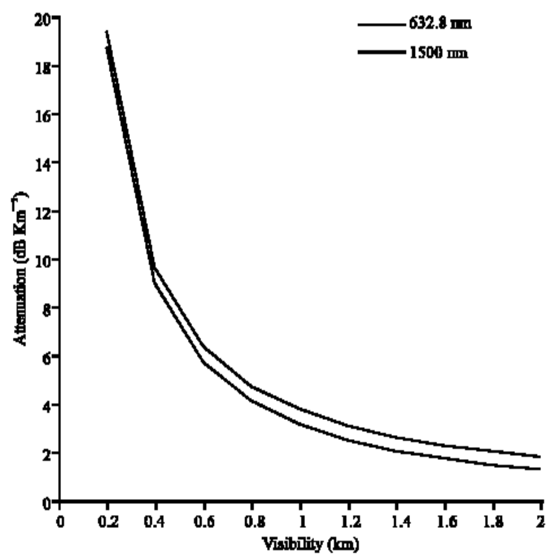

Fig. 4: Comparison of the attenuation between the laser wavelengths 632.8 and 1550 nm

analysis in study. The following figures show the graphs of intensity against time from both events.

The performance of FSO link is depending on different factors. These factors are to be considered as follow. Turbulence in the form of scintillation causes fading. This means bit errors may occur. The turbulence causes SNR-losses by phase distortion mainly for systems using coherent laser. The attenuation and scattering in aerosols and gases will cause worse Signal

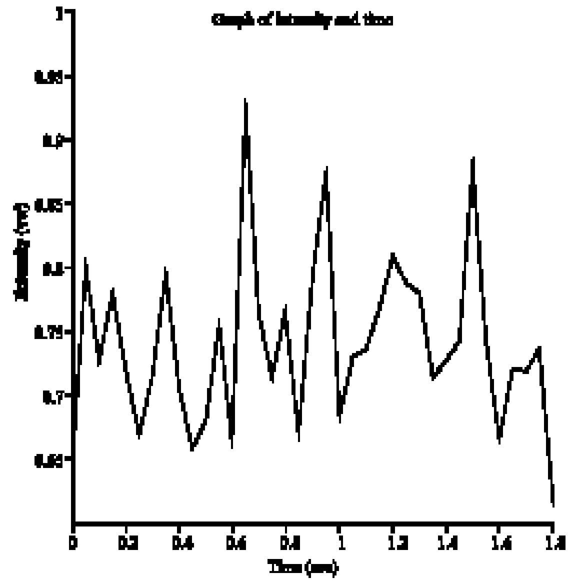

Fig. 5: The behavior of light beam when passes through turbulence box while fans are switched off

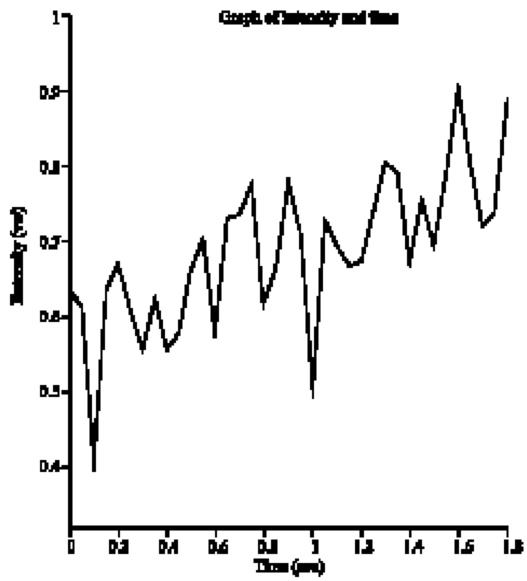

Fig. 6: The behavior of light beam through turbulence box while fans are switched on

to Noise Ratio (SNR) and losses in the link budget (Milner and David, 2004).

By Rytov approximation:

$$\sigma_{Rytov} = \sigma^2_I = 1.23\, c^2_n K^{7/6} L^{11/6} \text{ from Eq. 1}$$

$$c_n^2 = \frac{\sigma_I^2}{1.23 K^{7/6} L^{11/6}}$$

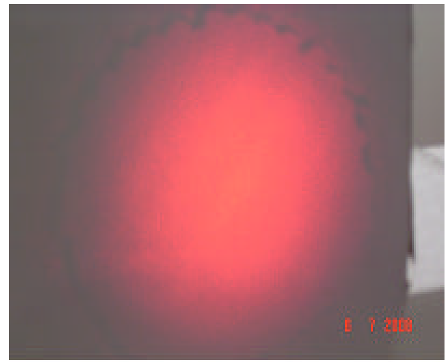

Fig. 7: Intensity distribution at no presences of turbulence

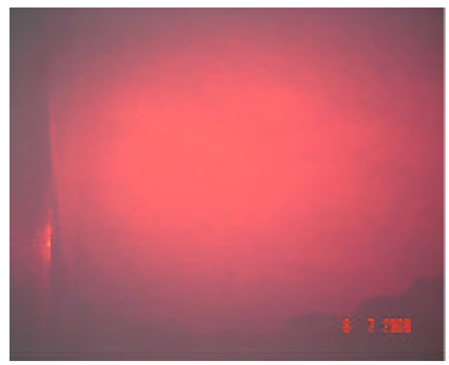

Fig. 8: Intensity distribution at presences of turbulence

c^2_m is often determined as a function of local differences in temperature, moisture and wind velocity at discrete points. This expression suggests that larger wavelengths would experiences a small variance. The energy cascades from larger to smaller scales (turbulent eddies break down into smaller and smaller structure but in turbulence theory the outer scale L_o is considered as parameter that defines the greatest size of eddies, this is valid only in the so called inertial range $l_o < r < L_o$ where, l_o is the inner scale that represents roughly the smallest eddy size. The irregularities of the beam intensity are shown below from this experiment.

The changing of light intensities in time and space at a plane of receiver that is detecting a signal from a transmitter, located at distance is defined as the atmospheric scintillation. The Fig. 7 and 8 show that the strength of the intensity fluctuation.

We have seen the break up of the laser beam into multiple patches and this causes the beam to losses its lateral coherence.

CONCLUSION

In this study, we have described an atmospheric turbulence on laser beam propagation. By using simulated turbulence box, a laser beam experiment was conducted to examine the turbulence of intensity fluctuation at laboratory. The optical path was 2 meters and the data analysis was mainly based on a turbulence theory. Both events were successfully achieved by producing results which are consistent with respect to activities performed. We have shown figures in this study, for easily analysis and comparison of other research finding. Our results presented lies in the intermediate turbulence region fitted between weak and strong turbulence. Theory shows excellent agreement with expected behavior; also we have seen the laser beam experiences fluctuation of beam (size, beam position) and intensity distribution within the beam. As we have said, the atmosphere is a homogenous medium with changing parameters, like temperature and pressure. And this is what causes some of its optical effects. From our point of view the atmospheric turbulence channel is regarded as statistical process whose statistical properties are tuned depending on the features of environment being surrounded. Finally it is worth to say that; one characteristic of turbulent air motion is that un-predictable, which made this more as a general study of optical through a random media. We have learnt that there are several limitations and uncertainties such as temperature gradients, moisture and these factors can make the results different in dealing with this random media but more effort is required to evaluate and define the unpredictable physical atmospheric behavior.

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