Study of the Atmospheric Turbulence in Free Space Optical Communications

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***Abstract*-In this paper the effect of atmospheric turbulence on free space optical (FSO) communications is investigated experimentally by designing a turbulence simulation chamber. The distributions of bits '0' and '1' levels are measured with and without turbulence. The bit error rate (BER) is then obtained from the distributions. The temperature gradient within the channel is less than 6 °C resulting in turbulence of log irradiance variance of 0.002. The received average signal is measured and used to characterise the simulated turbulence strength. We then evaluated the BER with turbulence and found that from an error free link in the absence of turbulence, the BER increased significantly to about 10^{-4} due to the turbulence effect.**

I. INTRODUCTION

Free space optical communications is currently seen as a promising alternative technology for bandwidth hungry applications, particularly within the last mile access networks. The applications of the FSO includes base station to base station in cellular networks, building to building, multi-campus university networks, airports, hospitals, a high-speed, high-capacity back up link and disaster recovery links [1]. In addition, FSO systems offer rapid deployment with no need for trenches and its spectrum is licence free unlike the radio communication spectrum [2].

FSO requires a direct line of sight for its operation and the achievable data rate is currently limited by the available optoelectronic devices. Atmospheric effects, such as rain, snow, fog, and temperature variation will affect the FSO link performance. The dominant atmospheric effect that impacts the link performance is attenuation of the signal by scatter and absorption. Molecular scattering and absorption of major atmospheric constituents is relatively insignificant. Rain and snow can result in power attenuation up to ~40 dB/km and ~100 dB/km, respectively. However, the highest attenuation is caused by fog, where ~ 300 dB/km has been reported in heavy fog [3]. Also affecting the FSO link performance and its availability is the atmospheric turbulence. Random variations in the refractive index of the atmosphere commonly referred to as the optical turbulence are responsible for random fluctuations in the signal carrying laser beam intensity (irradiance). This phenomenon is otherwise referred to as scintillations [4]. Scintillation results from thermal gradients and turbulence within the optical path caused by the variation in air temperature and density. Zones of differing density act as lenses, scattering light away from its intended path. These effects can cause scattered laser beam to travel along different paths and then re-combine. The recombination may be destructive or constructive at any particular moment. This results in recurring momentary losses of signal, thus degrading the performance quality of the FSO link [5,6].

Atmospheric turbulence affects the propagation of a beam of light within the channel in three ways. Firstly, the wave front is distorted by the variation due to scintillation index, thus creating the fluctuations in the intensity of the optical signal. Secondly, the beam wandering takes place due to the diffraction of the laser beam, when the diameter of the beam is smaller/equal to the size of the eddies. Thirdly, the atmospheric turbulence makes the laser beam to spread beyond the diffraction limit. Scintillation is a severe problem and can result in a significant deterioration of the link BER performance. [6].

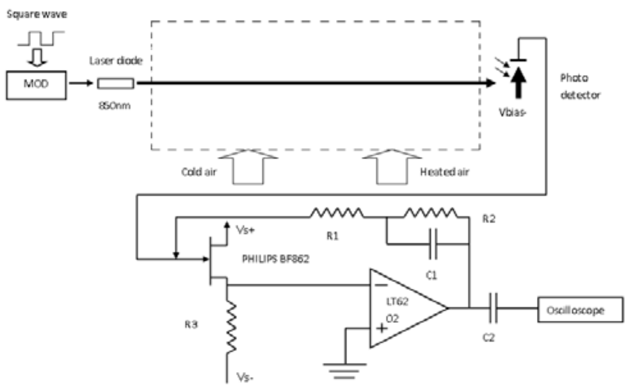
The coherence of the optical beam (laser) is affected by the atmospheric turbulence and thus changes the profile of its power distribution function [7]. The theoretical study of the impact of turbulence on the availability and performance of an FSO link has seen a tremendous attention in literature. Moreover, various methods to mitigate its effects have also been proposed. In his paper however, we demonstrate via a laboratory based experiment, the scintillation effect on an FSO link that uses the On-Off keying signalling.

II. EXPERIMENTAL SET-UP

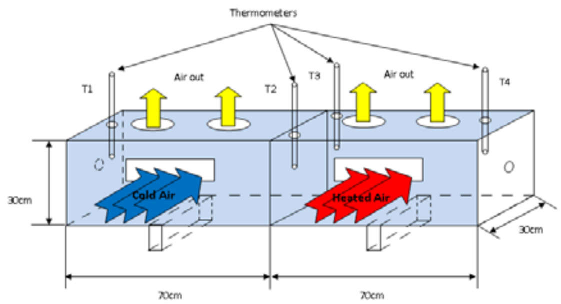
Table I: Simulation parameters

Parameters	**Values**
Laser diode class (Beta Tx)	Class IIIb
Laser diode wavelength	850 nm
Maximum laser power	3 mW
Maximum data rate	1 Mbps
PIN photo detector (SFH203PFA) switching time	0.5 µs
Modulation type	OOK
Optical band-pass filter	800 -1100 nm
Turbulence simulation chamber	140×30×30 cm
Temperature range	20°C - 80°C

An FSO link typically consists of the transmitter and receiver separated by the channel. Here we have setup an experimental system with the aim of observing the effect of atmospheric turbulence on the transmitted laser beam, see Fig. 1. The transmitter uses a laser source with a maximum optical output power of 3 mW and a wavelength of 850 nm. The near-infrared wavelength is chosen for cost and availability reasons. However, at this wavelength, the maximum power that can be transmitted is limited by the eye safety requirements. The optical receiver is composed of a PIN photodiode, an optical band-pass filter with a spectral bandwidth of 800-1100 nm to limit the background radiation light, and a trans-impedance amplifier. A square wave input signal with a maximum peak-to-peak voltage of 500 mV is applied to the optical source. The complete simulation parameters are given in Table I.



(a)



(b)

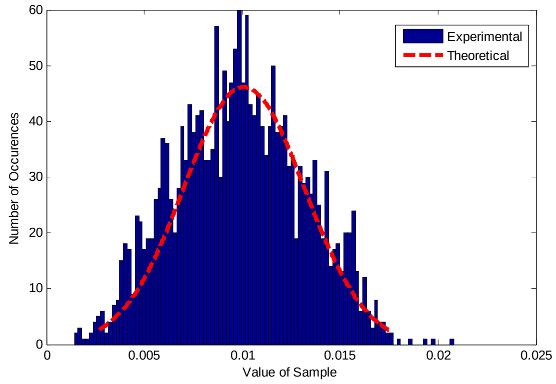
Fig.1. (a) The simplified diagram of the experimental setup, and (b) the turbulence simulation chamber

The turbulence simulation chamber shown in Fig. 1 has the following dimensions: 140 x 30 x 30 cm. Turbulence is simulated by blowing cold and hot air into the chamber as shown in Fig. 1(a). The cold air is set at about 20 °C and hot air covers a temperature range of 20 to 80 °C. Using a series of air vents, additional temperature control is achieved thus ensuring a constant temperature gradient between the source and the detector. Four thermometers are used to measure the instantaneous temperatures and the temperature gradient. The whole experiment is conducted in a dark room to further reduce the effect of ambient light to a barest minimum.

III. Experimental Results

In order to characterize the strength of turbulence generated within the chamber, we measured the received average signal with and without the cold/hot air combination. From the data, we plotted the signal distribution without and with scintillation, and fit them respectively to a Gaussian and log normal distributions (1), see Fig. 2. From the figure, we observed that the log intensity variance of the generated scintillation is 0.002 while without scintillation; the noise variance is 10^{-5}. Hence the generated scintillation is very weak.

$$y(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{\left(\ln\frac{x}{x_0}+\frac{\sigma^2}{2}\right)^2}{2\sigma^2}\right] \quad (1)$$



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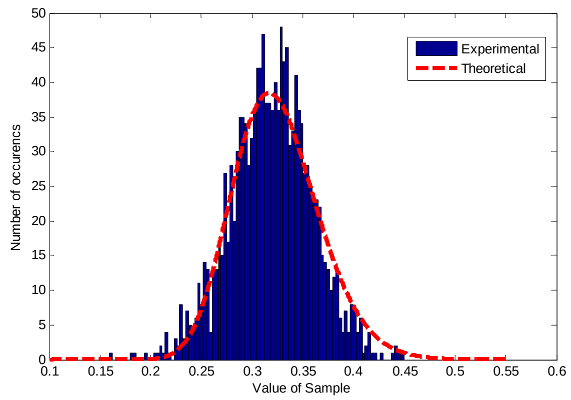

(b)

Fig. 2.The received average signal; (a) without scintillation, (b) with scintillation

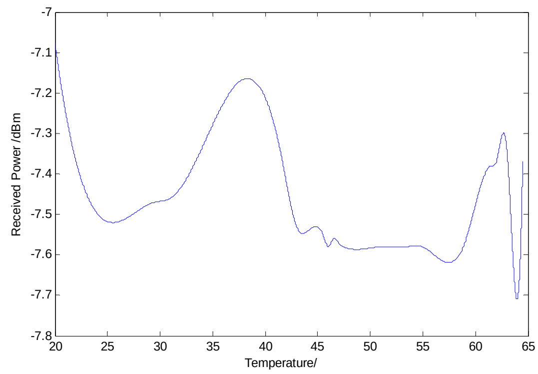

Fig. 3.Received power profile over a range of temperature

To further demonstrate the scintillation effect on the received signal, we measured the received power with turbulence over a period of time and plotted this in Fig. 3. The measured variance of the power fluctuation is 0.007, which also confirms that the turbulence generated is indeed very weak.

IV. BER EVALUATION

Considering Fig. 4, which represents a two-level signal and its corresponding Gaussian distributions; the BER is given by

$$\mathrm{BER} = \mathrm{P_e} = \mathrm{a_0 P_0} + \mathrm{a_1 P_1} \qquad (2)$$

where a_0 and a_1 are probabilities of transmission for binary ones and zeros, respectively and P_0 and P_1 are given by the (3) and (4) [8].

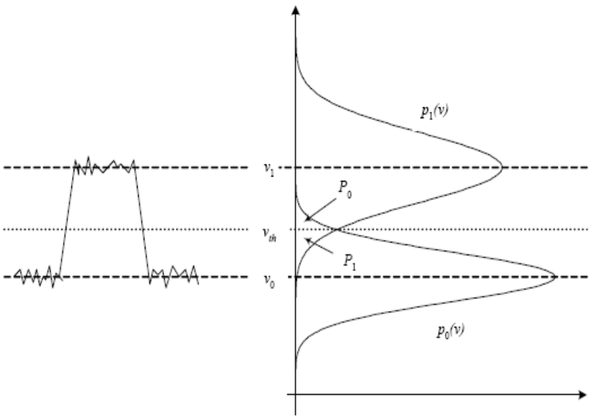

Fig. 4.The distribution of bits ‘0’ and ‘1’ for BER evaluation [8]

$$\mathrm{P_0} = \int_{v_{th}}^{\propto} \frac{1}{\sqrt{2\pi\sigma_0^2}} \exp\left[-\frac{(v-v_0)}{2\sigma_0^2}\right] dv \qquad (3)$$

$$\mathrm{P_1} = \int_{-\propto}^{v_{th}} \frac{1}{\sqrt{2\pi\sigma_1^2}} \exp\left[-\frac{(v-v_1)}{2\sigma_1^2}\right] dv \qquad (4)$$

Assuming the binary data is such that the number of transmitted ones and zeros are equal, then $a_0 = a_1 = 0.5$, and the net BER = ½[P_0+ P_1].

With scintillation, the received signal is the sum of two distributions: the Gaussian (due to noise) and the log normal (due to scintillation) distributions. But since the turbulence is very weak we assume that the received signal is Gaussian and this approximation is used to estimate the BER of the system. Without turbulence however, the received signal is Gaussian and is rightly assumed to be error free. This is so because the link is very short ~150 cm and the background radiations that might cause error have been grossly limited. In estimating the BER, we fit a Gaussian distribution curve on to the received data histogram as depicted in Fig. 5(a) and (b). The parameters of the fit are then used in (2) to evaluate the BER. This is then repeated a few times and the BER results are summarised in Table II.

The results show a high BER due to the scintillation. The simulated turbulence degraded the link BER performance from being error-free to about 10^{-4}. This brings to bare the amount of degradation turbulence can impose on the link if it unmitigated. The results of Table II also expose the lack of repeatability in the turbulence simulation technique used in this work.

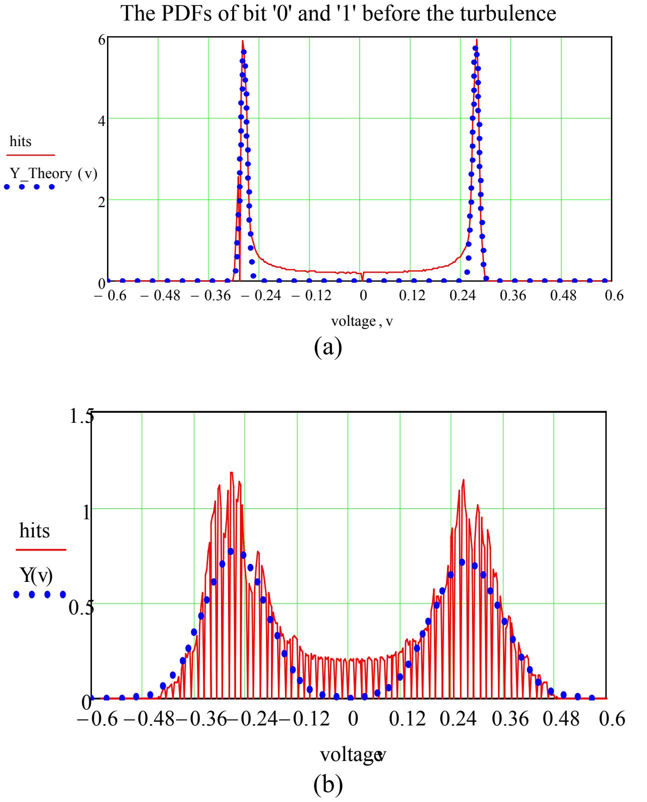

Fig. 5.The received signal distribution: (a) without scintillation, and (b) with scintillation. Dotted lines -Theoretical fit, solid line –experimental data

Table II
The evaluated BER at different times

Temperature (°C)		BER
T_4	T_1	
36	30	6.84×10^{-4}
39	34	3.94×10^{-4}
45	39	3.24×10^{-4}
55	49	2.74×10^{-4}
59	53	6.63×10^{-5}
60	54	1.93×10^{-4}

V. CONCLUSION

The effect of the atmospheric turbulence on free space optical communication under controlled environment is studied. The temperature was controlled via air flow to create temperature gradient for the study of the turbulence. With this approach we managed to simulate turbulence with log irradiance variance of 0.002. We then evaluated the BER performance with turbulence by approximating the received signal to be Gaussian. The experimental data showed that if scintillation effect is not mitigated, it can cause a serious impairment to the performance of an FSO link. From an error free link, the simulated turbulence caused the BER to degrade to about 10^{-4}.

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