Characterizing The Atmospheric Effects On Laser Beam Propagation For Free Space Optical Communication

Latsa Babu .P and Balaji Srinivasan
Department Of Electrical Engineering
Indian Institute Of Technology Madras, Chennai 600036, India
Email: latsa.ms@gmail.com, balajis@tenet.res.in

Abstract—In free space optical communication links, atmospheric turbulence causes fluctuations in both the intensity and phase of the received light signal, vitiating link performance. In this paper, we investigate methods to reduce the receiver impairments due to scintillations and beam wandering. Specifically, we explore aperture averaging to reduce the scintillation induced variance of the detected signal. Our experimental results agree well with theoretical predictions, providing confidence in our atmospheric turbulence model. We are currently characterizing our link for beam wandering effects and possible solutions for countering the same.

I. INTRODUCTION

Free space optical communication has drawn considerable attention recently for a variety of high data rate applications due to its large bandwidth potential (> 10Gbps), unregulated spectrum, relatively low power requirement, ease of redeployment, and the demonstration of low BER (< 10^-12) through coding techniques [1]. However, such optical links are susceptible to atmospheric wave propagation effects such as scattering (rain, fog, and snow), scintillations and beam wandering.

Our long-term goal is to characterize the link comprehensively and devise appropriate coding techniques to counter any impairment during transmission/reception. One such impairment is the scintillation and beam wandering across the receiver plane due to turbulence in the atmosphere [2]. Scintillations are random fluctuations in the intensity of the received signal caused by inhomogeneities in the atmospheric temperature and pressure along the laser beam propagation path. These random fluctuations lead to increased bit error probability, thereby limiting the system performance. On the other hand, beam wandering is due to relatively slower motion of the turbulent eddies in the beam path. In this paper, we have carried out theoretical studies of scintillation and beam wandering-induced variance in the received signal and explored methods to overcome these effects.

II. SCINTILLATION-INDUCED VARIANCE AT THE RECEIVER

Atmospheric turbulence has been studied extensively and various theoretical models have been proposed [2-5] to describe turbulence induced image degradation and intensity fluctuations and their consequences on bit error rate for plane wave and spherical wave approximations. Two useful parameters describing the turbulence induced fading are the correlation length (d_0) of intensity fluctuations, and the correlation time of intensity fluctuations (t_0). The correlation length or width (d_0) is defined as the e^-2 point of the normalized spatial covariance function. While the correlation time (t_0) is defined for temporal normalized covariance function.

The Rytov method provides a closed form expression for the intensity fluctuations of a plane wave in weak turbulence condition for a point receiver (receiver aperture is only a small fraction of the correlation length) [2]. The received signal scintillations variance is given by

$$\sigma_I^2 = 1.23 \times C_n^2 \times k^7/6 \times L^{11/6}$$

(1)

Where $C_n^2$ is the refractive-index structure parameter, $k$ is wave number of the transmitted beam and $L$ is link length (meters).

From the above expression, one can see that the variance due to scintillation can be due to increase in link length or due to strong turbulence $C_n^2$. The Rytov method predicts that the signal variance due to turbulence can increase without limit for stronger turbulence. However, in reality the log-intensity fluctuations have observed to saturate [4]. The Rytov variance is found to be accurate only when the log-intensity variance is less than 0.3, or in other words when weak turbulence condition exists [6]. The saturation effect is studied by D.A.DeWolf[4], who found that the variance may be expressed by an empirical relation.

$$\sigma_{ln I}^2 = \ln[2 - e^{-\alpha^2}]$$

(2)

When the receiver aperture ($D_0$) can be made larger than the correlation length $d_0$, then turbulent induced fading can be reduced substantially by aperture averaging [6,7]. Aperture averaging refers to the decrease in the variance of the scintillations due to increased receiver aperture and is defined as the ratio of the log-intensity variance as a function of receiver aperture to that of a point receiver. Andrews [7] have provided an empirical relation for aperture averaging factor.
\[ A = \frac{\sigma_{int}^2(\rho, L)}{\sigma_{int}(0, L)} = [1 + 1.07(k \times \rho^2 / L)^{7/6}]^{-1} \]

Where \( \rho \) is the radius of the receiver aperture, Using Equ. (2) and (3), one can determine the variance of the scintillations at the receiver as a function of the receiver aperture.

\[ \sigma_{int}^2 = \ln[2 - e^{-\sigma^2}] \times [1 + 1.07(k \times \rho^2 / L)^{7/6}]^{-1} \]

The effect of scintillations in producing the above variance has been investigated experimentally as a function of receiver aperture and is presented in Section IV.

III. BEAM WANDERING

In the absence of turbulence, a laser beam exiting a transmitting aperture diameter \( D \) would have an angular spread \( \theta_0 \) approximately \( \lambda / D \), where \( \lambda \) is the wavelength of the transmitted optical beam. This spread becomes larger at the receiver for turbulent atmospheric case, because moving turbulent eddies cause scattering of the optical fields. In addition to such beam spreading other effects such as beam wandering or even break up of the beam into multiple beams may occur.

Turbulent eddies tend to have smaller sections in which the refractive index varies faster compared to the overall turbulent region. As such, the beam spread may be short-term or long term or both. By definition when a laser beam interacts with turbulent eddies whose dimensions are larger compared to the diameter of the laser beam, the deflection of the beam is relatively pronounced (although relatively low). Such beam spreading is termed as long-term spread or beam wandering. In contrast, those eddies which are smaller compared to the beam diameter tend to broaden the beam, but do not deflect it significantly [2]. In general, the turbulent eddies continually flow across the laser beam with a transverse flow velocity \( \nu \) and cause the deflection of the laser beam in different directions with time intervals in the order of \( D/|\nu| \). If we observe the super positioned beams over the interval greater than \( D/|\nu| \), then resultant beam seems to be a single beam with larger diameter which is greater than the short term spread, see from Fig.2 and Fig.3.

For Gaussian beam propagation over turbulent media, with link lengths much shorter than \( (k^2 \times C_n^2 \times l_0^{5/3})^{-1} \) and \( \rho_0 >> D_t \), then mean square radius of the beam wander is approximated by Fante [8].

\[ \langle \rho_L^2 \rangle \approx \frac{4L^2}{k^2 \times D_t^2} + \frac{D^2}{4} \left(1 - \frac{L}{F} \right)^2 + \frac{4L^2}{k^2 \rho_0^2} \]

where

\[ \rho_0 = [0.5475 \times k^2 \times L \times C_n^2]^{-3/5} \]

The first two terms in (5) represents the beam spread in vacuum, the last term represents the additional spread due to scattering of the laser beam by the turbulent eddies. The long term beam spread is a zero mean normal random variable with variance given by equation (5). For the case of weak turbulence and shorter link lengths (less than \( (k^2 \times C_n^2 \times l_0^{5/3})^{-1} \) where \( l_0 \) is inner scale of the turbulent eddies), the variance due to beam wandering effect is strongly dependent on receiver aperture diameter.

IV. EXPERIMENTAL RESULTS

In order to study the effect of atmospheric turbulence-induced scintillations on the received signal variance and its...
dependence on aperture averaging, we constructed a setup to simulate turbulence in a controlled laboratory setup. As shown in Fig. 5, the setup consisted of an optical wireless link including a directly-modulated 850nm vertical cavity semiconductor laser (VCSEL) transmitter with appropriate collimating lens, and a Si PIN photodetector-based receiver with Fresnel lens for focusing the received optical beam. The atmospheric turbulence was simulated using multiple fans and heating elements. The signal variances was measured for different aperture sizes. The data was acquired for 180 seconds for each aperture radius say, at 0.18mm, 0.75mm, 1.625mm, 4.25mm and 6.5mm. The wave number spectrum structure parameter $C_n^2$ is measured from the variance measured with .18mm diameter aperture using Rytov approximation(1) to be $2.1 \times 10^{-11}$. The plot of experimentally measured variance in comparison to the theoretical values are given in Figure.5. The big difference in variance for smaller aperture sizes is due to non smooth holes made for blocking the remaining beam aperture. For calculating the variance of intensity The experimental results are roughly consistent with theoretical predictions. Such a result improves the confidence on our model, encouraging further study. Efforts are currently focused on improving our model based on the experimental results as well as conducting further experiments to quantify beam wandering effects. Details of such effects and the corresponding results will be presented.

V. CONCLUSIONS

The variance for different link lengths as a function of aperture diameter is a good model for measuring the system performance of any given link length provided that there is no beam wander effect. If beam wandering effect exists we need to design the system with aperture size,that at least a part of the beam is received. These studies indicate that the aperture size be increased to reduce variance due to scintillations and beam wandering. However, it is well known that large apertures can potentially result in high shot noise due to background photons. Hence, the receiver aperture should be optimized with respect to the expected channel turbulence to get desired signal to noise ratio for direct detection receiver systems.

REFERENCES