The Effect of Atmospheric Turbulence on the Performance of the Free Space Optical Communications

A. Chaman Motlagh*, V. Ahmadi*, Z. Ghassemlooy ** and K. Abedi*

*Department of Electrical Engineering, Tarbiat Modares University, Tehran, IRAN
** Optical Communications Research Group, School of Computing, Engineering and Information Sciences, Northumbria University, Newcastle, UK

Emails: achaman@modares.ac.ir, v_ahmadi@modares.ac.ir, fary.ghassemlooy@unn.ac.uk

***Abstract*—In free space optical (FSO) communication links, atmospheric turbulence has a significant impact on the quality of a laser beam propagating through the atmosphere. Turbulence results in intensity scintillation, which can severely impair the operation of target designation and FSO communications systems. Two important parameters for describing quality of FSO communications systems are the signal-to-noise ratio (SNR) and the bit error rate (BER). In this paper, using a modified model we analyze the effect of atmospheric turbulence on the SNR and BER for an FSO system in both weak and strong turbulence conditions.**

I. INTRODUCTION

FSO systems or optical wireless communication have many advantages when compared with the free space radio frequency based systems such as: high bandwidth, fast deployment, license-free, light weight and reduced size. Unfortunately, free space channel where light propagates is not ideal, thus leading to and suffers from a number of affects including absorption, scattering or displacement depending on the atmospheric condition. However, in clear atmosphere, with a typical attenuation coefficient of 0.43 dB/km, a major challenge facing FSO systems is the effect of turbulence induced irradiance fluctuation on the system performance especially for a link range exceeding 1 km. Atmospheric turbulence is caused by both spatial and temporal random fluctuations of refractive index due to temperature, pressure, and wind variations along the optical propagation path through the channel [1-8]. In this paper we investigate the turbulence effect on performance of an FSO link. We show that BER performance deteriorates with the index of refraction structure parameter (C^2_n). In Section II we outline the theoretical analysis for the SNR and BER. In section III results and discussion are introduced, and finally concluding remarks are presented in Section IV.

II. THEORY OF ANALYSIS

Base on the Rytov theory, the field of the plane wave in random media is given as [9]:

$$E_0\left(\vec{r}\right) = A_0\left(\vec{r}\right)\exp\left(i\varphi_0\left(\vec{r}\right)\right) \tag{1}$$

where $A_0(r)$ is amplitude of the laser beam in the atmosphere without turbulence, φ_0 and $E_0(r)$ the phase and laser beam profile, respectively. In presence of turbulence, three effects (Beam wander, Beam spreading, and Scintillation) impair the signal at the receiver. The rate of fluctuations for the beam wander is slow (<1 or 2 kHz), therefore using tracking schemes the effect can be overcome. Beam spreading leads to spreading of the average energy of the beam over a large area (~ 1m/Km). Scintillation is the most important effect that is created by changing the refractive index, due to atmospheric turbulence, which leads to the intensity fluctuations. Due to atmospheric turbulence, the refractive index changes leading to changes in the laser beam profile. The wave equation can be written as [9, 10]:

$$E\left(\vec{r}\right) = A\left(\vec{r}\right)\exp\left(i\varphi\left(\vec{r}\right)\right) = E_0\left(\vec{r}\right)\exp\left(\Phi\right) \tag{2}$$

where *A(r)* is amplitude of the laser in the turbulence atmospheric, Φ is the exponential factor due to turbulence given as:

$$\Phi = Ln\left(\frac{A(\bar{r})}{A_0(\bar{r})}\right) + i\left(\varphi\left(\bar{r}\right) - \varphi_0\left(\bar{r}\right)\right) = \chi + iS \tag{3}$$

where χ represents the fluctuations of the log of the amplitude of the field and S is the phase fluctuations. This equation predicts a fluctuation in intensity and phase of received signal due to turbulence that affects the signal to noise ratio (SNR) or bit error rate (BER). For a plane wave, when the turbulence is weak, and assuming that the refractive index structure coefficient C^2_n is symmetrical along the beam path), Rytov suggested a variance for the log intensity fluctuations given as [5]:

$$\sigma^2_{\ln IR} = \left\langle \left(\ln I - \left\langle \ln I \right\rangle\right)^2 \right\rangle = 1.23 C_n{}^2 k^{7/6} L^{11/6} \tag{4}$$

where $k=2\pi/\lambda$, L is the propagation length and I is the light intensity. The subscript R shows the variance is Rytov regime, where the turbulence is weak.

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As for a practical FSO system (plane wave) with weak and symmetrical atmosphere turbulence the log irradiance variance is given by [8, 9]:

$$\left\langle \chi^2 \right\rangle = 0.31 C_n^{\,2} k^{7/6} L^{11/6} \quad (5)$$

In this paper we assume the only dominant noise source is the atmosphere turbulence, neglecting all other noise sources, thus:

$$\chi = \ln\left(\frac{A(r)}{A_0(r)}\right) = \ln\left[\frac{A_0(r) + A_n(r)}{A_0(r)}\right] = \ln(1+\varepsilon) \quad (6)$$

where $A_n(r)$ is the amplitude of noise and $\varepsilon = A_n(r) / A_0(r)$.

Both SNR and BER are used to evaluate the quality of communication systems. BER performance depends on the average received power, the scintillation strength, and the receiver noise. With appropriate design of aperture averaging the received optical power could be increased as well as reducing the effect of the scintillation. With turbulence the SNR in terms of the mean signal and noise intensity I_0 and $\langle I_n \rangle$, respectively is given as:

$$SNR = \frac{I_0}{\langle I_n \rangle} = \frac{\left\langle A_0^2(r) \right\rangle}{\left\langle A_n^2(r) \right\rangle} = \left[\left\langle \varepsilon^2 \right\rangle\right]^{-1} \quad (7)$$

For FSO links with on-off keying (OOK) modulation scheme the BER can be written as [9]:

$$BER = \frac{\exp^{(-SNR/2)}}{(2\pi SNR)^{0.5}} \quad (8)$$

For weak turbulence model, ε is very small thus (6) is given as [9]:

$$\chi = \ln(1+\varepsilon) \approx \varepsilon \quad (9)$$

With this approximation SNR can be written as:

$$SNR = \left[\left\langle \chi^2 \right\rangle\right]^{-1} = \left(0.31 C_n^{\,2} k^{7/6} L^{11/6}\right)^{-1} \quad (10)$$

Without the above approximation (9) is written as:

$$\chi = \ln(1+\varepsilon) \Rightarrow \varepsilon = e^{\chi} - 1 \quad (11)$$

For weak turbulence ($C^2_n \leq 10^{-14}$), $\chi = 0.5\sigma_{\ln IR}$ and using (7) and (8) the SNR and the BER can be directly calculated.

When the turbulence is not weak ($C^2_n \geq 10^{-14}$) the relationship between the SNR and χ is much more complicated. But by using the Tailor series for function $f(\chi) = (e^{\chi}-1)^2$ and with some simplification, (7) can be approximated to:

$$SNR = \frac{1}{\left\langle \chi^2 + \chi^3 + \ldots \right\rangle} \approx \frac{1}{\alpha \left\langle \chi^2 \right\rangle} \quad (12)$$

where $1 \leq \alpha \leq 2$ and represents the strength of scintillation (for worst case $\alpha = 2$).

Including the beam spreading effect the effective SNR is defined as [10, 11, and 12]:

$$SNR_{eff} = \frac{SNR}{\left[1 + 1.33\sigma^2_{\ln IR}\left(\frac{2L}{kw_L^2}\right)^{5/6}\right] + F.\sigma^2_{\ln IR}.SNR} \quad (13)$$

where $W_L = (W_0^{\,2} + L^2\theta^2)^{0.5}$ is the spot size of the phase front at range L in the absence of turbulence, W_0 is the minimum spot size in transmitter, θ is the beam divergence angle. F is the aperture averaging factor defined as the ratio of the normalized intensity variance of the signal at a receiver with diameter D to that of a point receiver[10]:

$$F = \frac{\sigma^2_{\ln IR}(D)}{\sigma^2_{\ln IR}(D=0)} \quad (14)$$

In our model we have assumed that the surface area of the photodetector is large enough, therefore F is small, thus is negligible. The effective SNR is reduced to:

$$SNR_{eff} = \frac{SNR}{\left[1 + 1.33\sigma^2_{\ln IR}\left(\frac{2L}{kw_L^2}\right)^{5/6}\right]} \quad (15)$$

III. RESULTS AND DISCUSSIONS

In this section, we use above discussion and relationship for calculating SNR and BER for a range of parameters. The wavelength used is 1550nm rather than the lower wavelengths of 780-850nm. This is compatible with the 3rd window of optical communication backbone links, and also offering improved eye safety.

Fig. 1 shows the SNR against the distance for a range of C^2_n , whereas Fig. 2 illustrates the BER performance. Both figures depicts that SNR and BER deteriorate with the distance and with the strength of the atmospheric turbulence.

As shown in the Fig. 2, if we want an acceptable communication (BER of 10^{-9}), the maximum distance between transmitter and receiver can be 3600m for $C^2_n=10^{-15}$ m$^{-2/3}$, and 700m for $C^2_n=10^{-14}$ m$^{-2/3}$.

Fig. 3 illustrates the BER against the distance L for three values of wavelengths, showing a marked improvement in performance at higher wavelengths. For example at BER of 10^{-9} the range increases by ~1000 m at λ = 1550nm compared with λ = 780nm.

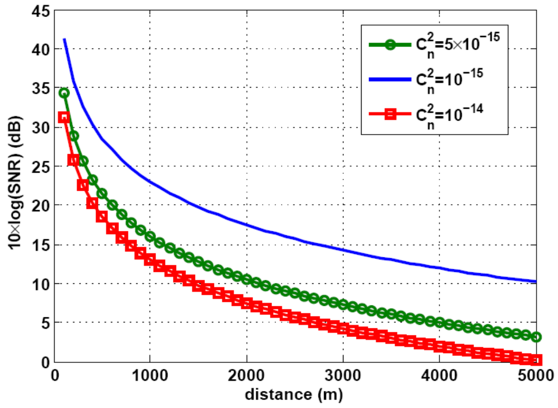

Figure.1 The SNR versus the distance for different values of C^2_n

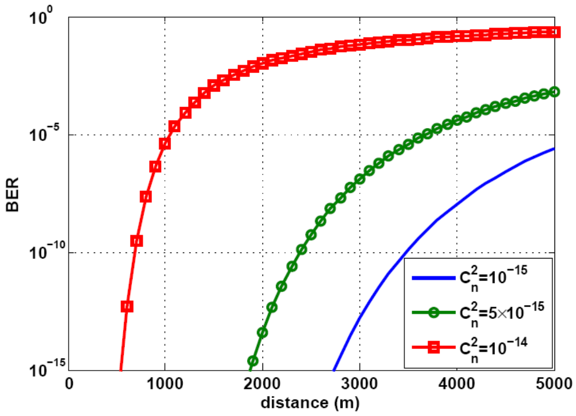

Figure. 2 The BER versus the distance for different values of C^2_n

Using the weak turbulence model with and without approximation for ε (i.e. (9) and (11)), the BER against L is plotted in Fig. 4. As the figure shows the actual maximum range for the FSO system decreases.

Fig. 5 shows the BER as function of distance, for weak and strong turbulence for different α values. It can be seen that, for strong turbulence (i.e. C^2_n=10^{-14} m$^{-2/3}$), the effective communication range drops ~300 (very short distance). With FSO links normally installed at a minimum height (relative) of 20-30 m above the ground, it has been shown that in these altitudes C^2_n<10^{-14} m$^{-2/3}$ is for all times.

Fig. 6 illustrates BER performance as a function of distance for SNR and SNR_{eff}. As shown BER display marginal improvement for SNR compared with SNR_{eff}.

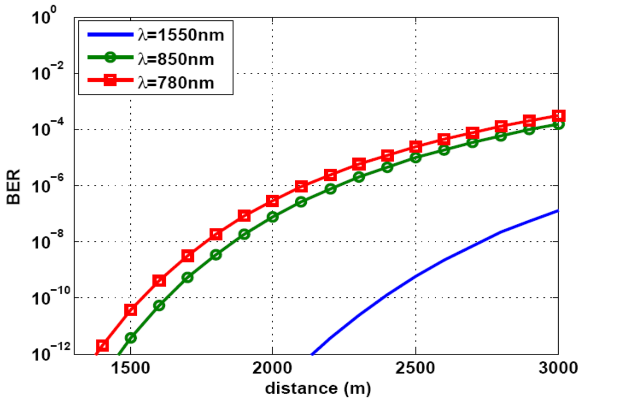

Figure.3 The BER versus distance for different values of λ

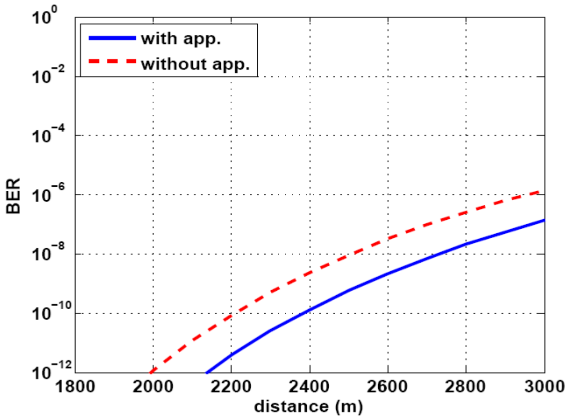

Figure.4 The BER versus distance for weak turbulence with / without approximation

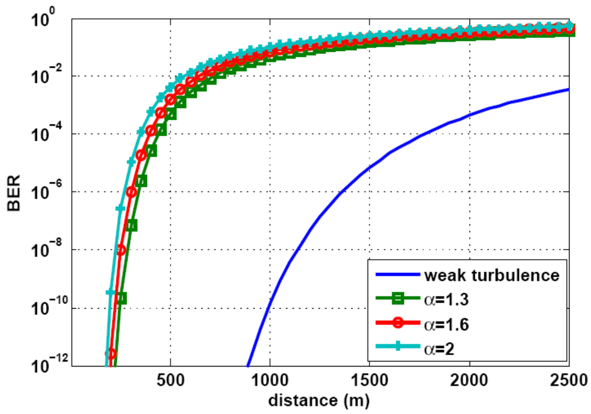

Figure.5 The BER versus distance for weak and strong turbulence

IV. Conclusion

In this paper, we focused on the scintillation as the most important parameter affecting the performance of FSO links. Analyses were carried out for the SNR and the BER in the weak and strong turbulence regimes. From the results, it was shown that the link BER performance deteriorates with higher values of C^2_n. To achieve a BER of 10^{-9} in weak turbulence regime, the link range very large (about a few kilometers) compare as strong turbulence.

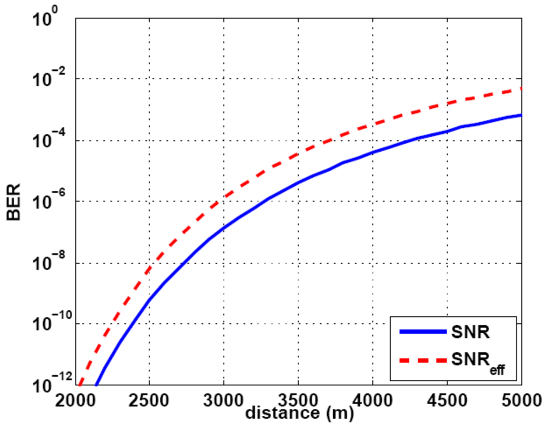

Figure.6 The BER versus the distance for SNR and SNR_{eff}

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