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Performance of Free Space Optical Communication using M-array Receivers at Atmospheric Condition

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Abstract: *In free space optical (FSO) communication links, atmospheric parameters including absorption, scattering and turbulence have significant impacts on the quality of laser beams propagating through the atmosphere. Absorption and/or scattering, due to atmospheric particles result in optical losses, whereas turbulence contributes to the intensity scintillation that can severely impair the operation of FSO communications systems. In this paper, using a modified model we analyze the atmospheric effects on the signal-to-noise ratio (SNR) and the bit error rate (BER) of an FSO system. We show that there is an improvement in BER when using M-array receivers instead of one a single receiver.*

Keywords: free space optical (FSO) communication, Absorption, scattering, scintillation, bit error rate (BER)

1. Introduction

FSO systems have a number of advantages when compared to the free space radio frequency (RF) based systems including: high bandwidth offered per user, fast deployment, license-free, and immunity to the electromagnetic interference. However, similar to the RF systems it suffers from a number channel related affects including absorption, scattering or displacement depending on the atmospheric condition. The combined effects of direct absorption and scattering of light carrier signal (i.e. laser) can be described by the path-dependent absorption coefficient α (λ). 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 within the channel [1-7]. In this paper we investigate the atmospheric effects on the performance of an FSO link. We show that the BER performance deteriorates with lower values of wavelength. We also show that the BER performance can be improved when using M-array receivers instead of a single receiver. The rest of the paper is organized as follow. In section 2 we outline the theoretical analysis of the parameters that impact on FSO link and introduce a model for investigating effects of atmospheric parameters on this system. Also we analyze SNR and BER in presence of atmospheric parameters. Then an M-Array receiver for reducing deleterious effects caused by scintillation is presented. In section 3 results and discussion are introduced, and finally concluding remarks are presented in Section 4.

2. Theory of Analysis

When an electromagnetic wave (particularly laser beam) propagates through the atmosphere, this wave is distorted. The most processes that affect optical wave are absorption, scattering and refractive index fluctuation (turbulence). Absorption and scattering due to molecule of gasses and particulates of the atmosphere attenuate the irradiance of laser beam. But the refractive index fluctuation create irradiance fluctuation, beam broadening, loss of spatial coherence of the laser beam. Most of the time in optical free space communication the output power of laser is low and the atmospheric effects are considered linear. Absorption and scattering are often in one grouped strong function of wavelength under topic of extinction, defined as the reduction or attenuation in amount of radiation passing through atmosphere. The atmospheric transmission of laser beam that has propagated a distance L is described by Beer's law:

$$\tau = \frac{P(\lambda, L)}{P(\lambda, 0)} = \exp\left[-\alpha(\lambda) L\right] \qquad (1)$$

where $P(\lambda,L)$ and $P(\lambda,0)$ are signal power in distance L and in transmitter, respectively, and $\alpha(\lambda)$ is the extinction coefficient. The most important optical effect on laser beam in atmosphere is small temperature variation that causes refractive index fluctuation. When flow of viscous fluid, like the atmosphere, exceeds a critical Reynolds number, it changes from a laminar to a more chaotic state (i.e. the turbulence). Turbulent air motion represents eddies of different scale size, extending from large scale size L_0 (outer scale of turbulence) to small scale size l_0 (inner scale of turbulence). In particular, turbulence effects on laser beam include the following [8]:

- Beam spreading: beam divergence that possibly causes a power reduction at the receiver
- Beam wander: continues random motion of the beam center about the receiver
- Beam scintillation: random fluctuations in the signal-carrying laser beam intensity

These effects cause to increase bit error rates in receiver. Usually beam wander is created by large-scale turbulence. Diffraction effects are often negligible in particular, whenever the receiver aperture diameter D is greater than the size of Fresnel zone $(L/k)^{1/2}$. In addition the rate of beam wander fluctuation is very slow and thus it can be cancelled with use of tracking transmitter schemes. The refractive index fluctuation usually described by refractive index structure parameter $\mathrm{C_n}^2(h)$, which is function of wavelength, atmospheric pressure, and atmospheric temperature, decreases strongly with the height above ground h. $C_n^2(h)$ can vary from 10^{-16} $\mathrm{m}^{-2/3}$ when optical turbulence is "weak" and up to 10^{-13} $\mathrm{m}^{-2/3}$ when it is "strong". Within the inertial sub range the refractive index structure function is described by Kolmogorov two-thirds power law [8-9]:

$$D_n(R) = C_n^2(h)R^{2/3} \qquad l_0 < R < L_0 \tag{2}$$

where $D_n(R)$ is the refractive index structure function, l_0 and L_0 are inner scale and outer scale of turbulence, respectively. With neglecting polarization effects, the propagation of a monochromatic optical wave trough a random media can be written by reduced wave equation:

$$\nabla^2 E + k^2 n^2(R) = 0 \tag{3}$$

where $E(R)$ is optical field at position $R=(x,y,z)$, $n(R)$ is the random index of refraction and $k=2\pi/\lambda$ is wave number. Wave propagates in atmosphere and scintillation effect causes the fluctuations in irradiance at receiver. These fluctuations is defined by variance of intensity:

$$\sigma_I^2 = \frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2} \tag{4}$$

Rytov approximation assumes that the optical field at propagation distance L from the transmitter is [8]:

$$\begin{aligned} E(R,L) &= E_0(R,L)\exp\left[\Psi(R,L)\right] \\ &= E_0(R,L)\exp\left[\Psi_1(R,L)+\Psi_2(R,L)+\ldots\right] \end{aligned} \tag{5}$$

where $E_0(R,L)$ is the free space Gaussian beam at the receiver and $\Psi(R,L)$ is the total complex phase perturbation of the field. $\Psi_1(R, L)$ and $\Psi_2(R, L)$ are the first and second order of perturbation, respectively. The mean field at distance L from transmitter is:

$$\langle E(R,L)\rangle = E_0(R,L)\exp\left[-0.39C_n^2k^2LL_0^{5/3}\right] \tag{6}$$

It is clear that the mean field is sensitive to large scale of turbulence, distance and C_n^2. The mean field inversely increases with each of these parameters. Based on Rytov theory, when a laser beam propagates in atmosphere such as a random media, the field of plane wave can be written as [10]:

$$E_0(\vec{r}) = A_0(\vec{r})\exp\left(i\varphi_0(\vec{r})\right) \tag{7}$$

where $A_0(r)$ is amplitude of the laser beam in the atmosphere without turbulence, φ_0 and $E_0(r)$ are phase and laser beam profile, respectively. Due to atmospheric turbulence, the refractive index changes and leads to change in laser beam profile. The wave equation can be written as [8,10]:

$$E(\vec{r}) = A(\vec{r})\exp\left(i\varphi(\vec{r})\right) = E_0(\vec{r})\exp(\Phi) \tag{8}$$

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

$$\Phi = Ln\left(\frac{A(\bar{r})}{A_0(\bar{r})}\right) + i\left(\varphi(\bar{r}) - \varphi_0(\bar{r})\right) = \chi + iS \tag{9}$$

where χ represents the fluctuations of the log of the amplitude of the field and S is the phase fluctuation. 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 $\mathrm{C_n}^2$ is symmetrical along the beam path, Rytov suggested a variance for the log intensity fluctuations given as [6]:

$$\sigma_I^2 \simeq \sigma_{\ln IR}^2 = \left\langle\left(\ln I - \langle\ln I\rangle\right)^2\right\rangle = 1.23C_n{}^2k^{7/6}L^{11/6} \tag{10}$$

As for a practical FSO system (plane wave) with weak and symmetrical atmosphere turbulence the log irradiance variance is given by[10,11]:

$$\chi = \ln\left(\frac{A(r)}{A_0(r)}\right) = \ln\left[\frac{A_0(r)+A_n(r)}{A_0(r)}\right] = \ln(1+\varepsilon) \tag{11}$$

where $A_\mathrm{n}(r)$ 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:

$$SNR = \frac{I_0}{\langle I_n\rangle} = \frac{\langle A_0^2(r)\rangle}{\langle A_n^2(r)\rangle} = \left[\langle\varepsilon^2\rangle\right]^{-1} \tag{12}$$

For FSO links with on-off keying (OOK) modulation scheme the BER can be written as [10]:

$$BER = \frac{\exp^{(-SNR/2)}}{(2\pi SNR)^{0.5}} \tag{13}$$

With including the absorption and scattering effects, beam spreading effect, and aperture averaging factor the effective SNR or mean SNR is defined as [8, 12 and 13]:

$$SNR_{eff}=\frac{SNR}{\sqrt{\left[1+1.63\sigma_I^{12/5}\left(\frac{2L}{kw_L^2}\right)\right]\exp(\alpha L)+A.\sigma_I^2.SNR}} \tag{14}$$

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. A 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 [12,14]:

$$A=\frac{\sigma_I^2(D)}{\sigma_I^2(D=0)}\simeq\left[1+1.06\left(\frac{kD^2}{4L}\right)\right]^{-7/6} \tag{15}$$

M-Array Receivers

For reducing the deleterious effects caused by scintillation through aperture averaging, instead of using large apertures detection system, we can use several smaller apertures detection system that the sum of surfaces is equal to large apertures detection ($D^2=MD_1^2$). It is supposed that the output from each of array detectors and a single large aperture experience the same aperture averaging effects (fig. 1).

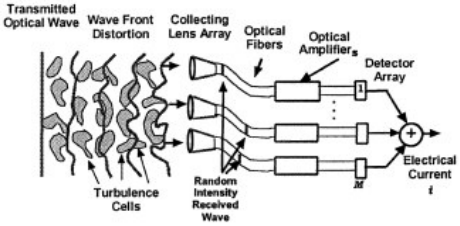

Fig. 1: M-Array Receivers

With this assumption we can write [8]:

$$A=\frac{\sigma_I^2(D/M)}{M\sigma_I^2(D=0)}\simeq\left[1+1.06\left(\frac{kD^2}{4LM^2}\right)\right]^{-7/6}\Big/M \tag{16}$$

3. Results and discussions

In this section, base on the presented analysis SNR and BER are calculated considering the effects of several parameters.

Fig. 2 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. Therefore the wavelength used here 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.

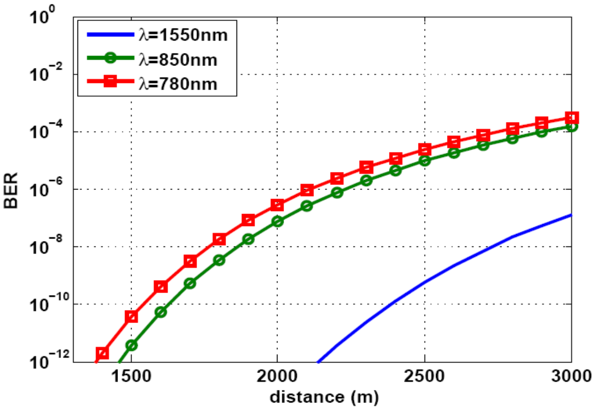

Fig. 2: The BER vs. distance for different values of λ

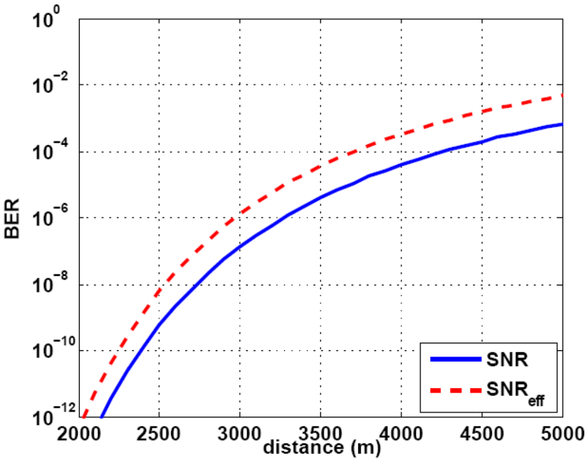

Fig.3: The BER vs. distance for SNR and SNR_{eff} when A≈0

Fig. 3 illustrates BER performance as a function of distance for SNR and SNR_{eff} when the surface area of the photodetector is large enough, therefore A is small, and negligible also absorption and scattering effects are ignored (α≈0). As shown, BER displays marginal improvement for SNR compared with SNR_{eff}.

Fig. 4 shows the SNR_{eff} against the SNR, for different values of A without considering absorption and scattering effects. When the surface of receiver is very large (A≈0) the SNR_{eff} increase linearly with SNR, and we can ignore the fluctuations of irradiance due to scintillation effect. But SNR_{eff} reduces for smaller surface of receiver and at last is saturated. Even for a point receiver (A≈1), when the SNR increase the SNR_{eff} approaches to zero.

Fig. 5 illustrates the SNR_{eff} against the SNR for three atmospheric conditions: 1) α=9dB/km (thin fog, about 1.5 km visibility) 2) α = 11dB/km (light fog, about 1.3 km visibility) 3) α = 13dB/km (lightly moderate fog, about 1 km visibility). It is seen that if the atmospheric condition becomes worse (increase of α) the SNR_{eff} decreases. And for all of the three conditions, when SNR increases (above of ~10 dB/km) the SNR_{eff} is saturated.

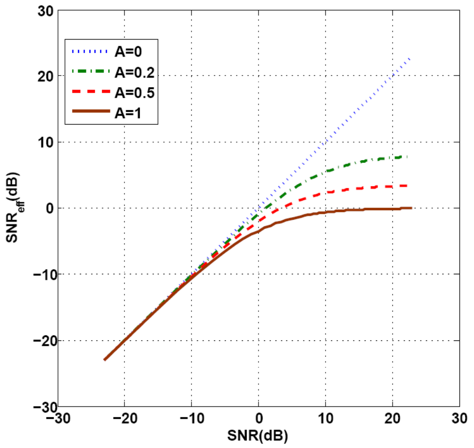

Fig. 4: The SNR_{eff} versus SNR for different values of *A*, without considering absorption and scattering effects (α=0)

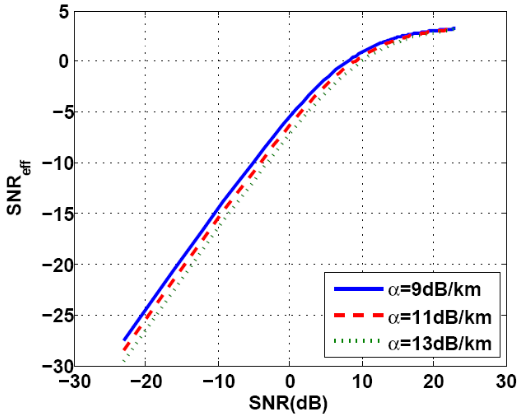

Fig. 5: The SNR_{eff} versus SNR for different values of absorption and scattering coefficient (A=0.5)

Fig. 6 shows the SNR against $(kD^2/4L)^{1/2}$ for different values of M (number of receiver in array). In all cases the glass area of the M collecting lenses is the same as that of the single large lens. The SNR improves clearly when the number of receivers in array increases. Also it is seen if $(kD^2/4L)^{1/2}$ increases (increase of receiver surface or decrease of distance) SNR is saturated.

Fig.7 illustrates the BER against the distance for different values of M. As shown in the figure, the performance of FSO link improves with larger number of receiver in array.

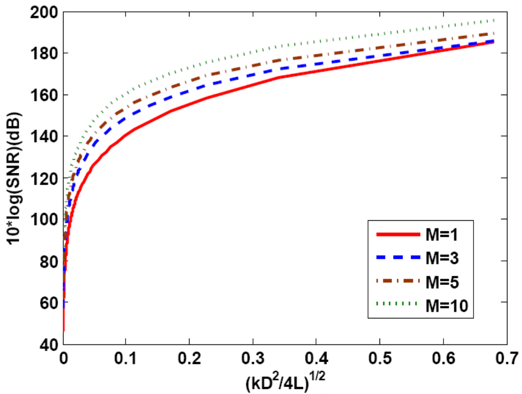

Fig. 6: The SNR versus $(kD^2/4L)^{1/2}$ with different values of M

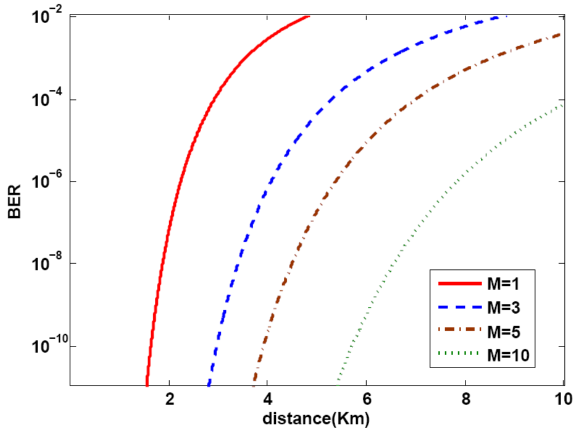

Fig. 7: The BER versus distance with different values of M

4. Conclusion

In this paper, we have analyzed the atmospheric parameters that affect the performance of FSO links. From the results, it has been shown that the BER performance deteriorates with lower values of wavelength. Also it has been shown that if the number of receiver in M- array receiver increases (in all cases the glass area of the M collecting lenses is the same as that of the single large lens) the performance of FSO links are improved.

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