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Simulation FSO System under Effect of Scintillation Index on Weak to Strong Turbulence

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Abstract-

Atmospheric turbulence is caused by the movement of air molecules, which can cause the refractive index of the atmosphere to vary. This variation in the refractive index causes the signal to be scattered, resulting in intensity fluctuations called the Scintillation is a phenomenon that occurs when a signal is transmitted through a medium that is subject to rapid changes in refractive index, Scintillation index (SI) is a measure of the magnitude of these fluctuations, and is typically expressed as a percentage. This cause the signal to be distorted or attenuated, resulting in a decrease in signal strength and an increase in bit error rate (BER) and signal to noise ratio (SNR), we in this paper performed numerical analysis the Gamma-Gamma and Log-Normal models, there RE most commonly used models for turbulence. These models are used to describe the effects of turbulence on the atmosphere, and it is used to predict the behavior of turbulent flows. This analysis under effect weak, moderated and strong turbulence with different parameters such as optical wavelength, and receiver diameter aperture on three different refractive-index structure. Numerical results showed that FSO link performance is enhanced when wavelength is increased, for both strong and moderate turbulence regimes and decrease the aperture receiver *diameter*.

Keywords: Free Space Optical, Scintillation Index, refractive index

I. INTRODUCTION

The performance of a free space optics (FSO) link can be greatly affected by atmospheric turbulence, which causes fluctuations in the refractive index of the air and results in distortions of the optical beam, known as scintillation[1]. These distortions can lead to a reduction in the signal-to-noise ratio, power loss and beam wander, which can result in a decrease in the link performance and reliability[2]. A number of factors can affect the performance of an FSO link under the effect of turbulence, including the link distance, the wavelength of the light, and the strength of the turbulence. In general, the link performance degrades as the distance increases, and as the turbulence strength increases. One way to quantify the effect of turbulence on the FSO link performance is to use the scintillation index (SI), which is a measure of the strength of the scintillation. A lower SI value indicates less scintillation and better link performance. The SI can be calculated using the point spread function (PSF) and the intensity scintillation variance (ISV) of the received optical signal[3]. Another important factor for the performance of the FSO link under the effect of turbulence

is the beam width of the optical beam. A narrower beam width reduces the impact of scintillation, but increases the pointing and tracking errors. There are several techniques that can be used to mitigate the effects of turbulence on the FSO link performance, such as the use of adaptive optics, beam-steering techniques, and diversity receivers. These techniques can help to improve the link performance and reliability[4]. But they have their own limitations, and the effectiveness of these techniques can depend on the specific system and operating conditions.

Fig.1 shows the effect with air pockets having different refractive indices Randomly formed pockets refract the optical wave front of the incoming beam due to which the signal cannot be received properly [5]. The

scintillation is
a function of the refractive index structure parameter C_n^2, modeled by the Hufnagel-Valley (H-V) model [6], which is a function of altitude h in meters and wind speed v in m/s, a typically measured in units of $m^{-2/3}$. It is used to describe the variations in the refractive index of air caused by temperature and pressure differences. The strength of these fluctuations can range from very weak ($C_n^2$of 10^{-16} $m^{-2/3}$) to very strong ($C_n^2$of 10^{-12} $m^{-2/3}$) and it is important for various fields, such as astronomical observation, atmospheric physics, and optical communication. The stronger the turbulence, the higher the value of $C_n^2$and the greater the distortion of images and the interference in signals, caused by the fluctuations .
This paper discussed the analysis of a free-space optical (FSO) link and its various parameters such as the optical wavelength and receiver aperture diameter, how these parameters are affected by weather conditions, specifically scintillation, which is a phenomenon causes fluctuate the intensity of light to rapidly in a random manner. This can have a significant impact on the performance of an FSO link, the paper discussed these effects or optimize the link for specific conditions, determine the efficiency of the system by measuring the signal-to-noise ratio and bit error rate.

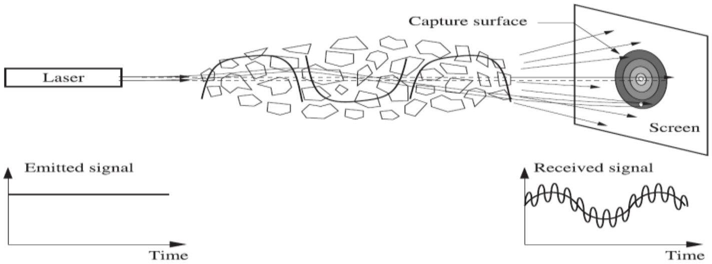

Fig 1. Effects of various different sized heterogeneities on a laser beam propagation *(scintillations).*

II. MODEL SIMULATION

Atmospheric turbulence model

Gamma-Gamma Model Distribution

The Gamma-Gamma distribution model is a statistical model used to describe the atmospheric turbulence-induced scintillation of laser beams in free-space optical communication links. The model is based on the assumption that the scintillation index (a measure of the intensity fluctuation of the laser beam) is a random variable that follows a Gamma-Gamma distribution. Turbulent channel was analyzed considering Gamma-Gamma distribution model as it is suitable for medium and strong regimes of atmospheric turbulence strength. its intensity I is product of two gamma random variables which represents fluctuations from small and large turbulence [7]. The received signal optical intensity I can be represented by [8]:

$$p(I) = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\left(\frac{\alpha+\beta}{2}\right)-1} K_{\alpha-\beta}(\sqrt{\alpha\beta I} \qquad I > 0 \tag{1}$$

$K_{\alpha-\beta}$ represents the modified Bessel function. The parameters α and β are the effective values of small scale and large scale eddies of the turbulent medium considered Where:

$$\alpha = [\exp(\frac{0.49\sigma_R^2}{\left(1+1.11\sigma_R^{\frac{12}{5}}\right)^{\frac{7}{6}}}) - 1]^{-1} \tag{2}$$

$$\beta = [\exp(\frac{0.51\sigma_R^2}{\left(1+0.69\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}}) - 1]^{-1} \tag{3}$$

σ_R^2 is Rytov variance and is described as:

$$\sigma_R^2 = 1.23\left(\frac{2\pi}{\lambda}\right)^{\frac{7}{6}} \times C_n^2 L^{\frac{11}{6}} \tag{4}$$

Where λ represent wavelength, distance between T$_x$ and R$_x$ link is L, C_n^2 shows atmospheric turbulence strength. The BER equation of Gamma-Gamma channel model is:

$$P_b = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \frac{D^6(\theta)}{(1-2D^2(\theta))^2} \tag{5}$$

$D(\theta) is\ given\ by$:

$$D(\theta)$$

$$= 2^{\frac{\alpha+\beta+4}{4}} C1\left(\frac{c_2}{\alpha}\right)^{\frac{\alpha-\beta}{2}} \left(\frac{\sin(\theta)}{\sqrt{\tau}}\right)^{\frac{\alpha-\beta}{2}} K_{\alpha-\beta}\left(2^{\frac{5}{4}}\sqrt{\frac{c_2\alpha\sin(\theta)}{\sqrt{\tau}}}\right) \tag{6}$$

The expression of c_1 and $c_2$are given:

$$C_1 = \frac{\sqrt{\pi\alpha^\alpha\beta^\beta}}{\Gamma(\alpha)\Gamma\left(\frac{\beta+1}{2}\right)} \tag{7}$$

$$C_2 = \beta\sqrt{\beta - \frac{1}{2} + \frac{1}{16}\left(\beta - \frac{1}{2}\right)^{\frac{3}{2}}}) \tag{8}$$

The Gamma-Gamma (GG) distribution is a probability density function (PDF) that is commonly used to model the received signal optical intensity in optical communication systems. The equation for the GG distribution is given by:

$$p(I) = \frac{1}{I\sqrt{2\pi\sigma^2}} exp^{\left(\frac{\alpha+\beta}{2}\right)} - \frac{(\ln(I) + \frac{\sigma^2}{2}}{2\sigma^2} \tag{9}$$

Where σ^2 is scintillation index parameter or log irradiance variance also called Rytov variance. Assuming plane wave propagation, Rytov variance is expressed by the equation[9]:

$$\sigma^2 = 1.23 C_n^2 K^{\frac{7}{6}} L^{\frac{11}{6}} \tag{10}$$

Where C_n^2 is refractive index parameter dependent on altitude level, K is optical wave no. and L is link distance.

The variations of the refraction index make a deflection of the optical beam and fluctuation of the power at the receiver. The variations in the refractive index of the medium($C_n^2(a)$) can be described by the following [9]:

$$C_n^2(a) = 0.00594\left(\frac{w_s}{27}\right)^2 (10^{-5}a)^{10} \exp\left(\frac{-a}{1{,}000}\right) + 2.7 \cdot 10^{-16} exp\left(\frac{-a}{1{,}500}\right) + 1.7 \cdot 10^{-14} exp\left(\frac{-a}{100}\right) \tag{11}$$

where w_s is the root mean square wind speed in m/s, and a is the altitude in m.

III. RESULTS AND DISCUSSION

FSO Link simulation is carried out using non return-to-zero on–off keying (NRZ-OOK) Horizontal link model for the attenuation due to turbulence losses. In this FSO Link Simulation We studied effects of turbulence on the signal attenuation, studied for different levels of turbulence, such as low, moderate, and high. The simulation also take into account variations in wavelength, receiver diameter that can affect the performance of the FSO link, that achieves the minimum BER, the maximum SNR. The system performance is dependent on various environmental scintillations; this paper focuses on the performance analysis of FSO systems under scintillation turbulence index By simulating these different scenarios, researchers can gain a better understanding of the factors that contribute to signal loss in FSO systems and develop strategies for mitigating these effects.

The system performance is dependent on environmental refractive index; this paper focuses on the performance analysis of FSO systems under effect of scintillation turbulence index, the parameters used for the system are given underneath in Table 1. In order to obtain the optimum performance of the system that achieves the minimum BER, maximum SNR.

Table 1: Considered simulation parameter for optical link

Parameters	***Valus***
Wavelength	850,1330 and 1550
Data rate	5 Gb/s
Transmitter Power	10 dBm
Refractive Index C_n^2	$10^{-15,}$ 10^{-14} and 10^{-13}
Receiver Aperture Diameter (m)	10mm, 20mm and 30mm
Beam Divergence	0.65 mrd
Turbulence Model	GG model

We noted Low turbulence conditions result in a relatively stable and consistent signal, while moderate and high turbulence conditions can cause a significant reduction in the signal strength and increase in the bit error rate.

Figure 2,3,4 shows the relation between the BER and SNR for three different wavelengths: 850 1,330 and 1,550 nm wavelengths at different Refractive Index C_n^2. At the transmission wavelength of 850 nm, it is seen that the turbulence loss characteristics are almost similar to all the low, moderate and strong turbulence irrespective of their different refractive-index structure parameters and wave types. owing to the low attenuation and the high signal to noise ratio. The results show that the BER decreases for wavelength 1550 nm compared to 850 and 1330 nm; For $\lambda = 850$nm wavelength, the attenuation scintillation is 16.1 dB for high turbulence while 12 dB at 1550 nm, so that the wavelength equals to 1,550 nm, which is the optimum wavelength at the worst case scintillation at range of 5 km. From the obtained result, it is noted that the higher wavelength has a higher potential for FSO transmission link.

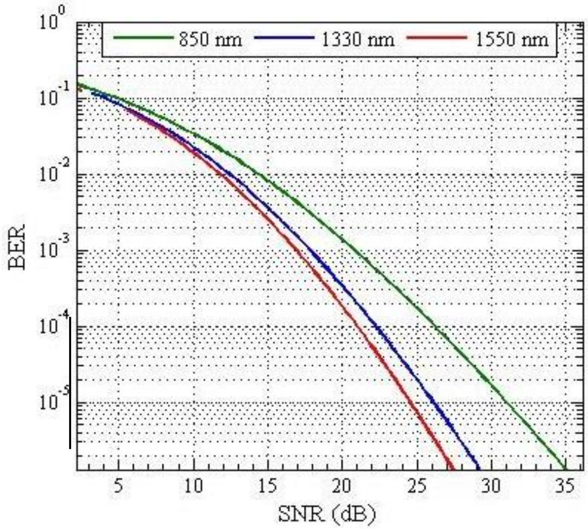

Fig 2. BER of OOK FSO links vs. Average SNR (dB) over weak atmospheric turbulence channels for various wavelength.

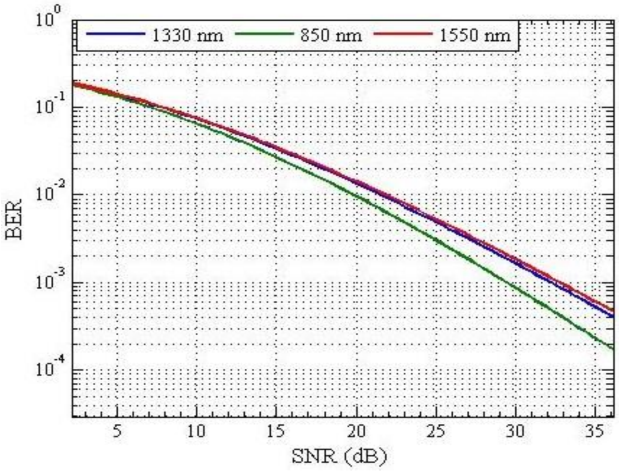

Fig 3. BER FSO links vs. Average SNR (dB) over moderate atmospheric turbulence channels for various wavelength.

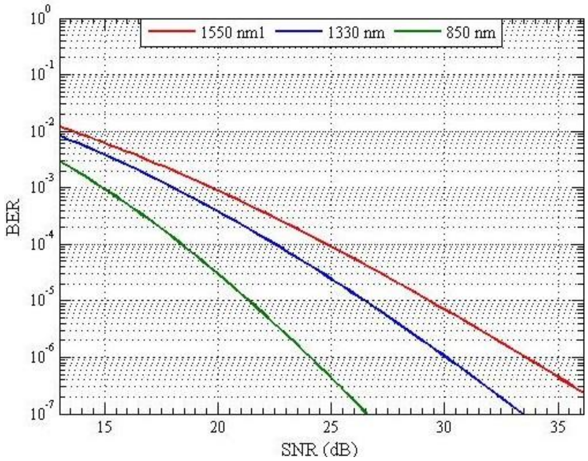

Fig 4. BER FSO links vs. Average SNR (dB) over strong atmospheric turbulence channels for various wavelength.

Figure 5, 6,7 shows the relation between the SNR and the BER at various receiver diameters equal to 10, 20, and 30 mm under different refractive index, for receiver diameter of 10, 20 mm, the SNR is decreased significantly while the BER decreases slightly. for example, with receiver diameters of 10mm the SNR up to 30 dB for high turbulence while 22dB for 30mm diameter the SNR decrease has a higher potential for FSO transmission link

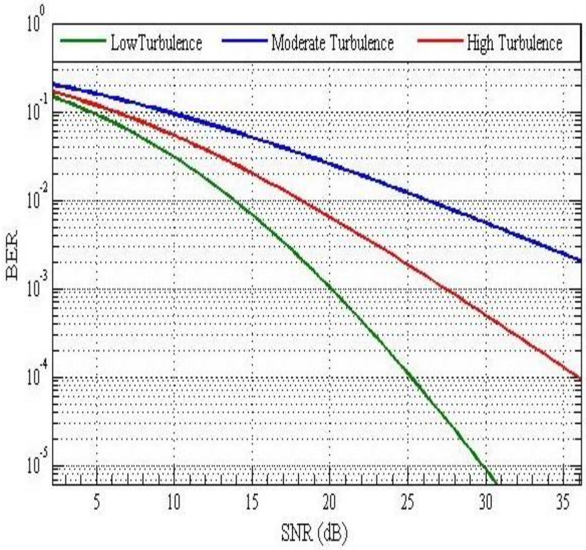

Fig 5. BER versus average SNR for receiver diameter 10mm at various weather conditions

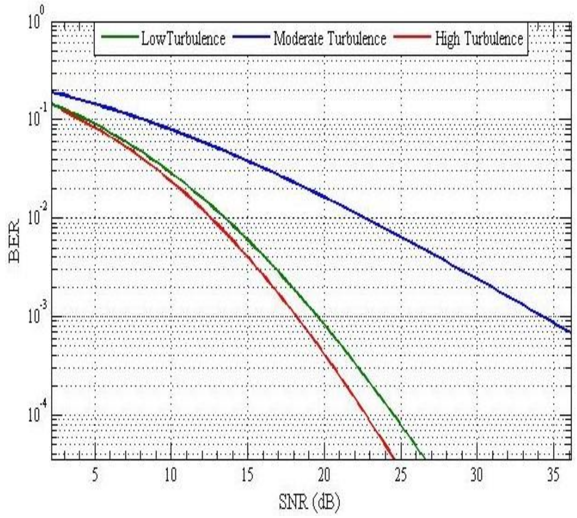

Fig 6. BER versus average SNR for receiver diameter 20 mm at various weather conditions

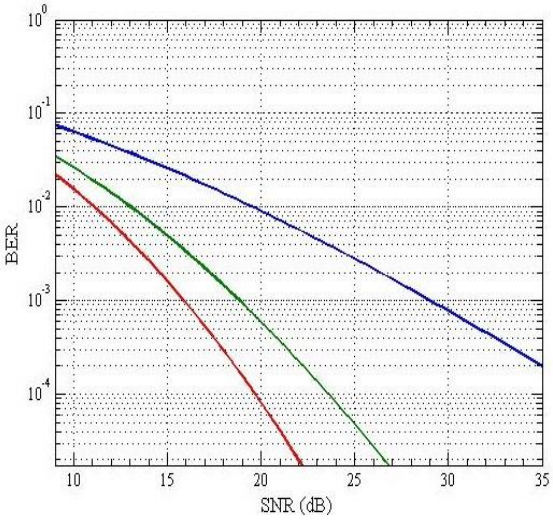

Fig 7. BER versus average SNR for receiver diameter 30 mm at various weather conditions

VI. Conclusion

This paper analyzed the performance of horizontal FSO link to for the turbulence attenuation due to the scintillation index using NRZ-OOK simulation. analytical relationship of bit error rate and signal to noise ratio for different wave length and receiver diameter. The results show reducing the scintillation index will increase the SNR and will thus reduce the value of BER. And 1,550 nm is the best wavelength in FSO windows and that improving the system performance and BER performance can be improved by increasing the receiving aperture diameter under high turbulence condition.

REFERENCES

[1] Hamza Gercekcioglu, Yahya Baykal "Scintillation and bit error rate in bidirectional laser communications between an aerial vehicle and a satellite using annular optical beams in strong turbulent atmosphere," Journal of the Optical Society of America, Vol. 38, No. 10, pp.335-341, 2021.

[2] M. Yousefi, R. Talatian Azad, F. D. Kashani, and B. Ghafary, "Scintillation index effects on the bit error rate in free space optical communication of incoherent flat-topped laser beam propagating through turbulent atmosphere," IJST (Special issue), vol.39 A3, pp.369-374, 2015.

[3] Michael T. Taylor, Aniceto Belmonte, Leo Hollberg, and Joseph M. Kahn "Effect of atmospheric turbulence on timing instability for partially reciprocal two-way optical time transfer link," physical review, vol. 3 ,pp.843-849, 2020

[4] Kolawole, O.O. Afullo, T.J.O, and Mosalaosi, M. "Initial Modeling of Atmospheric Turbulence Effect on Optical Wireless Communication Links in South Africa," In Proceedings of the Southern Africa Telecommunication Networks and Applications Conference (SATNAC) 2019, Ballito, KwaZulu-Natal, South Africa, pp. 68–72. 1–4 September 2019.

[5] Ziyi Zhu, Molly Janasik, Alexander Fyffe1, Darrick Hay1, Yiyu Zhou, Brian Kantor, Taylor Winder, Robert W. Boyd, Gerd Leuchs, and Zhimin Shi, "Compensation-free hi dimensional free-space optical communication using turbulence-resilient vector beams," nature communications vol. 12, pp.1666, (2021).

[6] Chaleshtori, Zahra, Gholami, Asghar, Ghassemlooy, Zabih and Zvanovec, Stanislav" Experimental Investigation of the Effective Spectrum Bandwidth of the FSO Link with Scintillation," 1st West Asian Colloquium on Optical Wireless Communications (WACOWC2018), 25 April 2018, Isfahan.

[7] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: a communication theory perspective," IEEE Commun. Surveys Tuts., vol. 16, pp. 2231- 2258, 2014.

[8] C. Abou-Rjeily and S. Haddad, "Inter-relay cooperation: a new paradigm for enhanced relay-assisted FSO communications," IEEE Trans. Commun., vol. 62, pp. 1970-1982, 2014.

[9] Kanchan Sharma, Surender K. Grewal "Capacity analysis of free space optical communication system under atmospheric turbulence," Optical and Quantum Electronics, vol.10, pp52:82, 2020.

[10] Muhammad et al., "Channel modeling for terrestrial free space optical links," in Proc. IEEE Int. Conf. Transp. Opt. Netw. (ICTON),20, pp. 407–410, 2005