Quantitative Analysis of Atmospheric Turbulence Effect on Laser Beam Wander

Harpuneet Singh Gill[1], Priyanka[2], Mandeep Singh[3], Paramdeep Singh[4], Maninder Lal Singh[5]
[1,2,3,5]*Guru Nanak Dev University, Amritsar*
[4]*Greens Pulse Solution, Bahrain*

***Abstract*:** The performance of free space optical (FSO) communication gets affected by several phenomena such as attenuation, absorption, scattering, atmospheric turbulence. The impairment losses due to atmospheric turbulence severely degrade the system performance. In this paper, the stochastic nature of atmospheric turbulence is discussed. The deviation in the variance of laser beam due to turbulence and its effect on the performance of the link has been experimentally determined.

Keywords: Atmospheric turbulence, free space optical communication, beam wander, intensity map, variance.

I. INTRODUCTION

In recent decades there has been congestion in the existing networks due to increasing traffic load. This problem calls for the technology that can provide high bandwidth links. Free space optical (FSO) communication is a growing technology capable of providing high bandwidth links for handling high data rates [1-2]. FSO communication systems are presented as an available alternative to the fiber based optics technology which is capable of full duplex transmission of data, voice and video in various applications. However, there are certain applications where free space is the only available means to establish a communication link between the transmitter and receiver [3-4]. Moreover the last mile problem is another disadvantage of the guided optical communication. It has many distinct advantages such as high directivity, narrow beam width, immunity to electromagnetic interference, ease of deployment etc.[4-6].The basic principle of optical wireless communication (OWC) is similar to fiber optics communication except that unlike fiber based optical communication, in this case the data is transmitted through the unguided medium instead of guided medium. However, the performance of FSO is challenged by several phenomena such as attenuation, absorption, scattering, atmospheric turbulence, misalignment between the transmitter and receiver terminals [5-7]. The atmospheric turbulence is a random process that occurs due to temperature differences between the earth's surface and the atmosphere. The variations in other factors such as pressure, humidity also affects the atmospheric channel but their effect is not significant and thus can be neglected. The temperature variations further results into the formation of unstable air pockets with temperature gradients. This results into the varying refractive index of the atmosphere. These variations in the refractive index of the atmosphere induce temporal and spatial fluctuations in the received signal. The atmospheric turbulence also affects the coherence of the laser beam [5]. Several methods that can be employed to mitigate the turbulence effect have been proposed in [5-6],[8-12]. The statistics of the optical link can be obtained from the knowledge of the probability density function of the received data [13].

The paper presents the quantitative analysis of atmospheric turbulence on laser beam propagation. With an eye towards this objective, we aim to recreate the physical phenomenon of atmospheric turbulence in the laboratory with a high degree of accuracy. From this experimental setup, we tend to investigate the nature of atmospheric turbulence and model the effect of deviation in variance of laser beam. The rest of this paper is organized as follows:

II. EXPERIMENTAL SETUP

The artificial simulation of atmospheric turbulence has been presented in [13-16]. Variance is effectively a means of dispersion which gives the spread of beam. Since atmospheric turbulence causes fluctuations in the refractive index, beam intensity gets redistributed due to scintillation effects. The effect of turbulence can be quantified in terms of relative spread of beam which is nothing but the variance of beam.The beam variance depends upon refractive index structure coefficient, propagation distance, beam width as given in [15]. The value of refractive index structure constant further depends upon spatial and temporal temperature variations. The relative variance of laser beam (σ_c^2) is:

$$\sigma_c^2 = 1.44 \times C_n^2 \times L^3 \times W_0^{-1/3} \quad (1)$$

where W_0 is half-width of laser beam, C_n^2 is refractive index structure constant, L is the propagation distance.

The experimental setup consists of an atmospheric turbulence chamber, laser source, driver circuit and image acquisition device. A laser of wavelength 650nm, power of 5mW has been used for this experiment. The divergence of laser beam is 0.75mrad. The propagation distance between the transmitter and the receiver is 120cm. The atmospheric turbulence was generated by differential heating inside the chamber of dimensions 112×30×30 cm^3. The setup is schematically illustrated in Fig. 1.

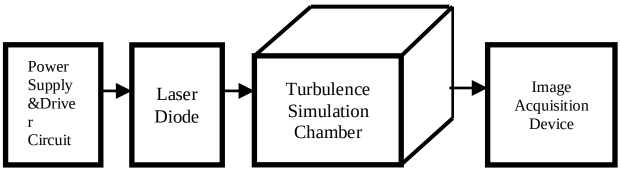

Fig. 1: Block diagram of the experimental setup

Heating elements were used to raise the temperature inside the box. Fans were used to ensure uniformity within the chamber. The rise in temperature results into the change in refractive index of the atmosphere inside the chamber. These fluctuations in the refractive index further results into the formation of eddies. These eddies behave as lenses resulting into constructive and destructive interference of the optical signal at the receiver [5]. Temperature sensors were used to observe the rise in temperature with time along the length of propagation.

III. METHODOLOGY

A reference variance value was obtained by taking the average of variance of laser beam in the absence of atmospheric turbulence. The deviation in the value of variance was calculated with respect to the reference value of the variance using the following formula:

$$\text{Variance Deviation} = \text{abs}(V_i - V_{avg}) \quad (2)$$

where V_{avg} is the reference value of variance and V_i is the variance of the image whose variance deviation of laser beam propagation has to be calculated.

There were subtle variations in the image intensity even in the absence of turbulence. This is mainly due to the presence of background noise. Thus the variance of the laser beam due to background noise is subtracted to get variance due to turbulence only.

IV. RESULTS AND DISCUSSIONS

The deviation in absolute variance of laser beam due to atmospheric turbulence is shown in Fig. 2.

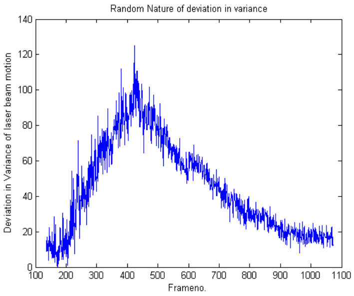

Fig. 2: Random nature of deviation in the absolute variance of laser beam due to turbulence

The results show that the variance of laser beam due to atmospheric turbulence is random in nature and the maximum variance in the laser beam motion occurs at high temperature differences. The turbulence rises to a maximum when the temperature differences inside the chamber become maximum and thus resulting in high error probability. The variance in laser beam motion decreases with the decrease in the temperature difference values along the length with time.

The distribution of the random deviation in the variance of laser beam due to turbulence is given in Fig. 3.

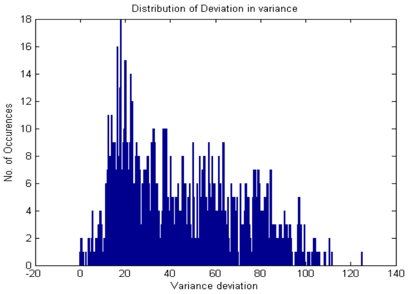

Fig. 3Distribution of the deviation in absolute variance of the laser beam due to turbulence

As shown in the above figure, the variance of laser beam is rarely zero. Hence, even slight turbulence lends the laser beam a grainier and nosier look. The different values of the temperature differences correspond to different values of variance in laser beam wander. Thus it can be inferred that higher the temperature difference goes, higher is the variance and correspondingly, the laser beam is nosier.

The distribution of deviation in the variance of laser beam is found to be best approximated by Weibull distribution as shown below:

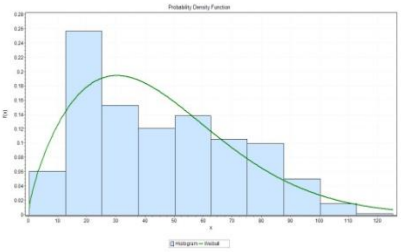

Fig. 4: Weibull distribution of variance of laser beam in the presence of turbulence

The probability density function of the Weibull distribution is given below:

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{x}{\beta}\right)^{\alpha}\right) \quad (3)$$

The corresponding cumulative distribution function (CDF) is given below:

$$F(x) = 1 - \exp\left(-\left(\frac{x}{\beta}\right)^{\alpha}\right) \quad (4)$$

where α is thecontinuous shape parameter, $\beta$is the continuous scale parameter, x is the variance of laser beam due to turbulence.

The α and β of the Weibull distribution is given as below:

$$\alpha = 1.7173$$

$$\beta = 50.519$$

Based on the chi-square goodness of the fit test, the Weibull distribution approximates better than any other distribution model.

There are certain frames in which the variance oflaser beam is minimum and maximum. The intensity maps of the frames that are most affected and least affected by turbulence areplotted to have a knowledge about the intensity redistribution in the presence of turbulence.

The X-Z view and Y-Z view of the intensity map for maximum affected frame i.e. frame no. 473 and minimum affected frame i.e. frame no. 173 are as follows:

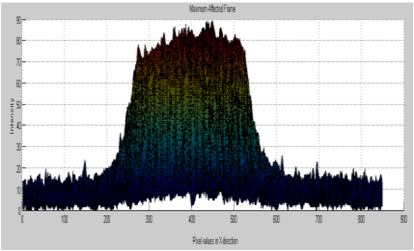

Fig. 5 X-Z View of maximum affected frame

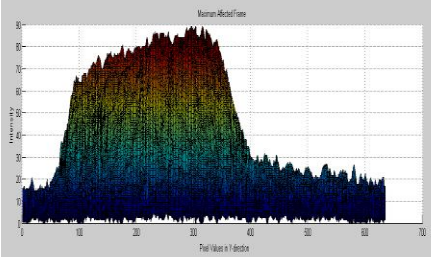

Fig. 6: Y-Z View of maximum affected frame

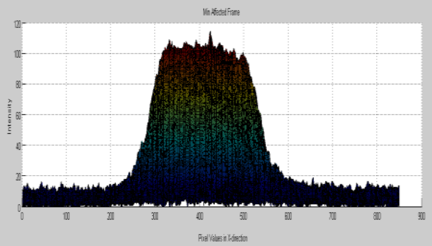

Fig. 7: X-Z View of minimum affected frame

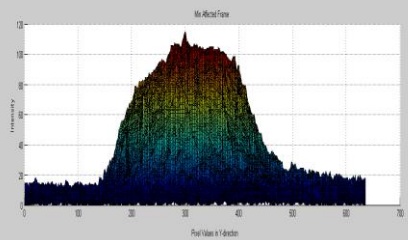

Fig. 8: Y-Z View of minimum affected frame

From the intensity maps of maximum affected frame and minimum affected frame, it is clearly shown that the intensity value for maximum affected frame remains up to 80 units whereas for minimum affected frame, the value of intensity is up to 100 units. The obvious explanation of this observation is the increase in variance of laser beam received at the receiver. The beam is found to be narrower in case of minimum affected frame as the pixels are more concentrated at the centroid. From the different X-Z and Y-Z views of the intensity maps, it is inferred that the beam spreads out more in vertical direction as compared to the horizontal direction.

V. CONCLUSION

The results show that the deviation in variance of laser beam acquires a random nature. This deviation is best approximated by Weibull distribution. Due to inclusion of this stochastic process, the performance of the FSO link requires statistical interpretation. From the intensity maps, it is clear that the randomness in the laser beam is not uniformly distributed rather it is a directional phenomenon. Based on this information, the mitigation techniques so employed to enhance the performance of FSO link need to have adaptive directional capabilities.

VI. REFERENCES

[1] V. W. S. Chan, “Free-space optical communications,” Journal of Lightwave technology, Vol. 24, no. 12, pp. 4750–4762, 2006.

[2] F.E.Goodwin, “ A review of operational laser communication systems,” Proceedings of the IEEE, Vol. 58, no. 10, pp. 1746–1752, Oct. 1970.

[3] Alsemmeari, Rayan A., Sheikh Tahir Bakhsh, and Hani Alsemmeari, "Free Space Optics Vs Radio Frequency Wireless Communication," International Journal of Information Technology and Computer Science (IJITCS), Vol. 8, no. 9, Sept. 2016.

[4] Babani, S., A. A. Bature, M. I. Faruk, and N. K. Dankadai, "Comparative study between fiber optic and copper in communication link," Vol. 2, pp. 59-63, 2014.

[5] Kaushal, Hemani, and Georges Kaddoum, "Optical communication in space: Challenges and mitigation techniques," IEEE Communications Surveys & Tutorials, Aug. 2016.

[6] Goyal, Poonam, Ashwni Kumar, and Vandana Nath. "Mitigation of atmospheric turbulence in free space optics: a review," presented at the 2015 Fifth International Conference on Advanced Computing & Communication Technologies (ACCT), IEEE, 2015, pp. 634-640.

[7] Kumar, Naresh, and Ashwani Kumar Rana, "Impact of various parameters on the performance of free space optics communication system." Optik-International Journal for Light and Electron Optics, Vol. 124, no.22, pp. 5774-5776, Nov. 2013.

[8] Kaur, Gurpreet, Harmeet Singh, and Amandeep Singh Sappal, "Free Space Optical Using Different Modulation Techniques–A Review," International Journal of Engineering Trends and Technology (IJETT), Vol. 43, no. 2, pp.109-105, Jan. 2017.

[9] Zhu, Xiaoming, Joseph M. Kahn, and Jin Wang. "Mitigation of turbulence-induced scintillation noise in free-space optical links using temporal-domain detection techniques." IEEE Photonics Technology Letters, Vol. 15, no. 4 , pp. 623-625, Apr. 2003.

[10] Zhu, Xiaoming, and Joseph M. Kahn. "Markov chain model in maximum-likelihood sequence detection for free-space optical communication through atmospheric turbulence channels." IEEE Transactions on Communications, Vol. 51, no. 3, pp. 509-516, Mar. 2003.

[11] Abtahi, Mohammad, Pascal Lemieux, Walid Mathlouthi, and Leslie Ann Rusch, "Suppression of turbulence-induced scintillation in free-space optical communication systems using saturated optical amplifiers," Journal of Lightwave technology, Vol. 24, no. 12, pp. 4966-4973, Dec. 2006.

[12] Hulea, M., Ghassemlooy, Z., Rajbhandari, S., & Tang, X., “Compensating for optical beam scattering and wandering in FSO communications,” Journal of Lightwave Technology, Vol. 32, no. 7, pp. 1323-1328, Apr. 2014.

[13] A. K. Majumdar and H. Gamo, “Statistical measurement of irradiance fluctuations of a multipass laser beam propagated through laboratory-simulated atmospheric turbulence,” Applied Optics, Vol. 21, no. 12, pp. 2229–2235, Jun. 1982.

[14] Hudcova, Lucie, and Peter Barcik, "Experimental measurement of beam wander in the turbulent atmospheric transmission media," in Proc. 22nd Int. Conf. Radio elektronika, Apr. 2012, pp. 1-4.

[15] H. Kaushal, V. Kumar, A. Dutta, H. Aennam, V. K. Jain, S. Kar, and J. Joseph, “Experimental study on beam wander under varying atmospheric turbulence conditions,” IEEE Photon. Technol. Lett., Vol. 23, no. 22, pp. 1691–1693, Nov. 2011.

[16] Bissonnette, L.R., “Atmospheric scintillation of optical and infrared waves: a laboratory simulation,” Applied optics, Vol. 16, no.8, pp. 2242-2251, Aug. 1977.

AUTHORS

Harpuneet Singh Gill is currently pursuing PhD from Dept. of Electronics Technology, Guru Nanak Dev University, Amritsar. He is a Junior Research Fellow (JRF) with University Grants Commission (UGC), Ministry of Human Resource & Development (MHRD), Govt. of India. His areas of interest are Optical Wireless Communications, Microwave Communications.

Priyanka received B.Tech in Electronics and Communication from Punjab Technical University in 2015. She is currently pursuing M.Tech in Communication Systems at Dept of Electronics Technology, Guru Nanak Dev University, Amritsar. Her areas of interest are Optical Communications.

Mandeep Singh is currently pursuing PhD from Dept of Electronics Technology, Guru Nanak Dev University, Amritsar. He is a Research Fellow underVisvesvarayaPhD scheme with DEITY, Ministry of Electronics & Information Technology, Govt. of India. His areas of interest are Free Space Optical Communication, Wireless communication.

Paramdeep Singh is presently working as Operations Manager in Greens Pulse Solutions. He received his Master of Technology degree in the Communication Systems from the Department of Electronics Technology, Guru Nanak Dev University, Amritsar. His areas of interest are Optical Communication and Optical Sensors.

Maninder Lal Singh did his B. Tech. (Electronics Technology) in 1991 form Guru Nanak Dev University Amritsar, M.Tech (Communication Systems) in 1997 from IIT Kanpur and PhD (Electronics Technology) in 2002 from Guru Nanak Dev University, Amritsar. He has 25 years of Teaching and research experience. Presently he is working as Professor in theDepartment of Electronics Technology, Guru Nanak Dev University Amritsar. He has coordinated several Research Projects. His field of research is Optical Communications. He has more than 100 research publications in National and International journals and conferences.