Exploration of Signal to Noise Ratio with Optical Compression Systems Utilizing Spectrum in Free Space Optics

Mehman Hasanov
Department of Radiotechnics and Telecommunication
Azerbaijan Technical University
Baku, Azerbaijan
mhasanovnew@gmail.com

Ali Tagiyev
Department of Radiotechnics and Telecommunication
Azerbaijan Technical University
Baku, Azerbaijan
ali.tagiyev.1974@mail.ru

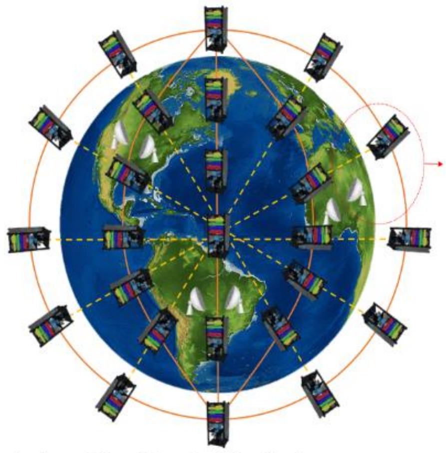
Nadir Atayev
Department of Radiotechnics and Telecommunication
Azerbaijan Technical University
Baku, Azerbaijan
nadir_atayev@mail.ru

***Abstract*—The presented topic examines the immense potential of Free Space Optics (FSO) applications and explores the impacts of varying environmental parameters on FSO's effectiveness, depending on the near-infrared wavelength range used. During the transmission phase, optical signals in the transmitter environment undergo extinction and attenuation, while changes in the environment's turbulent nature affect the transmitted and received optical signal parameters. The aforementioned atmospheric influences heavily impact the signal-to-noise ratio, which serves as a quality indicator of the optical channel and the likelihood of transmission channel bit errors. The results of the research conducted at 1.31 µm, 1.55 µm, and 1.62 µm wavelengths used in the formation of optical channels between inter-peak, peak-place, place-peak, and ground terminals are given in the article. By using optical compression systems based on the spectrum in FSO and considering the number of optical channels organized by multiplexing N_k, frequency efficiency $\eta_{SE}(\lambda_i)$, quality factor Q_F, and error probability per bit P_{BER} are investigated to achieve maximum transmission speed $SNR(P_S)$ while minimizing the signal-to-noise ratio.**

Keywords—Free-space optical communication, Environmental turbulence, Nanosatellite, Error probability

I. Introduction

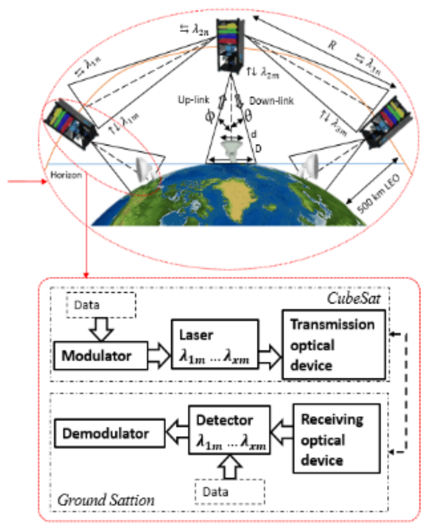
The analyses conducted indicate that in the near future, Free Space Optics (FSO) systems will experience wider utilization due to their superior technical and economic characteristics [1-8]. FSO holds significant value in the optical communication domain thanks to its vast transmission range, lack of need for additional equipment for the allocated spectrum (unlike the radiofrequency spectrum), high speed, ease of establishing optical links in different directions using both main and alternative routes, and other factors [4-7]. The impacts of atmospheric influences have a profound effect on transmission speed in optical channels, signal-to-noise ratio (SNR), and bit error rate (BER) - all of which are quality indicators of optical communication [9-15]. Currently, various FSO networks consisting of beams and nanobeams in varying structures are being proposed [9,10,11-13]. To illustrate, consider the FSO network scheme depicted in Figure 1, which links inter-beam and ground terminals.



a) π shape and Ring – Grid topology LEO satellite cluster

Fig. 1. (a) Low Earth Orbit (LEO) satellite constellation view.

b) Optical communication geometry on the same orbit in LEO



c) Simplified optical transmission line of CubeSat and Ground Station

Fig. 2. (b) its geometrical view, (c) block diagram of transmission principles.

The application of the topology of the optical communication system is envisaged between ($\mathrm{H} = 500 -$

DOI: https://doi.org/10.54381/pci2023.06

2000 km) N_n ($\mathrm{N} = N_1 - N_n$) number of ground-based and inter-satellite stations at a height of H meters from the surface. Each receiving and transmitting terminal of each individual satellite located at $L_1 - L_n$ different distances from each other is connected by optical channels that carry the optical information beam for the reception and transmission of optical laser signals between them. While in the Figure 2, each nanosatellite is connected to the ground terminal through an FSO channel of wavelength λ_1 to λ_n, as appropriate. Below the communication geometry of the dotted nanosatellite link, the process of optical-electrical data conversion and transmission oversimplified modulation techniques has been illustrated. As so the analysis and research are devoted to the dependence of the signal-to-noise ratio SNR (P_S) on the signal-to-interference ratio in free space optical (FSO) communication using optical compression technology according to the spectrum when using wavelengths λ_i = (1.31, 1.55, 1.62) µm as an indicator of the quality of the optical system for the delivery of optical signals in the empty phase.

II. Effects of Atmospheric Conditions on the Quality Parameters of Optical Signals

The rough association between FSO terminal transmitters and receivers for satellite-satellite, satellite-ground, and ground-satellite connections is evaluated with respect to signal-to-noise ratio (SNR), which serves as an indicator of optical system quality. The analysis is presented below [13]:

$$\mathrm{P_{received}} = \mathrm{P_{Transmitted}} \frac{\mathrm{d_L^2}}{(\mathrm{d_T} + \theta \mathrm{L})^2} 10^{-\alpha \frac{\mathrm{L}}{10}} \tag{1}$$

here, d_R is the aperture diameter of the receiver (M), d_T is the aperture diameter of the transmitter (M), θ is the divergence angle of the beam (in mill radians), L is the distance between the terminals (in km), and α, is the atmospheric attenuation ($\mathrm{dbkm^{-1}}$).

It is a well-known fact that the heterogeneity of the atmosphere, coupled with temperature and air pressure changes, can influence flicker intensity and the thermal coefficient of the environment, leading to optical turbulence. Several models have been proposed to describe flicker intensity in optical signals [13]. The channel models presented in this study simulate gamma-gamma turbulence across a broad spectrum [13].

In this case, the probability density function of the intensity of the light wave is:

$$\mathrm{P(I)} = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}) \tag{2}$$

$$\alpha = exp\left[\frac{0.49\sigma_R^2}{\left(1+1.11\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}}\right] - 1 \tag{3}$$

$$\beta = exp\left[\frac{0.51\sigma_R^2}{\left(1+0.69\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}}\right] - 1 \tag{4}$$

here, α and β are the number of small and large particles of turbulence, $K_{\alpha-\beta}(.)$ is the modified Bessel function of the second order [11, 15], $\Gamma(.)$ is the gamma function, and its probability density function is determined as follows:

$$P(x) = \frac{\beta^{\alpha} * x^{\alpha-1}}{\Gamma(\alpha)} * \exp(-\beta x), x > 0, \alpha \geq 1, \tag{5}$$

here, $\Gamma(\alpha)$is the well-known Qamma Eyler function, and $\alpha > 0$ and $\beta > 0$ are defined as follows within certain conditions of,

$$\Gamma(\alpha) = \int_0^\infty t^{\alpha-1} * \exp(-t) dt \tag{6}$$

If we substitute $\alpha = k + 1$ in equation (5), we obtain the k is order Hermite-Gaussian distribution of the intensity, and based on this, we can evaluate the loading factor and probability-time characteristics of the optical atmosphere distortion.

Let us ascertain the significant probability characteristics for optical atmosphere distortion using the Gamma distribution function:

Observational parameters:

$$m_X = E[X] = \int_0^\infty x * w(x) dx = \frac{\beta^\alpha}{\Gamma(\alpha)} * \int_0^\infty x^\alpha * \exp(-\beta x) dx \tag{7}$$

With that the final expression (7), can be expressed in such form for a simple for calculations.

III. Solution for Atmospheric Condition

With that, the variance of intensity σ_R^2, which is directly dependent on the magnitude of atmospheric turbulence, is determined by the formula,

$$\sigma_R^2 = 1.23 C_n^2 k^{\frac{7}{6}} z^{\frac{11}{6}} \tag{8}$$

where C_n^2 is the refractive index structure parameter whose values vary from $10^{-13} m^{\frac{2}{3}}$ for strong turbulence to $10^{-17} m^{\frac{2}{3}}$ for weak turbulence, $k = 2\frac{2\pi}{\lambda}$ is the optical wave number, and z is the distance of the Free-Space Optical Communication (FSO) link. The time fluctuations of the channel are computed using the theoretical quasi-static model, also referred to as the 16frozen channel model. This model operates under the assumption that channel fading remains constant during a symbol frame (known as coherence time), but changes to a new value between frames.

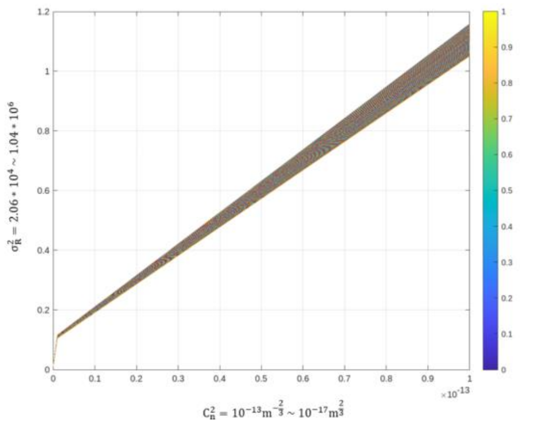


Fig. 3. 2D dispersion intensity of turbulence along the X, and Y axes.

Both 2D and 3D graphical results from MathLab is given in Fig. 3 and Fig. 4.

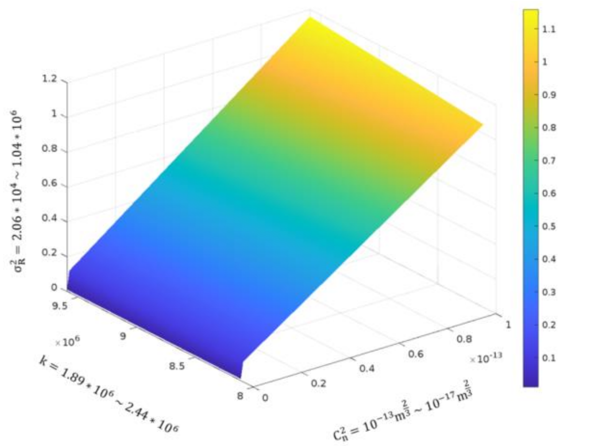


Fig. 4. 3D dispersion intensity of turbulence along the X, Y, and Z axes

Based on the analysis carried out, it is apparent that the parameters outlined in the aforementioned (1-8) formulas and visualized in both 2D and 3D graphs, exerts a considerable influence on the quality indicators of transmission rate in FSO communication channels. Therefore, the investigation of the quality indicators of the transmission rate in FSO communication between terminals, terminal-location, and ground terminals in the open phase using wavelengths of 1.31 μm, 1.55 μm, and 1.62 μm in the formation of optical links based on the optical compression technology foundation in the FSO environment is an important issue.

IV. Conclusion

In FSO, the effect of the variable parameters of the transmission medium, depending on the wavelength range of the optical signals, which are used near the infrared wavelength, has been investigated. In clear atmospheric conditions, the attenuation, scattering, and turbulence of the transmission medium cause the parameters of the transmitted and received optical signals to change. The effects of these atmospheric conditions have serious consequences on the transmission rate of the communication channels, which is the quality indicator of the optical communication, and the error probability in the bit transmission. The results of the research carried out at wavelengths of 1.31 μm, 1.55 μm, and 1.62 μm, which are used in the formation of inter-satellite, satellite-ground, ground-satellite, and terrestrial optical communication, have been presented in the article. By increasing the number of communication channels in FSO based on the optical compression technology, the system's transmission capacity has been increased by $C_{max}(\Delta F_k, \lambda_i, N_k)$, and the exponential law of the price of the quality indicator of the optical channels in the receiving terminals has been established.

The optical compression systems based on the spectrum in FSO were designed to accommodate multiple optical channels through multiplexing techniques, ensuring enhanced frequency efficiency and minimizing error probability per bit. The analysis of the obtained results allowed us to assess the impact of environmental factors, such as turbulence and attenuation, on the SNR and overall quality of the optical channel. The absence of critical remarks regarding the existing literature suggests that the authors have thoroughly reviewed and incorporated relevant works into their research.

References

[1] Himani Kaushal, Georges Kaddoum. Optical Communication in Space: Challenges and Mitigation Techniques. IEEE Communications Surveys & Tutorials (Volume: 19, Issue: 1, Firstquarter 2017)Page(s): 57 – 96.

[2] Hayal, M.R., Yousif, B.B., Azim, M.A.: Performance enhancement of DWDM-FSO optical fiber communication systems based on hybrid modulation techniques under atmospheric turbulence channel. Photonics. 8, 464 (2021).

[3] Maharjan, N.; Devkota, N.Kim, B.W. Atmospheric Effects on Satellite–Ground Free Space Uplink and Downlink Optical Transmissions. Appl. Sci. 2022, 12, 10944.

[4] N Nikbakht-Sardari, M Ghiamy, ME Akbari, A. Charmin. Novel adaptive hard switching based hybrid RF-FSO system architecture using two threshold values in the presence of atmospheric turbulence and pointing error. Results in Engineering, 2022

[5] M.H Hasanov, NA Atayev. Early Conceptual Model of Nanosatellite with Laser Beam Control and Active Transponder System. (SYNCHROINFO) IEEE. 2022/6/29.p.1-4

[6] M.H Hasanov, N.A Atayev. Algorıthm desıgn nanosatellıte based on radıo frequency and optıcal communıcatıon. Problems of ınformation technology (2022), vol. 13, no. 2, 61-68.b - jpit.az.2022

[7] Carrasco-Casado, A. & Mata-Calvo, R. (2020). Free-space optical links for space communication networks. Japan.66 p.

[8] K.A.Balaji.K.Prabu. Performance evaluation of FSO system using wavelength and time diversity over Malaga turbulence channel with pointing errors. Optics Communications, Volume 410, 1 March 2018, Pages 643-651.

[9] Alberto Carrasco-Casado, Ramon Mata-Calvo “Free-space optical links for space communication networks” Springer Handbook of Optical Networks pp 1057–1103.2012 .

[10] Yuhang Zhou, Zhiqun Gu, Jiawei Zhang, and Yuefeng Ji. Efficient deployment of aerial relays in FSO-based backhaul networks. Journal of Optical Communications and Networking, Vol. 15,Issue 1,pp. 29-42,(2023).

[11] Sung-Jin Kim And Sang-Kook Han, Power Efficiency Analysis of Spatial Diversity Based Vertical FSO Links With Pointing Error in Multiple Beam Transmissions. ieee /access.2022.3228528volume 10, 2022

[12] El-Nahal, F.; Xu, T.AlQahtani, D.; Leeson, M. Abidirectional Wavelength Division Multiplexed (WDM) Free Space Optical Communication (FSO) System for Deployment in Data Center Networks (DCNs). Sensors. 2022, 22, 9703.

[13] Bronshtein I. N., Semendyaev K. A. B 88 Handbook of Mathematics for Engineers and Students: Teaching Aid. - Publishing House - Wiley, 2010. 608 p.

[14] Ibrahimov B. G., Hasanov M. H., Tagiyev A.D. Research of the quality of functioning fiber-optical transmission systems on the basis modern technologies// 2022 Systems of Signals Generating and Processing in the Field of on Board Communications, IEEE Conference # 53456, (15-17 March), Moscow, 2022.–pp.1-5.

[15] Hasanov, M. H., Ibrahimov, B. G., Mardanov, N. T. (2019). Research and analysis performance indicators NGN/IMS networks in the

transmission multimedia traffic. InWave electronics and its application in information and telecommunication systems (WECONF), Saint-Petersburg, Russia .pp.1 – 4.https://doi.org/10.1109/WECONF.2019.8840117.