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INVESTIGATION OF SIGNAL-TO-NOISE RATIO BASED ON OPTICAL COMPRESSION SYSTEMS USING SPECTRUM IN FSO

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Abstract. The presented article analyzes the great potential of FSO application areas and investigates the effects of variable transmitter environment parameters on the effective characteristics depending on the near-infrared wavelength range used in FSO. In the open phase, the extinction and attenuation of optical signals in the transmitter environment, as well as the change in the turbulent nature of the environment, cause changes in the parameters of the transmitted and received optical signals. The effects of the aforementioned atmospheric influence seriously affect the signal-to-noise ratio, which is a quality indicator of the optical channel and the probability of errors in the bit in transmission channels. 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, optical compression systems, error probability.*

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1. Introduction

The analyses carried out show that in the near future, optical free-space communication (FSO) systems will be used more widely due to their high technical and economic characteristics (Kaushal & Kaddoum, 2017; Gill & Singh, 2021; Hayal *et al.*, 2021; Maharjan *et al.*, 2022; Nikbakht-Sardari *et al.*, 2022; Kumari & Arya, 2023; Hasanov & Atayev, 2022; Hosseini *et al.*, 2019). FSO is of great importance in the field of optical communication due to its wide transmission range, not requiring additional equipment for the allocated spectrum unlike the radiofrequency spectrum, high speed, the easy and fast establishment of the optical link in different directions by using the main and alternative routes, and so on (Maharjan *et al.*, 2022; Nikbakht-Sardari *et al.*, 2022; Kumari & Arya, 2023; Hasanov & Atayev, 2022). FSO mainly uses optical wavelengths near the infrared wavelength range (500-2000 nm), which is why it is a promising direction for the formation of ground terminals, passive optical networks (PON), and future 5/6G networks, including optical satellite links (Kaushal & Kaddoum, 2017; Hayal *et al.*, 2021; Maharjan *et al.*, 2022; Nikbakht-Sardari *et al.*, 2022; Kumari & Arya, 2023;

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Hasanov & Atayev, 2022; Hosseini *et al.*, 2019). Despite the great potential of FSO application areas, the effects of the changing parameters of the transmission environment that affect its effective characteristics depending on the wavelength range have not been thoroughly studied. In the open transmission environment, the attenuation and scattering of optical signals, as well as the changing turbulence of the environment, lead to changes in the levels of transmitted and received optical signals. The effects of this atmospheric influence have a serious impact on the transmission speed in optical channels, the signal-to-noise ratio (SNR), and the bit error rate (BER) as a quality indicator of optical communication (Nath *et al.*, 2022; Hasanov & Atayev, 2022; Carrasco-Casado & Mata-Calvo, 2020; NASA, 2017; Balaji & Prabu, 2018; Carrasco-Casado & Mata-Calvo, 2012; Zhou *et al.*, 2023; Kim & Han, 2022; El-Nahal *et al.*, 2022). Currently, various FSO networks consisting of beams and nanobeams in different constructions are proposed (Nath *et al.*, 2022; Hasanov & Atayev, 2022; Carrasco-Casado & Mata-Calvo, 2020; NASA, 2017; Balaji & Prabu, 2018). For example, let's take a look at the scheme (Figure 1) of an FSO network that connects inter-beam and ground terminals. The application of the topology of the optical communication system is envisaged between ($\mathrm{H} = 500 - 2000$ 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. Each nanosatellite is connected to the ground terminal through an FSO channel of wavelength $\lambda 1$ to λn, as appropriate.

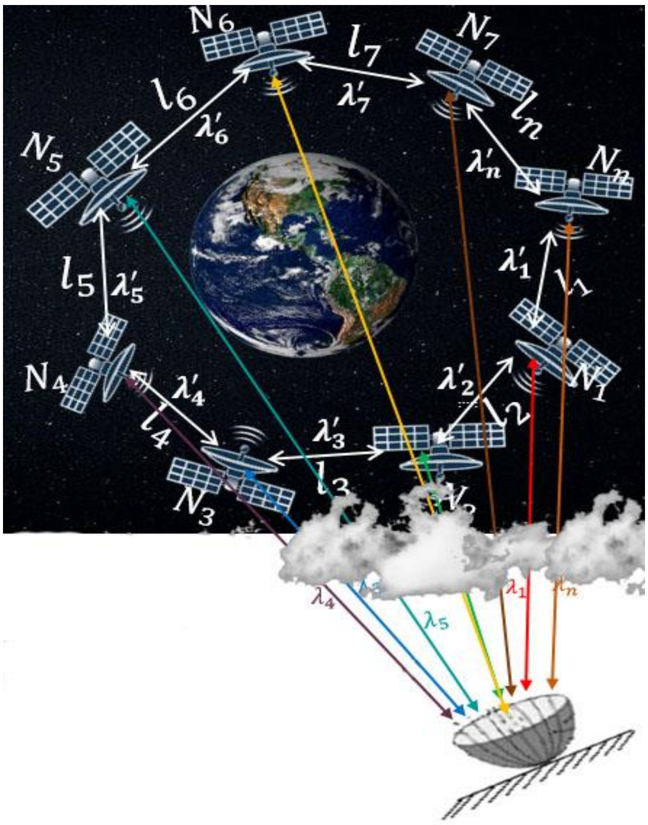

Fig. 1. Diagram of the arrangement of communication between nanopeak terminals and ground station terminals

Purpose: 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 λi= (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.

2. Impact of atmospheric environment on the quality parameters of optical signals

The approximate relationship between the transmitter and receiver of terminals in FSO for the satellite-satellite, satellite-ground, and ground-satellite connections is considered in terms of the signal-to-noise ratio (SNR) as an indicator of the quality of optical systems is showed below (Balaji & Prabu, 2018):

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

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 milliradians), L is the distance between the terminals (in km), and α, is the atmospheric attenuation (dbkm^{-1}).

It is known that the non-homogeneity of the atmosphere, along with changes in temperature and air pressure, can affect the intensity of the flicker and the thermal coefficient of the environment, resulting in optical turbulence. Various models exist to express the intensity of flicker in optical signals (Balaji & Prabu, 2018). The presented channel models simulate gamma-gamma turbulence over a wide range (Balaji & Prabu, 2018).

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

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

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

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

here, α and β are the number of small and large particles of turbulence, $K_{\alpha-\beta}(\cdot)$ is the modified Bessel function of the second order (Nath *et al.*, 2022; Bronshtein & Semendyaev, 2010), $\Gamma(\cdot)$ is the gamma function, and its probability density function is determined as follows:

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

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

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

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's determine the important probability characteristics for the optical atmosphere distortion based on the Gamma distribution function:

- Observational parameters:

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

The final expression (7), if we take into account the required conditions, can be expressed in such a simple form for calculation:

$$\int_0^{\infty} x^{\alpha} \exp(-\beta x) dx = \frac{\Gamma(\alpha+1)}{\beta^{\alpha+1}} \tag{8}$$

If we consider that it is so,

$$\alpha \cdot \Gamma(\alpha) = \Gamma(\alpha+1), \tag{9}$$

In that case, we can obtain such a simple expression for the mean value:

$$m_X = M[X] = \alpha / \beta \tag{10}$$

For the given case of optical atmospheric turbulence, the average value (intensity of the turbulence) of the turbulence can be determined as follows:

$$M[\mathrm{X}] = \beta / \alpha \tag{11}$$

- The dispersion is determined as follows, according to the corresponding formula:

$$D_X = D[X] = \alpha / \beta^2 \tag{12}$$

The intensity of dispersion depends on changes in atmospheric turbulence and is determined by the following expression:

$$\sigma_R^2 = 1.23 C_n^2 k^{\frac{7}{6}} L_{FSO}^{\frac{11}{6}} \tag{13}$$

Equation (13) represents the scintillation index, denoted by C_n^2, which varies in the range of 10^{-13} м$^{-2/3}$ for strong turbulence and 10^{-17} м$^{-2/3}$ for weak turbulence. $\mathrm{k} = 2\frac{2\pi}{\lambda}$ is the optical wave number, and L_{FSO} FSO is the distance between terminals in FSO.

According to the analysis conducted, the parameters reflected in the mentioned (1-7) formulas have a significant impact on the quality indicators of the 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 $\lambda = 1.31$ mkm, $\lambda = 1.55$ mkm, $\lambda = 1.62$ mkm wavelengths in the formation of optical links based on the optical compression technology foundation in the FSO environment is an important issue.

Solution: Based on consideration of the optimal conditions of the acceptable system, the performance indicators are generally evaluated as follows (Ibrahimov *et al.*, 2022; Hasanov *et al.*, 2019):

- The data rate in the communication channels:

$$V_b(t, \lambda_i) = \eta_{SE}(\lambda_i) \cdot \Delta F_k \tag{14}$$

here, $\eta_{SE}(\lambda_i) -$ is the spectral efficiency of the system based on optical compression technology for λ_i wavelength, $\Delta F_k -$ is the width of the frequency interval between channels, and $\Delta F_k = 50, 100, 150, 200$ GHs

- Taking into account the power of the useful signal P_S, the factor Q_F is for the signal-to-interference ratio at the input of the receiver system is determined as follows:

$$Q_F(P_S) = [\mathrm{I}(1) - \mathrm{I}(0)]/[\sigma(1) + \sigma(0)], \tag{15}$$

here, $\mathrm{I}(1), \mathrm{I}(0)$ - is the average value of the current in the photodiode at the time of receiving the digital signal 1 and 0, respectively, at the input of the receiver system; YY is the root-mean-square value of the interference signal during the reception of digital signals 1 and 0, respectively.

It should be noted that the Q_F factor is equivalent to $SNR(P_S)$ in terms of signal-to-noise ratio in high-speed optical compression systems based on spectrum. The probability of error due to bit is calculated using the P_{BER} function, i.e. $P_{BER} = E[\mathrm{Q_F}]$.

- In general, the signal-to-noise ratio $SNR(P_S)$ that is used as a quality indicator at the output of communication channels is determined as follows:

$$SNR(P_S) = Q_F \cdot \frac{\Delta F_E}{\Delta F_k}[(1+\mathrm{r})/(1-\mathrm{r}^{0.5})^2] \qquad (16)$$

here, ΔF_E is the bandwidth of the optical filter of the receiver system, and r is the ratio of the average value of the currents in the photodiode when the binary 1 and 0 signals are received, expressed as:

$$r = [\mathrm{I}(0)/I(1)] \le 1, \quad \mathrm{I}(0) \le I(1) \qquad (17)$$

- The power of the useful signal is determined as follows, depending on the distance XX, attenuation factor, and input signal power:

$$P_S = P_{in} - \alpha_S \cdot L_{FSO} \qquad (18)$$

This L_{FSO} is the distance required for the recovery, reception, amplification, and regeneration of optical signals, and it is calculated as $L_{FSO} = 50,...,2000\ km$ numerically. The transmission speed of communication channels in wavelength division multiplexing systems is determined as follows:

$$V(t,\lambda_i) = N_k \cdot V_b(t,\lambda_i) \qquad (19)$$

here, N_k represents the use of spectral technologies to increase the number of communication channels in optical spectrum compression systems, and $N_k \ge 40,...,240$ is determined by a numerical calculation.

Based on the FSO optical signal's sensitivity to turbulent environmental effects and its dependence on $\lambda = 1.31$ mkm, $\lambda = 1.55$ mkm, $\lambda = 1.62$ mkm wavelength, we have constructed a dependence graph of the transmission speed of optical systems in communication channels based on the technology of optical compression systems according to the signal-to-noise ratio (Figure 2).

$$V(t,\lambda) = \mathrm{W}[\mathrm{P_{BER}}, SNR(P_S), \lambda_i]. \qquad (20)$$

Based on the conducted analyses and graphical dependencies, it is evident that using the technology of optical compression based on spectrum, it is possible to achieve the maximum transmission speed of optical channels organized by the multiplexing method, taking into account the number of optical channels N_k, their effective frequency, quality factor $Q_F -$, and bit error rate P_{BER}, by minimizing the signal-to-noise ratio $SNR(P_S)$.

In these dependency graphs, an important parameter, the error probability per bit P_{BER} is calculated and determined by considering the signal-to-noise ratio $SNR(P_S, \lambda_i)$.

$$P_{BER} = (1/\sigma_ø \cdot \sqrt{2\pi})\int_{\mathrm{I_n}}^{\infty} \exp(-i_ø^2/2\sigma_ø^2) = 0.5\,erfc(\mathrm{I_n}/\sigma_ø\sqrt{2}) \qquad (21)$$

here, $i_ø$ and $\sigma_ø$ – correspond to the instantaneous and root-mean-square values of the obstacle signal at the input of the compensating device used in the regenerator system; I_n is the current of the signal at the output of the compensating device in the receiving system; $erfc(x)$ is an additional error integral that is determined using a table.

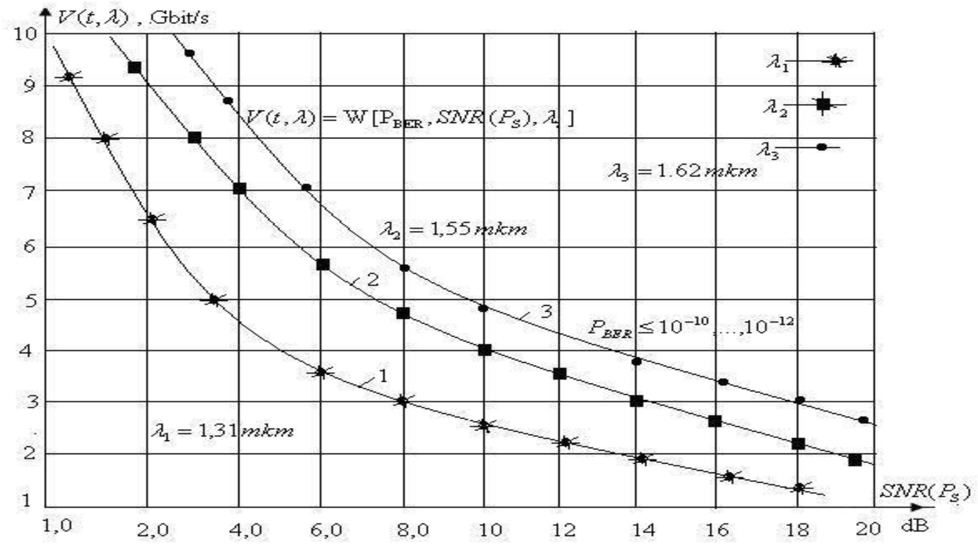

Fig. 2. Dependency graph of signal-to-noise ratio (SNR) on the transmission rate in optical channels based on FSO using spectral-based optical compression systems

From Figure 2, it can be seen that increasing the number of free-space optical channels based on spectral compression systems results in an increase in the system's transmission capacity by $C_{\max}(\Delta F_k, \lambda_i, N_k)$. However, this causes the quality metric value of the output optical channels to decrease exponentially.

Therefore, in optical systems, achieving high transmission rates requires optimizing the relationship between the number of channels, signal-to-noise ratio, and transmission capacity through the use of spectral compression technology. This involves finding the best balance between these factors to achieve maximum system efficiency.

Meaning,

$$V(t,\lambda_i) \geq V_{bb}(t,\lambda_i), \quad SNR(P_S,\lambda_i,Q_F) \leq SNR_{bb}(P_S,\lambda_i,Q_F) \ , \ \lambda_i = \lambda_1,...,\lambda_n \quad (22)$$

$$N_k(\lambda_i) \geq N_{k.bb}(\lambda_i) \ , \quad C_{\max}(\Delta F_k,\lambda_i,N_k) \geq C_{\max}^{bb}(\Delta F_k,\lambda_i,N_k), \quad \lambda_i = \lambda_1,...,\lambda_n \quad (23)$$

here, taking into account the $V_{bb}(t,\lambda_i)$, $SNR_{bb}(P_S,\lambda_i,Q_F)$, $C_{\max}^{bb}(\Delta F_k,\lambda_i,N_k)$ and $N_{k.bb}(\lambda_i)$ wavelengths with respect to the optical compression technology, it is a set of achievable values for the transmission rate, signal-to-noise ratio, emission capability, and number of transmission channels in optical telecommunication λ_i systems based on the optical compression technology.

The final expressions (22) and (23) represent the set of conditions for optimizing the quality, taking into account the optimal parameters of optical telecommunication systems based on the FSO with optical compression technology. These expressions can be used to analytically calculate the efficiency function of the system.

3. 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.

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